THE HIGH-ENERGY FLARE PLASMA

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1. Acceleration of Particles in Flares

A solar flare has various aspects: the *optical flare* is often associated with emissions in the microwave or X-ray regions: this indicates the occurrence of a highly excited plasma, which we call the *high-energy flare plasma*. The existence of the high-energy flare plasma was first shown by radio observations in the microwave regions (Hachenberg) and later confirmed by X-ray observations in the energy range 10^2–10^6 eV.

The picture that is gradually emerging from the various kinds of observations of flares and flare-associated phenomena is that during the very first phase of solar flares particles are accelerated to energies of the order 10^3–10^6 eV; observations pointing in that direction are the occurrence of X-ray bursts covering that energy range, the occurrence of microwave radiobursts in the first minutes of solar flares, and the emission of type-III radio bursts, also mostly occurring in the very first phases. The velocity of the type-III excitation sources, which ranges between $c/6$ to $0{\cdot}9\,c$ with maximum occurrence at $c/2$ points to electron energies in the range 7–700 keV with a maximum around 80 keV. This is in agreement with X-ray burst observations in the deka-keV range.

Other phenomena, like the emission of solar protons and the occurrence of metric type-IV bursts, are rather related to later phases of the solar flare event, and show that after some time further acceleration occurs to energies of the order 10^7–10^9 eV. Hence, secondary electromagnetic particle acceleration with a factor 1000 occurs in a second phase of solar flares.

2. The Origin of the Flare Energy and the Acceleration Process

According to Kiepenheuer and Bruzek the energy output in the form of *radiation* is (for strong flares) of the order of 10^{32} ergs, while in the acceleration of *particles* an energy of $10^{32{\cdot}5}$ erg is involved. Assuming for the high-energy flare a volume of 10^{26} cm^3, it is clear that this energy could be obtained if in this volume the magnetic field would be reduced from e.g. 500 to 400 gauss. No other energy sources seem likely to be sufficient for producing the flare energy. Hence, the energy of solar flares could arise from a partial annihilation of the magnetic field. This, in turn, means the

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establishment of a large electric field and consequent current flow, since the essential aspect of this annihilation process is the consumption of the magnetic energy of the current by a discharge.

Whereas it is difficult but not impossible to construct a model of a solar flare that might explain magnetic-field annihilation by a discharge (see e.g. Alfvén and Carlqvist, 1967), the real problems are those of the primary origin of this energy and of its accumulation in a magnetic field. Sinçe flares may recur at intervals of the order of a day in the same active region, it is clear that the flare process is due to a storage of energy and a subsequent release. The time-scale for the establishment of the field may be of the order of a day.

The only source that seems capable of producing sufficient energy is the subphotospheric convective energy flux, which we know to be suppressed in the region below sunspots. The missing energy flux in an average sunspot is of the order of 4×10^{29} erg sec.

If the mechanism which transforms the missing convective energy flux into magnetic energy had an efficiency of 100%, the energy necessary to produce a large flare would be provided in about 1000 sec. If the efficiency was only 0·01, one flare could be produced in 24 hours.

3. Conclusions

The purpose of this note was to draw attention to certain aspects and problems related to the origin of the flare energy, its transformation into magnetic energy, the acceleration of particles during the first phase of the flare, and the secondary acceleration in a later phase.

(a) The energy emitted in solar flares is so large, and flares occur so often that the energy can only be provided by a mechanism transforming the missing subphotospheric convective energy flux in a sunspot into magnetic energy.

(b) This magnetic energy should be released, perhaps through the establishment of a large electric field and a subsequent discharge.

Occasionally, this may produce the high-energy flare, where in a magnetic bottle about 10^{22}–10^{29} electrons are contained with energies of 10^3–10^6 eV. This means that the electric voltage over the discharge need not necessarily exceed 10^6 volts, which is smaller than assumed in most current flare theories.

(c) In a later phase of the flare, maybe 15–60 min later, secondary acceleration of the electrons may occur; this may lead to an average increase of the energy by a factor of about 1000. These accelerated particles may produce the metric type-IV radio bursts (electrons), and the high-energy particle fluxes observed near the Earth as sub-relativistic or relativistic particle events.

Reference

Alfvén, H., Carlqvist, P. (1967) *Solar Phys.*, **1**, 220.

DISCUSSION

Krüger: You mentioned the picture of the two steps of acceleration process of particles within a flare. Do you assume the action of different acceleration mechanisms or more likely of a cyclic acceleration process?

De Jager: Little is known, if anything, of the acceleration mechanism. Yet I believe the two acceleration mechanisms to differ. For the first phase I would think of a mechanism like the one proposed by Alfvén and Carlqvist (*Solar Phys.*, **1**, 1967, 220); the second phase might rather be a Fermi-type acceleration.

Krüger: In some cases there seems to be a relation between the duration of cm-type IV bursts or their rising time and the energy of emitted particles.

Schmidt: I wonder whether it might be conceivable that the comparatively young and closed field-lines of a flare-producing active centre intermingle on a scale much smaller than the flare dimension with the rather old fieldlines originating in the weak and extended field patches and stretching radially outward into the sector structure of the solar wind. It seems to me that such a concept would be also consistent with the observed formation of new photospheric flux occurring without much interference with the surrounding older flux as well as with the results of Mrs. Pick concerning the large solid angles filled by energetic protons.