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Solar flare plasmas

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The solar flare is discussed in terms of its three phases: energy storage, energy release, and dissipation. Some of the problems associated with theoretical modelling are considered, together with the limitations imposed by current observations. New measurements to be made by the N.A.S.A. Solar Maximum Mission satellite are expected to advance significantly our understanding of the flare mechanism.

INTRODUCTION

A solar flare involves the impulsive release of a large amount of energy, on a time scale of tens of minutes. The energy involved can range up to 10^{25} J for a large flare, and the time scale can be much shorter for some of the harder emitted radiation. Electromagnetic radiation is observed in the visible, ultraviolet, and soft and hard X-ray regions. For a few of the most energetic flares, γ-radiation is detected, and occasionally γ-line radiation from nuclear interactions is also detected. In addition, charged particles are emitted: electrons, protons and heavier-ion nuclei. Radio emissions are also observed, produced by the high-energy particles or plasma blobs, and their interaction with the magnetic field. Typical time profiles of many of these emissions are shown in figure 1, which has been taken from Svestka's (1976) excellent book on the subject. This shows that many of the low-energy fluxes show a slow rise and decay; the so-called thermal phase. The harder radiation, the radio emission, and often the x.u.v., show a fast rise and decay, referred to as the impulsive phase of the flare. For a comprehensive survey of recent work on flares, the reader is referred to the monograph of the Skylab Solar Flare Workshop (Sturrock 1980).

Observations of solar flares have been made for more than one hundred years, and yet we are still left with many unsolved questions as to their nature and mechanism. There are many reasons for this. Since the emissions cover such a wide range of wavelengths and particles, usually only one or two of these ranges have been covered simultaneously. Moreover, flares occur sporadically, and their variation is substantial, so that it is difficult to plan predictable observations, or to combine data obtained from different flares. Many of the observations can only be made from space. But during space missions like Skylab, not specifically designed for solar-flare studies, the probability of observing good flare data is small. As a result of these problems, good complete data sets on flares are very rare.

Theoretical modelling of flares suffers from the absence of such data sets to provide the necessary boundary conditions. Furthermore, the dynamic interaction of hot plasma with magnetic fields is a difficult and complex subject. Although the basic interactions are now understood, it seems that it is always possible to invoke new and more obscure types of instability to account for any observation that is not understandable by the simpler processes. Under these circumstances, a firm foundation based upon good and complete observations becomes essential.

In spite of the foregoing, many aspects of the physics of the flare process are generally accepted, and others present a choice between only a few alternatives. In this paper a brief review of the situation is given, by presenting a simple scenario of the flare. We can discuss this by separating the problem into three phases: the storage of the flare energy over a period, the impulsive release of this energy; and the subsequent dispersion and dissipation of the high-energy particles produced.

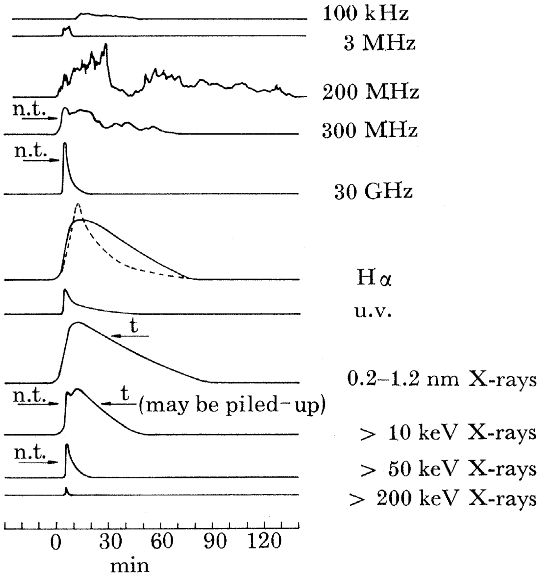

Figure 1. Typical curves of flare time development at different wavelengths (from Svestka 1976). ——, Intensity; – – –, effective linewidth; n.t., non-thermal; t, thermal.

ENERGY STORAGE

It is now generally accepted that energy for the flare is stored in the solar magnetic field. This is the one mode that enables stored energy to be built up over a long period, in a large volume, and then released, depositing the energy in a small volume. Many models have been proposed for this storage. However, it is possible, without being specific, to realize that such an energy build-up is almost inevitable. First, one must recognize that the Sun is an infinitely conducting plasma, which is permeated throughout by a magnetic field. Even at the lowest temperatures (*ca.* 4200 K), where the electrical conductivity is lowest, the rate at which plasma can diffuse across the magnetic field is negligible when related to the very large distances involved on the Sun. The situation is therefore one in which, in the absence of complex instabilities, the plasma is completely frozen to the field lines, or *vice versa*. To understand the dynamics of the Sun, it is necessary to consider the relative magnitudes of the pressures exerted by the plasma and the magnetic field. Figure 2 shows the plasma pressure plotted against height, from 10^5 km below to 10^5 km above the surface (visible limb). It can be seen that near the surface, where the temperature of the Sun is lowest, the pressure drops sharply by a factor of about 10^8, before levelling out again in the chromosphere and corona. Also shown on figure 2 is the pressure exerted by a wide range of solar magnetic fields, from *ca.* 0.5 mT for the mean quiet Sun to more than 3000*g* for a sunspot. The point to notice is that all of these magnetic pressures are small compared with the plasma pressure below the surface, but larger than the plasma pressure in the atmosphere (chromosphere and corona). Combined with the foregoing frozen-field principle, this means that below the surface the field plays only a small role in the dynamics, being moved about in a manner determined entirely by the other convection processes. On the other hand, plasma above the surface is totally dependent on motions of the field and will, in general, move freely to follow such motions. These two regions are linked by the field lines that pass from one to the other. The photosphere is the layer at which one normally measures the vertical component of the magnetic field with a solar magnetograph. This layer, which corresponds closely to height zero on figure 2, is also the boundary between the two pressure régimes. Thus it is possible to consider the observed photospheric field, which is determined entirely by convection patterns below the surface, as the boundary condition which determines the field and the dynamics in the atmosphere. Most of this field is closed within the atmosphere, returning to the Sun in some other region of opposite polarity. Only a small proportion is open, extending out to interplanetary space. Given this boundary condition, it is possible to construct a field in the atmosphere which will have the lowest possible energy. This will be the unique potential field, in which no currents are flowing, so that $\nabla \wedge \tilde{\boldsymbol{H}}$ is everywhere zero. Now, at some later time, when the boundary photospheric field has been moved to a new configuration by convection, it is possible to construct a new potential field in the atmosphere. Insofar as it is possible to change smoothly from one configuration to another by simple lateral motion of field lines, then there is no problem, and the atmospheric plasma simply moves to follow the field. However, this is, in general, not the case, and the new potential field would imply many of the field lines closing on regions of the solar surface different from those on which they previously closed. Clearly, to maintain a potential field it is necessary to invoke field line reconnection. Such reconnection is strictly prohibited by the simple frozen-field theory adopted above. One can avoid reconnection only by allowing a field distribution with currents flowing, and a non-zero $\nabla \wedge \tilde{\boldsymbol{H}}$. Such a field has a higher energy storage than that for a potential field. We have thus shown that if we start with a minimum energy field in the atmosphere, subsequent motions below the photosphere will in general lead to an increase of magnetic energy stored in the atmosphere.

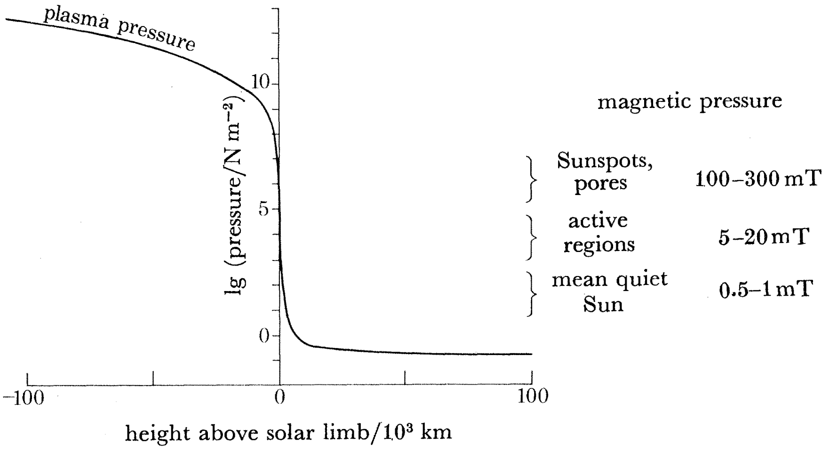

Figure 2. Comparison between plasma and magnetic field pressures in the Sun, as a function of height.

Many theorists have attempted to devise specific configurations to show how such storage can occur. Figure 3 shows some of these. Figure 3*a* shows how plasma carried upwards by emerging field lines can ultimately break open the configuration and stream out into space. Figure 3*b* shows how the lateral approach of two simple dipole regions causes a distortion of the potential fields. In both cases, the coronal currents set up flow in a current sheet region, shown shaded. Figure 3*c* shows how a simple rotation at the feet of a dipole loop will cause a helical field to be set up. In this case the coronal current flows around the loop.

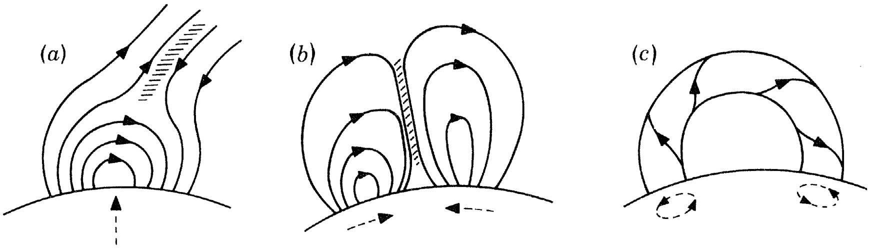

FIGURE 3. Some idealized configurations for magnetic energy storage in the corona.

Although such simple geometries are useful in attempting to quantify the storage, it should be remembered that the foregoing arguments indicate that even a totally random motion within the photosphere will serve to build up the energy stored in the atmosphere. Thus there is no need to assume that any of the configurations of figure 3 will apply. Indeed there is observational evidence to support the view that the more complex and interlaced are the north and south field-polarities in a region, the more likely are flares to occur. We will return to the simpler configurations of figure 3, to pursue the models further, always remembering that these may be merely representative of the real and complex situation.

There has been some discussion in the past concerning rival flare geometries, represented by current sheets as in figures 3*a* and *b*, or twisted fields as in figure 3*c*. The first would appear to concentrate the currents in small volumes, while the second involves extended regions. This is a misleading concept. It is clear that modest variations of figure 3*c*, involving either a tearing mode which separates the current flow into filaments along the field lines, or a second-order twist, as in an overwound rubber band, will produce a series of sheets throughout the volume. Furthermore, consideration of the full three dimensional configuration of figure 3*a, b* shows that these must also involve volume currents to complete the circuit.

ENERGY RELEASE

In this phase, the above field configurations relax, by means of a process involving field reconnection or annihilation, towards a closer approach to a potential field configuration, the energy being released in the form of accelerated charged particles. In an electromagnetic circuit, this relaxation is only possible through the existence of a high electrical resistivity. Classical resistivity of the solar plasma is always much too low, so that it is necessary to invoke collective effects to reduce the conductivity. These effects, involving the growth of waves in the plasma and particle–wave interactions, are difficult to support in large volumes of plasma. They are much more likely to grow in small filaments or sheets, where the current density is high. Consideration of the range of such instabilities that can grow in the solar plasma is a very complex area, which has involved a substantial body of theoretical study in recent years. For the purpose of this paper, it is sufficient to state there is no difficulty in explaining the rapid growth of appropriate instabilities that leads to reconnection and energy release in small filaments or sheets within the plasma. Many of the geometries can be considered as variations of the basic process of reconnection at a type-X neutral point, as considered by Petschek (1964). However, there is much dispute about the precise nature of the instabilities that occur. Figure 4 shows the geometry of such a point which, for small angles α, can be considered as an element of an extended current sheet. The opposing magnetic fields move into the reconnection region carrying plasma with them. Plasma then moves out sideways with the reconnected field. At the null point, the plasma pressure can be substantially greater than its surrounding value.

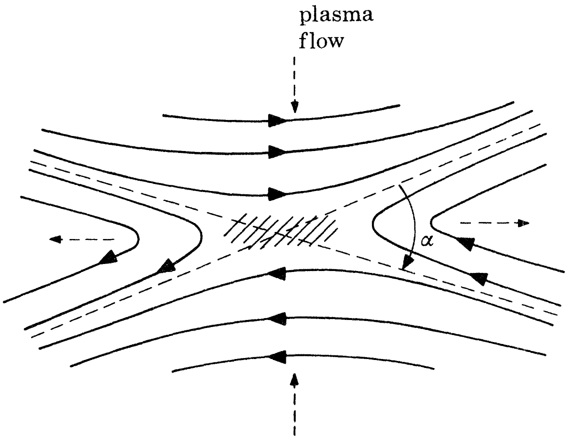

FIGURE 4. Reconnection occurring at a type-X neutral point.

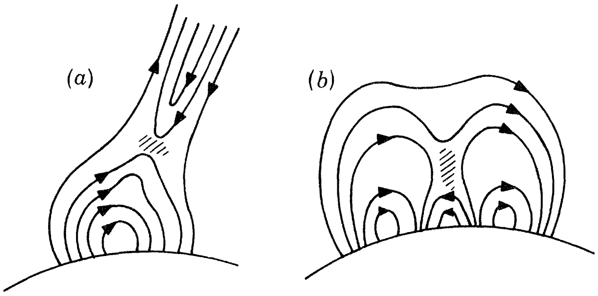

FIGURE 5. Reconnection and energy release in some idealized coronal configurations.

Application of the foregoing scheme to the configurations of figure 3 *a*, *b* leads to the models shown in figure 5 *a*, *b*. In each case, reconnection at a type-X neutral point leads to a relaxation towards a potential distribution. A similar effect arises from the configuration of figure 3 *c* after it has broken up into filaments.

Two major sets of problems arise in the theory of energy release. First, the range of instabilities available and their high growth rates lead to a difficulty in maintaining a stable configuration long enough for the stored energy to build up to the values observed in flares. The second set of problems concerns the energy release rate. The very small volumes, which are intrinsic to the reconnection region, lead to a release rate that is much smaller than that observed. In an attempt to solve this latter problem some theorists have proposed complex multiple forms of the above models, resulting in an increase in the total reconnection volume available.

The particles with energies of megaelectronvolts responsible for γ-radiation cannot be produced directly by the processes described above. In some flares there is distinct evidence that these are produced in a second-stage acceleration process lasting several minutes. Fermi-type acceleration processes are normally considered for this stage of the flare.

STORAGE AND DISSIPATION

Although perhaps less fundamentally exciting, these processes lead to the production of many of the observed fluxes. They therefore provide an important test of flare models.

An important problem here concerns the intensity of the hard X-ray-burst observed during the impulsive phase. The usual interpretation is that the X-rays are produced by bremsstrahlung when the accelerated electrons of 100 keV are slowed down or stopped by the ambient plasma. The most efficient emission would occur if the electrons were stopped, i.e. the so-called 'thick-target' model. However, even so, the efficiency is only *ca.* 10^{-4}, most of the electron energy being lost in elastic collisions. To account for the X-ray flux observed then requires an embarrassingly high figure both for the electron number and for their total energy. Such high currents of electrons will lead to the generation of a reverse electron current to maintain neutrality. This may help to solve the electron number problem, but still leaves the problem of total energy. One attempt to resolve this leads to the proposition that the hard X-rays are produced by thermal bremsstrahlung in a very hot plasma ($T > 10^8$ K). In a thermal plasma, elastic collisions do not lose energy from the system, and the X-ray efficiency approaches unity. Such a model solves the electron problem, but poses new difficulties. Conductive cooling of such a plasma would be very high. Furthermore, the magnetic field intensities required to contained it would far exceed those regarded as reasonable in such regions. For a discussion of this problem, and further references, see Brown & Smith (1980).

During some phases of the flare, local brightenings are observed in many regions of the spectrum from X-ray to the visible spectrum. The simple explanation is to interpret the additional energy radiated as being due to the flare energy deposited in those regions of the atmosphere from which each spectral region is normally emitted. Thus brightenings in, for example, carbon IV, Lyman α, Balmer α, 160 nm continuum and white-light continuum, would be interpreted as energy deposited in the transition region, high chromosphere, low chromosphere, temperature-minimum region and photosphere, respectively. Such an interpretation, although useful, has its dangers. Clearly if the energy deposited heats the atmosphere substantially, then a readjustment of ionization balance (which takes only seconds) will lead to, say, transition region radiation coming from previously chromospheric regions. Nevertheless, the simple model is useful, and can give a guide to the depth at which fluxes are deposited. It is possible to predict that electron streams of 100 keV–200 keV will be stopped in the transition region or upper chromosphere. This is consistent with the observation from Skylab that e.u.v. transition region lines show a spike corresponding to the impulsive stage. This can be seen more clearly by observing the effect on the Earth's ionosphere of absorption of the emitted e.u.v. radiation. The sudden frequency deviations (s.f.d.) observed in radio reflexion from the ionosphere give a good time-resolved record of the solar e.u.v. pulses. This technique (Donnelly 1968), which has no spatial resolution on the Sun, is very valuable for observing the impulsive time-profile of flares. For some flares impulsive brightenings are seen in the chromosphere, temperature-minimum region and photosphere. These cannot be due to electrons, which would need to have energies greater than 1 MeV. Other processes considered include the absorption of x.u.v. or X-rays emitted by the higher layers.

Later brightenings in low-energy radiation, notably Balmer α, are due to transport of energy from the flare site by processes of conduction, radiation and convection. Such flows are normally ducted along the magnetic field lines. The configuration in figure 5*a*, for example, is expected to deposit energy in the chromosphere at the two foot points of the loop. Since such structures normally exist in arcades (i.e. parallel structures in the direction perpendicular to the figure), this leads to the characteristic two-ribbon flares, observed in Hα. These are two bright ribbons which form each side of the magnetic neutral line.

Observational limitations

The critical region of the flare, i.e. the site of reconnection and energy release, has never been seen. Indeed it is doubtful whether there is any practical means of observing this, even if one had the required spatial resolution. One is therefore driven to observe the effects of this release, and thereby to deduce the nature of the source. The first effect is the production of hard X-rays. Although these are well observed, there is so far no spatial resolution which would enable the emission site to be determined. There is also the question of the need to observe the full wavelength-range of fluxes emitted from the flare.

Skylab made the important contribution of observing flares in the corona in broad-band soft-X-ray images. The notable feature here was the observation of loop brightening, on all scales down to the resolution limit of a few seconds of arc. A crucial role of loops in the flare process is thus firmly established.

Solar Maximum Mission

This N.A.S.A. satellite (S.M.M.) was launched into orbit on 14 February 1980. It has been designed and built specifically for studying flares. The six flare experiments on board have been built by groups from several countries. The basic parameters are listed in table 1.

Table 1. Summary of the solar flare experiments on S.M.M.

experiment	organization	spectral range	spatial resolution	field of view	time resolution
γ-ray experiment (g.r.e.)	University of New Hampshire Max Plank Institute Naval Research Laboratory	0.3–180 MeV	none	full Sun	64 ms–1 s
hard X-ray burst spectrometer (h.X.r.b.s.)	Goddard Space Flight Centre	20–300 keV	none	full Sun	1–128 ms
hard X-ray imaging spectrometer (h.X.i.s.)	University of Utrecht University of Birmingham	3.5–30 keV	8–32″	3–6′	1–4 s
soft X-ray polychromator (X.r.p.)	Lockheed, Palo Alto S.R.C. Appleton Laboratory University College London	0.15–2.5 nm	12″	7′	128 ms–12 s
ultraviolet spectrometer polarimeter (u.v.s.p.)	Marshall Space Flight Centre Goddard Space Flight Centre	110–300 nm	1–30″	4′	64 ms
coronograph polarimeter (c.p.)	high-altitude observatory	443.5–658.3 nm	6–12″	1.6–6.0 $R_\odot$	*ca.* 50 s

It can be seen that the basic requirement to observe flares simultaneously over a wide spectral range is well met. This is particularly so when it is realized that the S.M.M. will be operated in close collaboration with a number of ground-based optical and radio solar-observatories. It is to be regretted that a seventh experiment in the x.u.v. spectral region (2–13.32 nm) had to be deleted from the payload owing to cost and schedule problems. However, some of the transition region and coronal spectra, for which the x.u.v. is valuable, also fall within the range of the u.v.s.p. and x.r.p. instruments. It will be seen that the overall payload offers the possibility of identifying the origin and time development of spectra from 20 keV to 300 nm, as well as the time development of harder radiation. In addition, the outer corona can be observed, to study the effects propagating outward from limb flares. Summary descriptions of all these instruments are given in a set of papers in *Solar Physics* (Bohlin *et al.* 1980, and subsequent papers).

At the time of writing it is clear that all of these experiments are functioning, and giving much valuable data on the flare plasma. For descriptions of some of the early observations, the reader is referred to a set of papers to be published in *Astrophysical Journal Letters*. The extent to which S.M.M. will solve the problems of solar flares must await more complete analysis of the combined data sets. However, one may hope that this impressive array of experiments will lead to some significant advances in the understanding of flare mechanisms.

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