ENERGY RELEASE IN SOLAR FLARES

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In early research on solar flares, attention was focused on the impulsive or flash phase, and it was assumed implicitly that virtually all the energy of a flare is released during that short phase. In recent years, however, it has been realized that the long-lived soft X-ray emission which follows the impulsive phase may require a separate energy-release process, which has been termed the "gradual phase" (Kane 1974). The fact that the impulsive phase is often preceded by soft X-ray emission has also led to the suggestion that there may be a third phase of energy release, which might be termed the "onset phase" (Sturrock 1980). It has long been realized that filament eruptions frequently precede flares, and it has been suggested (Kiepenheuer 1964) that the two should be regarded as parts of the same process. For these and other reasons, it is appropriate to question how many phases of energy release are involved in flares and what are their characteristics.

There is no doubt that some of the soft X-ray emission is due to bremsstrahlung from hot plasma, trapped in coronal loops, which has been evaporated from the chromosphere during the impulsive phase. This causal relationship has the consequence that the time curve of soft X-ray emission is approximately a time-integral of the time curve of the hard X-ray emission (Hudson 1983). On the other hand, as indicated above, detailed study of some flares indicates that the soft X-ray emission is fed by a continued energy release after the impulsive phase has ended. In their analysis of the 1979 March 31 flare, Feldman et al. (1982) adduce evidence indicating that the energy release responsible for hard X-ray emission and the energy release responsible for most of the soft X-ray emission occurred in different magnetic-field systems. For instance, the soft X-ray emission varied in a smooth manner from the onset to the decay of the flare; there was no abrupt change in either the emission measure or the temperature characterizing the soft X-ray emission during the time when the impulsive hard X-ray burst was in progress. This analysis adds further support to the proposition that the impulsive phase and the gradual phase involve distinct and

M. R. Kundu and G. D. Holman (eds.), Unstable Current Systems and Plasma Instabilities in Astrophysics, 293–298.

independent processes. Indeed, it is known from H-α and X-ray studies that some flares do not possess an impulsive phase at all.

Although there appears to be a clear case in favor of the existence of two distinct energy-release processes responsible for the impulsive phase and the gradual phase of a flare, it is not so clear that a third process is required to explain the "onset phase". It is possible that, in some flares, such as the one analyzed by Feldman et al. (1982), the "onset phase" is simply the beginning of the gradual phase. It is also possible that, in other flares, the soft X-ray emission which begins early in the flare, before the recognized impulsive phase, is in fact due to early impulsive energy release at a sufficiently low level that it is not detected by its hard X-ray emission, yet is detected through the soft X-ray emission resulting from chromospheric evaporation.

The question now arises as to the distinction between the impulsive and gradual phases of energy release. Adopting the conventional view that energy released during a flare is the free energy of a current-carrying magnetic field which is released by reconnection, there are two classes of explanation of the difference between the impulsive and gradual phases. 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.

Recent research on the tearing-mode instability shows that there are indeed different possible stages in the time evolution of this instability. The work of Carreras et al. (1980) and Carreras et al. (1981) shows that the tearing process may involve the following three stages: (I) the initial phase described by FKR (Furth, Killeen and Rosenbluth 1963) linear theory in which there is a slow but exponential growth; (II) a nonlinear development in which the amplitude grows linearly with time; and, if two or more modes are unstable and if the spatial configuration is such that these modes can interact, a third stage (III) characterized by a very rapid stochastic variation of one or more modes involving growth rates considerably larger than the growth rate of the initial linearized regime. For a variety of reasons, it does not seem possible that one can understand the gradual phase as the manifestation of processes I and II and the impulsive phase as a manifestation of process III. On the other hand, it is possible that some of the rapid variation characteristic of the impulsive phase may be due to the stochastic behavior of the strongly nonlinear regime (III) of the tearing mode.

The analysis of Feldman et al. indicates that the distinction between the impulsive and gradual phases is to be found in the characteristics of different magnetic-field configurations. Of the possible distinctions, it seems most likely that the difference is due to the characteristic length scale of variation of the magnetic field. There are reasons for expecting at least three different length scales to arise in the magnetic-field configurations of active regions.

Observations by Tarbell and Title (1977) and others 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 1,000 to 1,500 gauss. In consequence, the magnetic field of the photosphere tends to be aggregated into "knots" in which the flux has values of order $10^{18.4}$ Mx. In consequence, 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. This leads us to the following three characteristic dimensions: (a) the thickness of the current layer separating adjacent elementary flux tubes (perhaps 10^4 - 10^6 cm); (b) the minor radius of an elementary flux tube (10^8 cm); and (c) the characteristic dimensions of an active region (10^9 - 10^{10} cm). It seems likely that currents of types (a) and (b) are both involved in the impulsive phase of a flare, and that the current of type (c) is responsible for the gradual phase of a flare. Indeed, the evolution of two-ribbon flares indicates that the impulsive phase is associated with activity very close to the neutral line, whereas the gradual phase is associated with magnetic-field lines which meet the photosphere far from the neutral line.

Recent detailed studies of the X-ray and microwave emission from flares indicate that much of the time-structure can be interpreted as due to aggregates of "elementary bursts". The time scale of an elementary X-ray burst is of order 1 s and involves the release of about 10^{28} erg. The time scale of an elementary microwave burst is appreciably less (tens to one hundreds of milliseconds). The energy actually radiated in microwaves is very small, but it represents only a small fraction of the primary energy release. There is sufficient uncertainty in the processes involved that the magnitude of energy involved in each elementary microwave burst may be in the range 10^{24} - 10^{27} erg.

The above characteristics are compatible with the proposed scales of fine-structure of the magnetic field of an active region. An elementary X-ray burst may be attributed to the release of the free energy of a single twisted elementary flux tube. An elementary microwave burst may be attributed to energy release of the current sheet separating an adjacent pair of elementary flux tubes or to energy release in one of the "magnetic islands" that one expects to develop in an elementary flux tube during reconnection. The time scale and energy characteristic of the gradual phase are consistent with the attribution of that phase to energy release of the distributed current system of an active region.

In the case that a flare follows the eruption of a filament, it is possible (a) that the eruption is a secondary process following early magnetic-field reconnection; or (b) that the flare is "triggered" by the filament eruption; or (c) that the flare involves the release of energy associated with a current system produced by the filament eruption; or (d) that magnetic-field reconnection and filament eruption form a pair of symbiotic processes. The detailed study of the early stages of some flares favors the last possibility (Moore 1983). A filament involves a magnetic-field configuration which typically has many "legs" tying the filament to the photosophere near the neutral line. Reconnection at the junctions of different legs can simultaneously lead to flare-producing energy release and to eruption of the filament. The continued eruption of the filament can then trigger the release of energy associated with both the elementary-tube structure and the gross structure, producing the impulsive and gradual phases of the flare.

This work was supported in part by NASA Grants NGL 05-020-272 and NAGW-92 and the Office of Naval Research contract N00014-75-C-0673. P.A.S. acknowledges the generous hospitality of the Instituto de Pesquisas Espaciais of Brazil during a recent visit to São Paulo.

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DISCUSSION

Vlahos: Why do we need large scale magnetic fields in cases that we have a gradual phase? Can this be one phase of the reconnection instability with elementary flux tubes? R. Lin has recently reported an interesting phenomenon in X-ray observation. A "gradual" burst was composed of small "spikes" that only low sensitivity instruments can detect. How does this fit to your suggestion?

Sturrock: I did not propose that the magnetic field structure responsible for the gradual phase necessarily has a larger size than the structure responsible for the impulsive phase. What I did propose is that the characteristic length scales of the current systems are different. It seems unlikely that the impulsive and gradual phases represent two consecutive phases in the development of reconnection in the same magnetic-field and current system. Reconnection even in a large current sheet will involve the development of small-scale structure - such as "magnetic islands" - which might be related to the small X-ray spikes which occur during the gradual phase.

Mullan: (i) Field "knots" are always present in the photosphere (even apart from flares). Therefore, one expects that interwoven flux tubes (such as you suggest) would always create current sheets in the corona. Can such current sheets heat the "quiet" corona in the way envisioned by R. H. Levine (Ap.J. 192, 1974)? In the latter, the time scale for field collapse in the corona ($T = 10^6$ K, $n = 10^9$ cm^{-3}) is ~ 1 second (as you require for "elementary X-ray bursts"). Maybe X-ray bursts are elementary flux reconnection events. (ii) Do you believe that the gradual phase involves essentially the same process as "normal" coronal heating?

Sturrock: I agree that interwoven flux tubes, separated by current sheets, must always be present in the corona. It is quite possible that slow, continued reconnection may play a role in coronal heating. However, the release rate involved in the gradual phase must be considerably more rapid, although it is not as rapid as the impulsive phase.

Tsinganos: What is the vertical extent of the loops? Do you take into account two facts: (i) that the tube expands at larger heights (ii) that the twist is concentrated in these expanded parts of the tube?

Sturrock: The vertical extent may range from a few thousand km up to many tens of thousands of km. We do take account of the variation of cross section and of twist along the length of the flux tube.

Lokanadham: What are the time scales of the microwave spikes observed? Are there observational evidences for any spikes observed on a time scale of seconds and, if so, what is the mechanism involved?

Sturrock: Structures have been observed with a wide range of timescales, from seconds down to below 100 msec. On times scales of seconds, the time structures are poorly correlated at different frequencies and between microwaves and hard X-rays, so it is unlikely that the structures are to be attributed to fluctuations of the primary energy-release process.

Kundu: There are many examples of the impulsive phase evolving into large loop prominence systems (VLA 6 cm and Nebyama 17 GHz data), which I believe you consider as "gradual phase". So the question is, do you really need two different mechanisms of energy release, (1) for the impulsive phase and (2) for the gradual phase?

Sturrock: If there is no continued energy release after the impulsive phase, there is no need for a "gradual phase" of energy release. However, if there is continued energy release, there clearly is need for another phase.

Rust: It may not be so easy to separate gradual and impulsive phases. Recent Hα and hard X-ray flare observations indicate that filaments (large scale features) rise gradually during the gradual phase onset - consistent with your picture - but also that they move suddenly during the impulsive phase. How can you fit this large-scale, impulsive phase phenomenon into your scheme?

Sturrock: In our picture, the initial rapid reconnection occurring below a filament during the impulsive phase gives rise to a magnetic disconnection of the filament from the photosphere which allows it to erupt. The eruption in turn produces a large-scale current sheet which reconnects during the gradual phase.