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Solar flares

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A summary is given of some recent observational data on solar flares. Particularly we discuss the flare build-up process and the time scales involved. We suggest as a possible magnetic field configuration a multiply kinked or supertwisted flux tube. The role of plasma turbulence and the Fermi mechanism in particle acceleration is discussed.

1. Average structure

Introduction

There are various flare components:

(1) The (cool) optical (Hα) flare, apparent from its emission lines in the visible spectrum. The parameters of the optical flare have been described by Švestka (1976), particularly noteworthy is the very small effective thickness, being of the order of tens of kilometres.

(2) The high-energy component, studied principally from X-ray and microwave observations.

(3) The particle aspect: flares are related to the acceleration of particles. These can be studied directly in interplanetary space or indirectly by the (sub)-metric waves generated by their passage through the solar corona.

Origin

The origin and structure of flares can be studied best by restricting the investigation to weak flares, which do not show the many complicated by-products of strong flares, and for which photographic overexposure does not occur so often as for strong flares. The CINOF campaign (De Jager 1975) of June 1972 was aimed primarily at the observation of weak flares. In less than four weeks about a hundred small brightenings could be observed during a period in which the Sun was fairly calm. Apparently it is for the Sun not difficult to produce the many small brightenings, known as subflares. Many subflares are not recorded by common observing programs, yet they give important information on the capability of the solar atmosphere to establish configurations in which particles are accelerated to large velocities.

The CINOF campaign confirmed that flares tend to originate at bright points which in most cases exist already as weaker brightenings at the cross-points of the chromospheric network.

In this connection it is perhaps interesting to list some of the transient bright features in the solar atmosphere:

(1) The X-ray bright points occur all over the disk, and are therefore not necessarily confined to large active regions. They have average life-times of about 8 h. It is thought that they consist of magnetic loops emerging from beneath the solar surface, ephemeral active regions (Harvey *et al.* 1975).

(2) About 10% of the observed flares occur outside active regions. These flares mostly show a slow development, are less bright and last longer than flares in active regions. These flares have a tendency to produce only type III bursts and particle acceleration to approximately 100 keV but not the second stage acceleration related to higher energies.

(3) Flares occurring in active regions have shorter life-times and reach greater brightness; they are more impulsive in character.

Relation with the field configuration

The probability for a flare to occur is larger when the field structure is more complicated. They show a clear preference to occur in regions with a so-called delta-configuration (which contains two umbrae of opposite polarity in a common penumbra). The very beginning of a flare tends to show two brightenings which occur close to the $H_{\parallel} = 0$ line (the so-called 'neutral line' which is not a line of zero field), but practically never on that line. They tend to coincide with regions where the lines connecting equal $H_{\parallel}$-values show a local maximum. From the values of magnetic field components the electric currents can be estimated (the perpendicular field components are known to be only estimates; the measurements are exceedingly difficult). Yet it seems that a *current* of approximately 10^{11} A seems to flow through the two initial flare brightenings. This suggests that they are connected by a current loop.

Static flare models

The observations described above yield a picture already presented earlier by one of the authors (De Jager 1969) and reproduced here in figure 1.

The essential part of the diagram is the current loop, connecting the two flaring areas over the neutral line.

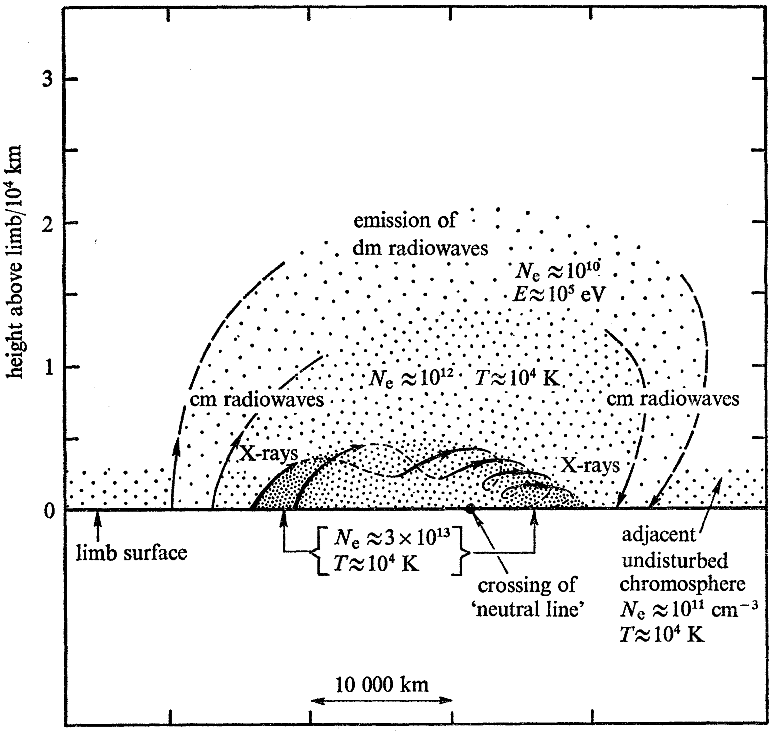

FIGURE 1. The drawing shows in a tentative way the cross-section through the projection of the flare structure on a plane perpendicular to the solar surface. The two flare areas are connected by a bright filamentary arch running more or less parallel to the 'neutral line'. Apparently the field lines connecting the two areas along this arch must be twisted: the arch represents a current system. At a height of about 10^4 km the electron density in the flare (dotted area) is decreased to about 10^{12} cm^{-3}. We think that the high-energy flare plasma surrounds more or less the optical flare plasma. Emission of dm radio waves should occur in high regions; that of X-rays and cm radio waves in lower regions.

In connection to that figure it should be noted that as observations available so far show, the positions and shapes of the X-ray flares and of the optical flares are identical within the error of the measurements. In figure 1 these two sources are assumed to be fairly close together but better observations (with higher resolution) of the sources of hard X-ray bright knots, might show the two positions to be identical. This would then mean that the high energy particles and the cooler Hα emitting particles are essentially contained *in* the *same* magnetic loop structure. Such observations are not yet available, but would be of great importance for the development of our understanding of the flare acceleration process.

2. Flare development and decay

There is growing evidence that the essential event in the flare is the formation and confinement of energetic particles, hence that the high energy flare is the primary event. We assume that the optical flare is a secondary phenomenon, and due for instance to (*a*) the penetration of energetic particles into the denser part of the photosphere and low chromosphere, or to (*b*) the heating of the low chromosphere by conductive cooling from the high energy flare plasma.

The elementary flare burst

An important feature, brought forward by observations with a fairly high time resolution (Van Beek, de Feiter & de Jager 1974) is that the X-radiation of a flare is emitted in individual bursts which are nearly symmetric in time and which have a duration of approximately 10 s.

Hence a flare must consist of a fairly large number of individual instabilities, leading to individual acceleration processes, which, presumably occur more or less independent of each other but are clustering together in time. It is perhaps significant that 'single' elementary flare bursts have never been observed.

It is also important, in this connection, that the rate of decay of an individual elementary flare burst appears to be the same for all photon energies. If the decay would be a relaxation phenomenon, due to energy loss of the accelerated particles by collisions with the ambient plasma, then the rate of decay would be energy-dependent. Since this is not the case, the characteristic collisional decay time must be much shorter than the observed duration of the declining phase of the bursts for all energies, so that burst profiles *essentially* represent profiles of the flux of the injected particles.

Another conclusion from this observation is that ambient particle densities published so far, and derived from the observed overall range of decline, of the X-ray bursts are too small. A lower limit for the ambient particle density should be $5 \times 10^{10}\ \mathrm{cm}^{-3}$.

The high-energy component

For the interpretation of the photon spectra of hard X-ray bursts it is of importance to know that the photon spectra are for the greater part strictly logarithmic and can be described by an $E^{-\gamma}$-law, with γ ranging between 2.5 and 5. This observation must have direct conclusions for the electron acceleration processes.

Only a few intense X-ray flares, those which have been observed over a wide energy range, have a different shape of the spectrum. Frost (1965) and Van Beek (1973) found for such cases that the spectrum consists of two logarithmic parts; the part in the highest energy range being the steepest. The position of the 'knee' as determined by Van Beek lies at approximately

60–80 keV and $\gamma_2 - \gamma_1 \approx 1$. The implications of this observation for the theory of the electron acceleration are not yet clear.

It has been suggested (De Jager 1969) that the acceleration of particles might go in two steps. In the first phase particles would be accelerated to energies of tens to a hundred keV. In the second phase acceleration to about a 1000 times higher energy should take place, for instance by a Fermi-type process. This was confirmed by Švestka who found correlation between the occurrence of MeV particles in interplanetary space, and flares with type II radiobursts. Also the gamma rays emitted during the solar flare of 4 August 1972, were emitted at the moment of start of the type II burst. Since type II radiobursts are related to a shock wave progressing through the solar atmosphere this is indicative of the secondary acceleration process. The amount of particles involved in the second phase would be about 10^{-3} of the number involved in the first phase.

It is not known whether the above-mentioned 'knee' in the photon-spectrum would be related to such an acceleration in two steps (cf. §6).

3. The flare build-up process

An important problem is where the flare energy originates, how it is supplied to the flaring region, and how the conditions are created that will later give rise to the flare process. This process is called the 'flare build-up process'.

Relation to magnetic field variation

The relation of the occurrence of flares to changes in the magnetic field has been suggested many times and was denied as often. Only recently Rust (1976) has found indications that the occurrence of flare brightenings is in all cases studied by him related to the appearance of new magnetic fields at the solar surface and reconnection with the pre-existing magnetic field. When pores were not observed the atmospheric seeing was usually poor. We may conclude that the occurrence of flares is related to changes in magnetic field topology.

Relations to surges, filaments, bright loops

During the CINOF campaign (De Jager 1975) it was noted on several occasions that filament activity took place, sometimes up to 4 h before the origin of a flare. In some cases flares were proceeded by a surge, or by material from a previously erupted filament, falling towards the Sun. In that case the brightenings did not occur at the place of impact but rather above the $H_{\parallel} = 0$ line. There are other cases in which flare-like brightenings do occur at the place of impact of falling material. However, it is certainly not a general rule that the impact of erupted material would lead to flare-like phenomena at the place of impact. In the cases in which this occurs, the flares are of the slowly developing type.

4. Time scales of field annihilation

It is now widely accepted that the energy liberated during a solar flare is energy that is stored in magnetic fields and that the release of this energy is associated with the annihilation of magnetic fields. The most extreme magnetic field configuration where this could occur is the magnetically neutral sheet which has since long been a model configuration for a solar flare (Sweet 1958).

However, the diffusion time $\tau_d = \sigma l^2$, where σ, the electrical conductivity, is too large to explain a sufficiently fast annihilation.

For $\sigma \approx 10^{-5}$ e.m.u. and $l \approx 10^7$ cm one finds $\tau_d = 10^9$ s. One is thus forced to look for a mechanism that could transfer magnetic energy in a much shorter time scale. This cannot be a pure annihilation with the above-mentioned values of σ and l since one would always end with a characteristic time of the order of the value determined above. It must therefore be either a magnetic field configuration that allows for topological changes in the magnetic field and/or a configuration in which plasma processes can occur that effectively reduce the value of σ.

In the first case much work has been done on so-called X-type neutral points in which most of the magnetic field is reconnected instead of annihilated (Parker 1963; Petschek 1964; Sweet 1969; Yeh & Axford 1970). These analyses lead indeed to a much faster reconnection rate than given by pure diffusion.

But it is still too long to explain the flare phenomenon and moreover it is not understood how the excessive plasma heating occurs. The reduction of the time scale is essentially caused by magnetohydrodynamic effects where the Alfvén velocity is the characteristic velocity and the Alfvén time $\tau_A = l/c_A$ is the characteristic time scale. But a pure magneto-hydrodynamic process around an X-type neutral point does not lead to the required heating of the solar flare plasma. One is thus forced to investigate mechanisms in which both, diffusion and reconnection play a part. Such a mechanism is the tearing mode instability in which the characteristic growth rate is approximately determined by a mean value of τ_A and τ_d given by $\tau^2 \approx \tau_A \tau_d$.

With $\tau_A \approx 1$ s and $\tau_d \approx 10^9$ s the instability growth time $\tau = 3 \times 10^4$ s which is still too large but comes closer to the characteristic time of the flare phenomenon. However for the tearing mode and for any diffusion determined process one needs a neutral sheet configuration much more than an X-type neutral line configuration.

The only way to reduce the time scale still more is to assume that the electrical conductivity is no longer determined by collisional processes but instead by the reduced mobility of the electrons in a collisionless plasma when a large level of plasma turbulence is present. This may for instance occur when the electric currents in the neutral sheet surpass a certain value determined by the condition that the drift velocity of the electrons is comparable with the thermal electron velocity $v_{T_e} = (kT_e/m_e)^{\frac{1}{2}}$.

The critical current density J^* is then approximately given by $J^* \lesssim n_e e\, v_{T_e}$. This may be too stringent a condition since it requires all the electrons to have a large velocity, whereas for an instability to occur only a fraction of the electrons should have superthermal velocities. If $J > J^*$ oscillations are set up which result in a very efficient reduction of the electrical conductivity. A reduction factor of the order of 10^{-5} is expected (Sagdeev 1972). Hence

$$\sigma_{\text{turb}} \approx 10^{-5}\, \sigma_{\text{coulomb}}.$$

This naturally leads to a strong reduction of the diffusion time. If one uses the tearing mode growth time, one finds $\tau \approx 10^2$ s, which is sufficiently short to explain the conversion of magnetic energy into thermal energy in a neutral sheet where the electric current density has grown to such a large value that the resistivity becomes anomalously large.

5. Magnetic field configurations for solar flares

A neutral sheet may originate when two bipolar fields are compressed (cf. Priest 1976, this volume). First an X-type neutral line is formed but after further compression a sheet occurs. However, there is no indication that flares originate in quadrupolar fields, but instead in bipolar fields, the common field configuration of an active region. How can a neutral sheet originate in a bipolar configuration? Barnes & Sturrock (1972) investigated how a cylindrically symmetric bipolar magnetic field evolves as the foot points of the field lines are rotated (cf. Schmidt 1976, this volume). The result of their computations is that a ring dipole expands under the pressure exerted by the generated azimuthal field component. This pressure effect increases over the tension thus leading to the expansion of the field. Under the assumption that the ring dipole evolves through a series of force free magnetic fields they find that the energy increases when the photospheric ring is rotated and becomes equal to the energy of an open magnetic field with an associated cylindrical current sheet when the inner ring has rotated over an angle π.

All the closed field configurations that contain more energy than the corresponding open field configuration are assumed to be unstable or at least metastable.

They suggest that the instability which converts a force free field into an open field is an explosive instability that should be identified with the solar flare in which the open field configuration is reached through a series of configurations with partly closed and partly open field lines. The open field configuration can relax to a closed potential configuration by magnetic field reconnection after which the field may again be wound up and burst open and another flare may occur.

Another field configuration in which a flare may occur is a flux tube which is rotated at one of the end points. Contrary to the above example the magnetic tensions may oppose any unlimited expansion. It is even expected that the twisted tube of force is constricted instead of expanding. However, a twisted flux tube may become kink unstable after some time, thus forming loops of twisted fieldlines. If a sufficient number of loops is present, they can interact with each other in the sense that magnetic annihilation and reconnection takes place along a helically wound X-type neutral line. This field configuration of a multiply kinked or supertwisted flux tube has been proposed as a basic solar flare configuration by Kuperus and Rosenberg (cf. Kuperus 1974*a*, *b*). It has certain advantages above other field configurations such as a sufficiently long build-up time.

6. Particle acceleration

From the discussion of the growth times of the flare instability we found that the conductivity in the neutral sheet had to be severely reduced, and the obvious candidate to explain such an anomalous conductivity is the presence of some sort of plasma turbulence. Large currents in the neutral sheet can generate plasma turbulence in the form of Langmuir waves (Coppi & Friedland 1971; Tomozov 1973; Friedman & Hamberger 1968, 1969). This turbulence mainly heats the electrons, and when T_e has become much larger than T_i, ion sound turbulence can develop. At present it is not clear whether all the electrons have to drift with superthermal velocities, or only a few runaway electrons (Kaplan, Pikel'ner & Tsytovich 1974).

However, it is clear that a high level of plasma turbulence is present in the flaring region.

This turbulence in turn is a most effective accelerator of electrons, by means of stochastic acceleration (Tsytovich 1970). The effective temperature of the plasma turbulence is many orders of magnitude larger than the initial electron temperature, (cf. Rosenberg 1976, this volume), and hence can accelerate electrons to equivalent energies. The efficiency of the acceleration process depends on the initial electron energy (electrons with subthermal velocities are difficult to accelerate), the spectrum of the plasma turbulence, and possible resonances. In particular the turbulence spectrum is very badly known, and the only conclusion at present that can be made is, that plasma turbulence can accelerate electrons very quickly, i.e. easily within time scales of the flash phase. It is therefore reasonable to associate the flash phase of the flare, and the sudden appearance of 10–100 keV electrons with the growth of a plasma instability. The exact critical current density for the instability to grow is not known, but the growth rates are very fast and the developed plasma turbulence leads to reduced conductivity and to particle acceleration. The saturation of the instability is the next badly known problem, and at present we only know from the observations that the typical saturation brightness temperature is $\lesssim$ 100 keV.

The secondary acceleration to much higher energies occurs only in large flares, usually accompanied by type II and type IV radio bursts. The fact that macroscopic motions are present, and that it takes considerable time before the high energies are obtained (5–10 min) suggests the Fermi mechanism involving magnetohydrodynamic motions as the acceleration mechanism. The Fermi mechanism is slower than the turbulence in accelerating particles, but it can lead to very high energies.

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