MAGNETOSPHERIC SUBSTORMS AND SOLAR FLARES

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Abstract. Assuming that basic plasma processes associated with magnetospheric substorms and solar flares are similar and thus assuming also that a flare ribbon is produced by the impact of field-aligned current-carrying electrons on the chromosphere, a chain of processes leading to solar flares is considered, including the dynamo process in the photospheric level in the vicinity of bipolar sunspots, the formation of a sheet current in the lower coronal level, the interruption of the sheet current, the subsequent diversion of it to the chromosphere, the development of a potential drop along magnetic field lines, the acceleration of current-carrying electrons and their impact on the chromosphere, producing a pair of flare ribbons.

1. Introduction

Auroral substorms and solar flares (in a narrow sense) are characterized by a sudden flash of highly structured (in space) optical emissions from atoms and molecules of the terrestrial and solar atmospheres, respectively. Figure 1 shows typical photographs of an auroral substorm. The green line (5577 Å), one of the main auroral emissions, arises from oxygen atoms, one of the main constituents in the auroral height of the terrestrial upper atmosphere. The dominant emissions from a solar flare are the Balmer emissions (Hα, Hβ, Hγ...), emitted by atomic hydrogen which is the major constituent of the solar atmosphere.

There are a number of phenomenological similarities between the two phenomena (cf. Akasofu and Chapman, 1972; de Feiter, 1975; Obayashi, 1975). The main optical emissions associated with auroral substorms and solar flares occur spatially in a highly structured manner. In fact, they are often referred to as 'ribbon-like' structures. Flare ribbons appear typically in a pair at the feet of 'arch' of magnetic field lines (cf. Bruzek, 1964; Švestka, 1976; Rust and Bar, 1973). Auroral ribbons in the northern and southern auroral ovals constitute a pair, appearing at the feet of 'arch' of dipolar field lines; auroral displays in the northern and southern ovals are very similar. During an early epoch of auroral substorms and solar flares a sudden brightening 'propagates' or 'extends' rapidly along narrow auroral and flare ribbons. The auroral substorm consists of two phases. During the initial brief ($\sim$30 min) *expansive phase*, auroral ribbons spread rapidly poleward (Figure 1); this active phase is followed by a gradual *recovery phase* which lasts typically for 2$\sim$3 hr. In addition to the above visible emissions, both phenomena are associated with EUV emissions and bremsstrahlung X-ray emissions. Both phenomena are also associated with various types of radio emissions. The light curve has a sharp rise and a slow decay for both phenomena.

Violent plasma motions associated with solar flares have long been known, since they can be observed 'visually' through the Hα filter; note that actually, since the

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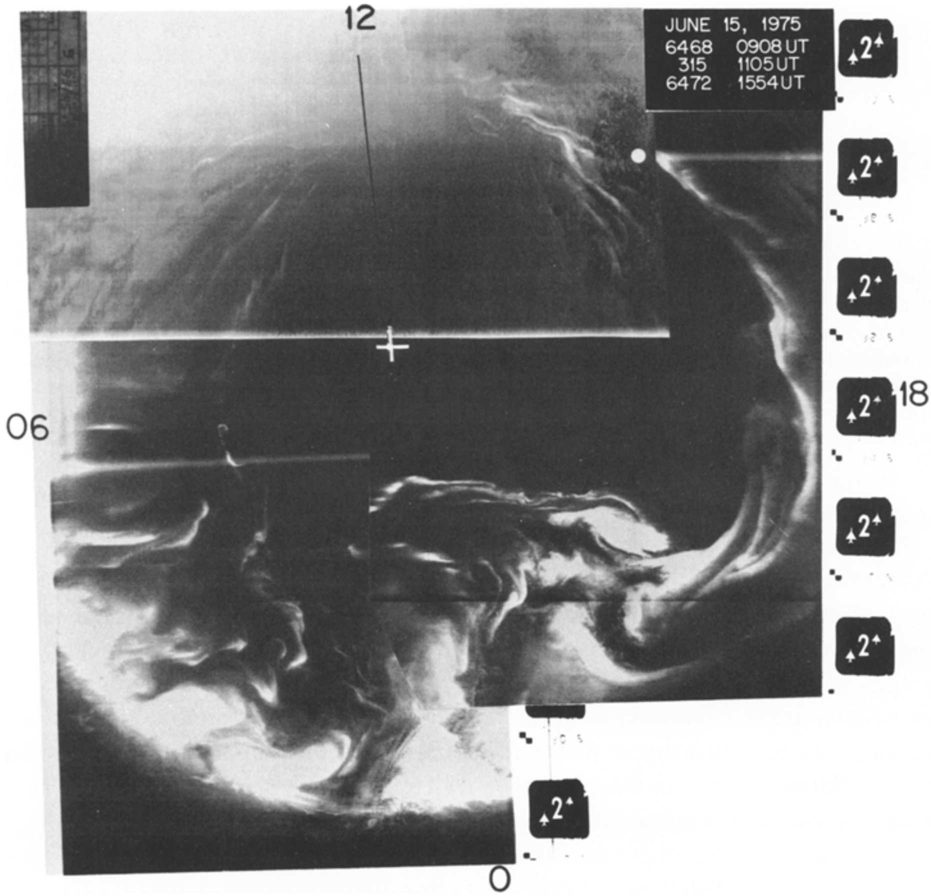


Fig. 1. A montage photograph of the auroral oval, the belt of auroras around the (invariant) magnetic pole (+mark) over the antarctic region. An intense auroral substorm is in progress, as indicated by a large-scale auroral activity in the night hemisphere (the lower half) of the photograph. The noon meridian is indicated by a line (12) from the pole toward the top of the photograph. The morning meridian (06) and evening meridian (18) are also indicated.

emission arises from atomic hydrogen, their motions are those of partially ionized clouds. Since magnetospheric plasma is not visible, it is only during the last two decades that its motions have become observable by satellite-borne particle detectors.

Magnetic field and electric field variations during auroral activity have long been studied, and the magnetospheric (three-dimensional) current system has been fairly well established. However, for solar flares, magnetic field variations associated with solar flares have been rather controversial. Observed electric field variations in the ionospheric level during auroral substorms are consistent with what one expects from the current system.

Solar flares are associated with the production of suprathermal particles, the so-called solar cosmic rays (solar protons) and relativistic electrons. The production of suprathermal particles during magnetospheric substorms has recently been reported. For details of solar flares and magnetospheric substorms, see Kiepenheuer (1953), de Jager (1959), Smith and Smith (1963), Zirin (1966, 1978), Zirin and Tanaka (1973), Massey *et al.* (1976), Priest (1976a, b), Akasofu (1967, 1977), and Russell and McPherron (1973).

It should be noted that the auroral substorm is only the optical manifestation of a particular type of magnetospheric disturbance. It is for this reason that the term 'magnetospheric substorm' was introduced as the source of all the substorm manifestations, such as ionospheric substorms, polar magnetic substorms, X-ray substorms, as well as auroral substorms. Similarly, Akasofu and Chapman (1972) introduced the term 'solar storm' as the source of all phenomena associated with solar flares. In this paper, however, the term 'solar flare' is used in a wide sense, including all flare-associated phenomena.

On the basis of the above striking phenomenological similarities, it is reasonable to suspect that basic processes involved in both phenomena are similar. Indeed, it is for this reason that theories of solar flares and magnetospheric substorms have been advanced closely together. The major differences are the total energies involved, being $10^{32\sim33}$ ergs and $10^{22\sim23}$ ergs, respectively, for a solar flare and a magnetospheric substorm

During the last decade there has been some major progress in studies of magnetospheric substorms, since *in situ* observations of plasmas, electric and magnetic fields have become possible by satellite-borne instruments within and outside the magnetosphere. The main purposes of this paper are: (i) to review briefly some of the basic features of magnetospheric substorms, and (ii) to attempt to understand solar flares in essentially the same way as magnetospheric substorms. In doing so, the only major assumption employed in this paper is that a flare ribbon is produced by the impact of *field-aligned current-carrying* electrons (and also, perhaps, protons). This assumption is based on our knowledge that an auroral ribbon is produced by the impact of field-aligned current-carrying electrons on the polar upper atmosphere.* The relationship between energy spectra of auroral electrons and visible auroral forms is reasonably well established (cf. Rees, 1969; Banks *et al.*, 1974; Meng, 1979). For solar flares, Brown (1973) and Brown *et al.* (1978) showed that the flare emissions can be explained by the impact of energetic electrons on the chromosphere, although other possibilities (such as the Joule heating and heat conduction) have been extensively investigated.

2. Magnetospheric Substorms

Our present understanding of the magnetospheric substorm is as follows (cf. Akasofu, 1979):

* There is one type of aurora, called the mid-latitude subvisual red arc, which may be caused by thermal conduction of the ring current energy (cf. Cole, 1968).

(i) The solar wind and the magnetosphere constitute a dynamo. The energy coupling function ε (erg s^{-1}) between the solar wind and the magnetosphere is given, as a first approximation, by

$$\varepsilon = VB^2 \sin^4(\theta/2) l_0^2,$$

where

V = the solar wind speed,

B = the magnitude of the interplanetary magnetic field,

$\theta = \tan^{-1}(|B_y/B_z|)$ for $B_z > 0$

$= 180° - \tan^{-1}(|B_y/B_z|)$ for $B_z < 0$,

l_0 = constant ($\sim 7\ R_E$).

The power thus generated is dissipated in the magnetosphere (including the ionosphere). The Joule heat produced in the ionosphere follows closely $\varepsilon(t)$. Figure 2 shows this relationship by comparing time variations of $\varepsilon(t)$ and the magnetospheric substorm index $AE(t)$, a measure of the total Joule heat produced in the ionosphere.

(ii) When ε is increased to a value of about $\sim 10^{18}$ ergs s^{-1}, the magnetosphere suddenly develops a different power dissipation mode which is more efficient than

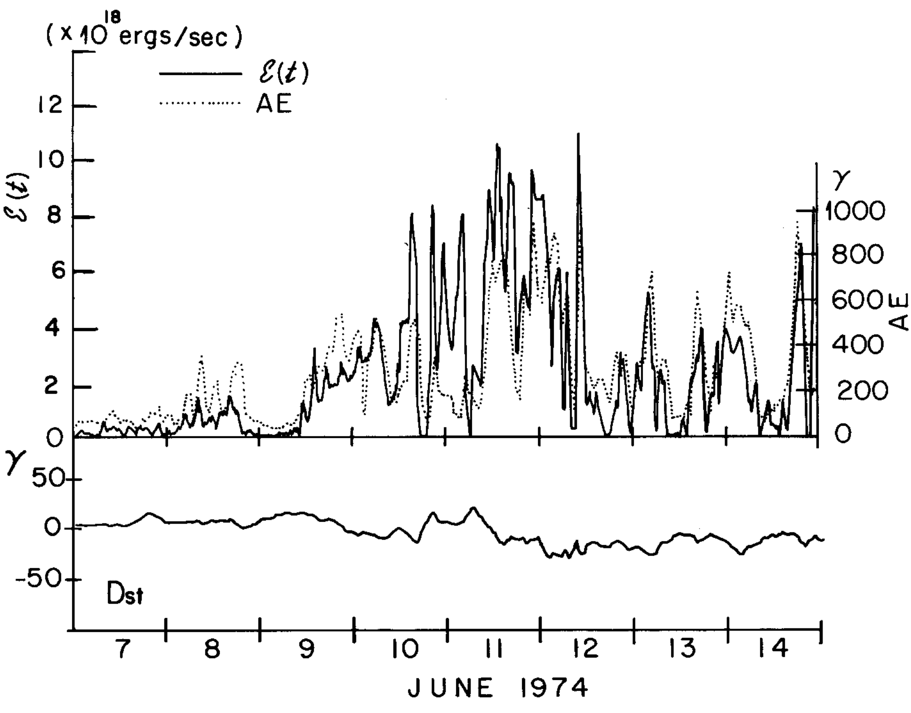


Fig. 2. The relationship between the energy coupling function $\varepsilon(t)$ and the magnetospheric substorm index $AE(t)$. The bottom curve shows the Dst index which is also a measure of the ring current intensity, another energy sink of the magnetospheric substorm.

that for $\varepsilon < 10^{18}$ ergs s^{-1}. We identify the magnetospheric substorm to be the manifestation of this efficient energy dissipation. Figure 3 shows a series of all-sky photographs which show an explosive feature of the substorm onset.

(iii) The magnetosphere achieves this efficient energy dissipation by interrupting suddenly the electric current which flows across the plasma sheet in the tail region of the magnetosphere and subsequently by diverting it along magnetic field-lines to the polar ionosphere (the resistive part of the circuit), thereby enhancing Joule heat dissipation. Figure 4 shows schematically how the current interruption and the subsequent diversion take place in the plasma sheet.

(iv) The field-aligned current increased by the diversion enhances the electric potential drop, the so-called '*V*-shaped potential structure', above the polar ionosphere; for the *V*-shaped potential structure, see Section 3.1. As a result, accelerated electrons descends to the polar ionosphere down to about 100 km altitude, ionizing and exciting atmospheric particles there, resulting in, among other things, the optical

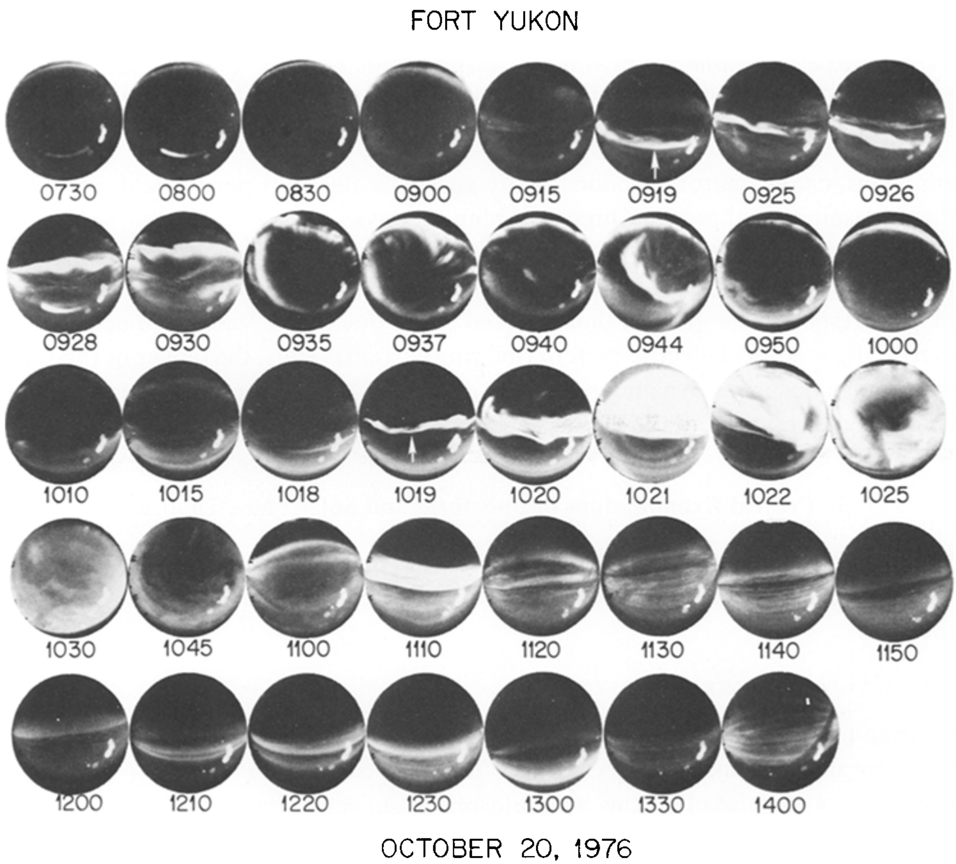


Fig. 3. A series of 'all-sky' photographs which shows an explosive characteristic of substorm onsets, at 09:19 and 10:19 UT, October 20, 1976, taken from Fort Yukon, Alaska. The substorm onset is best characterized by a sudden brightening of an auroral curtain (see the arrows).

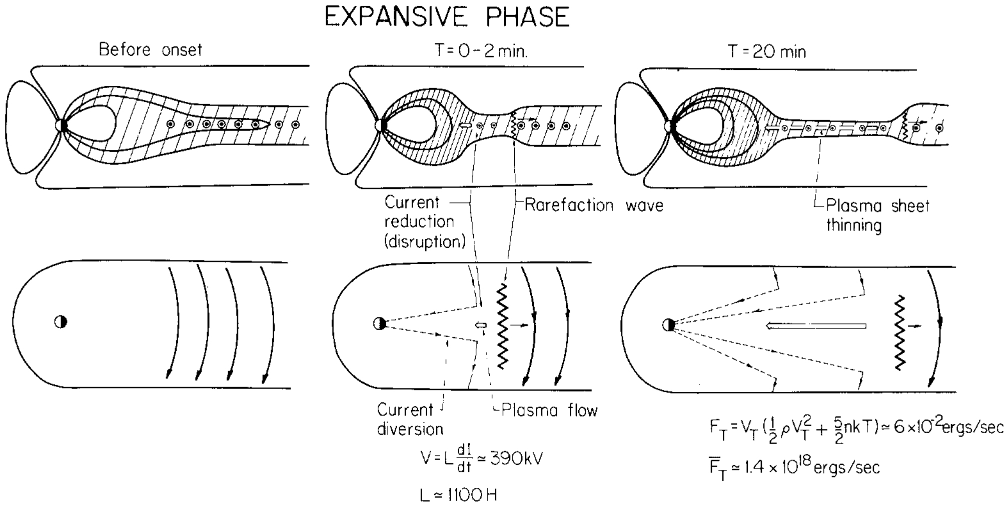


Fig. 4. The noon-midnight (above) and equatorial cross-sections (below) of the magnetosphere, illustrating schematically how the cross-tail current in the plasma sheet is interrupted and diverted during an early phase (the expansive phase) of the magnetospheric substorm. The inductance L of the magnetotail circuit is of the order of $1100H$, and the induced voltage $V = L(\mathrm{d}I/\mathrm{d}t)$ as a result of the current disruption is estimated to be 390 kV.

emissions, namely auroral ribbons. More energetic electrons penetrate deeper into the atmosphere and produce bremsstrahlung X-rays.

(v) A large induced electric field associated with $\partial B/\partial t$ which arises from the current interruption and diversion causes rapid plasma motions toward the inner magnetosphere. The plasma thus injected forms one of the Van Allen belts which carries the westward electric current (the ring current). Thus, the power of the solar wind-magnetosphere dynamo is partially dissipated in the process of producing the ring current belt around the Earth.

3. Critical Examinations of Substorm and Solar Flare Theories

In this section, we examine critically some of the important findings, basic assumptions made in substorm theories and also similar assumptions made in solar flare theories.

3.1. Magnetospheric substorms

(i) In spite of the fact that the optical manifestation of the magnetospheric substorm, the auroral substorm, appears explosive, the good correlation between ε and Joule heat energy generated in the magnetosphere suggests that the magnetospheric substorm may not be a simple unloading process of magnetic energy accumulated in the magnetotail prior to substorm onset. Figure 5 shows schematically an unloading process (right) and a driven process (left), respectively, contrasting basic differences between them.

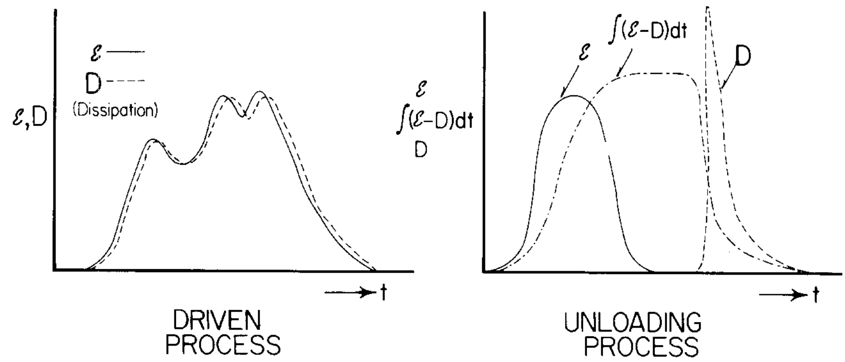


Fig. 5. Differences between a driven system and an unloading process are schematically shown by using an energy input function $\varepsilon(t)$ and an output (dissipation) function $D(t)$, together with $\int(\varepsilon - D)\,dt$.

When both the growth and decay of a magnetospheric process are closely controlled by an increase and decrease of a certain solar wind quantity, such a process may be considered to be a driven process which is the other extreme to the unloading process. Since a magnetospheric substorm occurs only when ε exceeds $\sim 10^{18}$ erg s^{-1}, it is not strictly a driven process. However, the relationship between ε and the *AE* index indicates that the solar wind-magnetosphere dynamo is driven harder during the expansive phase of the magnetospheric substorm than during a short period ($\sim$1 hr) prior to substorm onset (rather than the dynamo reaches the maximum efficiency prior to the onset). In this sense, the magnetospheric substorm process is closer to a driven process than an unloading process.

It should be noted that reconnection of the anti-parallel magnetic field lines in the magnetotail has been considered as the source process of magnetospheric substorm energy (cf. Schindler, 1975). At present, the correlation between ε and the *AE* index does not exclude the possibility of the formation of the *X*-line or tearing mode instability in the magnetotail, although the observational confirmation of reconnection in the magnetotail is highly controversial at the present time.

(ii) In a collisionless plasma (in which the conductivity is supposed to be practically infinite), a potential drop of $1 \sim 10$ kV is needed to drive field-aligned electric currents of order 10^{-5} A m^{-2}. It is for this reason that an electric field of order $0.1 \sim 1$ mV m^{-1} develops just above the auroral ionosphere, accelerating current-carrying electrons. This potential structure has a *V*-shape and is thus called the *V*-potential structure. Figure 6 shows the potential pattern constructed by Kan *et al.* (1979). The fact that a potential drop of about 10 kV (an electric field of 1 mV m^{-1}) exists along magnetic field lines in the earthward edge of the plasma sheet suggests that *the concept of frozen-in-magnetic field is not a good approximation in the magnetospheric plasma.*

(iii) *Auroral electrons are accelerated mainly in the V-potential structure.* Since the energy of electrons is typically a few kilovolts, the *V*-potential structure must be mainly responsible for the acceleration. This finding may also be contrasted with the

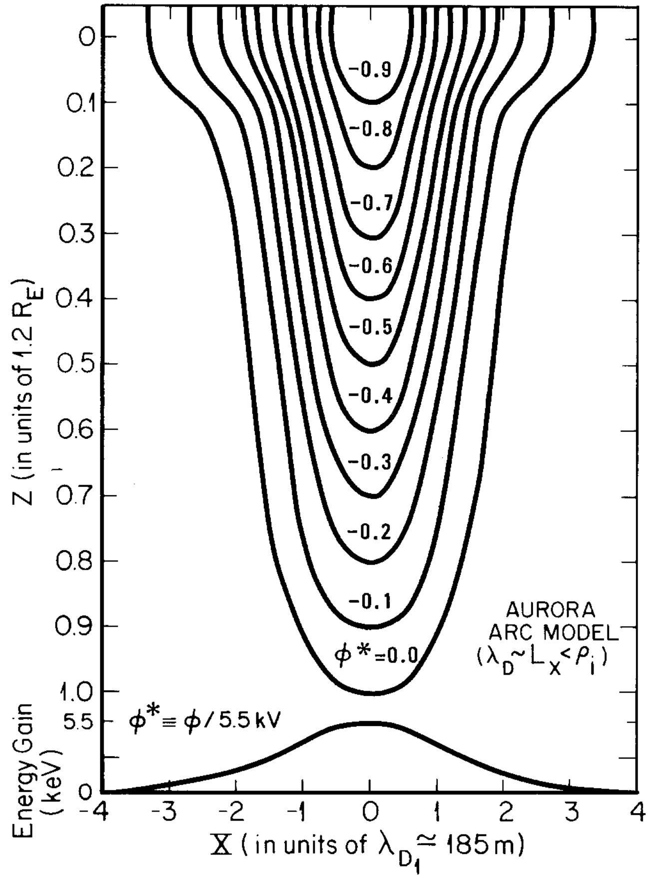


Fig. 6. The *V*-shaped potential pattern which develops when a thin current sheet interacts with the surrounding plasma (Kan *et al.*, 1979).

widely held view that a reconnection process is mainly responsible for the acceleration of auroral electrons in the magnetotail. Actually, the bulk of plasma in the plasma sheet is not accelerated during the expansive phase of the magnetospheric substorm; exceptions are suprathermal protons and electrons.

(iv) The brightness of an auroral ribbon is increased as the intensity of field-aligned currents is enhanced.* The field-aligned current intensity drastically *increases at the onset* of a magnetospheric substorm.

(v) One must find a mechanism to enhance the field-aligned current to explain the magnetospheric substorm.

3.2. Solar Flares

In most solar flare theories, it has been tacitly assumed that magnetic energy is accumulated as a result of the formation of either (i) a sheet current or (ii)

* As we shall explain later, several processes must take place before an enhancement of the field-aligned current; the increase of brightness of an auroral ribbon would not be related linearly to ε.

field-aligned currents *prior to the onset* of a flare. The conversion of magnetic energy associated with a sheet current has been treated by reconnection theories (Petschek, 1964; Sturrock, 1968; Priest, 1975, 1976a, b). For the latter (ii), the simplest case assumes that the magnetic field configuration prior to a solar flare is a force-free field, given by

$$\mathbf{j}\times\mathbf{B}=(\nabla\times\mathbf{B})\times\mathbf{B}=0\,.$$

The solution $\mathbf{B}$ of the above equation gives a helical field, so that the above assumption implies that the flare energy is stored in the helical magnetic field configuration. After a flare, the magnetic field configuration may approach the curl-free condition, $\nabla\times\mathbf{B}=0$. If a force-free configuration is assumed, an implicit assumption is that the field-aligned current reaches a maximum intensity *prior to* the onset of a flare, producing a tight helical field configuration and that after a flare the helical structure relaxes, releasing magnetic energy (Tanaka and Nakagawa, 1973; Sturrock, 1972, 1974; Jockers, 1976; Tanaka, 1978).

Recalling that the magnetospheric substorm is a driven process in spite of the fact that auroral displays appear to be explosive, it is worthwhile to examine whether or not there is any conclusive evidence that the magnetic energy available for a flare is stored prior to flare onset (in spite of the fact that a flare may appear to be an explosive conversion of the accumulated energy). In fact, as we assumed, if bright flare ribbons are caused by current-carrying electrons descending toward the feet of 'arch' of magnetic field lines, the intensity of field-aligned currents should increase sharply at the onset of a flare and continue to do so during an early epoch, suggesting that a flare is a driven process. It should be noted that Severny (1969) showed that the vertical component of currents deduced from $\nabla\times\mathbf{B}$ is large in flare ribbons, but there have been no follow-up observations of this kind. Further, there is no definite evidence that flare ribbon-producing particles are accelerated in the coronal level and are simply dumped toward the chromosphere. In the magnetosphere, most particles injected from the plasma sheet toward the inner magnetosphere mirror back and become trapped; they can be precipitated only by strong particle-wave interactions which are too slow to explain the precipitation into an auroral arc.

4. Proposed Chain of Processes Leading to a Solar Flare

On the basis of the above considerations, let us suppose the following chain of processes as the cause of a solar flare:

(i) A plasma motion and sunspot magnetic fields in the photosphere and the chromosphere constitute a dynamo and generate a current sheet in the coronal level.

(ii) As the dynamo efficiency is increased to a certain value and the intensity of the sheet current is increased, some plasma instability process disrupts the sheet current.

(iii) The disrupted current finds its way to the lower altitude along the arch of magnetic field lines.

(iv) The V-potential structure is formed by the interaction between the field-aligned current-carrying electrons and the surrounding plasma, and the current-carrying electrons are accelerated as they descend through it. In the following section, we examine the above chain of processes for a specific plasma motion in the photosphere.

(v) Downgoing particles collide with hydrogen atoms in the chromosphere, ionizing and exciting them.

(vi) The optical emissions arise as a result. More energetic electrons descend deeper into a denser atmosphere and generate bremsstrahlung X-rays.

5. A Specific Example

In this section, we consider a simple situation in which a current sheet develops in the coronal region, by dynamo action in the photospheric level, in the vicinity of a pair of newly growing sunspots between a pair of old sunspots. We examine how the current in the sheet may be disrupted to produce a pair of flare ribbons at the feet of arch of magnetic field lines.

5.1. Dynamo process

A dynamo theory in cosmic electrodynamics treats the current systems driven by a given plasma wind system in a given magnetic field configuration. The dynamo process has been extensively studied in geomagnetism (cf. Chapman and Bartels, 1940; Akasofu and Chapman, 1972). Complex photospheric motions are present in the vicinity of sunspots (cf. Martres *et al.*, 1973; Harvey and Harvey, 1973). Several workers have already examined current systems for a given horizontal wind system and magnetic field configuration (cf. Sen and White, 1972; Heyvaerts, 1974). Here, we consider a simple example in which an upward-downward plasma motion takes place between a pair of sunspots (Figures 7a and 7b). The resulting electromotive force ($\mathbf{V}\times\mathbf{B}$) is schematically shown in Figure 7c. Note that the conductivity is assumed to be isotropic in the dynamo level.

Let us assume that the dynamo process develops also a sheet of plasma just above the dynamo region in such a way that the Lorentz force arising from the resulting current intensity j and the magnetic field B is balanced by the pressure gradient ∇p, namely $\mathbf{j}\times\mathbf{B}=\nabla p$ (Figures 7d and 7e). This is essentially the process by which the current generated by the solar wind-magnetosphere dynamo is circuited into the plasma sheet in the magnetotail. The resulting current sheet has some resemblance to an example discussed by Sakurai and Uchida (1977; their Figure 4, here reproduced as Figure 8). Further, the resulting magnetic field configuration is expected to be similar to that produced by the birth of a pair of spots between the existing pair of spots (Uchida and Sakurai, 1977; Tur and Priest, 1978). In fact, it has been shown by Rust (1976) that a solar flare tends to occur in the vicinity of a newly emerging magnetic flux. The emergence of a pair of sunspots is, in this view, due to the dynamo process, rather than 'buoyancy' of the flux tube. In fact Hagiwara (1967, 1969) made an interesting simulation study of rising magnetic flux in a different context.

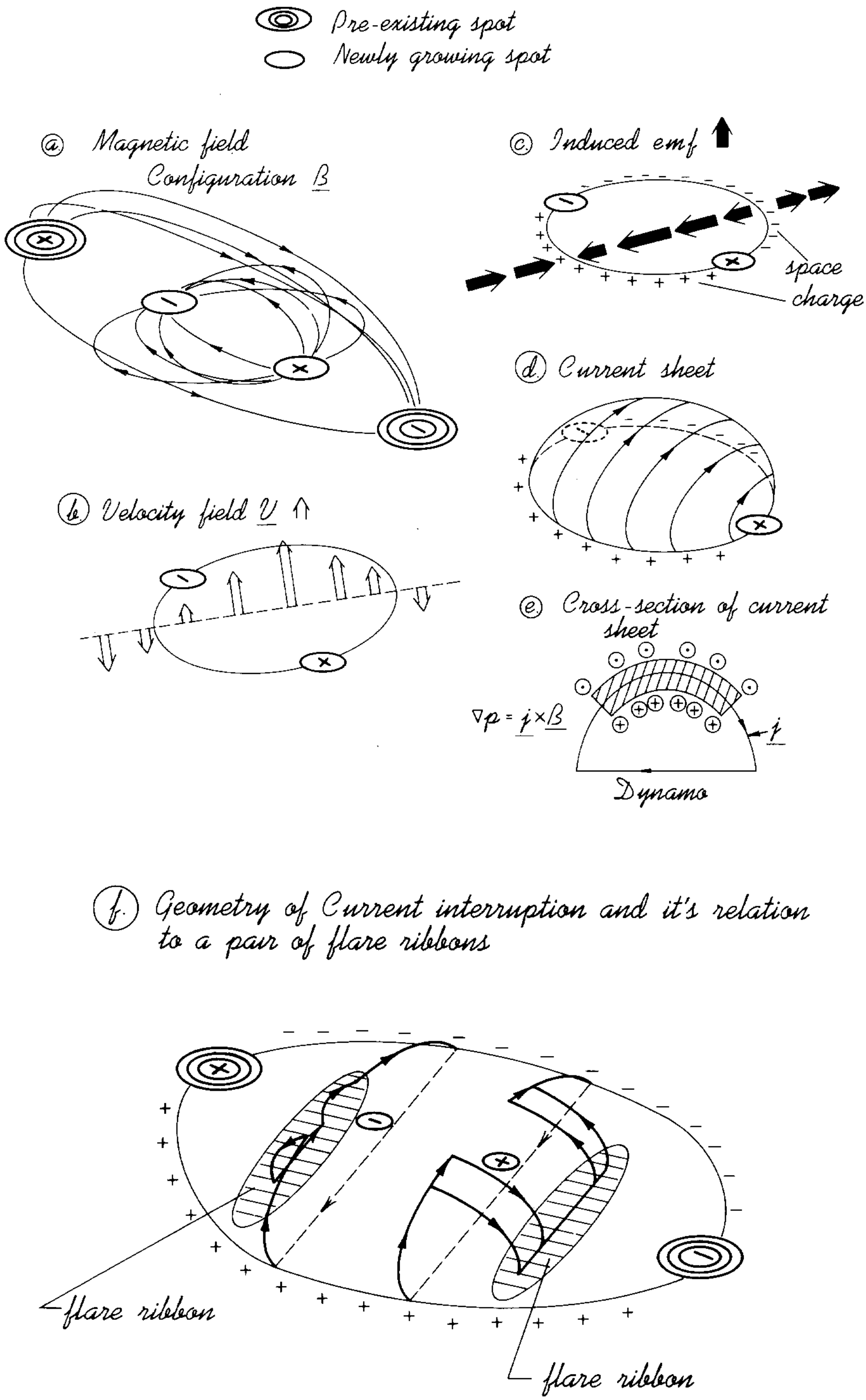
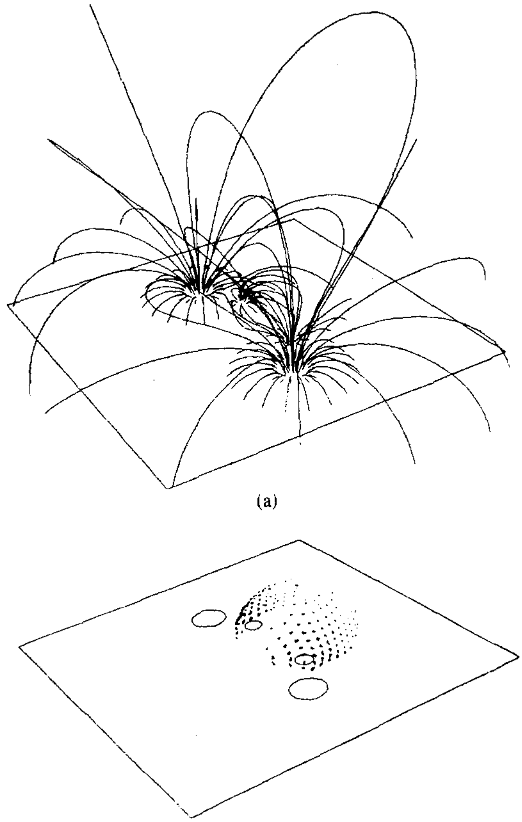


Fig. 7. (a) The magnetic field configuration. (b) The velocity field. (c) The distribution of emf. (d) The geometry of the resulting current sheet. (e) The cross-section of the current sheet. (f) The geometry of the interrupted current sheet and its relation to a pair of flare ribbons.



(a)

(b)

Fig. 8. The magnetic field configuration similar to that in Figure 7(a) and the associated current sheet (Sakurai and Uchida, 1977).

Let $\tilde{P}$ be the dynamo power output. The power $\tilde{P}$ generated by the dynamo is given by

$$\tilde{P} = \mathbf{F} \cdot \mathbf{V} ,$$

where

$$\mathbf{V} = \text{velocity of plasma motion} ,$$

$$\mathbf{F} = \text{Maxwell stress } (B^2/8\pi) \times S ,$$

$$S = \text{surface area} .$$

Let

$$V = 1 \text{ km s}^{-1} = 10^5 \text{ cm s}^{-1} ,$$

$$B = 500 \text{ G} ,$$

$$S = 10^5 \text{ km} \times 10^5 \text{ km} = 10^{20} \text{ cm}^2 .$$

Then

$$\tilde{P} = 10^{29}\ \text{ergs s}^{-1} = 10^{22}\ \text{W}.$$

This power should be equivalent to the quantity ε in the solar wind-magnetosphere dynamo. As the upward plasma motion begins to increase, both $\tilde{P}$ and the sheet current above the dynamo region will be increased. As we see in the plasma sheet of the magnetosphere, let us suppose that the sheet current is disrupted by some plasma processes when $\tilde{P}$ reaches a certain value. At present, it is not certain how such an interruption or disruption process would develop (cf. Alfvén and Carlqvist, 1967; Smith and Priest, 1972; Spicer, 1977). In the magnetospheric situation, in spite of considerable controversy on magnetotail observations and their theoretical interpretations, there is a general agreement that most of the available observations are consistent with an idea that the cross-tail current is partially diverted to the polar ionosphere during magnetospheric substorms (cf. Rostoker *et al.*, 1979).

For the magnetic field configuration under consideration, the disrupted current will find its way to the chromosphere along magnetic field lines; see Figure 7f. The current-carrying electrons descend from a collisionless plasma region (the coronal region corresponding to the plasma sheet) to a partially ionized region (the lower chromosphere corresponding to the ionosphere). Thus, it is expected that the V-potential structure is formed in the lower coronal region or in the upper chromosphere (namely, well above the region where the Pedersen conductivity is high). The current-carrying particles will be accelerated as they move through the V-potential region, ionizing and exciting the chromospheric constituents. It is at this moment that the flash phase of a solar flare begins.

Knowing that the amount of heat production during substorm is directly controlled by ε (in spite of the fact that the heat production increases sharply and decays slowly as if the substorm appears as an explosive process), one may speculate that $\tilde{P}$ begins to decline at the maximum epoch; note that the recovery phase of the substorms begins at about the time when ε begins to subside.

This is not to say that all time variations of flare and substorm phenomena are completely controlled by $\tilde{P}$ and ε, respectively. Certainly, the magnetosphere has its own time constants, such as the recombination time of ionized constituents, and quantities equivalent to inductance and capacitance as well as resistance for magnetospheric current systems.

It is important to note that like the substorm case the current interruption and the subsequent diversion to the partially ionized lower solar atmosphere (where the resistivity is high) are an efficient energy dissipation process in matching the increasing power $\tilde{P}$. This idea is thus quite different from those contained in reconnection theories of solar flares in which an attempt is made to dissipate most of the stored magnetic energy high in the coronal region, accelerating particles there and subsequently dumpting them into the chromosphere.

If the current disruption would occur in a manner similar to the plasma sheet of the magnetosphere, a pair of current sheets will appear between the pre-existing pair of spots.

It may also be interesting to examine carefully a sudden motion of dark filaments during a flare, if such a motion could be understood in terms of dynamical behaviors of the current sheet at the time of the current interruption. The plasma sheet during magnetospheric substorms undergoes a drastic change, such as thinning during the initial expansive phase and thickening of the recovery phase. During the expansive phase, a large induced electric field (associated with the current interruption and with $\partial B/\partial t$) injects the plasma in the plasma sheet toward the inner magnetosphere deflating the plasma sheet. Then, a fast earthward plasma flow rapidly reflates the plasma sheet during the recovery phase; the latter process is not understood.

6. Concluding Remarks

It is not the purpose of this paper to attempt to describe details of all flare phenomena. However, considering a rather remarkable morphological similarity between solar flares and magnetospheric substorms, the correct theory of magnetospheric substorms should be at least partially applicable to solar flares and vice versa. During the last two decades, reconnection has been extensively studied (Vasyliunas, 1975). However, there has been little advance of understanding solar flares in terms of reconnection theories.

Some notable exceptions to the reconnection theories were ideas proposed by Alfvén and Carlqvist (1967), Sen and White (1972), Piddington (1973, 1974), Obayashi (1975), and Spicer (1977). As these authors stressed, it is important to consider flare processes in terms of both energy source and sink processes. The dynamo process is one of the fundamental energy source processes in cosmic electrodynamics, and it should be a vital part of the correct theory of solar flares, as well as of magnetospheric substorms. Once this basic principle becomes understood, our problem will be reduced to the matter of finding a suitable combination of the correct wind system and magnetic field configuration, in addition to local plasma processes which lead to the current interruption. From this point of view, the idea presented in this paper is basically quite similar to those proposed by Alfvén and Carlqvist (1967), Sen and White (1972), Heyvaerts (1974), and Obayashi (1975).

This paper is based on the recent progress in magnetospheric substorm studies. Obviously, however, we have not fully understood all the major features of substorms. The understanding of some of the flare features will undoubtedly help in understanding the corresponding features of magnetospheric substorms.

Acknowledgements

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