Solar Flares: Ignition and Particle Acceleration

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Solar flares consist of two broad groups: the compact and the eruptive ones. The first develop in complicated magnetic environments close to sunspots; the others are larger, and extend farther from spots. The recent YOHKOH observations have shown the close correlation between the ignition of compact flares and flux tube interaction or instability. There is also evidence that the interaction in a compact flare is not a single act but that it occurs repeatedly. The eruptive flares are related to prominence instability. Since they extend higher up in the corona in a fairly open field-line configuration, their correlation with particle or plasma cloud ejection is stronger than for compact flares. We advance arguments that particle acceleration in a fully developed flare consists of three phases: the first occurs in an e.m. field originating during the current-loop interaction or the loop instability, the second occurs in the shockwave field that develops immediately after that phase and the third one happens in the shockwave field that originates higher-up in the corona after the flare.

1. Confined/Impulsive and Eruptive Flares

When, in the early eighties, after the launchings of Solar Maximum Mission and Hinotori, abundant data became available on the high-energy aspects of flares, one learned to distinguish between the impulsive and gradual phases of flares. That stimulated solar physicists to call those flares that show these two aspects the *impulsive* flares. It also became clear that certain flares only show the gradual phase; these were called the gradual flares.

Subsequent studies, and particularly the data provided by YOHKOH observations, have shown that the subdivision in *impulsive* and *gradual* flares is not the most appropriate one and we prefer another, more to the point, that in *confined* and *eruptive flares* (Švestka, private communication, 1985). There is some correlation between the two classifications in that sense that confined flares generally have a well-developed impulsive phase and that eruptive flares as a rule last longer than confined ones, but that correlation is not a strict one and it does not add to understanding the flare mechanism. In this paper we will talk of *confined/impulsive* and *eruptive flares* although we will often call the former just confined, for brevity. This subdivision leaves aside a number of flares, viz. those that fall between these two classes or that simply cannot be grouped into either of them. By itself this classification is already intricate enough, as will appear from the following.

Confined flares are spatially compact and as a fairly general rule they show impulsive hard X-ray and/or microwave bursts. Such bursts nearly always occur in the early phases of flares. All confined flares occur close to sunspots, and by preference in the most complicated (δ -type) magnetic fields. They are, fairly generally, situated over the magnetic inversion line (i.e. the line where the longitudinal B -component is zero), and preferably in regions with a steep gradient of the longitudinal magnetic field component. They are spatially compact, hence the classification *confined*.

The other group of flares, not obeying the definition “confined” are spatially more extended and last longer. Often, their gradual phase lasts long, and it dominates the flare’s lightcurve. For that reason they are often called *non-impulsive* or *gradual*. While this classification generally makes sense for flares seen in the optical range, it is not well chosen in the energetic domain. In this paper we will show, with a number of examples, that the designation *eruptive* fits better. One of the reasons for objecting the designation

“gradual” is that many flares with a gradual intensity variation also have an impulsive start and could therefore also be called “impulsive”. The *eruptive flares* extend till farther away from sunspots, and in comparison with the confined ones they occupy a larger volume, reach greater heights, and are in many cases associated with filament eruption (Zirin and Tang, private communication, 1990), and with mass ejections from the corona. The recent statement that CME’s (Coronal Mass Ejections) should bear no relation with flares (Gosling, 1993) seems to be exaggerated.

In the particle domain one prefers to distinguish between two classes of flares (Ramaty, private communication, 1993; see also Mandzhavidze and Ramaty, private communication, 1993): the first and the second class events. Those of the first class have a high electron-proton ratio (low for the 2nd class flares), are relatively rich in He-3 (poor in 2nd class flares), rich in heavy elements, have a high gamma-ray line flux and have a low flux in solar energetic particles (SEP). The first class events correlate best with confined flares, the second class rather with the eruptive ones (Yoshimori, 1994). The dynamic flares correlate well with type II radio bursts, with coronal mass ejections (CME) and with interplanetary events having large Solar Energetic Particle (SEP) and proton fluxes.

We note the importance of gamma ray observations for the diagnostics of the flare mechanism (Chupp, 1984, 1990; Yoshimori *et al.*, 1986): The continuous gamma spectrum has been observed in the energy range up to 10 MeV, with its main contribution below 1 MeV. It is well described by a power law spectrum and it is emitted by electrons, chiefly those in the high-energy tail of the electron energy distribution curve. The lines are emitted in the spectral range between 1 and 7 MeV, and all but one are due to nuclear reactions between nuclei with protons or α particles with energies up to a few tens of MeV’s. There are two kinds of lines, prompt and delayed ones. The latter require the previous generation of other particles, such as neutrons slowed down to the appropriate energy range. Gamma ray observations are important for establishing the properties of the high-energy plasma in a flare. Its emission puts stringent demands and requires high densities. Slowing down and annihilation of positrons needs $\log n > 14$. For enabling decay of pions resulting from GeV protons, one needs $\log n > 14$, but the observation that neutrons can escape to space yields an upper limit to the density: $\log n < 15$. Positron annihilation demands $\log n_e \approx 16$. Hence, generally one may assume that the main part of the gamma ray spectrum is formed in regions with densities $14 < \log n_e < 16$, which is fairly deep in the photosphere. For specific flares that range can be narrowed down considerably if suitable observations are available (Kawabata *et al.*, 1994; Yoshimori *et al.*, 1994).

To conclude this section we list the *primary characteristics* of confined/impulsive and eruptive flares.

Confined flares

- are compact,
- show low-lying loops,
- occur near spots,
- are situated over the magnetic inversion line, in a region of strong horizontal magnetic field gradient,
- have two or more *footpoints* situated on either side of the inversion line; these footpoints live as long as the hard X-ray burst are lasting,
- show the *Impulsive Phase Explosion* (cf. Section 2),
- can have prompt gamma ray emission, both in continuum and lines, with high corresponding temperatures,
- can have a high gamma-ray line flux,
- can be associated with solar energetic particles (SEP), and are rarely associated with CME’s,
- have an electron/proton number ratio that can vary greatly from one flare to the other,
- can have a number density ratio between He³ and He⁴ particles that is much larger than the “cosmic” value, sometimes even approaching 0.1 to unity. There is also some relative enrichment of all light elements, like He⁴ (up to a factor 10 with regard to H), Fe (up to a factor 7 to 10), and elements like Si, Mg, Ni (up to a factor 3).

Eruptive flares

- occupy larger volumes,
- occur till farther away from spots than confined ones,
- can occur high in the solar corona, up to 10^5 km,
- are associated with filaments, and with changes in these, such as filament lifting, eruption, or *disparitions brusques* (sudden disappearances),
- last usually longer than confined flares,
- emit a microwave spectrum that peaks at lower frequencies than those of confined flares,
- are associated with CME's,
- can have associated particle clouds with coronal abundances, and they do not show the He^3 enhancements,
- can have large SEP (proton) effects; the events are sometimes associated with Type II radiobursts (which indicate that shock waves are moving through the corona with velocities of 1000 to 2000 km/s).

2. The Impulsive Phase Explosion

The spacecraft Solar Maximum Mission and Hinotori, launched 1980 and 1981, yielded essential new data on processes occurring in the early phases of flares. The data allowed researchers to elaborate the concept of the *Impulsive Phase Explosion*. This concept refers to the totality of the events observable during the impulsive phases of flares, and to their mutual causal relationships. Since most or all confined flares have an impulsive start the Impulsive Phase Explosion is also part of the confined flares. In this subsection we give a summary and a scenario for this phase, but we do not claim that every confined flare or every impulsive phase strictly follows that line of events. Since a fairly detailed commented description of the impulsive phase was given earlier (De Jager, 1986a) we restrict here to the essentials, in so far as the 1986 model concerns; we add new information published since 1986 and that obtained by YOHKOH since 1991, and examine in how far this data modify and complete the earlier model.

A fully developed impulsive flare consists of three phases: the precursor, the impulsive and the gradual phases.

The *precursor* is a feature of which the existence had been suspected already since the sixties and seventies (Smart and Shea, 1971; Kai *et al.*, 1983), but at that time it was, statistically speaking no yet considered a significant part of flares seen in $\text{H}\alpha$ or in soft X-rays. $\text{H}\alpha$ precursors do occur, but not regularly, neither are they conspicuous, and if they occur it is only a few minutes before the start of the main part of the flare. Only when regular high-energy observations were obtained, with SMM (Rieger, private communication, 1989) and Hinotori (Yoshimori *et al.*, 1986) the precursor was identified as a real constituent of flares. Chupp (1990) finds that many gamma-ray flares are preceded by precursors, in some of them even hours before the flare. He gives a detailed description of some precursors in a description of three flares observed with SMM. Apparently, the precursor is a well-defined element of the flare seen in very energetic radiations, but also in X-rays of lower energy it is a common feature. The first, also spatially very well observed, X-ray precursor appeared at least twice during a ten minutes period before the limb flare of April 30, 1980 (the "Queens's Flare") in an area with a size of a few thousands km, located about 10,000 km above the limb (De Jager *et al.*, 1983), close to the apexes of two adjacent loops. Many fine examples of precursors in hard X-rays can be found in the YOHKOH HXT Databook (Kosugi, 1993). Inda-Koide (private communication, 1994) and De Jager *et al.* (1994) describe a few cases in which soft X-ray precursors were seen about ten minutes before impulsive flares. Takano *et al.* (1994) describe radio and soft X observations of an impulsive burst; soft X-rays radiation started 2 minutes before the onset of the impulsive phase. Sakao *et al.* (1992) showed an instructive specimen of a precursor in the flare of November 15, 1991. The hard X-ray image was initially a single source situated near the magnetic inversion line and it developed later into a double source in which the mutual distance increased with time. There were several spikes in the later part of the impulsive phase; they were emitted from the footpoints. These observations suggest, as in the case of the Queens's Flare, that the precursor was emitted in the apex

of a loop, and the obvious consequence is that this impulsive flare started with energetic particles being produced near the top of the fluxtube. The subsequent bombardment of the lower chromosphere by energetic particles from the apex thereupon leads to the appearance of the footpoints. From these footpoints the impulsive hard X-ray bursts are emitted in a so-called thick-target process.

The *impulsive phase* proper is characterized by the emission of impulsive spike-like hard X-ray and/or microwave bursts. Neupert (1968) was one of the first to study them and he discovered that they are strongest at the time when the soft X-ray intensity-time curve reaches its inflection point. Subsequently they were studied by Van Beek *et al.* (1974) and De Jager and De Jonge (1978) using observations from ESA's TD1A satellite. They found that for one and the same flare the individual impulsive bursts are homologous: they have the same time profile. This shows that the basic emission conditions and mechanisms are the same for all impulsive bursts from the same flare. For another flare the time profiles are usually different. These bursts were initially called "Elementary Flare Bursts"; we would now prefer to call them *Impulsive Phase Bursts*. They are emitted by the footpoints: small areas (10^4 km) normally situated at either side of the magnetic inversion line (Hoyng *et al.*, 1981; Duyveman *et al.*, 1982). Sakao *et al.* (1992) found very clear evidence that the Impulsive Phase Bursts are emitted from the footpoints, since in between the bursts the footpoints were not visible. This discovery was only possible thanks to the high time and spatial resolution of YOHKO. Canfield *et al.* (1992) noted that hard X-rays are emitted from sites with a high vertical current density. Sakao *et al.* (1992), confirming earlier results, found that the double footpoint structure becomes particularly manifest at photon energies above 30 keV. The earlier SMM and Hinotori observations showed that below 15 keV the footpoints are hardly visible, and can only be made visible by subtracting a general background. This is due (De Jager, 1986a) to the fact that electrons with energies below 15 keV have too small a mean free path to reach the deeper chromosphere. YOHKO observations demonstrated that the lower energy radiation as well as the radiation emitted in the absence of the impulsive bursts comes from in between the footpoints, in particular from the apex of the loop connecting the footpoints, while the burst radiation is emitted by the footpoints.

A fraction of 0.43 of the hard X-ray bursts have double structure and 0.28 have single (Sakao, private communication, 1993). There are cases in which one footpoint is small with a strong magnetic field and the other is large with a weaker field. This is explained by the "cornu copiae" model (Sakao, private communication, 1994): field lines converging towards the smaller footpoint and diverging towards the other.

As started above already, the footpoints are attributed to the bombardment of the chromosphere by energetic particles from "above". We will show further in this subsection that these particles are electrons. How deep they can penetrate, depends on their energy. Those with $E < 15$ keV do not reach the chromosphere (assuming usual loop densities), and those with MeV energies can penetrate into the photosphere and produce there the white-light footpoints (Hudson *et al.*, 1992). The sources of these are situated fairly deep in the photosphere, about 150 km above the level where $\tau_{\text{Ross}} = 1$ (Neidig *et al.*, 1993). A sufficiently intense flux of very energetic electrons (MeV range) is needed for producing them. A significant piece of information is that at least one of these white light footpoints was accompanied by 511 keV annihilation line emission, that persisted longer than the electron bremsstrahlung and γ -ray events. This is attributed to positrons formed in the photosphere and being partly diffused upward (Kawabata *et al.*, 1994). The positrons are chiefly due to deexcitation of excited O^{16} by e^- , e^+ pair emission. These have an energy of 2.5 MeV. Other positrons, due to decay of nuclei like S^{31} , P^{29} have energies in the range of 1 MeV. It is assumed that half of them penetrate down to the photospheric layers with $n_e = 2 \times 10^{16} \text{ cm}^{-3}$ (for 2.5 MeV particles) or 10^{16} (for 1 MeV), corresponding to large optical depths (>10 , hence subphotospheric layers).

The above described model can also explain how it can happen that in two successive homologous flares the second does not show footpoints, as was the case on August 31, 1980, when two about equally strong flares occurred at the same location briefly after each other. The second did not produce footpoints because the fluxtube was still filled with plasma from the first flare, which reduced the mean free path of electrons accelerated in the second flare.

Wuelser *et al.* (1992) find that the footpoint observations can be represented best by thick target

electron bombardment in an area of $(2.2 \pm 0.7) \times 10^7 \text{ km}^2$, which would correspond with a circular area of diameter 5000 km. In these footpoints chromospheric gas is heated and rises convectively upward with velocities of the order 150 to 400 km s^{-1} . These velocities have been observed spectroscopically (Antonucci *et al.*, 1984, 1985, 1990). From YOHKO data, Culhane *et al.* (1992) find about 250 km s^{-1} and Doschek *et al.* (1992) report line of sight velocities of 200 to 350 km s^{-1} , from the flare onset onwards. They find a static component smaller than 50 km s^{-1} , but the lines show large Doppler broadening, up to the surprisingly large value of 800 km s^{-1} . Sometimes, larger upward velocities are observed, up to 800 km s^{-1} (Antonucci *et al.*, 1990).

The upward motion is not homogeneous but occurs in jets with sizes smaller than those of the footpoints (Borman and Lemen, 1992), which confirms the small filling factors found earlier. These filling factors, applying to most part of the flare, are of the order 0.01 (De Jager, 1986a; De Jager *et al.*, 1994). The temperature of the rising gas is of order 30 to 50 MK (Tanaka *et al.*, 1982; De Jager, 1985b; Tsuneta *et al.*, private communication, 1984). The convection model is supported by the observation that the upward velocities are largest when the electron temperature T_{el} of the footpoints is highest in the soft X-ray rising part of the flare, while the upflow velocity decreases when T_{el} decreases (Culhane *et al.*, 1992). A thermal transition region with a typical temperature of the order 10^4 K (De Jager, 1987) originates between the heated gas and the undisturbed chromosphere, hence at the bottom of the evaporation “pit” from where the heated gas emanates. Subordinate and resonance lines like $\text{H}\alpha$ and $\text{Ly}\alpha$ are emitted from this transition layer. In this thin ($\sim 20 \text{ km}$ thick) layer (De Jager, 1985b) the particles undergo downward motion because of momentum conservation (Canfield *et al.*, 1987). This motion is observable by $\text{H}\alpha$ redshifts (Ichimoto and Kurokawa, 1984; Canfield *et al.*, 1987; Ellison, private communication, 1949; Svestka, private communication, 1951). The location of the sources of these redshifts coincides with the footpoints seen in soft X-rays, while the hard X-ray bursts are emitted at the *edges* of the sites of high vertical component current density (Canfield *et al.*, 1992).

This process of “evaporation” or “ablation” also leads to plasma streaming out over the surrounding chromosphere, guided by the magnetic field line system. These “coronal explosions” have been observed in soft X-ray images in the later phases of solar flares: plasma spreading with velocities of a 100 to more than 600 km s^{-1} (De Jager *et al.*, 1984; De Jager, 1985b, 1986a, 1987). Ogawara *et al.* (1992) give a fine example observed by YOHKO in the flare of November 15, 1991. Application of the conservation equations to the observations shows that the outflowing plasma moves in tubes with constant cross-sections and that the horizontal velocity component always decreases with increasing distance from the footpoints (Lemmens and De Jager, 1986). An well studied case of evaporation is in the flare of June 22, 1989 (Aschwanden *et al.*, 1993a) where the evaporating particles were apparently trapped in a long loop (68,000 km high). The individual electrons, moving at $v = 0.3c$ produced inverted U-type III radiobursts during their motion through the loop. There were about 45 such injections, indicating that many energizations. They moved ahead of the evaporating plasma, that moved with 200 km s^{-1} .

The totality of the processes described here may be summarized under the name *Impulsive Phase Explosion*.

After the discovery of the sequence of phenomena described here a few crucial questions remain: that of the position of the source of energetic particles—hence that of the location of the initial process of energization; that of the nature of the energetic particles: electrons, protons or plasma, and that of the mechanism of their energization. Before, we gave already a preliminary answer to the first question: the area of primary energization seems to be located at some 10,000 km above the photosphere, hence somewhere near the apex of a typical flare loop. Confirmation of this answer and the reply to the second question have been given by YOHKO observations. These could specify the average height of the source, this being $9700 \pm 2000 \text{ km}$ above the photosphere (Matsushita *et al.*, 1992). In addition, it was found that the average time differences between the start of brightening of two corresponding footpoints is always $0.0 \pm 0.2 \text{ s}$ (Sakao, private communication, 1994). This can only be so if the source is situated between the two footpoints, not necessarily exactly in the middle of a loop but presumably close to its apex. In view of the small time difference, in relation to the average length of the footpoints, the bombarding

particles must be electrons: protons would move too slowly. Neither can the footpoints be heated by hot plasma. The electrons should have an average velocity of $c/3$. This confirms a study by Brown and Emslie (1987) who found that the observed spatial structure of the hard X-ray emission during the impulsive phase is best explained by electron heating. The temperature at the loop-top has been measured a few times only (Takakura *et al.*, 1993; Wang *et al.*, 1994) and was found to range between 35 and 70 MK. The number density in the apexes of the loops was $(5 \text{ and } 2) \times 10^9 \text{ cm}^{-3}$ (Takakura, 1992).

Takakura *et al.* (1993) found that hard X-ray loops first brighten at their top, whereupon the X-ray brightening spreads to the footpoints. The observed velocities of about 10^4 km s^{-1} , however, do not agree with the above mentioned electron velocities and must relate to the motion of a plasma front. The same succession of events was reported by Zarro *et al.* (1995) who also found that the hard X-ray emission seems due to acceleration in a d.c. electric field, the strength of which increased from a preflaring value of 10^{-5} to $9 \times 10^{-5} \text{ V cm}^{-1}$, and remained constant during the impulsive phase. Aschwanden *et al.* (1993b) compared 100–3000 MHz radio observations and hard X-ray data, and found support for the view that there should exist a compact accelerating source, from where electrons are accelerated up- as well as downward, thus producing radio-emission (the upgoing electrons) or X-ray emission (downward moving electrons). This confirms an old suggestion by De Jager and Kundu (1963).

The next questions are then: what about the (subtelesopic) structure of the interacting loops; what about the process of energization, and: are we dealing with one or two loops.

With regard to the *fine-structure of the loops*: flaring loops seem to be inhomogeneous, with “filling factors” of the order 0.01. Therefore the fluxtubes must consist of many thinner tubes, the “fluxthreads”, a concept due to Tsuneta (1985) and De Jager (1985b), cf. also De Jager (1986a), De Jager *et al.* (1994). The fluxthread model finds support in a theoretical study by Koide and Sakai (private communication, 1994), who show that upon footpoint rotation a fluxtube develops a current and return current system, situated in a coaxial thin shell, which may split in many helical thin fluxthreads. A natural consequence is that interaction between fluxtubes may lead to a number of fluxthread interactions between threads in two interacting loops, a phenomenon for which evidence is found in several flares. This process is then called partial reconnection. Observational confirmation that partial reconnection is a repeating and ongoing process in some flares is found in studies of the flares of February 21, 1992 (Tsuneta, private communication, 1994; Tsuneta and Lemen, private communication, 1993) and of August 2, 1994 (De Jager *et al.*, 1994). Further support for these ideas may be found in the phenomenon of the subsecond flares, reported by Takano *et al.* (1994). They occur in groups and have a rapid rise and fall within typical lifetimes of the order of 0.1 s. Such flares may yield essential new information on elementary physical processes in flares. These extremely brief bursts have great resemblance to those studied by De Jager *et al.* (1987) in the flare of May 21, 1984. During that flare a dozen of shortlived (0.1 s) peaks appeared within a total time interval less than 2 s. They are attributed to the formation and conductive decay of very hot, small kernels of flare plasma, emitting thermal gyrosynchrotron radiation. The temperature of these kernels was estimated at 300 to 500 MK, the size was about 350 km and the consequent conductive energy loss time was 60 ms, which appeared to be in excellent agreement with the observed decay time of the individual bursts. Model simulations showed that this phenomenon can be attributed (Sakai and De Jager, 1991) to explosive coalescence of current-carrying fluxtubes. Impressive support for the repeating interaction model is found in a study of ~6000 type III radiobursts (Aschwanden *et al.*, 1994). The bursts appear in groups with on the average 13 ± 9 bursts per group, a mean duration of 21 ± 14 s and a mean time interval between successive bursts of 2.0 ± 1.2 s. Comparison with Monte Carlo simulations shows that the injection of electron beams is modulated by a compact particle acceleration source, or one that has a global organisation on a time scale of seconds.

With regard to the *interaction process* some direct information can be obtained from an approach developed by Loran and Brown (1985) and somewhat modified by the present author (1986a, page 81). Essentially it is assumed that in a plasma the conversion of magnetic energy to other forms of energy cannot proceed on a time scale shorter than the Alfvén time, and that the escape rate of electrons accelerated at loop-interaction cannot exceed the limit set by the stability of the neutralizing current. Thus,

one derives a lower limit for the magnetic field strength, and values for the velocity of interaction and for the length of the interacting region. For a number of flares studied by Loran and Brown (1985) one finds $B_{\min} = 100$ gs, an interaction velocity of the same order as the Alfvén velocity, and an interaction region shape that has the same size in all directions, which essentially means X- or Y-type interaction. Typical values for the magnetic field in a number of other cases (summary in De Jager, 1986a) range between 100 and 1000 gs, with preference for the lower values. Direct B -field measurements for the footpoints of the flare of June 26, 1992 yields most probable values of 160 gs and 400 gs (Wang *et al.*, 1994). Another typical value is the total number of energetic particles (>10 keV), which ranges between 10^{34} and 10^{36} s $^{-1}$ (Lin and Hudson, 1971; Hoyng *et al.*, 1976; De Jager, 1986b).

Finally, the *gradual phase*. It is important to realize that this phase is *not* a sequential one, just occurring after the impulsive phase. In the contrary, the impulsive and gradual phases start *at the same time*, as can be seen from a comparison of hard and soft X-ray observations. This is understandable, because the gradual phase is due to the plasma energized during the impulsive bursts and convected upward from the footpoints, spreading from these over the flare area, merging with that from the other footpoint as it spreads, while cooling down by radiative losses. This gas can eventually occupy a fairly large area and the cooling down process can take a long time, sometimes up to an hour, as appears from the duration of the gradual phase. The observational physical *link* between the impulsive and gradual phases is that during the impulsive phase the thermal electron content of the flare increases monotonically, to reach a maximum value at the end of the impulsive phase—hence after the last impulsive phase burst. Thereafter it decreases (De Jager and Boelee, 1984). We note the consequent physical explanation of the “Neupert effect” (1968) mentioned previously. Noteworthy is also the gradual softening of the hard X-ray spectra over 50–200 keV on and after the maximum phase (Lee and Gary, 1994). *Conclusion*: a high-temperature electron plasma is formed and injected into the flare area during the impulsive burst phase and thus the gradual phase begins. It ends when the hot plasma has radiated its excess energy. The above scenario was confirmed by Dennis and Zarro (1993).

We *summarize* the various evidences brought forward in this subsection: the confined/impulsive flares occur inside closed magnetic structures, that are only seldom disrupted by the flare. Inside that structure the flare originates by some process of energization in a point close to the top of a loop, most probably, but not necessarily by interaction of two loops, in a location, about 9000 km above the photosphere. Electrons, accelerated there, bombard the lower chromosphere, cause the footpoints, footpoint evaporation and coronal explosions. The gradual phase starts at the same time as the impulsive one and its duration defines that of the flare. It is due to gas emanating from the footpoints.

3. Eruptive Flares; Observations and Physics

The eruptive flares, which normally occur over a fairly elevated range of height levels in the corona, up to some distance from spots, in association with large coronal structures and/or filaments, are in one aspect less impressive than the confined ones because they may lack the impulsive phase with its high energy phenomena (although this is not always the case!), but they are more impressive insofar as their size and the associated phenomena are concerned: the phenomena in prominences like the *disparitions brusques* and prominence motion, elevation and ejection, and coronal phenomena such as expanding helmet structures and plasma ejection.

The highly improved (with regard to earlier spacecraft) soft X-ray imaging capabilities of YOHKOH gave rise to many interesting new studies on these complicated phenomena. YOHKOH's soft X-ray telescope (SXT) has unveiled the basic properties of the active regions, where we know that flares occur. These regions contain large numbers of loops and besides there are extended loops connecting active regions. The active region loops have average temperatures of $(5 \text{ to } 7) \times 10^6$ K and emission measures of $(5 \text{ to } 7) \times 10^{28}$ cm $^{-5}$. The average length, thickness and electron number density are 33,000 km, 7,000 km and $(7 \text{ to } 8) \times 10^9$ cm $^{-3}$ (Shimizu *et al.*, private communication, 1992). The coronagraph aboard SMM yielded many evidences of dynamic coronal features such as the Coronal Mass Ejections (CME's), which

are associated or at least correlated with eruptive flares.

An impressive example of one of the many possible appearances of eruptive flares, are the *giant coronal arches* discovered by Švestka *et al.* (1982), by means of observations made by the X-ray imaging facility (HXIS) in the Solar Maximum Mission. The phenomenon consists of the appearance (or: the formation?) of a large soft X-ray emitting arch, with a lifetime of many hours to some days, with a typical length of a few times 10^5 km, and extending up to and above 10^5 km above the photosphere. Repeated revivals appear to be possible (cf. Švestka, 1984). This discovery illustrates at the same time why the “gradual” classification (in contrast to the “impulsive” one) does not apply to this case because the first discovered giant arch originated after the two-ribbon flare of May 21, 1980, with its well-developed impulsive phase. The phenomenon by itself, however, had all the characteristics of an eruptive flare. From the few observations of giant arches yet available it appears that the association with two-ribbon flares is not uncommon.

A YOHKOH observation that may clarify the explanation of dynamic flares is that of the *cusplike flares* consisting of a loop with an enhanced apex part (Tsuneta *et al.*, 1992; Tsuneta, private communication, 1994; Inda-Koide *et al.*, private communication, 1995). The observations show the interaction between a loop enclosed within an X-type field line system with the effects of reconnection at the X-line. An interesting case was described by Masuda *et al.* (1994): reconnection *above* a loop. The flare should rank among the eruptive flares but the case is special since reconnection occurred first in the X-line area, which produced a downward moving plasma blob, whereupon a second reconnection at the loop apex was due to the collision of the neutral plasma blob with the loop, causing an impulsive flare with its cusplike appearance.

A fine example of the sequence of events in a *typical eruptive flare* is the limb flare of February 21, 1992 (Tsuneta *et al.*, 1992). A helmet streamer appeared in the corona, several hours before the flare, continuously expanding and restructuring. The expansion of the arch apparently created a suitable situation for the flare to start. The footpoints separated with velocities of 10 to 30 km s⁻¹. The flare lasted longer than an hour (L. D. E.: Long Duration Event). Such LDE's have been observed more frequently. In the later part of the event they may show a cusplike brightening at the loop-top, as described above. These cusps have a higher temperature than the other parts of the loops, and also in the decay phase the temperature in the outer arch was lower than in the middle part. It often appears that in dynamic non-impulsive soft X-ray flares the hottest part (≈ 20 MK) is located in compact regions on top of a loop (Acton *et al.*, 1992). These hot regions, with sizes as small as a few thousand km, form in the early rise part of flares, hence at flare onset or slowly thereafter, and they persist till well into the decay phase. The pre-existing material in the loop is being compressed, maybe due to the pinch effect of a strong electric current.

Related to the theme discussed in this subsection is the discovery of large *arcades of coronal loops* visible in X-rays (cf. Tsuneta *et al.*, 1992), with the *walking arcades* as a special category (Kosugi, 1994; Nakajima, private communication, 1994). Motions in the arcades have velocities of the order of 30 km s⁻¹ while the associated prominences have velocities up to and above 100 km s⁻¹ (Nishio *et al.*, 1994). Interaction between the loops of the arcade is not uncommon. Watanabe *et al.* (1992) observed a quiescent filament on November 28, 1991 that was associated with a flare; an arcade appeared in soft X-rays, 2 to 3 hours before the flare. Nakajima (private communication, 1994) described a long duration flare (>one hour) associated with an arcade and a large loop seen near the solar limb (Hanaoka *et al.*, 1994).

Shimizu *et al.* (1994) drew attention to the class of *single loop flares*. They occur less frequently than multiloop brightenings. Takakura *et al.* (1993) described four cases. They started with loop-top brightening, progressing downward with $v = 10^4$ km s⁻¹. The initial loop-top temperature was 40–70 MK and the corresponding electron densities were $(5\text{--}2) \times 10^9$ cm⁻³. These belong also to the class of confined flares.

In many cases the motions of loops are followed by restructuring of the loops, apparently caused by mutual interaction. Restructuring takes place on scales ranging from the size of an active region till the solar radius. Often the associated filaments undergo dramatic changes, disappearances or eruptions. This shows that filament eruption can be related to, or can trigger arcade formation (Kosugi, 1994).

There are clear connections between eruptive flares and coronal motions or restructuring. Tsuneta *et al.* (1992) describe the disappearance of a coronal crown filament that was followed by the appearance of a closed loop arcade that moved westward (a "walking arcade"). Thereupon a cusp structure appeared at the solar limb. This *global structural change* was ascribed to non-explosive ongoing reconnection. It makes sense to distinguish between "quiet" and "active" Active Regions (AR's) (Uchida *et al.*, 1992). While the corona may expand occasionally above Active Regions, this happens always above active AR's. during the expansion, with velocities between a few and some tens of km s^{-1} the overall structure of the corona remains preserved. The phenomenon must obviously be due to some form of energy injection into the coronal part of the AR.

The *emission of X-ray jets* (Shibata *et al.*, 1992; Shibata, private communication, 1996) is another property of flares, discovered by YOHKOH. Jets have typical sizes between 5×10^3 and 4×10^5 km, average 1.7×10^5 km, with translational velocities of 30 to 300 km s^{-1} , average 193 km s^{-1} . Electron number densities range between 3×10^8 and $3 \times 10^9 \text{ cm}^{-3}$. The analysis of the time development of the jet of November 12, 1991 and the associated coronal magnetic field offers a way for diagnosing the magnetic field structure and its development.

One of the first theories applicable to eruptive flares that was successful in this respect, was developed by Kuperus and Van Tend (1981), on the basis of previous work by Van Tend and Kuperus (1978). Basically, the process is assumed to be initiated by the increase of a current embedded in the background magnetic field of an active region. The current increases because of footpoint motions, an effect that might be (but should not necessarily be) related to the emergence of new flux. It is also possible that only one of the two mechanisms contributes to the increase of the electro-magnetic energy content of the configuration. This energy, being built up by the mechanical action, is stored in the loop system as long as such is possible. The consequent increase of the current-system will cause an expansion of the magnetic field which manifests itself as a slow increase of the size of the current-system but it may eventually result in more dramatic consequences: the increase of the non-force free current-system can make the filament rise and explode, the latter depending on the current intensity. This may end in its transformation into a configuration that is open towards interplanetary space. The process develops on the Alfvén time scale of the filament, and the theory seems capable of explaining the phenomena observed in eruptive flares and the start of the associated plasma cloud emission. In an alternative model Uchida and Shibata (1988) developed a theory for lifting chromospheric material into the loop tops, where it is heated and confined, leading to upward motion of the loop. The similarity with the cusp-type flares suggests itself. The streaming through the loop should proceed with velocities of hundreds of km s^{-1} , velocities that have sometimes been observed.

Such theories are supported by the observation that filament eruption often begins before the flare, as observed in X- and γ -ray emissions. The motion of the filament continues during the flaring period. This shows that the gradual change of the current system (as manifested by the filament) is the primary phenomenon. In that line of thought, also following the route set by Kuperus and Van Tend (1981), Mikic *et al.* (1988) studied the evolution of a solar coronal magnetic field subjected to shearing photospheric motions. For motions exceeding a certain threshold the bipolar magnetic field becomes unstable, which results in the formation of a current-sheet above the polarity inversion line. This instability causes upward plasma flow. These ideas have been worked out by Sakai and Koide (private communication, 1992), who could show that a current-sheet extending along the X-point of the magnetic configuration becomes thinner (horizontally) and more elongated during the growth of the current-system. The sheet, identified with the filament, rises with a calculated velocity of 100 km s^{-1} , in good agreement with the average observational value. The characteristic time for the process is the Alfvén time, estimated at about 300 s for typical conditions. The theory is claimed to be developed for confined/impulsive flares but it may turn out to apply rather to the eruptive flares. Takakura (1992) developed a scenario for single-loop instability based on heat input near the loop top. The consequent development of plasma waves increases the electric resistivity, followed by loop and footpoint heating. For the cusp-type flares a possible scenario, by Sakai *et al.* (private communication, 1994), is based on the fact that approaching field systems in an active region

may lead to plasmoid ejection (the “melon seed effect”). The downward moving plasmoid interacts with a lower situated loop and thus the cusp-type feature originates.

The various theories summarized above have many aspects in common and it may well turn out that several aspects of them find application in one flare or the other.

4. Phases of Acceleration in and After Solar Flares

De Jager (1988) and Sakai and De Jager (1991) suggested that there are three phases of acceleration in a fully developed eruptive flare. A confined flare, by its very nature, cannot have more than the first two phases, because the third phase implies a field line configuration, such that particles energized in the first two phases can be further accelerated and escape to space. Such a configuration is not expected for a confined flare.

There are several observational indications, which, upon their combination, lead to the suggestion that there are two early phase of acceleration in a well developed flare, no more than seconds apart but based on completely different physical mechanisms. They are—but only in a fully developed eruptive flare!—followed by a third phase, minutes later.

The relevant observations regarding the first two phases are:

- The acceleration times of electrons and protons to energies of the order of one MeV can be shorter than $\sim$ a second.
- Although MeV ions are accelerated nearly simultaneously with MeV electrons, observations with high time resolution show that the ionic emission up to energies of about 10 MeV can occur some seconds later. This requires a second phase of acceleration for which shock acceleration is proposed.

The scenario is as outlined below.

1. Phase of explosive coalescence and acceleration in a d.c. electromagnetic field. During the pre-flare implosion at reconnection the magnetic field is strongly amplified by the local magnetic pinch effect. Thus an almost one-dimensional current-sheet originates in which prompt high-energy particle acceleration can occur up to energies depending on the configuration. This theory is supported by the observation that non-thermal emission, due to electrons, appears to peak at the same time in all energy bands (keV, MeV; Yoshimori *et al.*, 1992) at the onset of the impulsive phase.

2. The coalescent explosion leads to a system of shock waves propagating outward. As suggested by Sakai and Ohsawa (1987) ions can be accelerated to high energies in a situation in which an electric field propagates at right angles to the $\mathbf{B}$ -field (in a spherical explosion such a situation must in any case occur at some place). If the electric field is strong enough for the ions to be trapped, they will be accelerated in a direction at right angles to $\mathbf{B}$ and $\mathbf{E}$. Acceleration over a path of a few hundred km (which may be the characteristic distance in the region of coalescence) yield proton energies of ~ 100 MeV, which is necessary to explain the observed γ -ray emission. If the available path length is longer, GeV energies can be obtained. The time needed for the turbulent medium to originate, and to steepen the turbulent waves to shocks, is of the order of the Alfvén time, which is ≈ 1 s. It is in this configuration that selective He^3 acceleration as well as differential acceleration of other ions is possible.

3. Many authors, cf. Cliver *et al.* (1985) have found observational support for the long-standing suggestion (De Jager, 1969; Wild, private communication, 1965) that there is a later phase of acceleration. Support is found in the observation of type-II radiobursts, and in the observation of Solar Energetic Particles in interplanetary space. These particles can have obtained their high energies by shock wave acceleration in a field line system situated above the flaring region, and which opens towards space. This type of acceleration, hence, occurs in principle only in dynamic flares, although we agree with Ramaty and Murphy's remark (1987) that there is no full separation between the cases. Confined flares do produce—small amounts—of particles observable in space.

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