ENERGY RELEASE IN SOLAR FLARES

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Abstract. We examine observational evidence concerning energy release in solar flares. We propose that different processes may be operative on four different time scales: (a) on the sub-second time scale of 'sub-bursts' which are a prominent feature of mm-wave microwave records; (b) on the few-seconds time scale of 'elementary bursts' which are a prominent feature of hard X-ray records; (c) on the few-minutes time scale of the impulsive phase; and (d) on the tens-of-minutes or longer time scale of the gradual phase.

We propose that the concentration of magnetic field into 'magnetic knots' at the photosphere has important consequences for the coronal magnetic-field structure such that the magnetic field in this region may be viewed as an array of 'elementary flux tubes'. The release of the free energy of one such tube may produce an elementary burst. The development of magnetic islands during this process may be responsible for the sub-bursts. The impulsive phase may be simply the composite effect of many elementary bursts.

We propose that the gradual phase of energy release, with which flares typically begin and with which many flares end, involves a steady process of reconnection, whereas the impulsive phase involves a more rapid stochastic process of reconnection which is a consequence of mode interaction.

In the case of two-ribbon flares, the late part of the gradual phase may be attributed to reconnection of a large current sheet which is being produced as a result of filament eruption. A similar process may be operative in smaller flares.

1. Introduction

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

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alternative configuration with similar provision for the storage and release of magnetic energy.

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

The above viewpoint is no longer accepted. In the Skylab workshop on solar flares (Sturrock, 1980), it was clearly recognized that most flares manifest release of energy during an 'onset phase' (including what is termed 'preheating') occurring before the impulsive phase. This energy is seen most clearly in the early buildup of soft X-ray emission. In this context, one should also recall that filament activity frequently occurs before a flare (Smith and Ramsey, 1964); this activity may be regarded as a 'precursor' if it occurs about an hour before the flare, or as part of the 'onset phase' if it occurs only a few minutes before the impulsive phase. Although Kiepenheuer (1964) argued some time ago that filament activity and flares should be regarded as different aspects of one complex process, it is still usual to regard filament eruption and flares as separate but related phenomena (Van Hoven et al., 1980). A gradual onset phase preceding the impulsive phase can also occur in flares having no visible filament eruption; an especially well observed example is the flare of November 1, 1980, studied by Tandberg-Hanssen et al. (1984).

Although radiation continues long after the impulsive phase, this long-lived radiation may often be interpreted as the slow decay of energy suddenly released during the impulsive phase. For instance, the soft X-ray emission can be attributed to hot plasma formed by 'evaporation' of gas from the chromosphere during the impulsive phase (Neupert, 1968; Hudson and Ohki, 1972; Hirayama, 1974; Antiochos and Sturrock, 1976). However, careful analysis has shown that, for some flares at least (Datlowe et al., 1975; Moore et al., 1980), there must be continued energy release in what has been termed the 'late phase' of a flare (Sturrock, 1980). Indeed, Hα data for 'two-ribbon' flares (Švestka, 1976) provide very strong evidence for such continued energy release. In this case, the two flare ribbons drift slowly apart (receding from the magnetic neutral line) so that, late in a flare, regions of the chromosphere are being heated which were not heated during the impulsive phase.

Substantially the same conclusion has been reached by Kundu (1965) in his analysis of flare-related radio emission. He finds that this emission occurs with two distinct phases, which he terms 'impulsive' and 'post-burst', demonstrating that radio emission requires continued energy release after the impulsive phase of a flare. The division of microwave bursts into two broad classes of 'impulsive' and 'gradual' was indeed proposed even earlier by Covington and Harvey (1958).

The facts listed above led, in 1980, to the view that there are not one but three phases of energy release in solar flares (Sturrock, 1980), namely, the onset phase, the impulsive phase, and the gradual phase. Feldman et al. (1982) have argued from their analysis of the hard and soft X-ray emission of two M-flares (Doschek et al., 1981) that, for these