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RAPID FLUCTUATIONS IN SOLAR FLARES

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ABSTRACT

Study of rapid fluctuations in the emission of radiation from solar flares provides a promising approach for probing the magneto-plasma structure and plasma processes that are responsible for a flare. It is proposed that "elementary flare bursts" in X-ray and microwave emission may be attributed to fine structure of the coronal magnetic field, related to the aggregation of photospheric magnetic field into "magnetic knots." Fluctuations that occur on a sub-second time-scale may be due to magnetic islands that develop in current sheets during magnetic reconnection. The impulsive phase may sometimes--or possibly always--represent the superposition of a large number of the elementary energy-release processes responsible for elementary flare bursts. If so, one faces the challenge of trying to explain the properties of the impulsive phase in terms of the properties of the elementary processes. For instance, if the impulsive phase produces a power-law energy distribution of energetic particles, this may be due to scaling laws governing the elementary processes rather than to power-law acceleration in the each elementary event. Magnetic field configurations that might produce solar flares are divided into a number of categories, depending on: whether or not there is a filament; whether there is no current sheet, a closed current sheet, or an open current sheet; and whether the filament (if present) erupts into the corona, or is ejected completely from the sun's atmosphere. Analysis of the properties of these possible configurations is compared with different types of flare, and to Bai's subdivision of gamma-ray/proton events. The article ends with a number of theoretical questions related to the study of rapid fluctuations in solar flares.

I. Selected Observational Data.

This introduction will present a brief review of some of the forms of rapidly fluctuating output produced by solar flares, and a brief discussion of some of the relevant aspects of the flare problem.

One of the earliest studies of rapidly fluctuating X-rays was carried out by van Beek and his collaborators (van Beek et al. 1974). They found indications that the fairly brief hard X-ray flares that they investigated could all be decomposed into a number of smaller bursts with rise and decay times of the order of a few seconds. These spikes were called "elementary flare bursts." They estimated the energy involved in such a burst, on the basis of a thick-target model, assuming that the electron beam is impinging on the chromosphere, and found the energy to lie within the range 10^{27} to 10^{28} erg.

Although the early analysis was carried out by eye, de Jager and de Jonge (1978) later made a more systematic study involving a procedure similar to the CLEAN algorithm used in radio astronomy. They found that it was possible to represent a typical record as a sequence of standard pulses with a selected triangular profile. See Figure 1.

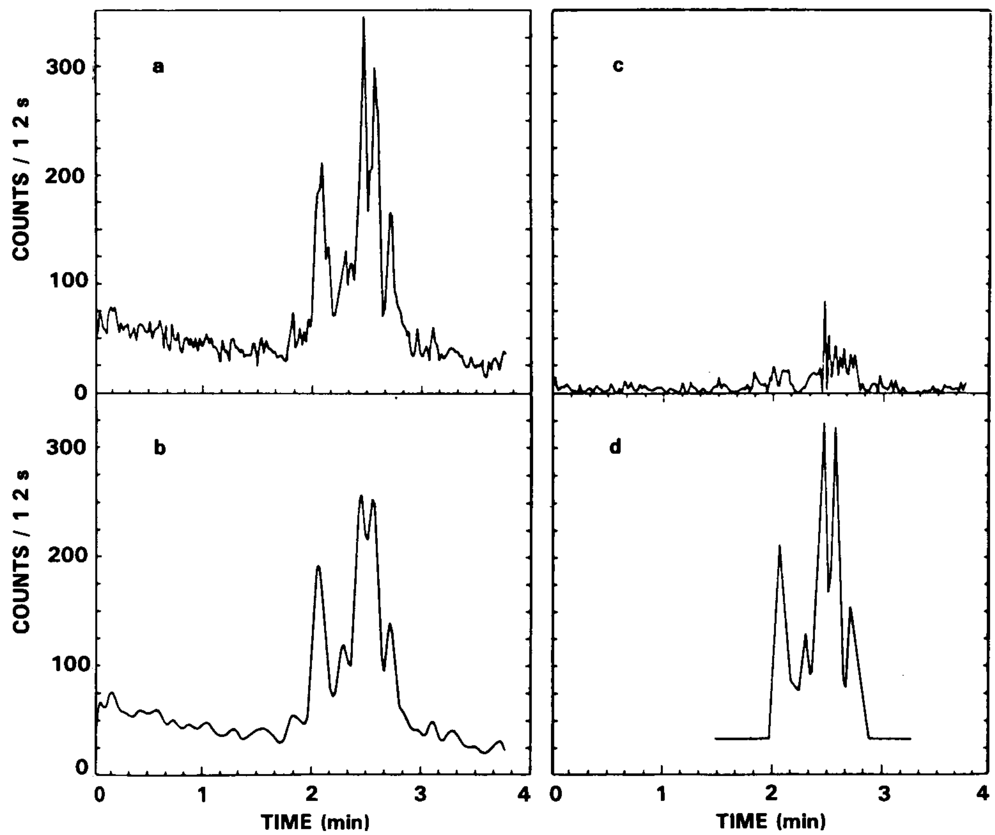

Fig. 1. *Filtering the noise, and decomposition into EFB's. (a) The X-ray flare of 1972, August 2, 18:39 UT as observed. (b) Filtered flare profile. (c) Residual noise after subtraction of the EFB's and continuous background. (d) Analytic flare profile, composed of the EFB's (de Jager and de Jonge 1978).*

Tremendous advances were made as a result of the Solar Maximum Mission. The HXRBS experiment provided data recorded in two modes, the normal mode having a time resolution of 128 ms, and a rapid mode having a resolution of about 10 ms. Only about 10 percent of flares were found to show fine structure. But, of that 10 percent, fine structure was detected on a time scale down to about 30 ms. An example of such a record, taken from Kiplinger et al. (1983), is shown in Figure 2.

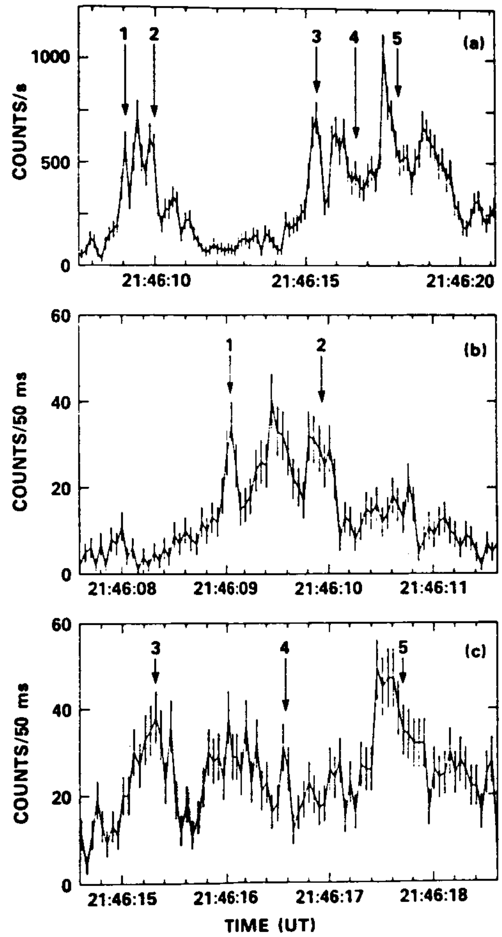

Fig. 2. *Hard X-ray time profiles (29-183 keV) of a solar flare which occurred on 1980 October 18. The curve in (a) shows PHS data at 128 ms per point, while curves in (b) and (c) show memory data at 50 ms per point. The numbered features indicate varying morphologies that are present within a single 9 s interval (Kiplinger et al. 1983).*

It is possible to make observations with an even finer time resolution in the radio part of the spectrum. Kaufmann and his collaborators have been carrying out such observations for several years with equipment at the Itapetinga Observatory, normally operating at 22 gHz and 44 gHz. Figure 3 is an example of a radio impulse (Kaufmann et al. 1984). The figure also includes data from Owen's Valley Radio Observatory that operates at 10.6 gHz. This burst is a few seconds in duration leading one to suspect that it is produced by basically the same process as produces the "elementary flare bursts" discovered by the Dutch solar X-ray astronomy team.

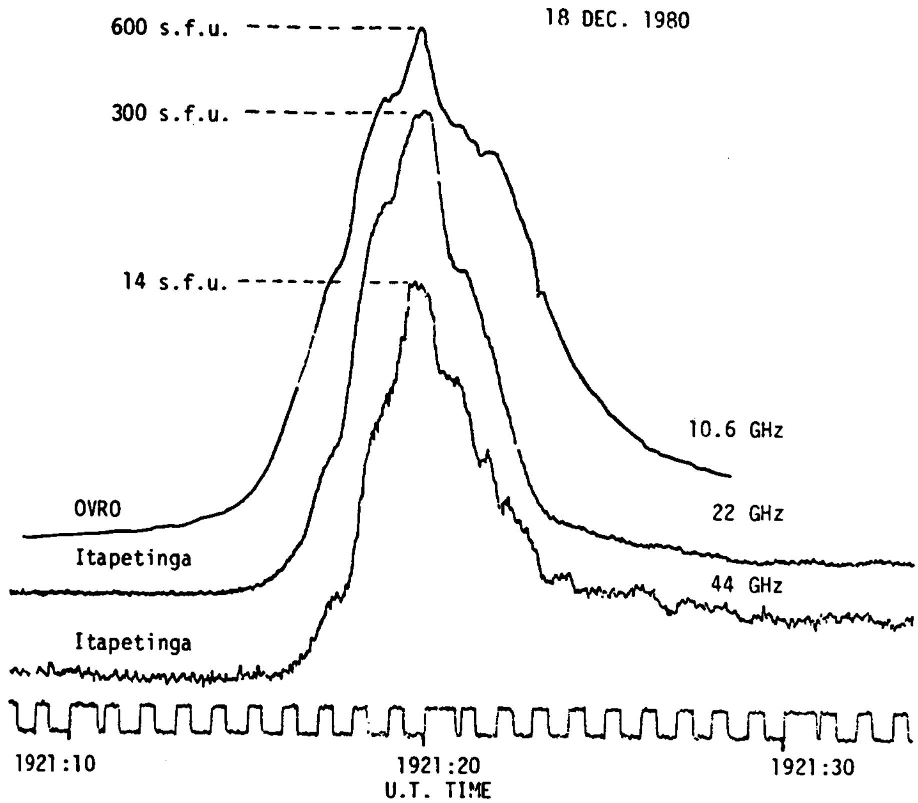

Fig. 3. *The 18 December 1980, 19:21:20 UT spike-like burst, as observed at 44 GHz, 22 GHz, and 10.6 GHz. Slower time structures are evident, especially at 44 GHz (Kaufmann et al. 1984).*

However, the radio observations offer much higher time resolution than the early X-ray observations. It is found that there is clearly good correspondence between the records obtained at 22 gHz and 44 gHz, so that the fluctuations are real and probably represent fluctuations of the process producing the high-energy electrons responsible for the radio emission.

Kaufmann et al. (1985) have more recently published data concerning a very interesting burst that is clearly evident at 90 gHz, but is barely detectable at lower frequencies. This is a very surprising event and a real challenge for theorists.

Another very exciting development has been Lin's balloon-borne experiment. This experiment is much more sensitive than the instruments on board SMM, and we see from Figure 4 (Lin 1984) that very low-level bursts are continually present on the sun. There are reasons to believe that these bursts are due to active regions that were present on the sun at that time.

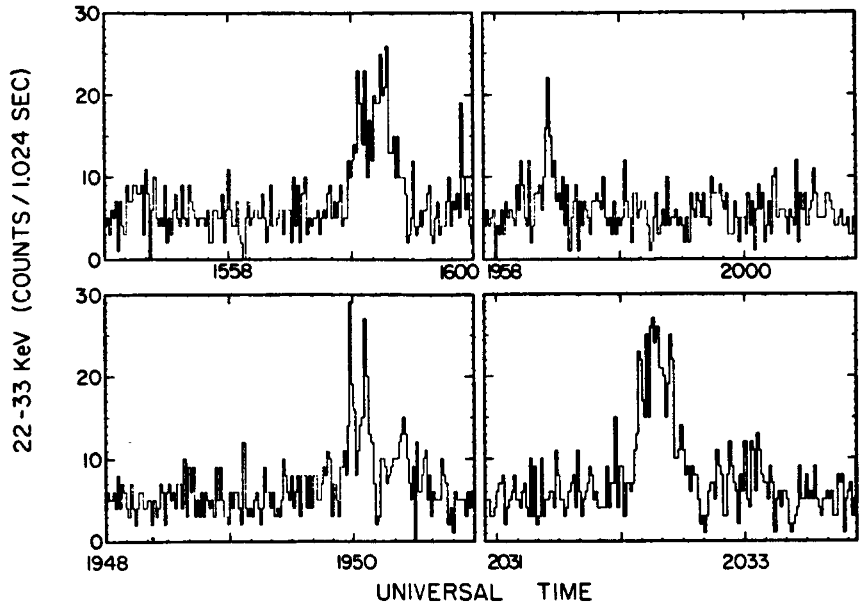

Fig. 4. *The four largest hard X-ray microflares are shown here at 1.024 s resolution (Lin et al. 1984).*

We need to ask whether these low-level fluctuations are related to solar flares. Figure 5, taken from Lin et al. (1984),

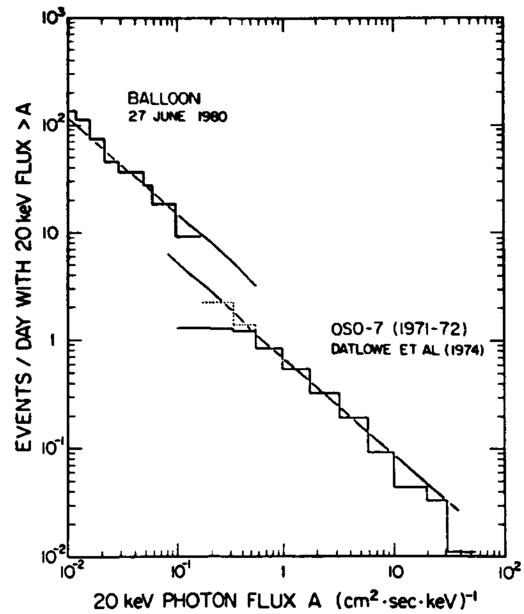

Fig. 5. *The distribution of the integral rate of occurrence of events vs. peak 20 keV photon flux for the solar hard X-ray microflares observed in this balloon flight. Also shown for comparison is the distribution of solar flare hard X-ray bursts reported by Datlowe, Elcan, and Hudson (1974) (Lin et al. 1984).*

presents a histogram of the number of events per day as a function of photon flux, for photons of energy 20 keV or more. In the same diagram, Lin has reproduced comparable data derived by Datlowe et al. (1974) from analysis of OSO-7 data. We see that each experiment produces a well defined power-law histogram, and one can well imagine that if instrumental differences and/or variations in time were taken into account, the two histograms would be found to form one continuous curve. It certainly appears from this work that the same process is operative in both ranges of photon flux, suggesting that flares do not cut off at any particular level but continue down to a much lower level than we had previously thought. Lin has indeed introduced the term "microflares" to describe these low-level fluctuations.

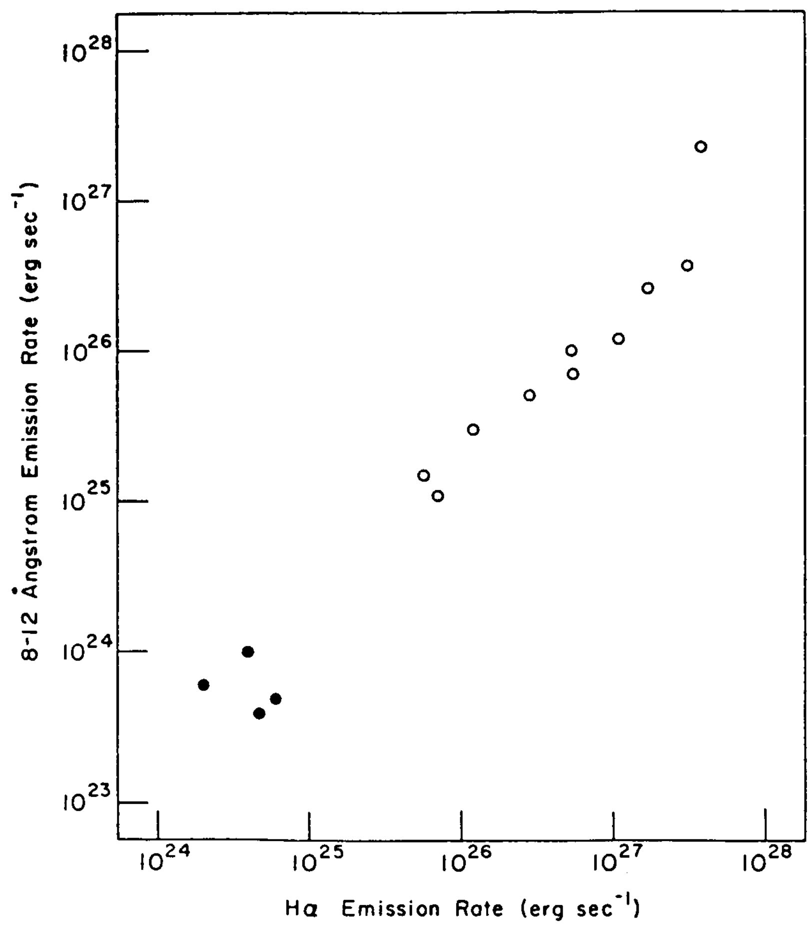

Fig. 6. *Relationship of mean peak emission rates in H-alpha and in soft X-rays for flares (open circle) and for spike events (filled circles). Flare data have been taken from Thomas and Teske (1971) (Teske 1971).*

A very important question to be addressed is the relationship between X-ray bursts and radio bursts. Kaufmann and his collaborators (Takakura et al. 1983) have indeed analyzed a few bursts in terms of both X-ray and microwave data. For the events they analyzed, there appeared to be little correspondence on the one-second time scale, but some correspondence on a finer time scale. A significant study was carried out about 15 years ago by Teske (1971) using soft X-ray data obtained from the instrument on board OSO-3. Teske searched for a correlation between soft X-ray fluctuations and Type III bursts and found that about ten percent of the X-ray bursts were in fact correlated with Type III bursts. Teske was concerned also to search for corresponding H-alpha events. He selected periods when active regions were on the limb of the sun, and then examined the X-ray data for small isolated bursts. He found that there was a very high correlation between H-alpha events on the limb and X-ray bursts. The H-alpha events could be classified into several types, but the one which showed the strongest correlation with small X-ray bursts of a few seconds duration were small surge-like or spike-like ejections (large spicules or small surges) reaching heights of between 10,000 and 40,000 km. Teske compared the ratio of mean peak emission rates in H-alpha and in soft X-rays for these spike events and for flares (Figure 6) and found that the ratio for spike events was indistinguishable from the ratio for flares. This again suggests that the flare process continues to a lower energy level than that for which events are usually recognized as "flares."

It is unfortunate that the time resolution of the H-alpha data was only about 15 or 20 seconds (as is typical of flare patrols). There is a need for this work to be repeated using H-alpha observations that have as high a time resolution as the radio and X-ray data. Teske's analysis indicates that the X-ray event tends to occur shortly before the Type III event. This is a curious result, and it would be interesting to see if further investigations confirm it and also to determine the relative timing of the X-ray and radio events with respect to the optical event.

II. Selected Theoretical Concepts.

In order to see how the flare problem has progressed, it is interesting to look back at flare theories that were advanced more than 20 years ago. At that time, a theorists considered that he had only two facts to explain. One is that a large flare involves an energy release of order 10^{32} ergs, and the other is that the time scale for energy release is (or was at that time thought to be) about two minutes. Although the first fact needs little modification, the second fact requires a great deal of elaboration in both directions. We now believe there is energy release on a much longer time scale than two minutes, and--as is the focus of this workshop--we also believe that there is energy release on a very much shorter time scale.

Early models were already based on the idea that the stored energy is magnetic and that a flare releases the free energy associated with the coronal current system. In order to achieve sufficiently rapid energy release, theorists were soon lead to the concept of current sheets. The first explicit current-sheet model (Figure 7) was that of Peter Sweet (1958) who considered that approaching sunspots would develop a current sheet that would persist for some time, then suddenly disappear as the result of magnetic reconnection.

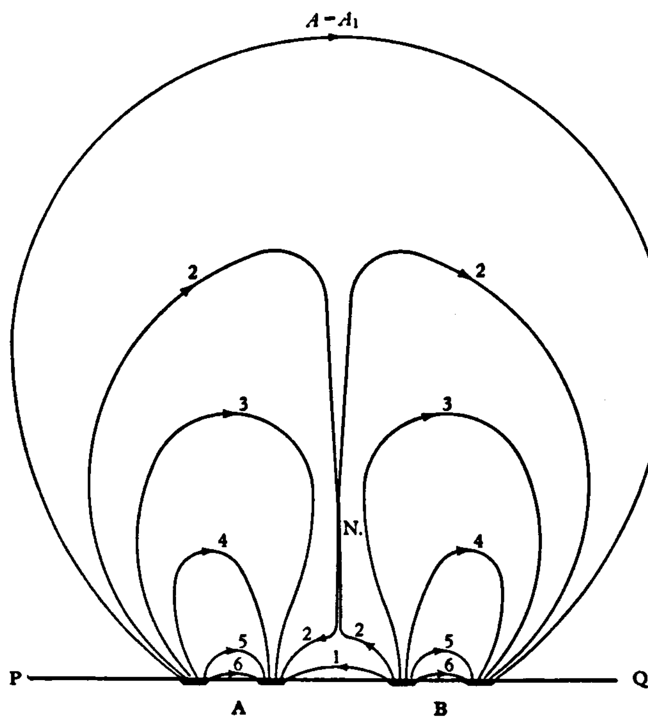

Fig. 7. *Sweet model. Movement towards each other of magnetic dipoles A and B produces a current sheet with "neuteral line" N in an atmosphere assumed to be perfectly conducting (Sweet 1958).*

In one form or another, this idea still persists. One of the flare models that is still very much alive and well is the flux-emergence model of Heyvaerts et al. (1977) and others (Figure 8), in which it is imagined that a new flux region emerges into an old pre-existing flux region, and that the interface comprises a current sheet. In an early stage, there may be only a "soft" instability that is considered to be responsible for "preheating." At a later stage, if the sheet becomes sufficiently thin, there may be a "hard" instability that produces an impulsive energy release, considered to be responsible for the impulsive phase of a flare.

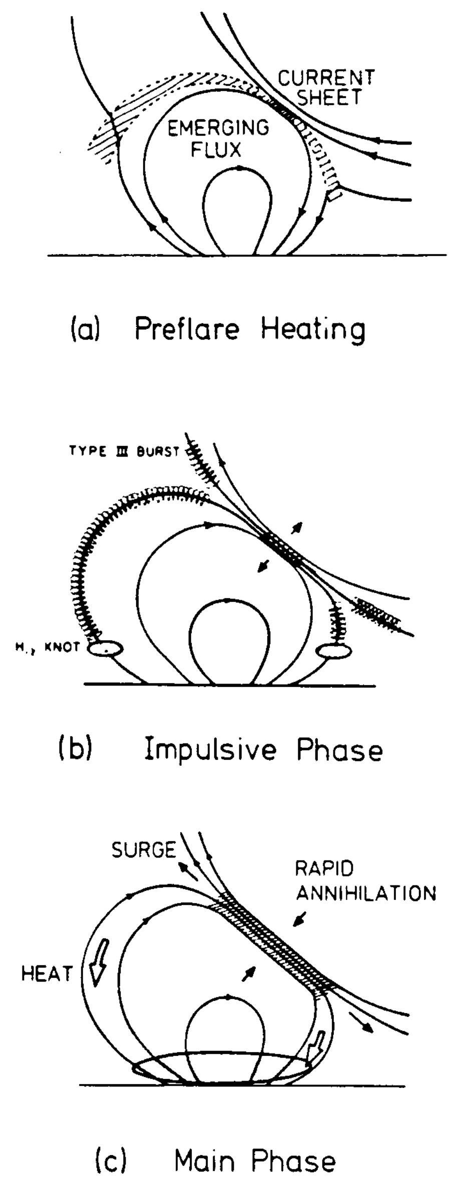

Fig. 8. *Emerging-flux model. (a) During the "preflare phase" ("onset phase"), the emerging flux begins to reconnect with the overlying field. (b) During the impulsive phase, the onset of turbulence in the current sheet causes a rapid expansion with rapid energy release. (c) During the "main phase" ("late phase"), the current sheet reaches a new steady state, with reconnection based on a marginally turbulent resistivity (Heyvaerts et al. 1977).*

The instability that leads to magnetic reconnection is named the "tearing-mode instability." The linear theory was first developed by Furth, Killeen and Rosenbluth (1963), but numerical studies by Carreras et al. (1980) and others have shown that nonlinear effects have the important effect of speeding up the reconnection rate.

Within the solar physics community, Dan Spicer was the first to draw attention to the importance of mode interaction in speeding up the energy-release process. One mode tends to interact with another and develop small-scale structure including current sheets and "magnetic islands" (Kahler et al. 1980) (Figures 9, 10). It seems to me that if we are to understand energy release on a time scale of milliseconds, we need to understand more fully the development and implications of this small-scale island structure.

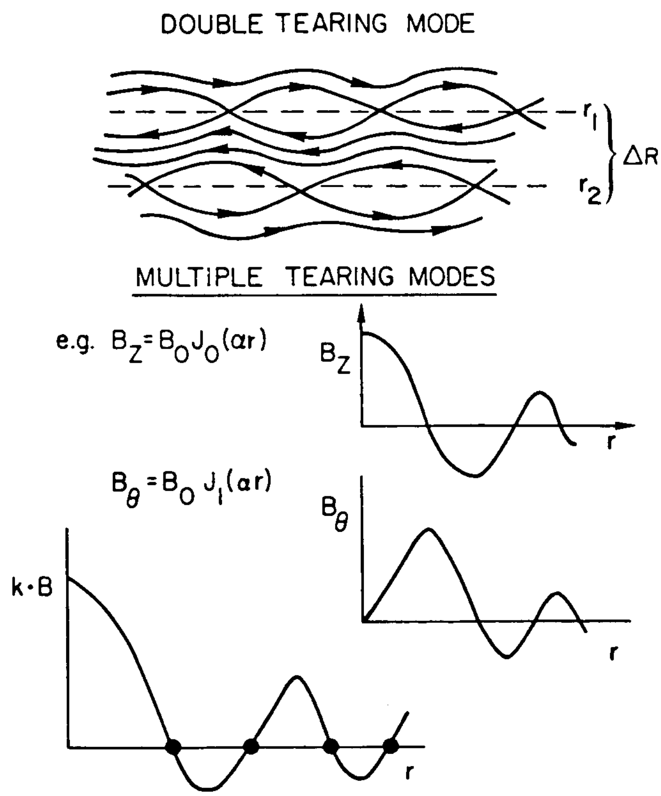

Fig. 9. *Top: The simplest example of multiple tearing modes, the double tearing mode, in which* $k.B_o=0$ *occurs at two different radii from the center of the loop. Bottom: The Lunquisst field in which multiple tearing modes can occur (Kahler et al. 1980).*

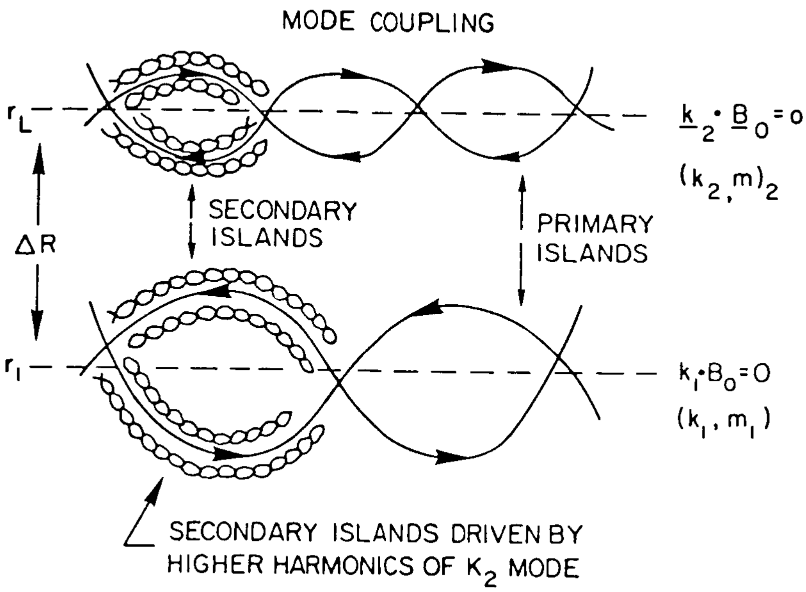

Fig. 10. *The phenomenon of mode coupling. Primary islands are generated when* k.B_o=0 *for different wave number vectors* k. *The coupling between these primary islands results in the generation of secondary islands of shorter wavelength* k^{-1} (Kahler et al. 1980).

Recent computer modeling, such as that of Carreras et al. (1980), is providing more information on this topic. Since their work is directed at Tokomaks, they use a toroidal geometry. Figure 11 shows the growth in time of the radial size of various

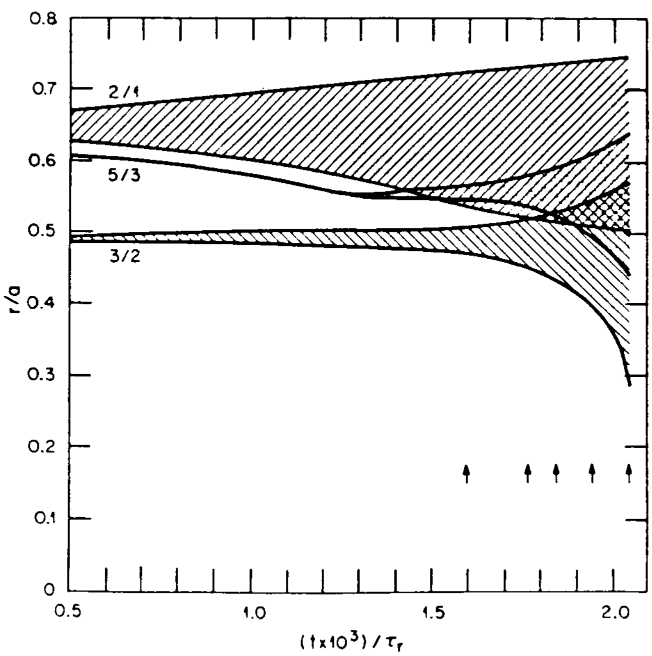

Fig. 11. *Time evolution of the magnetic island width for the (m=2; n=1), (m=3; n=2), and (m=5; n=3) modes in a multiple-helicity calculation (Carreras et al. 1980).*

modes. Different modes develop at different locations in the minor radius. Initially they are well separated and develop according to single-mode theory. However, at a certain time they may be sufficiently large that the modes begin to overlap. At this stage, the behavior is changed drastically. For instance, Figure 12 shows a plot of the growth rate of two modes (the 2-1 mode and the 3-2 mode), and we see that when the modes begin to interact, the growth rate increases rapidly. The growth rate can increase by at least an order of magnitude.

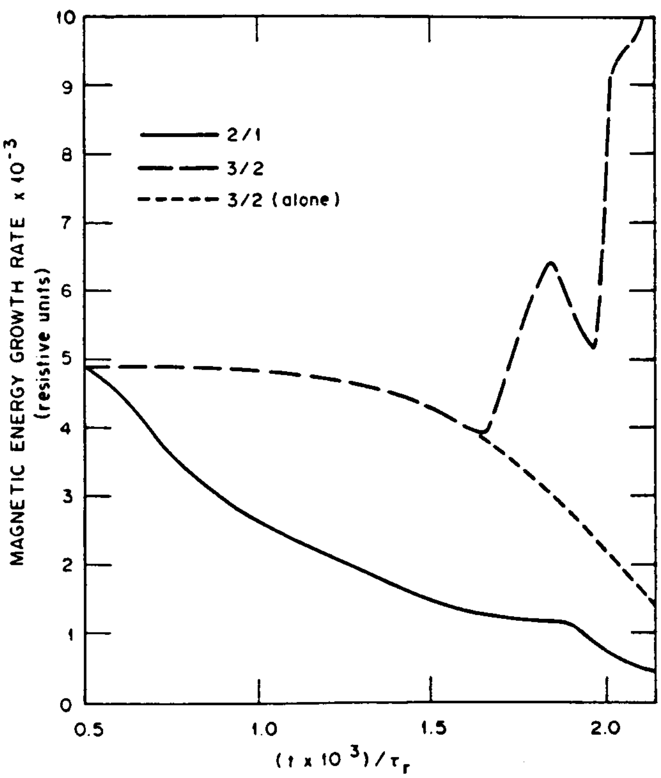

Fig. 12. *Nonlinear magnetic energy growth rate of the* (m=2; n=1) *mode (continuous line) and* (m=3; n=2) *mode (broken line). The* (m=3; n=2) *growth rate is compared with its value in the single 3/2 helicity evolution (Carreras et al. 1980).*

If more modes are included (Figure 13), mode interaction gives rise to an even more rapid increase in the growth rate. Another important aspect of these results is the following: In the early stage, the growth is fairly smooth and follows closely the linear FKR theory. However, when the modes begin to interact, leading to an increase in the growth rate, the current pattern becomes stochastic. The electric field also will become stochastic, and I think that an important topic to investigate is the process of particle acceleration in the stochastic electromagnetic fields that will develop in a reconnecting region when mode interaction takes place.

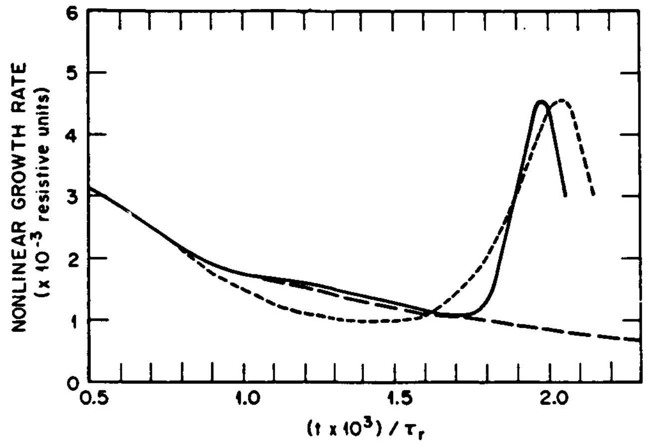

Fig. 13. *Nonlinear growth rate of the (m=3; n=2) mode for a calculation in which 5 modes were included (----) compared with the same case with 29 modes included (______). It is also compared with the case in which only the 3/2 helicity is included in the calculation (-- -- --) (Carreras et al. 1980).*

Spicer also pointed out some time ago that reconnection may not be spontaneous, but may instead be "driven." This certainly occurs in laboratory experiments such as that of Baum and Bratenahl (1985). The more recent experiments of Stenzel and his collaborators (Stenzel and Gekelman 1985) show similar effects. Large currents are suddenly driven through two plane conductors in such a way as to develop a field reversal region between them. The development of the magnetic field depends very much on the aspect ratio. If the width of the current sheet is no more than the separation between the conductors, an X-type point develops. However, if the width of the current-carrying conductors is larger than the separation, then there develops a series of magnetic islands (O-type points) separated by X-type points. The number of islands is approximately the same as the ratio of the width to the separation.

Leboeuf et al. (1982) have set up a numerical code to study the Stenzel-type experiment, and confirm that when the width to the separation is larger than unity, a sequence of X-points and O-points develops. However, these do not survive in the form in which they are created. Their numerical studies show that there is a strong tendency for adjacent magnetic islands to coalesce, as shown in Figure 14.

Leboeuf et al. find that the current densities, and therefore the electric fields, are very much stronger in the coalescence phase than they are during the tearing phase. Tajima et al. (1985) argue that this process is significant for solar flares. It is certainly conceivable that, if the process occurs, it might be responsible for the fine structure in X-ray emission.

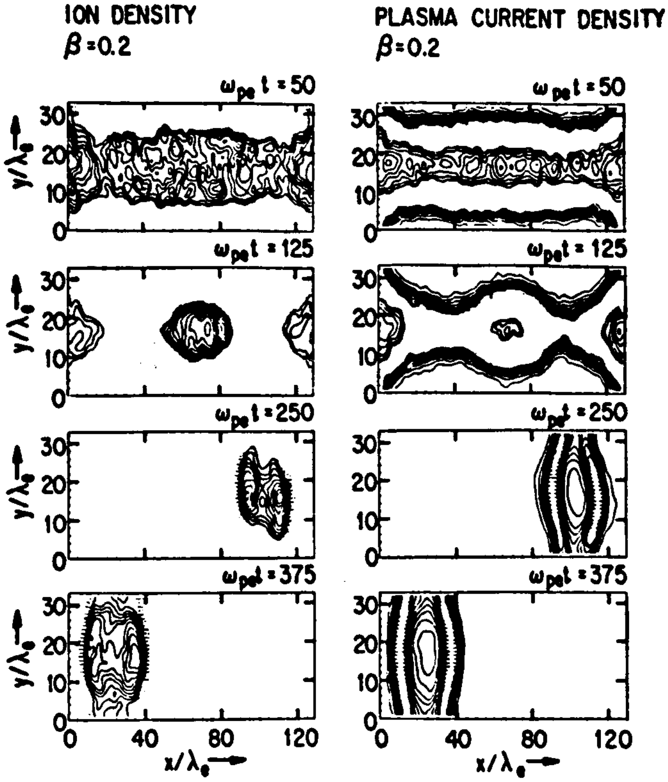

Fig. 14. 127x32 island coalescence run. The ion density is displayed on the left at, from top to bottom, $\omega_{pe}t$=50, 125, 250, and 375. The dotted contours represent levels below the average density at a particular time, full contours levels above. The plasma current density in the z direction is shown on the right at equivalent times. Dotted coutours indicate regions of highest return current (Leboeuf et al. 1982).

It must be emphasized, however, that one must be cautious in carrying over results from laboratory experiments to solar situations, since the parameters differ enormously. One must similarly be careful in carrying over the results obtained from numerical experiments. For instance, Leboeuf et al. (1982) adopt a "particle in a box" model, and there are on the average only four particles per box, which is not very many, and the ion-to-electron mass ratio is taken to be 10 rather than 2,000. Furthermore, laboratory and numerical experiments typically have magnetic Reynolds numbers very much smaller than those that are relevant to solar situations. Since the coalescence instability depends upon the magnetic attraction of two current filaments, it clearly depends sensitively on whether or not the field can adopt a vacuum configuration on a small scale, hence on the plasma density.

The fine structure of the X-ray flux or radio flux from some solar flares gives the impression that the elementary process is a very rapid process producing a spike of short time scale, and that the overall development of the impulsive phase is the occurrence of a very large number of such elementary bursts. If this is so, we need to think carefully about the interpretation of the total flux from the impulsive phase of a flare. In many cases, the flux will indicate that the electron energy spectrum has the form of a power law. We then face the question: Does the power law represent the spectrum produced by an elementary energy-release process, or is it the result of the convolution of many elementary processes, each one of which produces a spectrum differing from a power law?

In this context, it is worth considering once more the radio burst detected by Kaufmann et al. (1985), that was clearly detectable at 90 gHz but barely detectable at 30 gHz. This is suggestive of a peaked electron-energy spectrum. Even for a more typical microwave burst, it is difficult to understand the energetics if each burst of electrons has the form of a power law extending down to a few keV (Sturrock et al. 1984). Hence we should consider the possibility that the elementary energy-release process produces something other than a power-law spectrum.

Let us consider, for example, that the elementary process produces a spectrum of the following form:

$$\frac{dJ}{dE} = L^{\lambda} f(L^{\varepsilon}E) \ . \qquad 1$$

In this equation L is the length scale, and we suppose that the intensity and the characteristic energy each depend in a power-law fashion on L.

Now suppose, as an example, that the length scale increases linearly with time,

$$L = Vt \qquad 2$$

and let us consider the integral flux, integrating over time. This is seen to be

$$J_T(E) = \frac{1}{V}\int dL \ L^{\lambda} f(L^{\varepsilon}E) \ . \qquad 3$$

If we now write

$$x = L^{\varepsilon}E \ , \qquad 4$$

we see that the total energy spectrum is expressible as

$$J_T(E) = \frac{1}{V}\left[\int dx \ x^{\frac{\lambda+1}{\varepsilon}-1} f(x)\right] E^{-\frac{\lambda+1}{\varepsilon}} \ . \qquad 5$$

Hence, in this example, we have obtained a power-law spectrum even though the elementary process need not have a power-law spectrum.

My purpose here is not to argue that this is an accurate representation of what occurs in a solar flare, but simply to point out that the spectrum of the entire impulsive phase may differ significantly from that of each elementary burst.

III. Phases of Solar Flares.

So far I have been referring to bursts that proceed either in isolation or as part of the impulsive phase of a flare. However, there are more phases of energy release than simply the impulsive phase, as is exemplified by Figure 15 that is taken from Kane (1969). This flare shows a sharp impulsive phase, but it also shows a steady growth of soft X-ray emission before the impulsive phase, and extended soft X-ray emission after the impulsive phase. Some time ago, it was tempting to consider that the extended soft X-ray emission simply represents the decay of energy released during the impulsive phase. However, Moore et al. (1980) and others have shown conclusively that during many flares such extended emission must be the result of extended energy release.

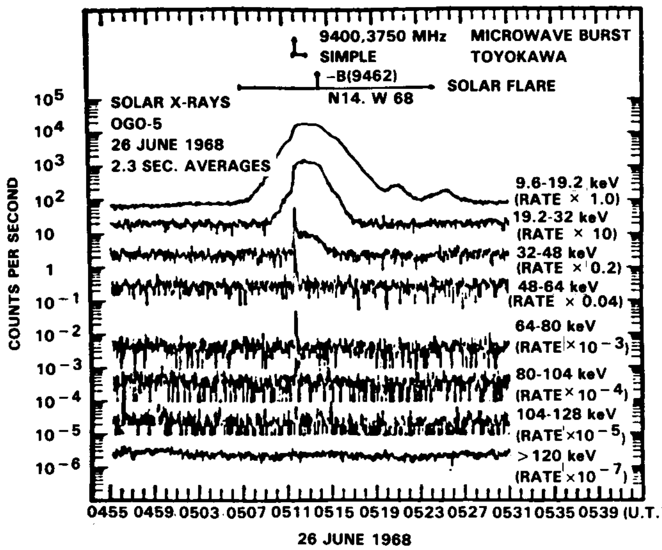

Fig. 15. *Example of an X-ray burst with the impulsive hard component occurring 4 min after the onset of the soft X-ray burst (Kane 1969).*

Similar conclusions can be drawn from study of the H-alpha maps of two-ribbon flares. As the two ribbons separate, the energy-release region excites different regions of the chromosphere, indicating that energy is being drawn from different regions of the corona. Hence it is clear that the separation phase of two-ribbon flares, that corresponds to the extended phase of soft X-ray emission, must be ascribed to continuous energy release, not simply to the decay of energy released during the impulsive phase.

Another significant development is the analysis by Bai (1986) of the properties of flares that produce gamma rays and particle events. Bai subdivides gamma-ray/proton events into two classes: those that are impulsive, with a spike duration of less than 90 seconds and total duration of less than 10 minutes, and those that are gradual, with spikes longer than 90 seconds and durations longer than 10 minutes. These two classes have certain properties in common, as we see in Table 1, but the two classes have more points on which they differ, as we see in Table 2.

Table 1.
COMMON PROPERTIES OF
IMPULSIVE AND GRADUAL GAMMA-RAY/PROTON FLARES
(These properties are in general not found from ordinary flares)

	CATEGORIES	IMPULSIVE FLARES	GRADUAL FLARES
1	H.X.R. SPECTRUM	HARD (average index 3.5)	HARD (average index 3.5)
2	H.X.R. SPECTRAL HARDENING	SOME (6 out of 13)	YES (22 out of 23)
3	ASSOCIATION WITH TYPE II OR IV	GOOD (9 out of 13)	GOOD (20 out of 23)

The first four points of Table 2 concern the temporal development, that are clearly a reflection of the definition of the two classes. However, the last seven items (excepting perhaps item 8) are not so obviously related to the selection process. The overall impression is that gradual flares involve something that is ejected from the sun, and that this ejection process facilitates the escape of high-energy particles. Item 7, the "microwave richness index," may give some clue as to the difference in conditions in the flare site in the two classes of flares. It seems that the gradual flares involve something that is ejected from the sun, and that during the ejection process it is possible for particles (electrons and protons) to escape from whatever kind of trap they were formed in.

These considerations of the various stages of a flare and the various types of flares suggest that it would be worthwhile to draw up a category of conditions in which flares can occur. Since we believe that the magnetic field is the main context in which a flare occurs, we face the following question: What are the possible categories of magnetic-field configurations that

Table 2.
DIFFERENCES BETWEEN
IMPULSIVE AND GRADUAL GAMMA-RAY/PROTON FLARES

	CATEGORIES	IMPULSIVE FLARES	IMPULSIVE FLARES
1	HIGH-ENERGY H.X.R.DELAY	SHORT (< 4 s)	LONG (> 8 s)
2	H.X.R. SPIKE DURATION	< 90 s (<30 s)	> 90 s
3	H.X.R. TOTAL DURATION	< 10 min	> 10 min
4	SOFT X-RAY DURATION	< 1 hr	> 1 hr
5	H-alpha AREA	SMALL	LARGE
6	LOOP HEIGHT	LOW ($<10^9$ cm)	HIGH ($>10^9$ cm)
7	MRI	< 1.0	> 1.0
8	AVG. TYPE II DUR.	14 min	25 min
9	I.P. PROTONS / ON SITE PROTONS	SMALL (<<1)	LARGE (>1)
10	INTERPLANETARY SHOCK	NO	YES
11	CORONAL MASS EJECTION	SOME	YES
12	[e/p] RATIO	LARGE	NORMAL
13	I.P PROTON FLUX DECAY	RAPID (2)	SLOW

could give rise to flares and might have some bearing on the different phases (and other aspects of the time structure) of those flares?

I think we should begin with the fact that magnetic flux at the photosphere is not spread uniformly over the photosphere. We know from the work of Harvey, Sheeley, Title, and others (see, for instance, Tarbell and Title 1977) that the magnetic flux at the photosphere tends to be aggregated into knots of less than one arc second in size, with field strengths of 1,000 to 1,500 gauss. This is bound to have an important influence on the magnetic-field structure in the corona, where we believe the main energy-release of a flare occurs. Rather than think of a distributed field pattern in the corona, this flux concentration at the photosphere leads one to consider that the field in the corona is really made up of individual flux loops, each loop ending in one of these knots, although there may be two or three elementary flux tubes arising from the same knot (Figure 16).

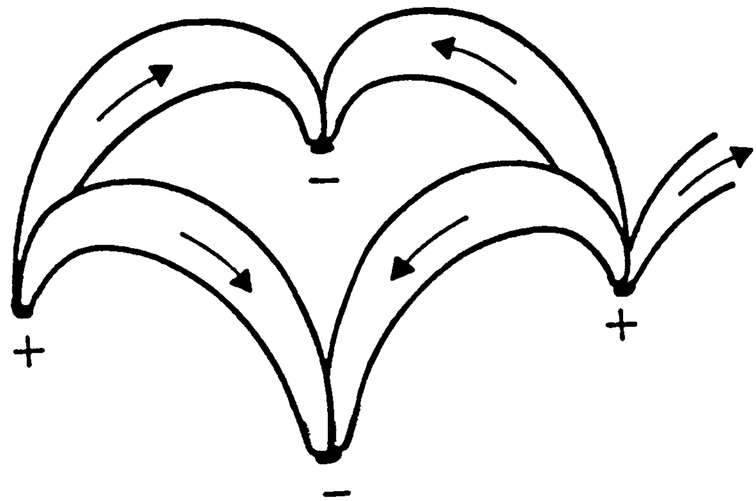

Fig 16. *Schematic representation of possible coronal magnetic field structure, determined by the aggregation of photospheric magnetic field into discrete knots (Sturrock et al. 1984).*

If one pursues this idea and inquires into the typical length of such an elementary flux tube in an active region, and how much energy can be stored in such a tube due to twisting of the foot points, we find that the time scale for energy release should be a few seconds and the energy released should be in the range 10^{27} to 10^{28} ergs (Sturrock et al. 1984). Hence energy release from such elementary flux tubes may well be the explanation of the elementary X-ray bursts identified by van Beek and his collaborators. The "microbursts" with time scales of 10 to 100 milliseconds, that are found in both X-ray and microwave data, may be attributed to energy release in "magnetic islands" that develop during reconnection in such flux tubes.

In what follows, I depart from the earlier idea that a flare is simply the manifestation of magnetic-field reconnection, and that the only requirement for a flare is a pre-existing current sheet. In a talk given 22 years ago at Goddard Space Flight Center during a symposium on the "Physics of Solar Flares" organized by Bill Hess, the great solar astronomer K.O. Kiepenheuer made the following remarks (Kiepenheuer 1963):

> "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."

All large two-ribbon flares involve the disruption--maybe eruption--of a filament. It is not the case that the filament is disrupted because of the flare, but rather the other way round. Some time ago, Sara Martin and Harry Ramsey (Smith and Ramsey 1964) studied the behavior of filaments near the time of occurrence of flares and found that there are definite signs of disturbance in the filament long before the flare occurs. These "precursors" may occur many minutes or even hours before the flare. The fluctuations become larger and larger until the onset of the flare. This suggests either that an instability of the filament creates the conditions that lead to the flare, or that a flare is simply one manifestation of a complex instability that leads to the disruption of the filament.

In order to pursue this line of inquiry, it is essential to have a clear understanding of the nature and structure of filaments. Unfortunately this understanding does not exist at this time. I suggest that a filament comprises a rope-like structure involving many intertwined magnetic flux tubes, each tube linked to the photosphere at both ends. The foot-points are close to the magnetic neutral line, so that the rope tends to run along the neutral line (Figure 17). The interplay of the different flux tubes will lead to regions of field that are concave upwards; these are the regions that support the cool gas responsible for the visible H-alpha appearance of a filament.

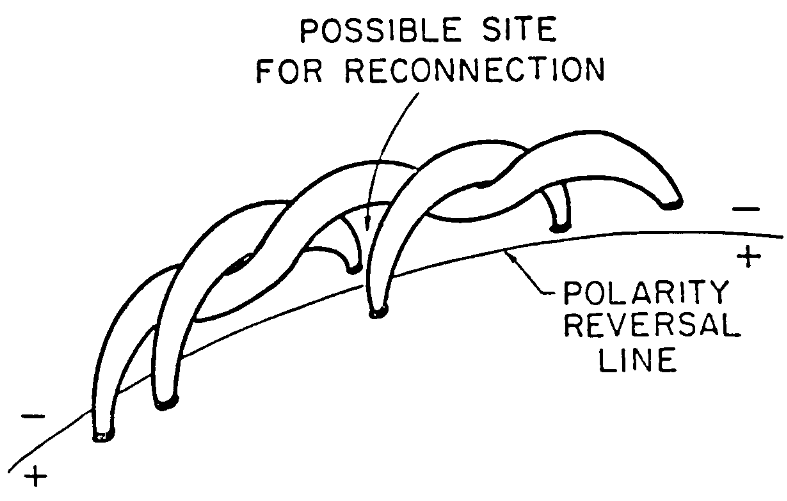

Fig. 17. *Schematic representation of possible magnetic field configuration of a filament (Sturrock et al. 1984).*

When viewed in the wings of H-alpha, a flare always begins with two bright points very close together on opposite sides of the neutral line. Moore et al. (1984) have found that the time of this initial brightening is also the time when the filament first begins to show rapid upward motion. Our interpretation (Sturrock et al. 1984) is that reconnection has begun to occur between the feet of two adjacent flux tubes, as indicated in Figure 17. This reconnection has two effects. One is that energy is released that gives rise to the two H-alpha brightenings. The other is that two strands tying the filament to the photosphere have been severed. This is rather like the severing of ropes that hold a buoyant balloon to the ground. When the strands are severed, the filament begins to rise. This change of configuration of the filament puts more strain on the remaining flux tubes connecting the filament to the photosphere. As a result, there may occur a runaway action in which similar reconnection occurs sequentially, running in both directions along the neutral line. The end effect of this process would be the formation of a large twisted flux tube rooted simply at its end points, as shown in Figure 18. The eruption of such a tube looks very much like movies of erupting prominences that are visible in H-alpha above the limb.

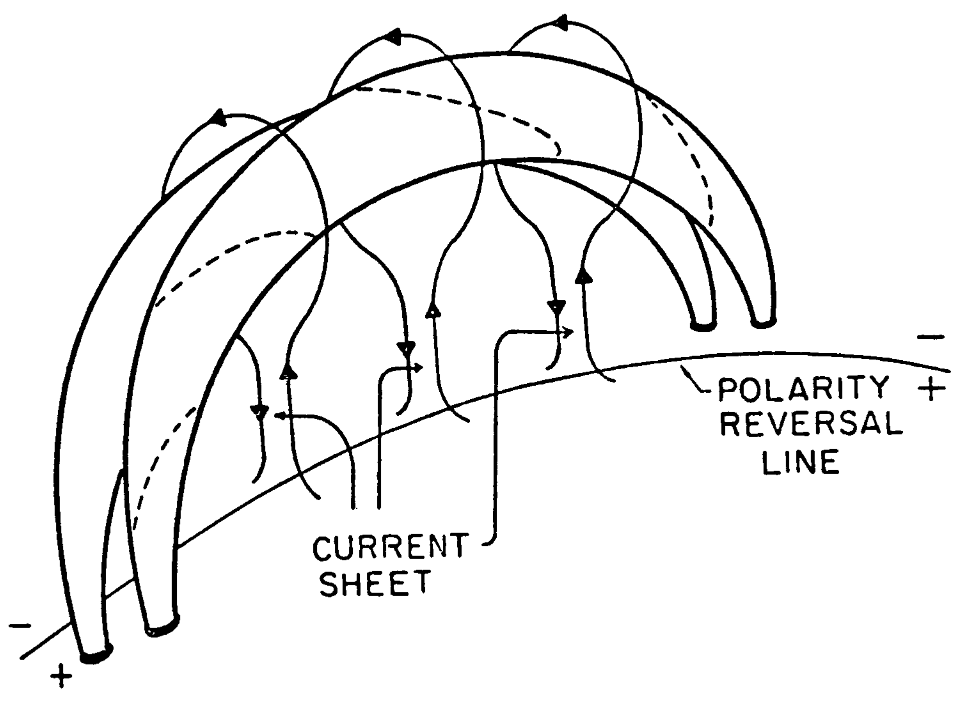

Fig. 18. *Schematic representation of the development of an extended current sheet beneath an erupting filament (Sturrock et al. 1984).*

The eruption of the filament may lead to the end result that the filament forms a large loop high in the corona.

Alternatively, if the stress due to twisting is sufficiently great, the filament may expand into interplanetary space by attempting to adopt an open-field configuration. Which of these two processes occurs depends partly on the initial stress in the filament and partly on the strength and topology of the surrounding magnetic field.

In either case, the eruption of the filament is going to disturb the overlying magnetic field, and the disturbance is such that it will produce a current sheet below the filament. This situation is rather like the the Stenzel experiment in which a current sheet is suddenly formed. In this situation, reconnection of the sheet is more in the nature of "driven reconnection" rather than spontaneous reconnection.

The end result of reconnection of the newly formed current sheet is that a region of magnetic field near the filament is returned to its current-free state. In addition (Sturrock 1986), a toroidal magnetic trap forms that embraces the filament (Figure 19).

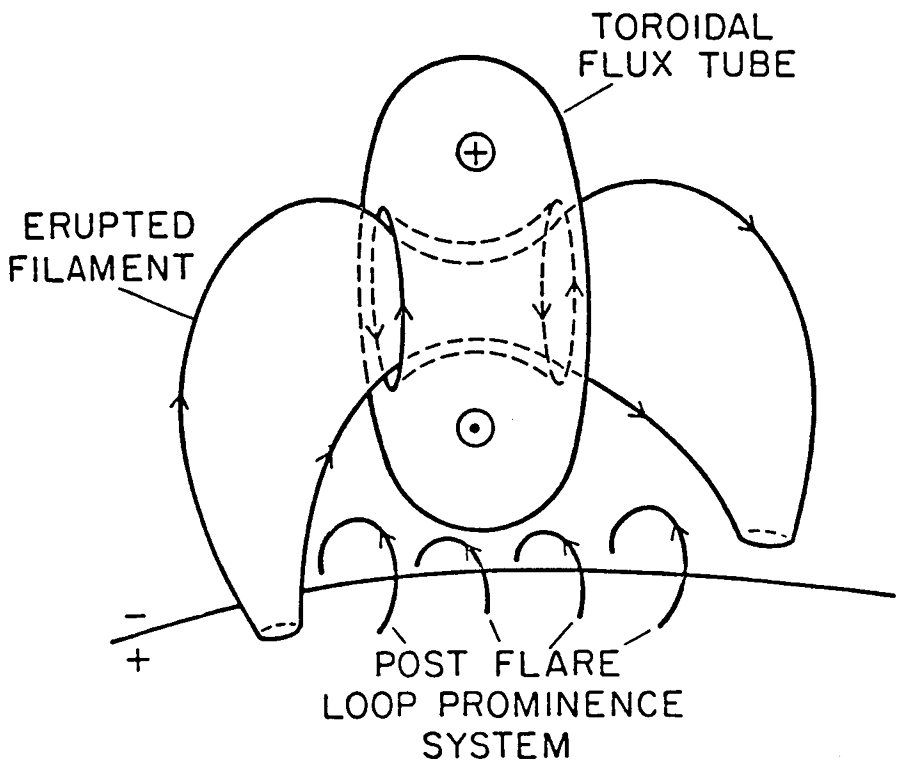

Fig. 19. *Schematic representation of a toroidal magnetic flux tube encircling an erupted prominence, as a result of the reconnection indicated in Fig.18. The toroid would be detectable as a stationary type IV radio burst (Sturrock 1986).*

The reconnection is likely to produce high-energy electrons, so that the magnetic trap when formed would already contain a population of energetic electrons; this may be the explanation of Type IV radio bursts. If the filament simply rises up into the corona, we would observe a *stationary* Type IV burst. However, if the stresses are such that the filament expands out into interplanetary space, we would observe *moving* Type IV burst. This ejection may also be the explanation of coronal transients. If the ejection is sufficiently rapid, it should produce a bow shock which could in turn produce a Type II radio burst (Figure 20).

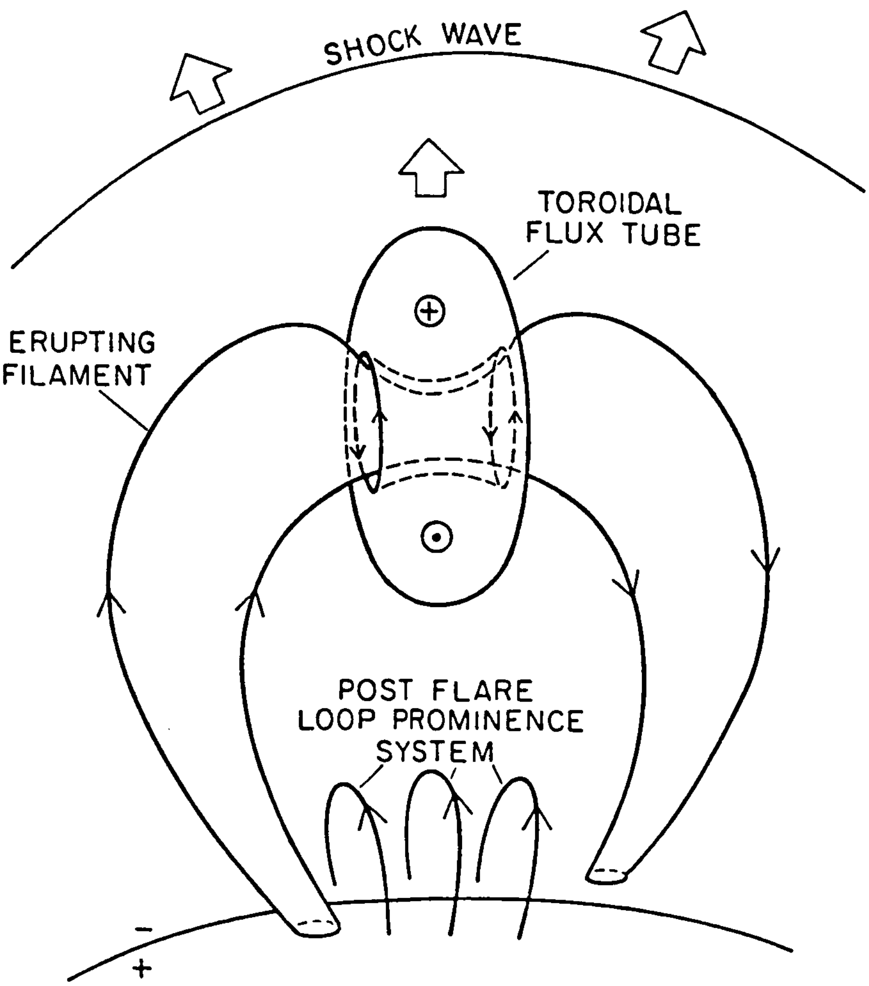

Fig. 20. *Schematic representation of situation that arises when a filament, encircled by a toroidal flux tube, is completely ejected from the sun. The toroid would be detectable as a moving type IV radio burst. The shock wave would give rise to a type II radio burst (Sturrock 1986).*

Table 3 shows another way of categorizing magnetic structures, and the properties of the resulting flares. In this table, we focus on only four properties. Does the flare produce a mass ejection? Does it produce a shock wave? Does it produce gamma-ray emission? Does it produce a particle event?

TABLE 3.
CATEGORIES OF MAGNETIC STRUCTURES AND PROPERTIES OF RESULTING FLARES

	AN	AC	AO	PCR	POR	PCJ	POJ
Mass Ejection	X	X	X	X	X	√	√
Shock Wave	X	X	X	√	√	√	√
Gamma-Ray Emission	X	√	√	√	√	√	√
Particle Event	X	X	√	X	√	√	√

A: filament absent
P: filament present
N: no current sheet
C: closed current sheet
O: open, or partially open, current sheet
R: filament eruption, but no ejection
J: filament ejection

Concerning the environment in which the flare occurs, we first notice that there may be no filament in the system, that we denote by "A" (the filament is absent). It may be that there is simply a small flux tube that becomes stressed and then reconnects releasing energy. I do not know whether this ever occurs, but Hal Zirin has expressed the opinion that any flare - no matter how small - always involves the disappearance of some dark feature, implying that any flare always involves something like a filament disruption. This viewpoint would appear to be consistent with the work of Teske referred to earlier.

Assuming that there is a configuration that does not involve a filament, we next ask whether there is a current sheet. If there is no current sheet (AN), there is no reason to expect mass ejection or a shock wave. I suggest that intense electric fields, causing strong electron acceleration, occur only in reconnection in a current sheet, not in reconnection in an extended tube. If this is the case, there should be no gamma-ray emission and no particle event if there is no current sheet.

If there is a current sheet, but the sheet is completely closed (AC), the high-energy electrons could give rise to gamma-ray emission, but there should be no particle event. On the other hand, if the current sheet is open or partly open (AO), some of the particles can escape so that there may also be a particle event.

Next we suppose that a filament is present (P), but we distinguish between eruption (R) and ejection (J). In either case, the existence of a filament necessarily requires the existence of a current sheet at the interface between the filament and the ambient magnetic field. This initial current sheet may be either closed or partly open. If the filament erupts (but is not ejected), and if the initial current sheet is closed (case PCR), there should be no mass ejection, there may be a mild shock wave (a blast wave), and there may be gamma-ray emission, but there should be no particle event. On the other hand, if the filament erupts and if the initial current sheet is partly open (case POR), some of the high-energy particles may escape and produce a particle event. Events of these two types may be responsible for the impulsive gamma-ray/proton flares in Bai's classification (Table 2).

We now consider the final possibility that a large filament is ejected from the sun into interplanetary space. This produces a mass ejection, and - if the speed is high enough - it may produce a bow shock. Such a shock would tend to maintain its strength as it propagates, whereas the strength of a blast wave tends to decrease rapidly as it propagates. In this case, the expansion of the magnetic-field system will weaken the magnetic trap, so that particles can escape into interplanetary space. If the filament is ejected from the sun, we get the same end result whether the initial current sheet was closed or open, so that cases PCJ and POJ have the same properties:- There is mass ejection, a strong shock wave, gamma-ray emission, and a particle event. However, the ejection of a filament takes longer than does its partial eruption into the corona. For this reason, it seems likely that this category of flares is responsible for the gradual flares of the gamma-ray/proton flares studied by Bai (Table 2).

IV. Looking Ahead.

Since this is the beginning of the Workshop, it is a good time to consider what one would like to see come out of it. We would surely like to get additional insight into a number of questions that face us in trying understand solar flares. I now list a few of these questions.

1. What is the pre-flare magneto-plasma configuration? I do not think it is enough to ask only about the pre-flare magnetic-field configuration. A filament or a similar structure is usually involved, and the stress of plasma contained in the filament may be significant.

2. Is the instability responsible for a flare macroscopic, microscopic, or a symbiotic combination of the two? There are good reasons to be suspicious of the earlier idea that a flare simply represents reconnection of a current sheet. As I have

indicated, it is quite possible that the basic instability involves an MHD effect that gives rise to an erupting filament. Hence we can ask whether the instability is macroscopic like an MHD eruption, whether it is microscopic like a simple tearing mode, or whether it is a combination of the two.

3. **What fine structure develops as a result of the macroscopic flow?** It is clearly possible that the macroscopic flow leads to the development of a shock wave, but it may be that the macroscopic flow is unstable and leads to some form of turbulence.

4. **What fine structure develops as a result of the microscopic flow?** As I have indicated, numerical simulations of the reconnection process indicate that very fine structure may develop. It is clearly important to pursue this line of inquiry if we are to understand the development of fine structure on the sub-second time scale.

5. **Do shocks usually occur? If so, what is their role in particle acceleration?** Any sudden change of magnetic configuration is surely likely to develop a shock wave, either as a propagating blast wave or as a convecting bow shock. Since shocks are known to be promising locations for particle acceleration, it is clearly important to have a better understanding of how and where shocks are generated during flares.

6. **Is flare energy release always composed of elementary bursts?** For some flares, the X-ray time curves show a great deal of fine structure strongly suggesting that the energy release process comprises as many elementary events. When such structure is not evident, is it because of a real difference in the energy release process, or is it simply a reflection of our imperfect observational capabilities?

7. **Is the energy release process sometimes periodic?** There has been a debate for many years as to whether apparent periodicity of X-ray emission or microwave emission is really significant. Some years ago, Lipa and Petrosian (1975) looked into this question but were unable to find a case for real periodicity. On the other hand, Roger Thomas many years ago obtained a "light curve" of X-ray emission that seemed to present a very strong case for periodicity. If periodicity does sometimes occur, it is a real challenge to the theorist to come up with an explanation that is even plausible.

8. **What is the relationship between the energy spectrum of the integrated flare emission and the energy spectrum of the elementary bursts?** This is the question that was raised earlier in this review. The first requirement is to have more detailed information of the energy spectrum of an elementary burst. If this resembles the energy spectrum of the entire impulsive phase, there is no further work to be done. If, however, the spectrum of an elementary burst usually differs significantly from that of an entire impulsive phase, we must seek to understand the

relationship between the two, perhaps along the lines suggested in Section II.

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