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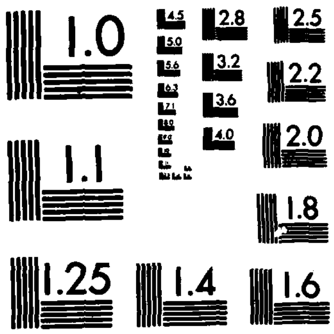
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by

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# ENERGY RELEASE IN SOLAR FLARES

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## ABSTRACT

We examine observational information concerning various phases of the solar-flare process:- (a) Recent evidence strongly suggests that the soft X-ray emission before and after the impulsive phase should be regarded as one process—the "gradual phase." (b) Microwave and X-ray data indicate that the impulsive phase is comprised of a large number of similar bursts of energy release. (c) Large flares are usually preceded by filament eruptions, and it is possible that the same process occurs on a smaller scale for smaller flares.

We propose that most flares are initiated by the eruption of a filament. The eruption opens up magnetic field lines to form a large current sheet. This current sheet may persist as a coronal streamer, or it may immediately reconnect. Reconnection of this current sheet is responsible for the gradual phase of a flare.

Since magnetic field at the photospheric level is concentrated into small knots of high field strength, the coronal magnetic field may be regarded as an aggregation of small flux tubes, each with an internal current, adjacent tubes being separated by current sheets. The gradual phase of a flare may leave the fine-scale current system undisturbed, in which case the flare has only a gradual phase. Alternately, it may trigger reconnection of the fine-scale current system. In the latter case, we propose that the release of the free energy of the fine-scale current system is responsible for the impulsive phase.

# ENERGY RELEASE IN SOLAR FLARES

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## I. Introduction

It has been realized for some time that magnetic reconnection plays an important role in solar flares. It was realized by Giovanelli (1947, 1948) that flares are essentially electromagnetic phenomena. Dungey (1958) pointed out that magnetic neutral points offer favorable sites for particle acceleration. Sweet (1958a,b) noted that such energy release may occur in entire current sheets. Gold and Hoyle (1960) proposed an alternative configuration with similar provision for the storage and release of magnetic energy.

In developing theories of solar flares, such as those referred to above, there has been a strong tendency to concentrate on the very sudden release of energy occurring during the "impulsive" phase, which is closely related to what has been called the "flash" phase or "expansion" phase in earlier work based primarily on H-alpha data. It was implicitly assumed that to explain the impulsive phase is to explain the complete flare.

The above viewpoint is no longer accepted. In the Skylab workshop on solar flares (Sturrock 1980), it was clearly recognized that most flares manifest a release of energy during an "onset phase" (sometimes termed "pre-heating") occurring before the impulsive phase. This energy release is seen most clearly in the early buildup of soft X-ray emission. However, it has long been recognized that filament activity frequently occurs before a flare (Smith and Ramsey 1964), and this activity may be regarded as a "precursor" if it occurs about an hour before a flare, or as part of the onset phase if it occurs only a few minutes before the impulsive phase. Nevertheless, the filament eruption and the flare have been regarded as separate but related phenomena, rather than a single complex event (Van Hoven et al. 1980).

Although radiation continues long after the impulsive phase, there was for some time a tendency to regard the long-lived radiation as representing a slow decay of energy suddenly released during the impulsive phase. For instance, the soft X-ray emission can be attributed to hot plasma formed by "evaporation" of gas from the chromosphere during the impulsive phase (Neupert 1968; Hudson and Ohki 1972; Hirayama 1974; Antiochos and Sturrock 1976). However, careful analysis of certain flares (Moore et al. 1980) has shown that, for some flares at least, there must be continued energy release in what has been termed the "late phase" of a flare (Sturrock, 1980).

Indeed, H-alpha data for "two-ribbon" flares (Svestka 1976) provide very strong evidence for such continued energy release. In this case, the two flare filaments drift slowly apart (receding from the magnetic neutral line) so that, late in a flare, regions of the chromosphere are being heated which were not heated during the impulsive phase.

The facts listed above led, in 1980, to the view that there are not one but three phases of energy release in solar flares (Sturrock, 1980). However, a recent article by Feldman et al. (1982) points to a significant simplification in this picture. They have analyzed the time curves of hard and soft X-ray emission for two M flares (Doschek et al. 1981). Their findings are as follows:

1. The intensity of the soft X-ray flux in certain emission lines varies in a "smooth" manner during a flare.

2. The electron temperature is almost constant during the rise phase of the soft X-ray event. When the X-ray intensity begins to decrease, the

temperature can either decrease monotonically or decline slightly and then remain constant.

3. The soft X-ray emission varies in a smooth manner from the onset to the decay of the flare. There is no abrupt change in these quantities during the time when the impulsive hard X-ray burst is in progress. In particular, at the time of the hard X-ray burst, the temperature shows no change at all.

4. On comparing the X-ray emission for the M flare of 1979 March 31 with H alpha data (Zirin et al. 1981), it is found that the initial and main flare brightenings at visible wavelengths are coincident in time with the first hard X-ray "spike" burst. The soft X-ray event is associated with a new stage of the flare, the simultaneous formation of new bright loops which do not increase in size. Flare images in the lines of Fe XXIII and Fe XXIV recorded by the Skylab spectroheliograph, and observations by the Soflex experiment, indicated that the soft X-ray emission was confined to an area small compared to the H alpha flaring region and that the images did not increase in size during the flare.

Based on this and other data, Feldman et al. (1982) argue that the hard X-ray and soft X-ray events are not causally related to each other and that they probably occur in different flare volumes. Our own interpretation of the data leads us to accept the second conclusion, with the interpretation that the processes responsible for the soft X-ray burst and the hard X-ray burst probably occur in disconnected magnetic-field regions. On the other hand, the fact that the hard X-ray burst and soft X-ray burst occur in the same flare indicates to us that there must be some causal connection between these two processes.

For present purposes, the most important aspect of the work of Feldman et al. is to point out that the "onset phase" and "late phase" of a flare should be considered as a single phase—a phase manifested by soft X-ray emission--

which we term the "gradual phase." This use of the term is an extension of the use first proposed by Kane (1974), who had in mind only the soft X-ray emission following the impulsive phase.

In view of these recent developments, we here take the position that there is evidence for two distinct energy-release processes going on in a typical solar flare. One process is responsible for the impulsive phase and another for the gradual phase. For the time being, we retain the widely accepted proposition that energy release in solar flares is due to the release of the free energy associated with current-carrying magnetic-field configurations. Hence these two processes may represent either (a) two different modes of reconnection in otherwise similar magnetic-field configurations; or (b) two different current-carrying magnetic-field systems. We examine these two possibilities in Section II and tentatively conclude that the distinction is best interpreted by option (b). In reaching this conclusion, we have taken account of recent information (Tarbell et al. 1977) concerning the fine-scale structure of magnetic field at the photospheric level. Evidence indicates that the magnetic flux is typically concentrated into small amounts of order $10^{18.4}$ Mx. If this fact is accepted, it implies that the coronal magnetic field is comprised of similar flux tubes, each in a force-free configuration, and one must expect that there will be current sheets between adjacent flux tubes. In Section III, we attribute the impulsive phase of the flare to the release of the free energy associated with this fine-scale current system, including the current in each tube and the current between contiguous tubes.

By contrast, we attribute the gradual phase of energy release to reconnection of a large-scale current system. The identification of this current system leads to questions addressed in Section IV. In this section, we return to consider pre-flare activity in searching to identify the large-scale current system responsible for the gradual phase. We consider large two-filament flares and argue that a large current sheet develops as a result of the eruption of a filament. This eruption is itself to be interpreted as an MHD instability. It is possible that a similar, but less obvious, process arises in smaller flares. It is also possible that a similar configuration can arise in other ways, for instance, by the "flux-tube eruption" process considered by Priest and Haeverts (1974).

Further aspects of the flare energy-release problem are discussed in Section V.

## II. Gradual and Impulsive Phases

The purpose of this section is to examine the possible interpretations of the distinction between the gradual and impulsive phases.

It is useful to divide possible explanations of the difference into the following two categories:

A. The distinction is due to the time evolution of an energy-release process; or

B. The difference is due to the plasma-magnetic-field configuration in which energy release is occurring.

We first consider possibility A. If this explanation were strictly correct and were to explain observed flare behavior, then the energy release in a given flux tube must begin by being slow and smooth, suddenly become rapid and noisy, and then return to being slow and smooth. However, this interpretation does not fit the facts concerning two-ribbon flares. In these flares, it is clear that different magnetic-field configurations are involved in different stages of the flare, since the region of H-alpha brightening moves in the course of the flare. Moreover, the detailed analysis of two M flares by Feldman et al. (1982) indicates that different magnetic-field regions were, in those two cases, involved in the hard X-ray burst and soft X-ray burst which we associate with the impulsive and gradual phases.

A somewhat more flexible interpretation of this classification is the following. In some configurations, energy release begins slowly, then becomes rapid; in other configurations, the energy-release process never gets beyond the slow phase. In this case, we would be attributing the difference between the initial, gradual rise and the more rapid increase of the impulsive phase to a time sequence in the development of the energy-release process.

However, we would be attributing the distinction between the impulsive phase and the "late" phase of the gradual energy release to something else--the configuration of the regions involved.

Once again, we may refer to the analysis of Feldman et al. (1982) to evaluate this possibility. If the above hypothesis were correct, then part of the "early" phase, preceding the impulsive phase, would originate in a region different from that of the "late" gradual phase. However, for each of the two M flares analyzed, the evidence indicated that the gradual phase was a single coherent process.

On the other hand, it is possible that, when energy release does proceed through a slow to a fast mode, the slow part is so brief that it plays no part in the final form of the time-curves of the soft X-ray emission and hard X-ray emission. In this case we are simply saying that different types of configuration have different time-sequences of energy release. We have now lost the sharp distinction between categories A and B proposed at the beginning of this section, and we need to examine the possibility that the difference between the gradual and impulsive phases rests in the plasma-magnetic-field configurations involved. This then leads us to consideration of possibility B.

However, before proceeding to B, it is worth pointing out that there is evidence that the reconnection process of energy release does admit more than one form for the time-curve of the energy output. We refer to recent studies concerning reconnection carried out within the fusion community (Carreras et al. 1980, Carreras and Rosenbluth 1981). In an attempt to understand sudden current disruptions in tokamak devices, the reconnection ("tearing") process has been studied by computer simulation and by nonlinear analytical analysis. It is found that if reconnection leads to the development of a single tearing mode, or to modes which do not interact with each other, then reconnection proceeds in two phases: (I) The initial phase described by FKR (Furth, Killeen, and Rosenbluth 1963) linear theory, in which there is a slow but exponential growth, followed by (II) a nonlinear development in which the amplitude grows linearly with time.

If two or modes are unstable and begin to grow, they will proceed through the above two stages and, if the spatial locations of these two modes are sufficiently close together, they will enter a third stage (III) in which the "islands" which develop in each mode come into contact. When this occurs, the interaction of the two modes leads to a very rapid exponential growth of one or more modes, the rate of growth at this stage being considerably larger than the rate of growth in the initial regime of linearized theory.

In the cases investigated by numerical simulation by Carreras et al. (1980), the initial growth did, in fact, occur at a rate consistent with FKR theory, i.e., at a rate which is approximately the geometrical mean of the MHD rate and the diffusion rate. On the other hand, when mode-interaction occurred leading to the third stage of growth, the rate was closer to the MHD rate and, therefore, substantially faster than the FKR rate. If a similar distinction were to occur in the reconnection processes occurring in solar flares, it is likely that the difference in the growth rates between phases (I) and (III) would be much more pronounced, since the magnetic Reynolds numbers are much larger in solar flares than in laboratory devices due to the fact that the length scales are so much larger.

An important aspect of the third stage of the reconnection process is that the magnetic-field behavior becomes stochastic. Depending on the time scale, this may contribute to the rapid fluctuation in energy release during the impulsive phase of a flare. During the rapid mode of energy release (III), components of electric field parallel to the magnetic field attain higher values, which could explain the acceleration of electrons to many tens

/ during the impulsive phase. Furthermore, strong MHD turbulence is ›ped, which can help explain the acceleration of electrons and ions to .vistic energies via stochastic acceleration.

'o sum up, it appears that if in a given configuration only a few modes and those not to large amplitude, then the energy release will be slow. the other hand, many modes simultaneously grow to large amplitudes, ınergy release may enter a rapid stochastic mode. It is important to .ccount of these possibilities in evaluating the rate of energy release given model and in considering the rate of particle acceleration. :heless, for reasons given earlier, we do not consider that the :ence in rates of the linear and nonlinear reconnection processes is to explain the difference between the gradual and impulsive phases of a

'e now consider possibility (B) that the distinction between the gradual ıpulsive phases is due to a difference in the configurations in which ection occurs. We consider in turn the possibilities that the crucial :ence is in (a) plasma density, (b) magnetic field strength, or (c) ı scale.

f one region has a higher plasma density than another, then the Alfvén will be slower and the reconnection rate should be slower. There is evidence that, during the impulsive phase of a flare, the chromosphere ıbarded by high-energy electrons and this bombardment leads to evapora- f the chromosphere into the corona (Neupert 1968; Hudson and Ohki 1972; ma 1974; Antiochos and Sturrock 1976). Hence the impulsive phase leads increase in density of the coronal region by a factor of 100 or possibly It is therefore tempting, at first sight, to ascribe the difference n the rapidity of the impulsive phase and the slowness of the late part gradual phase to a decrease in the Alfvén speed due to chromospheric evaporation. There are, however, two objections to this interpretation:- One is that some flares have no impulsive phase (see, for instance, Kane 1969); the second is that chromospheric evaporation, due to the impulsive phase, has not occurred at the time of the early part of the gradual phase. For these reasons, we believe that this interpretation of the distinction between gradual and impulsive phases must be discarded.

We next consider possibility (b), that the distinction rests in the magnetic field strength. This might be a viable interpretation if there were evidence that the distribution of magnetic-field strengths at coronal heights in active regions tends to be bimodal—for instance, that the magnetic field strength tends to be of order 10 gauss or of order 1000 gauss. There is unfortunately no direct evidence concerning the magnetic field strength at coronal heights. At the photospheric level, there is a great deal of fine structure which will be discussed later. However, the coronal field strength at heights of, say, 10,000 km should be determined by the photospheric field strength averaged over such length scales. There is no evidence from magnetograms that such averages yield a bimodal distribution of magnetic field strengths. It therefore seems unlikely that the distinction between the impulsive and gradual phases is due to possibility (b).

We are now left with possibility (c), which we shall discuss in more detail in the next two sections.

## III. Attribution of the Impulsive Phase to Fine-scale Structure of the Magnetic Field

If a distinction between the gradual and impulsive phases is to be ascribed to the length scale of the magnetic-field configurations involved, then we must find evidence that two different types of length scales are involved in magnetic-field configurations, one yielding a large-scale current pattern responsible for the gradual phase, and the other yielding a fine-scale current structure responsible for the impulsive phase. If this bimodal classification of length scales exists, it should be apparent from photospheric data, since the coronal magnetic-field structure is determined by the photospheric field structure.

The large-scale structure of the magnetic field of active regions is readily apparent from magnetograms. One of the simplest examples is that of a bipolar region in which regions of positive and negative polarity are divided by a magnetic polarity reversal line. Many types of more complex configuration have been classified. In some cases, attention is drawn to the signficance of small regions such as a small region of emerging flux (Priest and Haeverts 1974) or "satellite sunspots" which are responsible for surge activity (Rust 1968).

In recent years, we have learned that the early magnetograms have been misleading in indicating a continuous sequence of magnetic field strengths from the smallest detectable values (a few gauss) to the values characteristic of sunspot umbrae (several thousand gauss). Observations by Tarbell and Title (1977) and others now indicate that, at the photospheric level, magnetic field lines tend to be pulled together into small flux regions with dimensions of order 500 km or less, in which the magnetic field strength is of order 1000-1500 gauss. In consequence, the magnetic field at the photosphere tends to be aggregated into "knots" in which the flux has values of order $10^{18.4}$ Mx. There is insufficient data to determine the range of values of magnetic flux in such knots. For simplicity, we adopt the value $10^{18.4}$ Mx, recognizing that this is an arbitrary value in a range of likely values. This leads to the picture, which is undoubtedly oversimplified, that the magnetic field penetrating the photosphere is "quantized" in flux. This suggests that the magnetic field in the corona will comprise an assembly of flux tubes, which could be termed "elementary flux tubes", each originating in a strong-field knot in the photosphere and terminating in another knot. In general, one must expect each knot to be connected to more than one such tube. If this is the case, the magnetic flux of these tubes will normally be less than that of a typical knot, but the value of the flux should have the same order of magnitude.

If the magnetic field of the photosphere were structured as indicated above, the magnetic field at coronal heights will show little evidence of this structure if the magnetic field is current-free. The effect of the elementary-flux-tube structure would decay with height in a distance comparable with the distance between flux tubes. If the average photospheric field strength is 100 gauss, this inter-knot distance is about 1500 km.

However, as has been pointed out elsewhere in connection with the problem of coronal heating (Sturrock and Uchida 1981), one must expect that granular motion of the photosphere will produce random rotations in these elementary flux tubes. These rotations will lead to distributed current, in the form of a force-free field, in each such tube, and will also lead to intense current sheets separating contiguous tubes.

We may estimate the thickness b (cm) of the current layers between the flux tubes by estimating the distance diffusion may proceed within a time $\tau_0$

characteristic of the rate of change of the configuration of the flux tubes. Hence

$$b = (D\tau_0)^{1/2} \quad , \tag{3.1}$$

where D is the diffusion coefficient, which is expressible (Spitzer 1962) as

$$D \simeq 10^{13.0}\ T^{-3/2} \tag{3.2}$$

if diffusion is due to coulomb collisions.

The characteristic growth time $\tau_L$ (s) of the linear phase of the tearing-mode instability, given by Furth-Killeen-Rosenbluth (1963) theory, is given by

$$\tau_L = \tau_D^{1/2}\ \tau_A^{1/2} \tag{3.3}$$

In this equation, $_D$ is the diffusion time, which is given by

$$\tau_D = D^{-1} b^2 \quad , \tag{3.4}$$

and $\tau_A$ is the time required for an Alfvén wave to travel across the layer, which is given by

$$\tau_A = v_A^{-1}\ b \tag{3.5}$$

where the Alfvén speed $v_A$ is given by

$$v_A \simeq 10^{11.3}\ B\ n^{-1/2} \quad . \tag{3.6}$$

In this expression, n ($cm^{-3}$) is the density of electrons or protons.

On combining the above equations, we find that $\tau_L$ may be expressed as

$$\tau_L = 10^{-12.1}\ B^{-1/2}\ T^{3/4}\ n^{1/4}\ b^{3/2} \tag{3.7}$$

if we assume that b is known. If, on the other hand, we assume that b is determined by the diffusion process according to equation (3.1), then the growth time is expressible in terms of $\tau_0$ as

$$\tau_L = 10^{-2.4} B^{-1/2} T^{-3/8} n^{1/4} \tau_0^{3/4} \quad . \tag{3.8}$$

To assess the significance of the above ideas, we consider values typical of an active region: $B = 10^2$, $T = 10^{6.4}$, $n = 10^{8.5}$. If the change of configuration of flux tubes is attributed to granular motion, then we may choose for $\tau_0$ the characteristic lifetime of granules, about $10^{2.6}$ s. With these values, we find that b is about $10^{3.0}$, i.e., the current layer is about 10 m in thickness. The growth time of the linear phase of the tearing-mode instability is then found to be $10^{-1.7}$ s, or 20 ms.

The time taken to release the energy in an elementary flux tube will be determined by the time it takes to reconnect the internal field of the flux tube in such a way as to release the free energy associated with the distributed current in the tube. If the total flux is $10^{18.4}$ Mx and $B = 10^2$, then the radius R (cm) of the tube is $10^8$. We then find from (3.7) that the growth time of the linear phase of the tearing-mode instability is of order $10^6$ s, which is negligibly slow. However, if the tearing mode starts in the current sheet between flux tubes, and develops into the nonlinear phase described by the model of Carreras <u>et al</u>. (1980), then reconnection can proceed almost at the Alfvén velocity. In this case, we may estimate the energy-release time as

$$\tau_R = v_A^{-1} R \quad . \tag{3.9}$$

For the example under discussion, we find that $\tau_R = 10^{-1}$ s.

The free energy U (erg) stored in a single flux tube may be estimated from calculations presented by Sturrock and Uchida (1981):

$$U = \frac{\Phi^2(\Delta\chi)^2}{16\pi^2 L} \quad , \tag{3.10}$$

where $\Phi$ (Mx) is the magnetic flux, L (cm) is its length, and $\Delta\chi$ (radian) is the angle of relative rotation of the ends of the tube. In reality, it is likely that the maximum permissible value of $\Delta\chi$ is set by the requirement of stability of the flux tube. Stability analysis of a realistic model will be difficult and is deferred for a subsequent study. For present purposes, we adopt the limit $\Delta\chi = 2\pi$, which we infer by applying the analysis of Anzer (1968) to the Gold-Hoyle (1960) model of a force-free field. Then, adopting $\Phi = 10^{18.4}$, we find that

$$U = 10^{36.2} L^{-1} \quad . \tag{3.11}$$

For a typical length $L = 10^9$, we find that $U = 10^{27.2}$.

We see from the above calculations that the fine-scale structure of the coronal magnetic field leads us to expect that reconnection can lead to the sequential release of energy in many distinct locations. This is rather like a "firecracker" in which the explosion of one element, after a short delay, triggers energy release in an adjacent element. We propose that this process is responsible for the impulsive phase of a solar flare.

If this interpretation is correct, there should be some evidence that energy release during the impulsive phase is comprised of a sequence of individual explosions. Such evidence has been presented recently by Kaufmann _et al._ (1980), who claim that detailed analysis of millimeter-wave solar bursts is indicative of a "quasi-quantization" of this radiation. It has been found that impulsive millimeter-wave solar bursts are typically comprised of a sequence of narrow spikes. For bursts examined in detail, the half-rise-time of an individual spike ranges from less than 6.3 msec to 80 msec. The flux level of bursts rises as the repetition rate of spikes increases, following an approximate linear relationship. Consequently, Kaufmann _et al_. propose that "the flare energetic injections are quasi-quantized in energy."

A somewhat similar structure of the impulsive phase of a solar flare has also been suggested by time-resolved flux structures of hard X-ray bursts (Frost 1969; Van Beek _et al_. 1974) and at decimetric wavelengths (Dröge 1977; Slottje 1978). In an earlier publication, Kaufmann _et al_. (1978) consider the relationship between microwave radiation and X-ray radiation, and conclude that each microwave spike is to be associated with the radiation of $10^{27}$ erg in X-rays, in agreement with the energy associated with the X-ray emission of "elementary flare bursts" proposed by van Beek _et al_. (1974) and by de Jager _et al_. (1976). This association needs more detailed analysis, but we accept this estimate for present purposes. The above conclusions of Kaufmann _et al_. appear to be consistent with the main thesis of this section.

The energy associated with reconnection at a current sheet is only a small fraction of the energy associated with an elementary flux tube, but reconnection at a sheet may be sufficiently fast and violent to trigger reconnection in a tube. The amount of energy in an individual tube may be estimated from equation (3.11). If a typical active region contains an array of flux tubes ranging in length from $10^{8.5}$ cm to $10^{10.0}$ cm, we see that the free energy in each tube will range from $10^{26}$ erg to almost $10^{28}$ erg. This provides a reasonable fit to the energy of elementary X-ray flare bursts.

We found earlier in this section that, if reconnection of an elementary flux tube were to proceed according to linear theory, the reconnection rate would be negligibly slow. However, if the reconnection is sufficiently violent to enter the nonlinear phase described by the model of Carreras _et al_. (1980), then reconnection of a flux tube with $B = 10^2$, $R = 10^8$ would proceed in about $10^{-1}$ s. On the other hand, a low-lying flux tube near a pair of sunspots might have $B = 10^3$ and $R = 10^{7.5}$, which would then lead to a reconnection time of only $10^{-2.5}$ s, i.e., 3 ms. We see, therefore, that a reasonable range of lengths and field strengths of the elementary flux tubes can explain the observed rise times of microwave spikes examined by Kaufmann et al. (1980).

It appears, from the above, that the fine-scale magnetic field structure the corona, which is to be expected from the fine-scale structure in the photosphere, offers a tentative explanation of both the energy scale and time scale of elementary spike bursts from solar flares.

## IV. Attribution of the Gradual Phase to Large-scale Structure of the Magnetic Field

We now consider, for definiteness, a typical (and therefore hypothetical) two-ribbon flare. The gradual phase of the flare as inferred from soft X-ray emission corresponds to the duration of the slow separation of the two flare filaments. This separation typically occurs at a speed of order $10^6$ cm $s^{-1}$ or less (Svestka 1976). Hence, if the overall extent of a flare is order $10^{10}$ cm, the gradual phase will last for many hours. However, it should be remembered that the gradual phase of soft X-ray emission usually begins before the impulsive phase of the burst, that is, before there is obvious H-alpha emission.

We examine the possibility that the gradual phase is attributed to reconnection of a large-scale current sheet as proposed in an earlier model (Sturrock 1968). Consider the possibility that reconnection is occurring in the high corona where the magnetic field strength is only 10 gauss and the plasma density is of order $10^8$ $cm^{-3}$. Then the Alfvén speed will be $10^{8.3}$ cm $s^{-1}$. If reconnection were to occur at this rate over dimensions of order $10^{10}$ cm, the duration would be only $10^{1.7}$ s.

We first note, however, that the H-alpha emission shows what is occurring at the foot-points of the magnetic field. If the average magnetic field strength at the photospheric level is $10^2$ gauss, then a reconnection rate of $10^{8.3}$ cm $s^{-1}$ in the high corona would give a projected speed of only $10^{7.3}$ cm $s^{-1}$ at the chromospheric level. Even this is too high to explain the slow rate of separation of the flare filaments.

One must therefore conclude that reconnection of the large current sheet is not proceeding at the rapid rate described by phase III of the sequence described by Carreras et al. (1980). If we suppose, as an alternative, that reconnection proceeds at the rate described in the Petschek (1963) model, the rate will be reduced by a factor of ten. In this case, the projected rate of separation of the flare filaments at the chromosphere would be only $10^{6.3}$ cm $s^{-1}$, which is close to the observed values.

It is notable that acceleration of particles to high energies appears to be associated with the impulsive phase of a solar flare, not with the gradual phase. This is consistent with our conjecture that reconnection in the fine-scale magnetic-field structure proceeds by the large-amplitude stochastic tearing mode, whereas reconnection in the large-scale magnetic field proceeds at a slower rate characteristic of the quiescent nonlinear mode. However, it remains to be determined whether the Petschek model offers a realistic description of reconnection in a large current sheet as we have here assumed.

Since the gradual phase of a solar flare begins before the impulsive phase, it is clear that reconnection of the fine-scale magnetic-field must be triggered as the result of reconnection of the large-scale magnetic field (in which case we must determine what starts reconnection of the large-scale magnetic field), or that large-scale reconnection and small-scale reconnection are triggered sequentially by some other event. In either case, we are led to seek one more-or-less sudden event as the initiator of a solar flare.

It is known that two-ribbon flares occur in active regions containing a prominent filament (Smith and Ramsey 1964; Svestka 1976). Some hour or so before the flare, the filament will become disturbed. Shortly before the flare, the filament will erupt. A filament eruption produces a coronal transient, which in turn leads to a high-speed ejection from the sun (Rust and Hildner 1980). It is well known that the energy associated with such an ejection is normally the dominant form of energy release associated with such a flare.

The close association between filaments and flares was emphasized by Kiepenheuer (1964), who wrote, "Those who have seen in an accelerated movie the brightening of a flare out of a dark filament, and the almost chaotic interaction of bright and dark structures, will not doubt the existence of a causal relation between the activation of a dark filament and the formation of a flare." We consider that, in view of the above facts, it is reasonable to regard the filament eruption as the primary process, and the solar flare as a subsequent secondary event. Since only a small fraction of filament eruptions lead to solar flares, we may infer either that a filament eruption may or may not produce a magnetic-field configuration susceptible to reconnection, or that it invariably produces a field configuration susceptible to reconnection but reconnection does not always occur.

When a prominence eruption is seen in H-alpha light in high resolution, it gives the appearance of a twisted magnetic flux tube (see, for instance, Kiepenheuer 1953). This suggests that a filament initially has the configuration of a low-lying twisted flux tube, which is held in place by an overlying magnetic-field structure. If the twist increases, or the configuration changes in some other way, the balance of forces may change so that the configuration becomes unstable. We conjecture that the instability is such as to lead to the sudden eruption of the flux tube; this will certainly disturb the surrounding magnetic field. It has been proposed (Sturrock 1974) that the eruption of a filament will give rise to the Y-type magnetic-field configuration which has been suggested (Sturrock 1968) as a model for a large solar flare.

One possibility is that filament eruption produces a large current sheet which does not reconnect. This would then lead to the appearance of a coronal streamer, which does in fact occur in the event that a filament eruption and coronal transient are not associated with a flare. If, on the other hand, the large-scale sheet does reconnect, then this would represent the gradual phase of the solar flare. Reconnection of the large-scale field will give rise to MHD disturbances, which can in turn trigger energy release in the fine-scale magnetic-field structure. This represents the initiation of the impulsive phase of the flare.

## V. Discussion

The preceding sections are presented as a possible scenario to explain the main phases of energy release in a solar flare. It is proposed that the flare process really begins with the eruption of a filament. This may or may not lead to reconnection of a large-scale current sheet, which would then be recognized as the gradual phase of the flare. Reconnection of the large-scale current sheet may or may not precipitate reconnection of the fine-scale magnetic-field structure associated with the small knots of magnetic field known to exist at the photospheric level. If this occurs, the flare would display an impulsive phase.

This scenario appears to give a causal relationship between the above three processes. Simple dimensional estimates suggest that the time scales and energy scales of the gradual and impulsive phases are consistent with this model. However, it is desirable that numerical experiments, similar to those carried out for cylindrical geometries of the tokamak type, be carried out also for geometries such as the Y-type current sheet geometry to confirm or modify the Petschek estimate of the reconnection rate.

Such calculations are important also for understanding which geometry provides the more favorable conditions for particle acceleration. If the impulsive phase is due to stochastic reconnection in magnetic-field configurations of high field strength and small length scale, conditions should be favorable for acceleration. If the gradual phase is due to reconnection of an extended current sheet of lower magnetic field strength, conditions may or may not be favorable, depending upon the process of reconnection and the length-scales of magnetic-field fluctuations generated in this process.

r discussion in Section IV concerned large two-filament flares, but re only a small minority of all observed flares. We must therefore ask the above scenario is relevant to flares of all types, or only to the bbon category. The answer to this question is not clear. If this o is applicable to all flares, then all flares would involve the erup- a filament or of a smaller structure which plays the same role in a flare that a filament plays in a large flare. Zirin (1982) is of the n that the former is in fact the case. He claims that in almost all one can detect the presence of a "filament" before the flare, which es in the course of the flare. In this context, Zirin defines a nt" as an elevated structure, which is observed to be dark in H-alpha located above a polarity reversal line. The sequence of events is that lament rises and that there may or may not be some brightening in H it that time; this activity is followed by the impulsive phase of the

the above scenario is adopted as a working hypothesis for the sequence its in a solar flare, many questions remain to be examined in more It is essential that we have a clear understanding of the nature and re of filaments, and that we determine whether or not such structures sent in all regions which produce flares. It is also essential that we tand the stability of such structures and the evolution of the lity, if the filament becomes unstable. This should help us to under- he generation of coronal transients as well as the initiation of solar

need to understand what magnetic-field configurations can be produced sult of a filament eruption. We then need to understand whether the urations are of one type (for instance, whether they always involve a t sheet) which is susceptible to reconnection, or whether a filament eruption can generate two (or more) distinct configurations, only one of which can reconnect. Answers to these questions would help us to understand why some filament eruptions give rise to flares but others do not.

We also need to obtain a more detailed understanding of the fine-scale structure of the sun's magnetic field at the level of the photosphere and in the corona. It has been proposed elsewhere (Sturrock and Uchida 1981) that quiescent energy release of free energy associated with the fine-scale magnetic-field structure in the corona is in fact responsible for coronal heating in active regions. Hence, further study of the structure and evolution of active regions may confirm or disprove the existence of fine-scale magnetic-field structure at coronal heights.

If the existence of such fine-scale structure at coronal heights is confirmed, it is important to make more realistic estimates of the structure of the elementary flux tubes and of the current sheets which separate these tubes. A critical investigation will be that of the stability of twisted flux tubes, which must of course be based on realistic models of the quiescent structure of these tubes. One of us (P.A.S.) has recently developed such a model, which will be published in the near future. The stability analysis is critical for answering two questions: (a) how much free energy may be stored in a twisted flux tube? and (b) what happens to a flux tube when it becomes unstable?

Our case for attributing the impulsive phase of a flare to reconnection of fine-scale magnetic-field structure is supported by arguments concerning the time scale and energy scale of such energy release. However, there are two types of currents involved in the fine-scale structure: the current sheets between adjacent tubes, and the distributed currents in the tubes themselves. It is likely that the former would provide more rapid energy release than the latter, and acceleration to higher energies, but the amounts of energy released would be much smaller. It is therefore, possible that the current sheets are mainly responsible for acceleration producing microwave radiation, whereas the distributed currents are mainly responsible for the heating which produces the X-ray bursts. Examination of these conjectures will require more detailed comparison of the time curves of microwave and X-ray bursts.

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