THE EFFECTS OF DIFFERENT BASIC PROCESSES IN SOLAR FLARES

B. Vršnak
Hvar Observatory, 58450 Hvar

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ABSTRACT
Current flare classifications are presented briefly, to illustrate observational evidences of the differences among flares. Possible mechanisms of energy release processes in different magnetic structures are discussed and the interplay between ideal and resistive MHD processes and plasma microinstabilities is emphasized. The interacting loop flare model is taken as an example to show that there are observational evidences for at least two different mechanisms of energy release processes (coalescence instability and driven reconnection) in this kind of flares. Another example, which concerns the process of reconnection driven by an erupting prominence (magnetic flux tube), is presented, and it is shown that this process is basically different from the emerging flux model, although they appear in similar magnetic configurations. It is also shown that this type of process can be related to flares with three or four ribbons and in some cases also to flares which remind to the two ribbon flares. This was used as an illustration of the ambiguities concerning the interpretation of energy release processes in flares.

1. INTRODUCTION

There are two viewpoints concerning the problem of energy storage (ES) and energy release (ER) in solar flares. On one side there is a concept of a "typical" flare (Figure 1) or an "average" flare (de Jager, 1986) stressing the most prominent properties of flares and extracting the commonly observed processes. On the other hand, there is a concept of the "individual" flare since there are great differences among flares, appearing in observations from radio waves to X-rays (Švestka, 1985) even between flares of the same morphological class. Discussing flares generally, following scenario is usually adopted: motions of photospheric plasma in which the coronal magnetic fields are anchored drag the field lines and drive the dynamo process which induces currents and so creates nonpotential magnetic configurations where free energy is stored (Priest, 1984).
Fig. 1. "Typical" flare emission in different wavelengths (from Priest, 1982a)

This energy is abruptly liberated when the magnetic structure becomes unstable after a steady evolution through a series of force-free configurations (Priest, 1984). However, the details of ES process, as well as ER process and its triggering are far from being clear.

Various flare models exist, which were established to explain certain classes of flares that follow a rather common scenario, and obviously an unique model which can explain all flares does not exist. I.e. there are different types of flares (Svestka, 1985). Flares differ a lot, not only in their basic properties such as the total liberated energy ($10^{22}$ - $3 \times 10^{23}$ J) and the time scales involved, but also in many other aspects as well. Sometimes the
ER consists of series of elementary bursts (de Jager, 1986) while sometimes the ER appears to be "continuous" and gradual. There are also large differences in morphology, time development, form of liberated energy, trigger, location, ES process, and the energy transport. There are two possible causes of these differences. First, the basic mechanisms causing the ER process can be different and second, the characteristics and signatures of a certain ER mechanism can be significantly modified by the environment, different trigger, etc. On the other hand, it is possible that sometimes flares caused by different ER mechanisms can have similar signatures, and do not differ very much from the observational point of view. So, one has to be aware that when a certain flare is considered, the interpretation may contain a certain degree of ambiguity.

2. FLARE MORPHOLOGY

There are observational evidences which indicate that basically different ER processes can be involved in various classes of flares. The most general classification of flares, recently proposed by Švestka (1983) clearly exposes the differences between two categories of flares. In dynamical flares the overall magnetic configuration undergoes violent structural changes, while in confined flares the ER process takes place within a certain magnetic structure whose general shape does not change in the course of the process. This is an abstracted form of a previous, more specific and frequently used classification, according to which flares can be divided into two ribbon flares and simple loop flares (Priest, 1982b). This classification connecting observations and theoretical models, again exposes differences in the ER process. Two ribbon flares are composite dynamical processes. A sheared arcade in which free energy is stored erupts together with the embedded filament, the field lines open, and the current sheet forms below the filament. The reconnection proceeds, causing the lateral expansion of the chromospheric ribbons which appear at the footpoints of the reconnected field lines (Kopp and Pneuman, 1976). Subsequently, a new system of closed field lines appears, forming a new arcade disclosed by a system of postflare loops. The second class, flares occurring in loops, are confined, since they are result of internal instabilities which do not change the overall shape of the loop. There are also flares in which two or more loops are involved (Kundu, 1983) and where the ER process is caused by the interaction of individual loops. This class of flares can be either confined (Kundu, 1983; Tajima et al., 1985; Vršnak et al., 1987) when no violent structural changes of the magnetic field occur, or dynamical, if the process is triggered by an eruption of one of the loops (Vlahos et al., 1982). The ER Process can also take place in the current sheet formed between the old magnetic structure and the new one which emerges from below (Heyvaerts et al., 1977) and this type of flares may be very frequent.

Apart from this common morphological classes, described by several models, there are also peculiar flares. However, a part of these flares can
still be described as four or three ribbon flares, flare-sprays, flares shaped like rings with central flare brightening etc. Moreover, there are even more intricated flares which are even hard to describe (Švestka, 1985). Finally there are flares which I call "complex" flares since several different, but closely associated processes develop in a common magnetic structure (Ishkov et al., 1985; Ruždjak et al., 1984).

The morphological classes as those described above involve flares that have certain common properties regarding development and appearance, but however, there are also considerable differences even among the flares, of the same class. As the simplest example one can stress that the flare process may be different depending on the location of the ER process and its environment. The ER site can be at high or low altitudes; the magnetic field lines protruding the ER site can be anchored in regions of weak photospheric magnetic fields (spotless flares; Dodson and Hedeman, 1970; Ruždjak et al., 1987) or strong fields (umbral flares; Kosugi, 1982; Dwivedi et al., 1984). This may significantly modify the ER process because different magnetic field strengths and gradients are involved (Spicer, 1977; Hong-Wei Li et al., 1987) and such modifications of the process can be documented by observations Vršnak et al., 1988a. A nice example of the influence of the environment was presented by Strong et al. (1984) in the case of a "double" impulsive flare, where the second flare took place in much hotter and denser atmosphere which resulted from the first flare.

Two further important observational facts should be noted: the process of flare triggering, and the type of magnetic structure in which flares occur (e.g. sheared arcade, loop, a system of loops, emerging or merging flux configurations). Decisive in this context are the magnetic shears, photospheric flows, presence of delta-configurations, vortex motions, presence and motions of satellite spots, emerging flux, etc.

3. FLARE MODELS

Various magnetic structures and different processes of flare triggering were combined with several probable ER mechanisms in a number of models for certain classes of flares. A model is applicable to a given flare if it can explain: the ES process (build-up phase) which must provide sufficient energy to account for the energy liberated in the flare; the trigger responsible for the flare onset; and finally the flare morphology and development. I will consider the ER process as crucial and discuss it in detail.

Prior to flare, the energy is stored in a form of free magnetic energy in a nonpotential magnetic field configuration. There are two different families of magnetohydrodynamical (MHD) mechanisms which can release this energy: ideal and resistive ones. The first category does not involve reconnection of magnetic field lines as the electric conductivity is taken as infinitely large, i.e. magnetic diffusion is negligible. The second type of processes involves reconnection since the electric resistivity (magnetic diffusivity) is not negligible. Considering ideal processes related to flares, the kink

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instability, the eruptive instability or the coalescence instability are usually stressed (Priest, 1984). On the other hand, the reconnection can be caused by the resistive instabilities such as tearing instability (Furth et al., 1963; Cross and Van Hoven, 1971; Biskamp and Schindler, 1971; Drake and Lee, 1977; Spicer and Brown, 1981; Priest, 1985), or it can be driven by external forces. The driven reconnection can proceed in different regimes depending on the merging velocity of the oppositely directed fields, prescribed by external driver, and on the boundary conditions (Priest and Forbes, 1986). These regimes are usually denoted as Sweet-Parker, Sonnerup-Petschek, pile-up and impulsive bursty regime (Priest, 1984).

Another important point is the role of plasma microinstabilities which cause modifications of transport properties of the plasma and can drastically decrease the electrical and heat conductivity (Kuperus, 1976). Of course, such a change of transport properties causes serious modifications of “MHD” processes (Dum, 1985), i.e. it puts severe constraints to the applicability of the MHD approximation. The plasma microinstabilities cause anomalous transport properties and the anomalous Joule heating and they can be expected when the electron drift velocity exceeds a certain threshold (current driven instabilities; Spicer and Brown, 1981) or in the presence of large temperature or density gradients (gradient instabilities; Somov and Titov, 1985).

Interesting, and in my opinion of crucial importance, is the interplay between microinstabilities, and the ideal and resistive MHD processes. The ideal instabilities develop fastly on an Alfvén time scale, and so they can provide the driving force for powerful processes. If they have the lowest threshold and develop first, and they are able to produce strong current concentrations in which current driven instabilities develop increasing magnetic diffusivity, making the resistive processes important. So, the violent motions caused by ideal MHD instabilities can drive the reconnection in the so-called resistive layers. In this way the problem of frozen-in condition, which has been valid before the ER and enabled the ES process, is surpassed.

The mentioned scenario was just an illustration of possible processes. The development of the system can proceed in a number of ways depending on the initial magnetic field, density and temperature distribution, boundary conditions, etc. Unfortunately, the considerations of the stability of various simplified magnetic configurations can not be applied to solar magnetic structures straightforwardly. The development of simple configurations such as neutral current sheets (slab geometry) or pinches (cylindrical or toroidal geometry) are rather well understood (Priest, 1985) but it is necessary to involve additional effects appearing in the solar atmosphere. These effects are line tying (the field lines are anchored in the photosphere); influence of the photospheric boundary and reverse currents in it (“mirror-current” effect); curvature of filaments and loops; inhomogeneities in the current distributions (current threads) etc.

There are also defences in the available observational material. When a certain flare is analysed the observations usually do not cover the whole
range of the electromagnetic spectrum with all existing techniques, and many times the quality of observations (spatial, time or spectral resolution) is not sufficient to give a complete insight into all the processes involved. Furthermore, there is the problem of a correct interpretation of the observational results, i.e. to associate a proper process with various observational signatures, especially in the radio range (e.g. Benz et al., 1983). So, the comprehension of physical processes in a given flare is often ambiguous and competitive explanations are possible.

4. OBSERVATIONAL EVIDENCES OF VARIOUS ER MECHANISMS

The first example concerns the interacting loop process and illustrates that diverse ER mechanisms can appear even within the same class of flares. The interaction of loops can proceed by several mechanisms. According to Sakai et al. (1987) the coalescence instability may be expected in the corona very often. A necessary condition is that the azimuthal component of the magnetic field in the loops is larger than the axial one (Tajima et al., 1985). Tajima et al. (1987) predicted numerically basic properties and signatures of this process, and it was found that e.g. the flares of June 7, 1980 or November 26, 1980 were really exposing similar characteristics. However, much more complete observational material is needed to overcome the remaining ambiguities, since only few observational evidences have been taken into account.

Another attempt to determine the ER mechanism in the interacting loop process was presented by Vršnak et al. (1987). They showed that the observed microwave and H-alpha morphology and development in one phase of the complex flare of May 16, 1981 can be interpreted as interacting loop process spreading through the system of loops with the velocity in the order of 100 km s⁻¹. This velocity is too low for the coalescence instability process, since it should proceed on the Alfvén time scale, i.e. it would spread at about the Alfvén velocity. (The same holds also if the process consisted just of a series of simple loop flares triggered inductively one after the other or by a blast wave.) So, it was proposed that current sheets were formed between neighbouring loops and that Petschek-type reconnection of the azimuthal magnetic field components took place. Typically, the merging velocity attains values up to 10% of the Alfvén velocity (Priest and Forbes, 1986), which is consistent with the observed velocity of 100 km s⁻¹. It was also shown that the proposed interpretation is consistent with the observed rise time of microwave flux at a certain position as the process comprised it. However, much better coverage of the electromagnetic spectrum and different observational techniques would again be needed to diminish the ambiguities.

The next example concerns a different type of process. It was applied to the flare of May 14, 1981 (Vršnak et al., 1986; 1988b) which can be classified as a three ribbon flare (Tang, 1985). It was shown by Vršnak et al. (1986; 1988b) that it is hard to explain this flare using the "ordinary" two ribbon flare model and so another explanation was proposed which fits the
Fig. 2. The process of reconnection driven by an erupting filament (F) which was used in the analysis of the three-ribbon flare of May 14, 1981 (the ribbons are denoted by A, B and C, while small arrows mark the direction of their expansion). The hot plasma (shaded) is situated between Petschek's slow mode standing shocks (broken lines).

observations much better. In this model, a magnetic configuration similar to the one used in the emerging flux flare model was assumed (Heyvaerts et al., 1977), since the observations strongly favor it (Figure 2). Such a geometry can account for flares with four and three ribbons as shown in Figure 3. We see again that the same type of process (arcade eruption) can produce several types of flares depending on magnetic field configuration and geometry. Furthermore, as can be seen in Figure 3c, the eruption of Kippenhahn-Schlüter type of prominence can produce a flare resembling the ordinary two-ribbon flare. So we find, that even flares which can be similar from observational point of view are not necessarily the result of the same mechanism.

According to the proposed model the current sheet forms between the erupting flux and the overlying field, and energy is released there when the reconnection starts. Although such an interpretation resembles the emerging flux flare model, there is however a crucial difference, since the rising flux is carried by the erupting filament which implies much higher
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Fig. 3. Sketch of the reconnection driven by an erupting filament in different magnetic configurations: a) the Kuperus-Raadu type filament in symmetrical configuration (four ribbon flare); b) the Kippenhahn-Schluter type filament ("two ribbon" flare). Small arrows indicate ribbons and the direction of their expansion, while the thick lines represent post-flare loop systems.

velocities and a much larger height of the current sheet. This causes a completely different sequence of processes, which is most obvious if the onset of plasma microturbulence is considered: in the standard emerging flux flare model plasma microturbulence is triggered impulsively by thermal instability, while in this model it is present from very beginning of the process (Vršnak et al., 1988b).

A situation similar to the proposed one was analysed numerically by Forbes and Priest (1984) in an investigation of the emerging flux process. They took a high emerging velocity \( v = v_A/8 \), and uniform overlying field, and uniform density and temperature distribution, which is much more appropriate for the proposed erupting flux process than for the emerging flux model. The simulation outlines the MHD frame of the process, but Vršnak et al. (1988b) have shown that some of the low frequency microturbulences should have been present in the current sheet during the soft X-ray precursor of the flare, which can modify the process significantly. Because of this, a qualitative analysis of hot turbulent current sheet was applied in a fashion similar to Somov's (1986). The Petschek-type geometry was used, since it was shown that it is the appropriate reconnection regime for a wide range of merging velocities: practically from the very beginning of the reconnection up to the merging velocities about 0.015 \( v_A \) when the transition to some other regime of the reconnection (possibly a pile up regime) should occur (Priest and Forbes, 1986). I shall present a short analysis of the conditions in the current sheet characterized by increasing merging velocity, sin-
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...ce a similar situation should be expected in all driven reconnection processes. This very simplified analysis is based on the more detailed analysis by Somov (1986) and Vršnak et al. (1988b) in which the difference between electron and ion temperature \( T_e \) and \( T_{\text{ion}} \) respectively was taken into account, and where it was shown that in the marginally stable state the ratio \( T_e / T_{\text{ion}} \approx 6.5 \) does not depend on the merging velocity. Using stationary MHD equations (it was assumed that the system is evolving slowly), energy equation and ideal gas law, one finds following order of magnitude equations:

\[
\begin{align*}
  n_i \, v_i \, b &= n_o \, v_o \, a \quad (1) \\
  B_i / \mu_o \, a &= j = n_o \, e \, w \\
  B_i^2 / 2 \mu_o &= n_o \, kT_o \\
  a &= \eta \, \nu_i \quad (4) \\
  B_i^2 / \mu_o \, \nu_i &= 5 / 2 \, n_o \, kT_o \, v_o \, a + \frac{M_{n_o} \, v_i^2}{2} + \frac{x_o}{b^2} (T_o - T_i) \quad (5)
\end{align*}
\]

where \( n_i, T_i \) and \( B_i \) are the electron density and temperature and the magnetic field strength in the plasma inflowing into the diffusion region with the velocity \( v_i \); the electron density and temperature of the plasma outflowing with velocity \( v_i \approx B_i / \sqrt{\mu_o \, n_o \, M} \) (Priest, 1982a) are denoted by \( \eta_n \) and \( T_o \), respectively; \( a \) and \( b \) are the diffusion region halfwidth and halflength, respectively (Figure 4) and the electron drift velocity is denoted as \( w \). The anomalous electric resistivity \( (\eta^s) \) and heat conductivity \( x_o^s = \frac{x_o}{b^2} \) (Horton et al., 1976) are incorporated, where \( \eta = 10^9 \, T^{-3/2} \) and \( x_o = 3 \cdot 10^{-11} \, T^{5/2} \) (Priest, 1982b). In the inflowing region \( B_i = 2 n_k T_o / B_i^2 < 1 \), \( T_o > T_i \) and \( T_e > T_{\text{ion}} \) is approximated (the last condition is valid only roughly since \( T_e / T_{\text{ion}} = 6.5 \)) which gives a simplified form for the energy equation (5).

From the upper set of equations one receives:

\[
\begin{align*}
  v_{A1}^2 / 2 &= N c_s \quad (6) \\
  v_{A1}^2 &= 5 c_s^2 / 2 + v_{A1}^2 / 2N + w^2 c_s^2 K / 2v_{A1}^2 \quad (7)
\end{align*}
\]

where \( c_s = \sqrt{kT_o / M} \). \( v_{A1} = B_i / \sqrt{\mu_o \, n_i} \), \( K = 5.1 \) (S.I.) and \( N = n_o / n_i \).

For the marginally stable state the electron drift velocity can be expressed as \( w = \alpha c_s \) to \( \alpha \) depends on the ratio \( T_e / T_{\text{ion}} \) and for the value 6.5 it can be evaluated as \( \alpha = 7.15 \) (Somov, 1986), and so one finds:

\[
T_o = N \, v_{A1}^2 \quad (8)
\]

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Fig. 4. The diffusion region (width $2a$, length $2b$) and Petschek's slow mode shocks. Values of the parameters of the plasma inflowing into the diffusion region with velocity $v_i$ are denoted by the subscript $j$, while outflowing values of the parameters are denoted by subscript $\alpha$.

where $X$ can be expressed numerically as $9.1 \cdot 10^{-6}$. Thus, for $v_{Al}$ in the order of $10^3$ km s$^{-1}$ one finds temperatures in the order of $10^7$ K. A similar expression results from the more detailed analysis (Vršnak et al., 1988b) where saturated heat flux is incorporated in energy equation. The temperature (8) does not depend directly on the merging velocity but rather, only indirectly, through $v_{Al}$ which however, depends on it (Parker, 1979; Priest and Forbes, 1986). Because of increasing merging velocity, the angle between Petschek's slow mode shocks increases, leading to decrease of $B_i$ (and thus $v_{Al}$). Because the tension of the curved field lines (Figure 4) increases and so must be compensated by decrease of magnetic pressure (Parker, 1979). The situation changes when the system enters into the pile-up regime, when $B_i$ becomes larger than the external value $B_e$ (Priest and Forbes, 1986). So a new increase of temperature should be expected, following a temperature bump caused by current sheet formation and subsequent drop of temperature in the Petschek's regime. The emissivity of the hot plasma between shocks can be expressed as:

$$I_\nu \sim n_e^2 T_0^{-1/2} \exp(h\nu/kT_0)$$  \hspace{1cm} (9)$$

(Tucker, 1975). If the pressure balance across the sheet is incorporated, as well as the dependence (8), one receives that the total soft X-ray radiation emitted in the $1.8$ Å range from the hot plasma between the shocks is proportional to:

$$\Phi \sim I_\nu^2 D \cdot v_i \cdot \exp \left[ -1.8 \cdot 10^7 / Xv_{Al}^2 \right]$$  \hspace{1cm} (10)$$
where $L$ is length of the system (Figure 4) and $D$ is the transverse length of the current sheet normal to the plane of Figure 4. Taking into account that $v_{Al}$ depends on $v_1$ and following the simple analysis by Parker (1979) one finds the maximum of the function (10) for $v_1$ in the order of $v_1/v_{Ae} = 0.01$ where $v_{Ae}$ is Alfvén velocity based on the external conditions, which is consistent with the observations of May 14, 1981 flare (Vršnak, 1988). So the described process can explain the appearance of the soft X-ray precursor. Furthermore, one finds that a new increase should be expected after $v_1$ attains the value at which the Petschek's regime is no more applicable, i.e. when the pile-up regime starts, leading to a new increase of $v_{Al}$ and thus $T_0$ (relation (8)). Again, let me note that a similar sequence of processes should be expected in all driven reconnection processes where $v_1$ attains values larger than the maximal velocity in Petschek's regime, and so similar observational signatures should be expected.

5. CONCLUSION

The examples concerning interacting loop processes illustrate that the ER process in a certain type of magnetic configuration is not necessarily always related to the same ER mechanism. Moreover, the interacting loop model does not necessarily imply that energy is released by the interaction itself: a flare can be a result of ER processes in each loop due to some single loop mechanism, which is just triggered by interaction, either mechanically (Emslie, 1981) or inductively (Spicer et al., 1986). The initial conditions determine which type of ER process will occur. Different processes should develop on different time scales and this property can help to exclude some of the possibilities when a certain flare is analysed: e.g. fast coalescence instability develops on the Alfvén time scale, ER process caused by driven reconnection will proceed at some fraction of the Alfvén velocity (up to about 10%), while in simple loop mechanism the internal (resistive) kink instability will proceed on a time scale $\tau = \tau_A^{2/3} \tau_D^{1/3} \approx 100\, s$ ($\tau_A$ is the Alfvén travel time, and $\tau_D$ is diffusion time). Flares in single loops which are caused by the coalescence instability of current threads (de Jager, 1986) should consist of a series of very impulsive and powerful elementary bursts ($\tau \approx r/v_A \approx 0.1 - 1\, s; 10^{20} - 10^{21}\, W$) and this mechanism seems to be the fastest one at all. Comparing all these time scales, one receives values ranging from a fraction of a second (coalescence instability of current threads) to hundreds of seconds in the case of resistive instabilities where anomalous resistivity is assumed, and in driven reconnection processes in large current sheets.

The second example (emerging/erupting flux model) also showed that completely different processes can be expected in very similar magnetic configurations depending on the properties of the environment, and initial conditions (cold current sheet in the case of the emerging flux model, and hot turbulent current sheet in the case of the erupting flux model).
Furthermore, this example shows that an ER process exists, which is not commonly used, although it is quite probable in the solar atmosphere. On the other hand, this example shows that completely different processes can have similar appearance in certain type of observations: when the Kippenhahn-Schlüter type of prominence is involved in erupting flux process, it can produce similar chromospheric effects as the "ordinary" two-ribbon flare process (Figure 3c).

REFERENCES


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EFEKTI RAZLIČITIH OSNOVNIH PROCESA U SUNČEVMIM BLJESKOVIMA

B.Vršnak
Opservatorij Hvar, 58450 Hvar

UDK 523.985
pregledni članak

SAŽETAK: Ukratko je prikazana klasifikacija bljeskova da bi se ukazalo na njihovu različitost. Izloženi su mogući mehanizmi oslobađanja energije u različitim magnetskim strukturama te je razmotren odnos idealnih i rezistivnih MHD procesa te plazminih mikronestabilnosti. Primjer modela interagirajućih petlji ukazuje da je moguć veći broj osnovnih procesa oslobađanja energije. Također je prikazan model procesa rekonekcije vodene eruptirajućim filamento te je pokazano da je ovaj proces bitno drugačiji od modela izranjajućeg magnetskog toka iako se oba odvijaju u sličnim magnetskim konfiguracijama. Ovaj tip procesa objašnjava pojavu bljeskova s četiri i tri vlakna .