ENERGY RELEASE AND ENERGY TRANSFER IN FLARES

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It is of primary importance to understand the preflare stage which leads to the triggering of the flare instabilities. However, despite of the fact that the increase of entropy associated with an explosive phenomenon reduces the useful information, we might expect to improve our understanding of the solar flares mechanisms by studying also the characteristics of the energy released in flares.

I.- Distinction between p.e.r. (primary energy release) and secondary phenomena.

All the observations give some information on the flare energy output. However, they do not discriminate between p.e.r. and secondary phenomena. The p.e.r. is the in situ liberation of energy associated with a local conversion of magnetic field free energy in other forms of energy. On the other hand, in secondary phenomena there is no in situ dissipation of magnetic energy. The energy comes from the vicinity of the observed site via different modes of energy transport.

Theorical arguments give some information on the p.e.r. Therefore in order to check the theory with the observations it is necessary.

1°) To discrimate between p.e.r. and secondary phenomena in the observed flares.

2°) To determine the p.e.r. characteristics i.e. nature duration and location.

These two points will be considered in this paper using existing observations The emphasis will be put on the location and on the amount of the nergy released. Then, as a conclusion, an attempt will be made to discriminate between flare models using existing observations.

I.A.- Model of p.e.r.

To determine the location and the nature of the p.e.r. process we need a model giving a first approximation of these parameters. Then the secondary phenomena will be estimated and compared to the observations. The major difficulty of such an approach is that the unicity of any proposed solution cannot be proved.

The proposed model must include the location the nature and the duration of the p.e.r. The relevant mode of energy transport to be considered must include particle beams, convection, conduction, radiation. The transport coefficients could be modified from their classical values by waves-particles interactions. The geometry of the magnetic field has to be included and transfer technics have to be used. The building of a model is therefore so complex that there is not yet any fully satisfactory approach of the problem. The existing works deal with limited aspects of it in order to reduce the number of terms to consider.

I.B.- Nature of the p.e.r.

All the products of the p.e.r. phenomenon will not be considered here in detail. Despite of the fact that, in some events, mass motions and shock waves could carry more energy than radiation or particles they will not be considered here. From the conclusions of the Standford SERF workshop (1980) and of the Skylab flare workshop there is a lack in our knowledge of the precise timing of the initiation of transients vis a vis other flare effects. Then it is impossible now to distinguish between effects and causes.

Ion and proton acceleration also will not be considered in detail. A still valid review on this topic is given in the Skylab flare workshop. Proton beams will be invoked only to explain some characteristics of the radiative output from the low atmosphere.

The main effects of the p.e.r. to be considered here are electron heating and electron acceleration. Our knowledge of the high energy electrons comes predominantly from X-ray and γ continuum emission. These high energy electrons appear to be produced during the impulsive phase of the hard X-ray emission. They are sometime present in the preflare phase too, which will not be considered here.

I.C.- Duration of the p.e.r. phase

I.C.1. Impulsive phase

Most of the flares show an impulsive phase in X-ray emission. However from the study of more than 100 X-ray bursts. Datlowe et al., (1974) concluded that 1/3 of the events they observed did not show any detectable impulsive emission. The processes which take place in the decay phase of flares with impulsive phase are probably not too different from the ones taking place in flare without impulsive phase. Therefore we will restrain ourself to the study of flares with an impulsive phase.

1.a- Site of the p.e.r. models of X-ray sources during the impulsive phase.

The p.e.r. site is most probably located inside the observed X-ray source. Very little is known about the vertical structure of the impulsive X-ray source. Observations with two spacecraft separated in heliographic longitude (Kane et al., 1979) indicate that the X-ray source ($E > 50$ KeV) extends from low altitude up to well above 25 000 Kms.

SMM observations (Hoyng et al., 1980) have shown that 20-30 KeV X-rays originated from the feet of flare loops. On the other hand radio-observations at centimetric wavelengths (Marsh et al., 1979) using the VLA showed that the microwave source was located between the Hα kernels at the time of peak emission. Contrary to the X-ray source the cm radio source appears to be located at the top of loops.

Some information on the velocity distribution fonction of energetic electrons could be derived from the measurement either of the directivity or of the linear polarization of hard X-ray emission. No significant observation has been obtained yet.

No quantitative information on the total energy carried by the high energy electrons and on their total number can be derived from the hard X-ray spectrum without taking into account the interaction between the p.e.r. site and the surrounding atmosphere.

There is no unique and satisfactory model of hard X-ray sources. Two extreme situations have been considered which are the thick-target and thin-target models. In the thin-target model electrons escape from a low density target. In the thick target model electrons lose all there energy by colliding with a dense atmosphere. A somehow more realistic model is the trap model where the electrons are partially trapped in magnetic arches. If the target inside the arch is made of cold electrons and protons the emission is thick target emission. If all the trapped particle have the same mean energy we obtain the quasi thermal model corresponding to smaller energy requirements. The only common feature of all these models is that the p.e.r. site is located in the corona in any of them.

In the thick-target emission energetic electrons lose their energy in Coulomb collisions. The hard X-ray energy yield is small (10^{-5} to 10^{-6}). Therefore the total energy E and the total number of electrons N_e required to explain the observed X-ray flux are very high. For events associated with 3B flares $N_e \simeq 10^{39} - 10^{40}$ and $E = 2\ 10^{31} - 10^{32}$ ergs. If we assume that the electrons come from the low corona and that the energy is taken from a 100 gauss magnetic field huge volumes up to 10^{29} cm^3 are required. Thin target models use the energetic electrons rather inefficiently, and hence they are putting more stringent requirements on the acceleration process.

To overcome the efficiency problem different authors (Brown et al., Smith and Lilliequist 1979, Smith and Auer 1980) discussed a quasithermal model. Before discussing further this model and before discussing the need of confining the energetic electrons the observed interaction between the p.e.r. site and the surrounding medium will be presented.

1.b.- Interaction between the energic electrons and the low atmosphere.

The most convincing evidence of interaction between the energetic electrons and the lower atmosphere comes from the comparison of the temporal variation of the hard X-ray and EUV emission (10-1030 Å). The studies by Donnely and Kane 1978 have shown that the maxima of X-ray and EUV emission are coincident within ± 1 s. Because more than 50 % of the 10-1030 Å flux comes from chromosphere or transition zone these observations are supporting a model of thick-target emission where the electrons are bombarding the low atmosphere. This model has been checked in two different ways :

1) by computing the Φ (EUV) / E_B ratio where Φ (EUV) and E_B are respectively the total energy radiated in the EUV and the total energy deposited by electron bombardment in a tick-target model. This ratio is always much lower than one leading to the assumption that only a fraction of the energetic electrons are bombarding the atmosphere.

2) the second approach is the one used by Brown et al., (1978) who compared Hα profils observed in flare kernels with computed profiles for electrons heated models. These models were calculated assuming thick-target X-ray emission and neglecting the effects of the return current. The computed Hα profiles are much stronger than the observed one and the energy input has to be reduced by more than one order of magnitude to minimize the disagreement. Including the return current effects would not change the conclusion (Emslie 1979).

Then it appears that :

- There is no need of in situ energy release in the chromosphere during the impulsive phase
- The high energy electrons must be partially confined in the X-ray source.

1.c.- Confinement of the energetic electrons in the p.e.r. site.

There is some addition evidence of the need of confining the X-ray source. Mäzler et al., (1978) observed in small flares a variation of the emission measure

$Em \sim T^{3/2}$ in agreement with what can be expected from an adiabatic compression of the plasma. X-ray observation from TANSEI IV of small flares suggest a compression of energetic electrons (Tanaka et al., 1980). These models require some confinement mechanism to keep the electrons trapped during the compression.

There is no satisfactory model of electron confinement. The most promising approach uses collective interactions of the beam with the plasma target. In a recently proposed model of quasithermal source (see references in 1a) the plasma is confined between two ion acoustic turbulents fronts which are created by an ion acoustic instability driven by the return current associated with the beam.

In this model electrons of high energy ($E > 2.6\ KT_e$) are no scattered by the turbulence and escape freely. The main interest of the model is to be more efficient than the thick target model. The gain being of the order of $V_e/C_s = 40$. The rate of energy deposition in the low atmosphere is reduced by this factor, leading to a better agreement with the observations quoted in 1b, and the energy requirement are relaxed. On the other hand this model fails to reproduce two observational facts i.e. first HXIS observations (Hoyng et al., 1980) show simultaneous impulsive brightenings at the feet of loops indicating velocity higher than sound speed and no X-ray emission (20-30 KeV) between the feet contrary to model predictions. Secondly VLA observations seems to indicate that energetics electrons are at the top of loops contrary to model predictions.

I.C.2.-Decay phase

The decay phase is the phase following the impulsive phase. There is no hard X-ray emission during this phase and soft X-ray and Hα emission reach their maximum intensity. The study of the decay phase rises two questions :

- Does the p.e.r. terminate with the impulsive phase or not ?
- Is there enough energy transferred from the hot plasma towards the lower atmosphere to explain the observed energy release from these layers as a secondary phenomenon ?

2.a. - Morphology and origin of the thermal X-ray plasma.

Soft X-ray filtergrams and EUV spectroheliograms from Skylab have established than the basic structural form of the thermal X-ray plasma in the decay phase of flares is that of closed loops or arches.

It is very uncertain just how the thermal X-ray plasma is generated. Among the proposed mechanisms are direct heating of the plasma either in the upper portion of the magnetic arches by current dissipation or heating at the feet of arches by the high energy electrons impinging on the chromosphere. There is no obvious reasons why the first process would stop at the end of the impulsive phase.

2.b.- Is there some p.e.r. during the decay phase ?

From the analysis of Skylab data, Moore et al., (1980) made a distinction between large two ribbon flares and compact flares. In large two ribbon flares heating of the thermal X-ray plasma continues far into the decay phase. The required heating seems to be associated with the continued growth of the loop system. This growth seems to support the hypothesis of continuous heating by reconnection, and not the heating by anomalous dissipation. However we do not clearly know what would be the driver of the reconnection.

In small compact flares which occur in small bipolar regions far away from the main neutral line there is no clear indication of continued heating.

2.c.-Atmospheric response to the energy input from the thermal source. The low temperature flare as a secondary phenomenon.

In the T.Z. (transition zone) and low corona the studies of Underwood et al., (1978) and Machado and Emslie (1979) show that there is more material above 10^6 K than predicted by assuming that energy is deposited from above by conduction. Such excess of 10^7 K material could result from the heating of the chromospheric material to coronal temperature during the impulsive phase. Chromospheric emission is observed in flares even in the absence of hard X-ray emission. Some other mechanism of energy input than electron bombardment has to be invoked in order to explain the chromospheric emission as a secondary phenomenon.

In the high chromosphere above $10^{4\circ}$ K, Ly α flux is the most efficient radiator Comparison of the Ly α flux with the conductive flux in the middle of the T.Z., made by Machado and Emslie (1978), indicates that the radiative output from the high chromosphere can be explained by thermal conduction from above.

Machado et al. (1980) have build empirical models of faint and bright flares. One interesting result of their radiative losses computations is the backwarming of the high chromosphere by Ly α radiation. However the Hα cooling exceeds the heating and an extra heating is needed. Heat conduction, the effect of which is negligible in the low chromosphere, cannot produce the required extra heating. This extra heating can be provided by XUV radiation.

Indeed a subtantial amount of energy is radiated at soft X-ray wavelengths. Half of this energy is radiated downwards and heats the chromosphere. The height dependance of the X-ray energy deposit was computed by Somov (1975) and Henoux and Nakagawa (1977). The flare model computed by these last authors for a given XUV irradiation does not greatly differ from the Machado et al. model F1. Moreover taking into account the actual shape of the X-ray source during a specific event, Henoux and Rust (1980) showed that X-ray illumination can produce a two ribbon structure in the horizontal variation of the energy deposit very close to the observed Hα two ribbon flare.

With a 50 % accuracy there is no need of in situ energy release in the low atmosphere. The observed energy deposit in these layers is provided by the hot plasma above via conduction and radiation. The chromospheric flare in the decay and in the impulsive phase of flares is a secondary phenomenon.

On the other hand the energy balance of the lowest part of the solar atmosphere is not understood in any of the flare phases. Therefore the heating of the temperature minimum region (TMR) and upper photosphere (UP) will be traited separatly.

I.D. - Location of the p.e.r. site and in situ heating of the upper photosphere and TMR.

Using Ca II lines and UV SiI ^{3}P and ^{1}D continua Machado et al extended their models down to the U.P. These models show a subtantial temperature enhancement at the TMR. Electron beams, protons beams and soft X-ray can penetrate down to the U.P. However the flux required to explain the observed heating is more than one order of magnitude higher than the one inferred for large events.

Analyzing the effect of EUV radiation Machado and Henoux (1980) and Chambe (1980) concluded that EUV radiation strongly modify the ionization balance of Si and C atoms. The first authors have shown that non L.T.E. effect are induced in the SiI continuum. Hence SiI continuum observations alone cannot be used to measure temperature enhancement. Anyhow previous studies of CaII spectra are not affected and in situ heating of the upper photosphere is not yet ruled out.

Observations of white light flares can be interpreted also as a heating of the upper photosphere. The two independant observations of two differents events by Machado and Rust (1974) and Hiei (1980) lead to two radically different interpretations. The first authors concluded that white light emission was due to free bound transition of hydrogen at 8500 °K. On the other hand Hiei found a flat continuum above 3646 °K which he interpreted as H^- emission from the upper photosphere. Proton flux of the order of magnitude of the one observed in other large flare events could provide the required energy deposit. Unfortunatly there was no γ-ray observations for this event. Therefore the origin of white light flares and their association with proton beams is still on open question.

The origin of the heating, if any, of the temperature minimum region and upper photosphere is not understood yet. The present interpretation of existing observations implies some in situ energy release. Ohmic dissipation due to a large electric current in layers where the resistivity is maximum was suggested by Spicer (1980) and Sturrock (1980). The required current is unreasonably high. However multiply reversed currents over the flare area could explain the observations.

Such interpretation is supporting the hypothesis of a participation of the whole atmosphere to the flare energy release via the effects of electric currents.

I.E.- Conclusion of chapter I

A good deal of progress has been made in the modelling of the energy distribution in the flaring atmosphere. Nevertheless there are still some open questions: on the nature, the amount, and the location of the primary energy release. More work has to be done on :

1°) The confinement of energetic particles,

2°) the heating of the upper photosphere and temperature minimum région,

3°) the dynamics of the atmospheric response.

II.- Observations and flares models

There is not enough satisfactory tests to discriminate between flare models like reconnection in neutral sheet, reconnection in sheared magnetic field or current interruption. These tests could deal with :

The location of the p.e.r. site. Models of reconnection in sheared field or current interruption could be in agreement with a wide extension of the flare site from corona to upper photosphere. Unfortunatly the required spatial resolution to localize the instabilities greatly exceeds the capability of existing or planned solar telescopes.

The identification od the driver for the neutral sheet models like new magnetic field emergence.

The current characteristics and current evolution associated with current interruption or reconnection in sheared magnetic fields.

The investigation of turbulence which is required in some models (reconnection in neutral sheets, quasithermal model of X-ray source, current interruption).

SMM and the international coordination of the Solar Maximum year will help to understand the flare problem. However there will still be some questions left open for the next solar maximum.

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