SOLAR FLARES AND MAGNETIC TOPOLOGY

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ABSTRACT. This article is a very brief review and comparison of the observational properties of flares and theoretical concepts of models of flares, especially the concepts of magnetic topology and its evolution. We examine the "environmental" aspects of flare behavior. Some of these aspects must be consequences of unknown processes occurring below the photosphere. Other aspects involve structures--such as filaments--that are closely related to flares. We then examine properties of flares to try to distinguish the different phases of energy release that can occur in the course of a flare. Finally we offer a schematic scenario and attempt to interpret these phases in terms of this scenario.

1. INTRODUCTION

It is normal practice for a conference organizer or an editor to categorize a talk or an article as either "observational" or "theoretical." This may be an indication --if not a reason--that we spend too little time looking at the interface between observation and theory. In addressing a very complex problem, such as that of solar flares, the relationship between observation and theory needs at least as much attention as pure observational studies or pure theoretical studies. This article represents only a quick look at this relationship.

It is interesting to see how the nature of the solar flare problem has changed in response to observational information and theoretical concepts. When Carrington (1859) first observed a flare in 1859, he described it in meteorological terms as comprising "clouds" high above the surface of the sun. It is notable that Carrington did not assert a cause and effect relationship between the flare and the remarkable geomagnetic and auroral disturbances that followed 26 hours later.

From the theoretical side, understanding of the flare process was strongly influenced by Kelvin's theorem (Kelvin, 1892) that the sun could not possibly be responsible for geomagnetic disturbances. His mathematics was impeccable, but of course his model was incorrect since he had no way of knowing about the solar wind! Kelvin's influence was so

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great that, even in 1931, Hale (1931) himself still referred to "solar eruptions and their _apparent_ terrestrial effects." One is reminded of three famous statements (especially the second) attributed to Arthur C. Clark:

> "If a famous scientist says something is possible, he is probably correct.
>
> If a famous scientist says something is impossible, he is probably wrong.
>
> Science of the next century would be regarded as magic if it were seen today."

The introduction of the magnetograph showed the clear association of flares with magnetic field. As early as 1933, Swann (1933) proposed that flares may involve particle acceleration by the betatron process. Probably the first theoretical analysis that takes account of the high conductivity of the solar atmosphere was that of Giovanelli (1946), who proposed that flares are to be interpreted as electrical discharges due to changing magnetic fields. At this time, flares were referred to as "chromospheric flares," since the only data available were from visible light (primarily H-alpha), that was believed to be produced entirely at the chromospheric level. It was implicitly assumed that the energy released in the flare was also confined to the chromospheric layer, and this led to high estimates of the required magnetic field.

In 1953, Dungey (1953) showed that at an X-type neutral point, the electric field due to a change in magnetic field leads to a current that tends to enhance the change in the magnetic field. That is, Dungey introduced the two concepts of _instability_ and _reconnection_. These concepts have dominated theoretical studies of solar flares ever since.

It was not until the late 1950s that rocket-borne experiments made it possible to detect X-rays from solar flares (Chubb _et al._, 1961). X-ray images obtained from the OSO series of spacecraft and other spacecraft have shown that flares are primarily _coronal_ phenomena; the chromospheric response is now regarded as a "secondary" aspect of the flare process.

In the late 1950s and 1960s, a variety of models of flares were proposed (Sweet, 1958; Gold and Hoyle, 1960; Carmichael, 1964; Sturrock, 1968). Each proposed a magnetic field configuration that was supposed--implicitly or explicitly--to be metastable but subject to an instability that would suddenly release free energy associated with coronal currents. This energy release was identified with the impulsive phase of solar flares. Hence, in most cases, the comparison between observation and theory comprised just two numbers: the energy released in a large solar flare (about 10^{32} erg), and the time scale for the impulse phase (about 10^2 sec).

2. SELECTED ITEMS RELEVANT TO THE FLARE PROBLEM

It was implied, in the previous section, that early flare models addressed only a restricted aspect of the flare problem, namely, the nature of energy release that occurs during the impulsive phase. Subsequent research indicates that there are more phases of energy release that need to be considered. Furthermore, there are other aspects of the flare problem that constitute a challenge to theorists. Some of these are listed below.

Concerning the "environmental" situation in which flares occur, it has long been recognized that they occur in active regions, and the case is overwhelming that the connection is due to magnetic field. However, there are some puzzles concerning the relationship between flares and active regions. For instance, in any solar cycle there is a tendency for flares to occur in certain bands of longitude, sometimes called "active longitudes" (Svestka, 1976). Even taking the longitude factor into account, it is remarkable that some active regions produce far more than their "fair share" of flares; these are sometimes termed "super-active regions" (Bai, 1987). It was recognized long ago by Ellison and his collaborators (Ellison et al., 1960) that flares sometimes occur in sequences, with the remarkable property that the flares of a given sequence are very similar to each other. These are called "homologous" sequences of flares. As Ellison once remarked, it is as if the magnetic field that is destroyed by one flare is rebuilt in its original form in time for the second flare.

More recently, analysis of gamma-ray flares observed by instruments on board the Solar Maximum Mission spacecraft led to the remarkable discovery that these flares tend to recur at an interval of about 150 days (Rieger et al., 1984). This periodicity is found to be present also in microwave data and appears to be present in other related data as well (Bogart and Bai, 1985). Bai and Sturrock (1987) have shown that the simplest interpretation, that the periodicity is due to the interplay of two different factors rotating at different rates, is invalid. The periodicity appears instead to be a global solar phenomenon.

Another important "environmental fact" concerning solar flares is that large two-ribbon flares are invariably associated with filaments. This association was stressed some years ago by Kiepenheuer (1963) 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."

Further important evidence of the association between filaments and flares comes from a study of precursors to solar flares. It was pointed out some years ago by Smith and Ramsey (1964) that filaments are typically "activated" before a flare. This activation shows up as movements that can be detected in dopplergrams. Kahler et al. (1987) have pointed out that the commencement of the flash phase of a solar flare, as observed in H-alpha, occurs at the same time as rapid motion of the associated filament.

Another form of pre-flare "activation" was discovered during the Skylab Mission. It was found that X-ray brightenings typically occur in an active region shortly before a flare occurs. This process was referred to as "pre-flare heating" (Van Hoven et al., 1980). It would indeed be interesting to know what relationship, if any, exists between filament activation and pre-flare heating.

3. PHASES OF SOLAR FLARES

The simplest flares involve a sudden brightening in H-alpha on a time scale of minutes. This is usually referred to as the "impulsive phase." Earlier studies, based entirely on H-alpha data, use the terms "flash phase" and "expansion phase." This phase has traditionally been the main focus of attention of theorists, as was pointed out in the introduction. However, it is not clear that the impulsive phase itself provides the secret of the entire flare phenomenon. We have already noted that there is often activity in an active region just before the flare occurs. Furthermore, there is evidence for independent energy release following the impulsive phase. Different sequences of energy-release phases seem to take place in different classes of flares. In what follows, we attempt to identify the minimum number of phases of energy release.

A. Activation Phase. This term subsumes filament activation and pre-flare heating described in the previous section. These processes clearly represent the sudden conversion of energy from one form to another. It is likely that the basic form of energy that is being tapped is magnetic free energy, that is the energy associated with currents in the solar atmosphere.

B. Impulsive Phase. This is probably the most dramatic phase of a solar flare. In H-alpha, it can be visible as the sudden appearance of an H-alpha brightening that rapidly extends along the length of a filament. It may be accompanied by a rapid hard X-ray burst and by continuum gamma-ray emission and line gamma-ray emission. When there is hard X-ray emission, there is usually also microwave radiation. It appears that there is a sudden conversion of energy, probably beginning with magnetic free energy, into the heating and acceleration of electrons and ions. The various forms of radiation may then be interpreted as secondary processes due to this heating and acceleration. Beginning with the impulsive phase, but extending much later, there may be a soft X-ray burst that can be interpreted as bremsstrahlung from a hot dense coronal plasma. The current view is that this "flare plasma" is produced by "chromospheric evaporation," in response to the sudden flux of energy from the corona to the chromosphere.

C. Gradual Phase. Bai (1986) has summarized data showing that, in some flares, there is a second more gradual period of particle acceleration after the impulsive phase. It may come five or ten minutes after the impulsive phase and last for five or ten minutes or more. When this phase occurs, it may be more effective at accelerating particles to very high energies than was the impulsive phase. Hence such flares may be "microwave rich," and the inferred electron energy distribution may have a harder spectrum than that produced during the impulsive phase. Flares that exhibit a gradual phase of particle acceleration appear to be associated with coronal mass ejections.

D. Late Phase. It has already been pointed out that the soft X-ray emission that begins during or before the impulsive phase typically extends considerably after the impulsive phase. It is likely that, in some cases, this continued X-ray emission is due simply to bremsstrahlung from the hot flare plasma that was evaporated from the chromosphere during the impulsive phase. However, from detailed analysis of the flare of 1973 September 5, Moore et al. (1980) showed that the energy content of the flare plasma increased after the impulsive phase, showing conclusively that there was continued energy release after the impulsive phase (see also Wu et al., 1986). The time scale of this release was of the order of hours. It is this process that is referred to as the "late phase" of energy release.

H-alpha observations alone give evidence for such a late phase of energy release. In the case of large two-ribbon flares, one finds that the ribbons slowly separate, with speeds of order 1 km/s, and this drift can continue for many hours. It is clear that, in such cases, new regions of the chromosphere are receiving a flux of energy from the corona. This phenomenon also points to a slow energy release high in the corona, and we assume that this is another manifestation of the "late phase" of energy release.

Observations reveal other forms of energy associated with solar flares. For instance, the bulk of the energy released during a flare may be associated with the kinetic energy of a coronal transient. Coronal transients are closely related to filament eruptions. Hence we see once more that it is difficult to disentangle the so-called flare process from the process of filament eruption.

During most gradual flares all the above-described phases occur. However in some gradual flares, the hard X-ray emission time profiles do not show impulsive behavior but show gradual behavior from the beginning (e.g., 1981 May 13 gradual flare). In impulsive flares, the gradual hard X-ray emitting phase does not develop, and the late phase also is lacking. The gradual soft X-ray emission observed after the impulsive phase is thermal radiation by plasma heated during the impulsive phase.

4. A SCHEMATIC SCENARIO FOR SOLAR FLARES

Part of the flare problem is to understand the "environmental" factors that were discussed in Section 2. This means that part of the flare problem requires an understanding of subphotospheric processes. The existence of active longitudes and the development of superactive regions may be a manifestation of long-lived giant convection cells. The interpretation of the 150-day periodicity remains a puzzle.

Some of the environmental factors can be understood on the assumption that an active region develops from the eruption of a twisted subphotospheric flux tube. After the tube penetrates the photosphere to extend into the corona, it is energetically favorable for the subphotospheric portion to unwind and transmit the subphotospheric twist through the photosphere into the corona. This has the effect of producing rotations at the photosphere, as indicated in Figure 1, including in particular a high shear along the neutral line. Such shear is a notable property of flare-producing regions. Furthermore, such shear is indicated by the fine-scale structure of filaments.

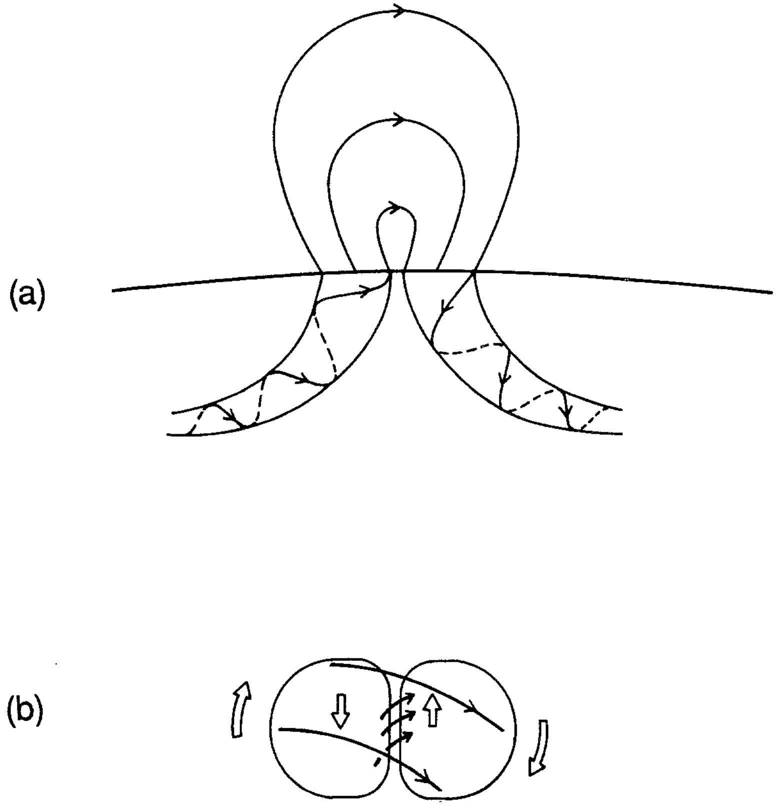

Figure 1. Schematic model of evolution of a twisted sub-photospheric flux tube after it erupts through the photosphere. (a) A "side view" ignoring the effect of the sub-photospheric twist on the coronal configuration. (b) An "overhead view" showing how the coronal field will be modified by the sub-photospheric twist.

The concept of untwisting of the subphotospheric field provides a natural interpretation of homologous flare sequences. As the twist proceeds, it builds up a stressed magnetic field that ultimately reconnects to return the coronal region to an unstressed current-free form. However, continued unwinding reconstructs the stressed field so that the flare recurs, and the sequence can continue until the sub-photospheric tube is relieved of its helical stress.

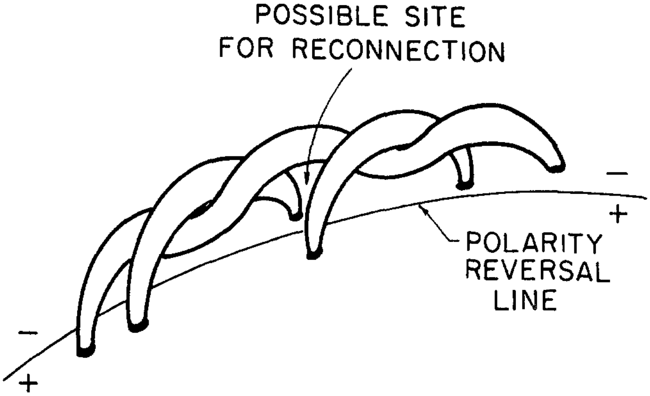

Figure 2. Schematic representation of possible magnetic field configuration of a filament (Sturrock _et al._, 1984).

A crucial question for understanding the flare process is that of the structure of the magnetic field associated with a filament. The field is certainly highly sheared, and it probably also contains a great deal of fine structure, since it is known that most of the magnetic flux at the photosphere is confined in small "magnetic knots," with field strengths of order 1,000 to 1,500 gauss and diameters of order 300 kilometers (see, for instance, Tarbell and Title, 1977). This implies that the magnetic field of a filament probably resembles a rope with many strands, as indicated in a highly simplified form in Figure 2. Each magnetic strand is rooted in the photosphere, one root on either side of the neutral line. Where two feet, on opposite sides of the neutral line, are in close proximity, there is the possibility that reconnection will occur. Reconnection has two consequences. One is that energy is released that may lead to heating of the atmosphere, resulting in X-ray emission from the coronal level and H-alpha brightening at the chromospheric level. The other effect is that the balance of forces is changed, so that part of the filament can now move upwards, and more stress is placed on the remaining strands of the filament. This may lead to further reconnection of adjacent strands, and this process may at some point develop into a catastrophic process in which all connections along the length of the filament tear (rather like tearing a piece of cloth), except that the field must remain rooted at the two ends of the filament. The effect of this process is then the formation of a large twisted flux tube, rooted at its end points, as shown in Figure 3.

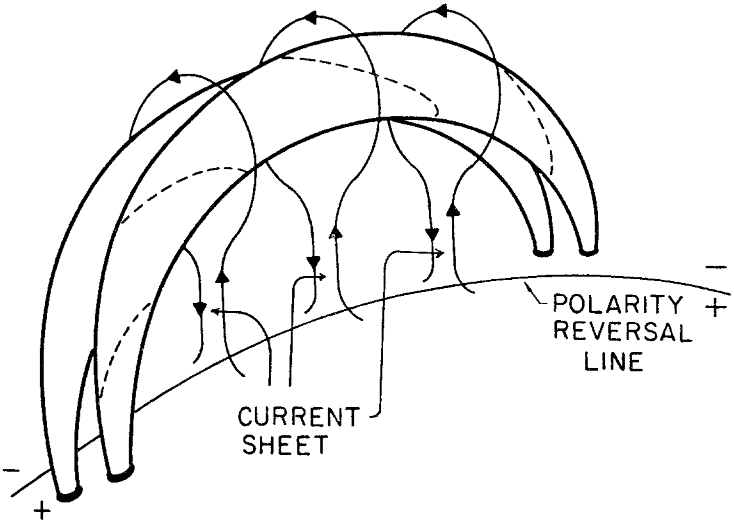

Figure 3. Schematic representation of the development of an extended current sheet beneath an erupting filament (Sturrock et al., 1984).

The early spasmodic reconnection is interpreted as the cause of both filament activation and preflare heating that comprise the "activation phase" of a flare. The rapid runaway tearing that disconnects the filament almost entirely from the photosphere is identified in this model with the impulsive phase of the flare. As we shall see, this particular model leads to a two-ribbon flare.

After the filament is disconnected from the photosphere, magnetic stresses will cause it to rise. However, in so doing, it is attempting to move through a region that already contains plasma permeated by magnetic field. Hence this stage of the process involves the "brushing" of one set of field lines past another. This stage seems to correspond to the gradual phase of acceleration. If the relative velocity of the "filamentary" field lines with respect to the "coronal" field lines is sufficiently large, then the Kelvin-Helmholtz instability should occur (Dobrowolny, 1972). This will lead to MHD turbulence in the vicinity of the interface, that could then lead to acceleration of electrons and ions. It is possible that acceleration during the impulsive phase also is due to such a mechanism since it has proved difficult to explain particle acceleration as a direct result of magnetic reconnection.

As a result of the eruption of a filament, the overlying coronal field lines will form a current sheet below the erupting filament, as indicated in Figure 3. It has been proposed (Sturrock et al., 1984; Cliver et al., 1986) that the slow reconnection of this current sheet is responsible for the "late phase" of a solar flare, resulting in soft X-ray emission and in the drifting two-ribbon topology of large flares.

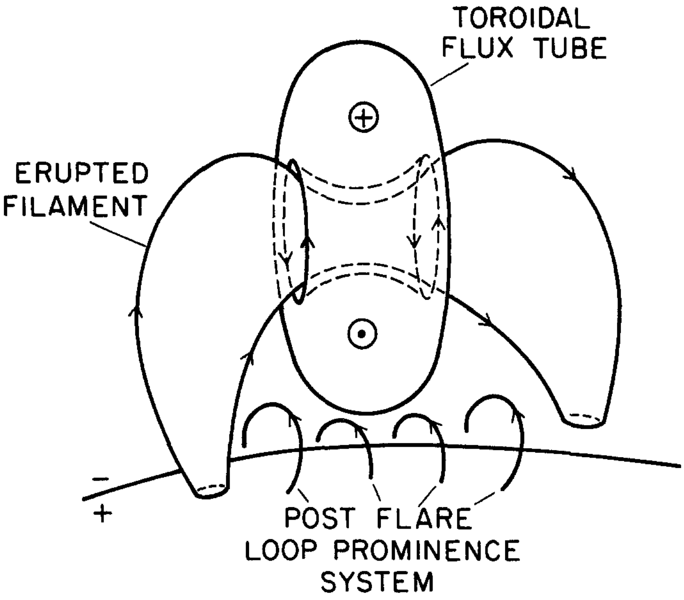

Figure 4. Schematic representation of a toroidal magnetic flux tube encircling an erupted prominence, as a result of the reconnection indicated in Fig. 3. The toroid would be detectable as a stationary type IV radio burst (Sturrock, 1986).

As a result of this reconnection, the coronal field below the filament can return to a current-free form, being visible as a post-flare loop-prominence system (Figure 4). However part of the coronal magnetic field is likely to form a toroidal configuration wrapping around the filament. Some high-resolution coronograph photographs and images of coronal transients show evidence that the magnetic field of a transient is comprised of two different flux systems as would be expected on the basis of the present model.

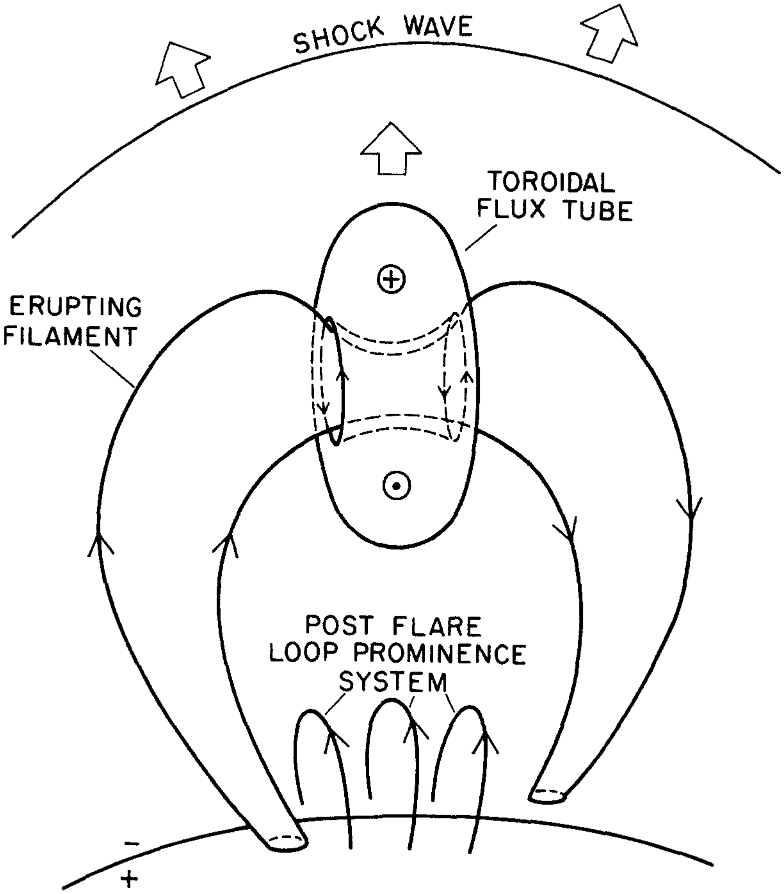

Figure 5. Schematic representation of situation that arises when a filament, encircled by a toroidal flux tube, is completely ejected from the sun. The toroid would be detectable as a moving type IV radio burst. The shock wave would give rise to a type II radio burst (Sturrock, 1986).

It may be that, in some cases, the filament erupts but does not expand out into interplanetary space. In other cases, the filament may be so highly stressed that it expands outward, attempting to form an open field configuration. If this occurs, one must expect a shock wave to develop ahead of the expanding configuration, as indicated in Figure 5.

5. DISCUSSION

The flare problem, at its current stage of evolution, now comprises a closely interlocking set of sub-problems involving the acquisition and interpretation of data, the analysis (by a combination of analytical and numerical techniques) of theoretical concepts, and the difficult task of assembling these concepts into a comprehensive model that is theoretically self-consistent and in accord with observational facts. After this brief review of the interface between observation and theory, we are clearly faced with the need for more detailed and specific observational data. We need observations with higher spatial resolution, and sufficiently high temporal resolution, to help us determine the spatial and temporal relationship of various forms of radiation from flares, and hopefully to obtain a more detailed picture of the magnetic field structure that precedes a flare and how that structure changes as the result of the flare. The continuous acquisition of high quality vector magnetograph data will be most valuable, but they should be supported by high-resolution X-ray images.

These observational challenges are matched by comparable theoretical challenges. We are faced with the general problems of trying to model possible pre-flare plasma-magnetic-field configurations, and then following the evolution of that system, realizing that a plasma process in one part of the system is likely to influence a neighboring region and stimulate a similar--or a different--process in that region. To take a specific example: It is usually assumed that reconnection plays a key role in the flare process; the theory that is invoked follows the pattern of the Furth, Killeen and Rosenbluth (1963) tearing-mode analysis. However, in such analyses, it is assumed that conditions over a large current sheet evolve only as a function of time. A more likely evolution in a solar flare is that reconnection commences in one part of a large sheet and then propagates to other parts of the sheet. How does this occur? Can it occur sufficiently rapidly to be consistent with the proposal that such reconnection is the explanation of the impulsive phase of a flare?

However, after a general picture has emerged, has been tested, and appears to be satisfactory, observers and theorists will face a more difficult challenge--that of understanding the development of a specific solar flare from detailed observations of the pre-flare state, and detailed theoretical modeling based on those observations. Perhaps we will be ready for this challenge at the beginning of the 21st Century.

ACKNOWLEDGEMENTS

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DISCUSSION

HUDSON: You must be wrong about the energetic significance of the filament though, because, first of all it's a low energy thing, low temperature, relatively low magnetic field intensity, and then when it does disrupt, it does so without any apparent energetic significance. It must be easy to disrupt; it must be flimsy.

STURROCK: If you look at the breakdown of energy in a solar flare, most of it is in the energy of mass motion. I think that the mass motion aspect of the flare is the most important to try to understand, and my estimates of how much energy you can get by shearing show that you can get a lot of energy stored in the shearing of the magnetic field.

MOORE: Yes, I think it is important to emphasize that when Peter says "filament" he is talking about a sheared field configuration like that which is present when the filament is there, but it doesn't have to contain H-alpha material. That's not the point. It's this sheared field configuration that has the energy configuration.

HUDSON: In a word, the "invisible filament."

STURROCK: Yes, that's right. The fraction you see is tiny.

KAI: You mentioned the bipolar structure associated with the moving type IV burst. I've done some statistics on the structure of such events, and bipolar structure is not there in general. Usually it is unipolar, but in some cases the polarization structure is multiple, with a mixture of right-hand and left-hand polsarization. I think that the polarization structure is closely related to the underlying magnetic field as measured at optical wavelengths.

ZIRIN: I have a question that bothers me. I've a picture not far from yours. I see these big prominences erupting and the energy is kind of the energy that would push them back down through the magnetic field. What I don't see is how they reconnect at the bottom. I do not understand how they could go all the way up to infinity and still maintain their ties to the surface.

STURROCK: Why not?

ZIRIN: Well, it seemed to me then the integral of $B^2/8\pi$ might be rather large, if I go from here to eternity.

STURROCK: Excuse me. No, no.

ZIRIN: If they're still attached to the surface - you're stuck, aren't you?

STURROCK: Yes, but let me point out that if you start with a bipolar field and start to twist it; now if nothing is holding it down the field would expand rapidly as you twist it. It is driven toward an open configuration, and that's the maximum energy you can put into it. However, if you have overlying field, you're stopping the field from going to that maximum. You put more energy in than it would take to go to infinity, so if you can then kind of allow it to expand, then the field can expand to infinity and give up energy in the process.

ZIRIN: That's fine, but I'm worried about the fact, if you look at some of these old HAO movies of "grandpa," the big arch, it's always still connected. How long can it continue to be connected? Sometime it has to....

STURROCK: No. I think what you end up with is completely open field, so you have one flux tube coming from one end, you see, the other from the other end to infinity.

QUESTIONER: How far do you have to go before you call it infinity?

STURROCK: For me, about two solar radii.

MELROSE: I just had a minor quibble that you referred to Simnett, and a number of people have referred to Simnett's ideas recently and have forgotten that Colgate put forward those ideas 10 years ago. I think that Colgate's work on solar flares has been overlooked partly because he made his flare model so specific, but there's an enormous amount of physics that he put in that people have forgotten about. In particular one of the things is the large potential drop that you need. If you're going to power a flare and you've got a current, then you could work out what the potential drop is, and he got 10^9 volts. There are a number of aspects like that, including current limitation, which I think we've dismissed because Colgate's model was so specific in other ways which we don't accept.

STURROCK: Thank you very much, I'll make sure we'll reread Colgate's paper.

SVESTKA: I would like to know how you accommodate these giant postflare coronal arches; we see them above the growing system of loops.

STURROCK: I'd like your suggestions on that.

SVESTKA: We actually do not know whether there are mass ejections associated with these events or not because, due to the law of nature, coronagraphs were not looking just at those times when we got these data.

STURROCK: Let me ask a question. Is the scale of these magnetic field loops which you infer similar to the scale you need to explain U-bursts?

SVESTKA: I must admit I do not know the size of the U-bursts, but it would be the altitude between 100,000-200,000 km.

STURROCK: I think they are even bigger for u-bursts. But they could be related phenomena.

CHENG: I' like to ask you about reconnection theory. Reconnection has been with us for many years, and everybody talks about it and, as you pointed out in your talk, the correspondence between theory and observation is not very good. I wondered what's your feeling. Is it an established theory? Is there any basis for this? I don't see any way that observers can any confirmation of reconnection, maybe because the gradient is so high and the scale is so small.

STURROCK: I'll tell you my guess, my feeling is that we are asking too much of reconnection. We've been asking it to do everything we require of a flare. I think it's not going to do everything we require. I think it is going to allow field lines to reconnect and that'll have dynamical consequences giving rise to mass motion, and perhaps to turbulent mass motion. So it can give rise to situations where you have a strongly turbulent, or rapidly moving plasma, and that may be what we require for acceleration. But we shouldn't necessarily look to the electric fields developing in reconnection itself as being sufficient to explain acceleration. I think we have to put other processes into a complete flare model.

UCHIDA: Your last table suggests that there are a variety of configurations and situations with magnetic fields. Does that mean that in some of them, an essential feature considered by somebody, is missing, and in another some other feature would be missing? My question is, may there be no unique mechanism explaining flare, but that any substantial amount of energy release can lead to some other phenomena?

STURROCK: Good question, as to what is regarded as being essential for a flare. I'd say from a theorist's point of view that you'd start with a field configuration with coronal currents and therefore with magnetic free energy, and you have to find a way to tap that energy very rapidly. Reconnection offers an opportunity of doing that. Perhaps there are other ways.

UCHIDA: So, for example, in some of the situations, perhaps magnetic reconnection is not the essential process?

STURROCK: Well, I'd be surprised if that was true, but I'd be open minded about it, and say it could turn out that way.

SPICER: I was wondering, in your discussion you never mention things like anomalous jewel heating, double layers, parallel collisionless shocks, all mechanisms which have clearly been demonstrated, at least in magnetospheric situations...

STURROCK: That is more detail than I wanted to go into. But you're quite right. If you wish to understand the primary and secondary processes, you must go into all those details.

SPICER: The reason I bring that up, is that I see the emphasis throughout the solar flare community is always on reconnection, but from all the experimental work that is done in the lab and also in the ionosphere and magnetosphere situation, most of the reconnection energy seems to go in bulk motion. Bulk mass motion, as opposed to reacceleration. Those other mechanisms seem to be doing the job of accelerating.

STURROCK: Yes. As I say we have to look for a mechanism other than reconnection to play a part in energy release.

HIRAYAMA: In your mind, what is left for flare theory as its most essential tasks?

STURROCK: Well, I'd say many valuable bricks have been put together to make a coherent structure.

CANFIELD: Let's say that we won't have a real flare theory until we get to the point where Peter Sturrock can stand up in the front of the room and predict the time, place and particle spectrum of the next solar flare (and its composition)!

HIRAYAMA: Just persisting one more moment, do you think we already have all of the basic physical mechanisms identified? Do present-day physicists already know all of the instabilities they need to explain flares?

STURROCK: No, I'm not sure of that.