Plasma and solar physics. The solar flare phenomenon

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Résumé. — Les principaux aspects de la physique solaire ayant trait à la physique des plasmas sont rapidement présentés. Le phénomène d'éruption solaire est décrit et certaines théories actuelles concernant l'état pré-éruptif et le mécanisme de déclenchement passées en revue, à savoir : la théorie de l'existence d'un point de retournement dans les états d'équilibre possible et la théorie basée sur l'analogie avec les instabilités résistives observées dans les Tokomaks. La microphysique qui, croit-on, permet le confinement turbulent d'un plasma de 100 millions de K dans le plasma coronal est évoquée, et on montre enfin qu'une turbulence cyclotron ionique dans la région éruptive possède une signature assez caractéristique dans les abondances isotopiques et états de charges des ions accélérés.

Abstract. — The main topics of solar physics to which plasma physics is relevant are briefly presented. The solar flare phenomenon is described and some present theories concerning the preflare state and flare triggering reviewed, namely the theory based on the existence of a turning point in the set of possible preflare equilibria and the theory based on an analogy with resistive instabilities observed in Tokomaks. The microphysics which is believed to be responsible of the confinement by turbulent processes of a 10^8 K plasma in the coronal plasma is evocated and it is finally shown that ion cyclotron turbulence in the flaring region is evidenced by a characteristic signature in isotopic abundances and charge states of accelerated ions.

This communication is intended to be a short survey of our present state of knowledge and partial understanding of the solar flare phenomenon.

The reader may not be very familiar with solar physics, and so I shall first make a rapid description of the sun as a whole. This will give me the opportunity to allude to some plasma physics problems of interest far solar physicists other than the flare problem.

The sun is a normal typical star, that is a self gravitating sphere of hot plasma which sustains its energy output by the nuclear conversion of hydrogen into helium in an interior core, very hot (15×10^6 K) and very dense (120 g cm^{-3}, or 7×10^{25} cm^{-3}). The plasma there is a strongly coupled plasma. The largest part of the rest of the sun up to near the surface is made of a similar type of plasma. The energy liberated inside is radiatively transferred outwards, very slowly of course because the opacity of the solar matter is very large there. The physics of energy transport changes somewhat near the surface because the radiative model predicts sharp temperature gradients there. It turns out that in this model the opaque region just below the visible surface of the sun should be unstable to convective motions, or in other terms the gravity-wave modes become purely growing. One gets then a convective superficial layer which is certainly turbulent.

The convection manifests itself at the photosphere (the visible outer layer of the sun in ordinary white light) in the form of the so-called granulation. The granulation is shown in figure one. Bright regions represent slightly hotter ascending pieces of plasmas,

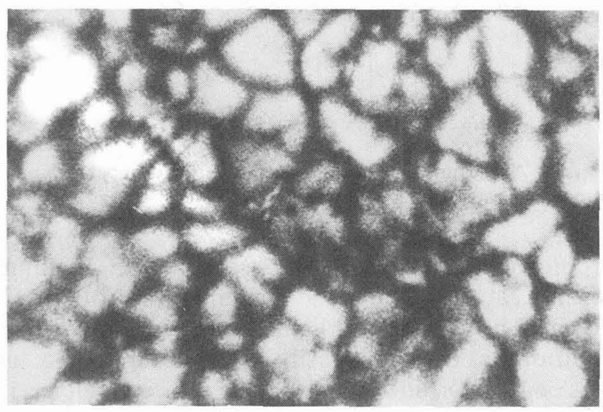


Fig. 1. — The solar granulation. The size of each granule is typically 700 km.

while in the cooler, darker interstices the matter is sinking again downwards. Granules are small (700 km). The theory of convection in a system in which a strong density difference exists between the top and the bottom and where magnetic fields exist and are even perhaps generated is not at all in a satisfactory state now. This convective flow transport energy to an overlying static radiatively stable thin layer above, which is what is properly called the sun's atmosphere. It also exists there a number of waves which propagate upward and represent an outgoing flux of mechanical energy.

Superposed to the granular motion one has been able to detect another type of cellular motion too, the supergranulation. The size of a supergranule is much larger than that of a granule (30 000 km) and its life time, is some 10 hrs. The supergranular motion sweeps the magnetic field and concentrates it on the boundaries of the cellules. Figure 2 represents an artist view of granular and supergranular motions. In the atmosphere itself, the mean temperature decreases with height up to a certain point, where it reaches 4 300 K. For definiteness we shall consider here that this is the surface of the interior sun. Above this point the temperature raises again as a result of the dissipation of the mechanical flux of energy driven in the outer atmosphere by the convection zone. The theory of the generation, propagation in the outer layers, and dissipation of waves in the solar atmosphere is also a difficult aspect of solar physics which will not be our point today. Ideally it would involve a theory of compressive convection turbulence, in the presence of a magnetic field, of the propagation of resulting waves in a strongly inhomogeneous medium and its ultimate dissipation in the very rarefied medium which constitutes the outer layers : the chromosphere and the corona. The

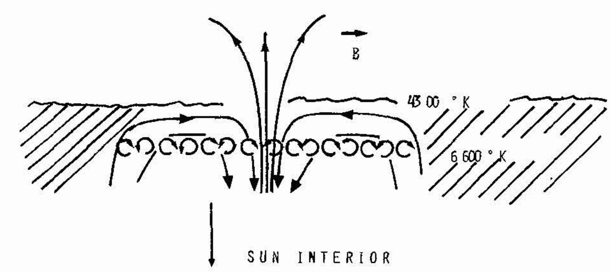


Fig. 2. — A schematic drawing of granular and super granular motions and solar magnetic fields.

chromosphere above the surface is a tenuous medium (density 10^{11}-10^{12} cm^{-3}) at a temperature of 10^4 K. It cannot be seen in full light in normal non eclipse, conditions, but may easily be photographed at wavelengthes of lines which form in these regions, in particular the $H\alpha$ line of hydrogen and a violet line of ionized calcium (*K* line). Figure 3 is a picture of the sun in this latter radiation. The granular aspect is the chromospheric counter part of the supergranulation pattern and bright patches are regions of enhanced magnetic field. The magnetic field dominates the higher chromosphere as can be seen on $H\alpha$ photographs which show a hairy structure of magnetic field lines.

The chromosphere is in contact on its upper boundary with the corona, an even more tenuous medium (10^9 cm^{-3}) also heated by the mechanical energy flux, it is thought, though this is far less evident than for the chromosphere. The temperature of the corona is between 1 and several million degrees. The contact between these two regions is characterized by very strong temperature gradient. It is called the transition region. The corona is perhaps an even more structured region than the chromosphere, as you can see on the ecclipse photograph shown in figure 4.

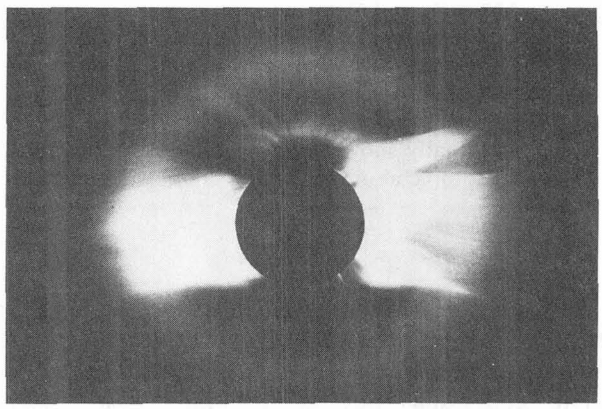


Fig. 4. — The solar corona as seen in white light eclipse photograph.

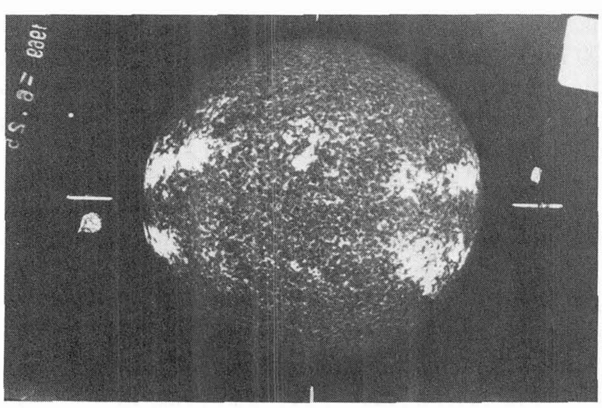


Fig. 3. — Calcium II *K* line photograph of the sun. Brighter regions coincide with magnetic field enhancement.

Active regions appear as concentration of magnetic flux around special regions, the sunspots, like the ones shown in the picture (Fig. 5). In these spots, the average field may range from 500 to several 1 000 G, and the extension of the spot in the nearby region, the penumbra, shows that one could conceive the spot as a bundle of magnetic fibers. I shall leave apart also in this brief survey the extremely interesting and difficult problem related to the dynamo action of the photosphere and the creation of the sun's magnetic field. It is quite probable of course that the

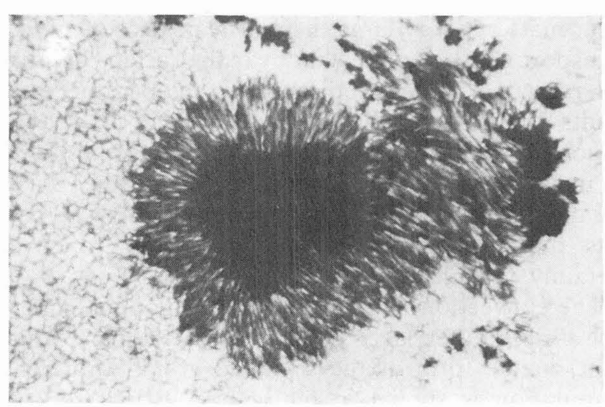


Fig. 5. — A white light photograph of two sunspots.

origin of this field is intimately related to the convective motions rather deep in the sun, as evidenced in the fact that fields are patterned by the supergranular motions, and in the fact that spots grow at corners of supergranules. Active region flux concentrations exert a strong influence on the neighbouring corona which we can now see even against the disk by soft X ray imaging. The thermal radiation of the hot corona is detected by this instrumentation, and the following picture (Fig. 6) shows essentially map of the corona which is sensible to both density and temperatures. It is seen that the corona is threaded by a system of loops of all sizes, presumably underlying the magnetic structure. We have also observed « holes » which are regions of open magnetic fields, with lower densities or temperatures, and which must be

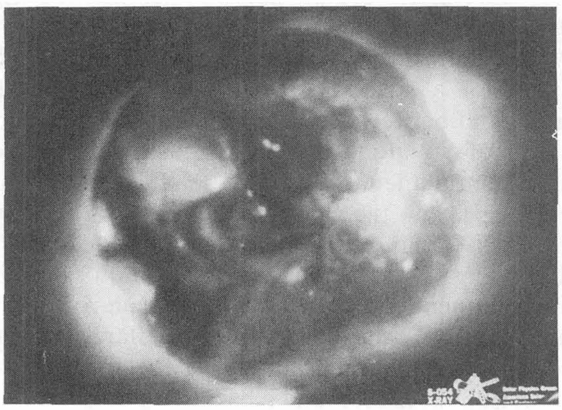


Fig. 6. — X ray picture of the solar corona.

considered as the source of the solar wind. Magnetic flux in the form of flux tubes emerge in the outer atmosphere, presumably because of buoyancy forces exerted on them on the photosphere, in which they are also at smaller pressure, but at equal temperature because of the effectiveness of radiative energy transport. They are then lighter and suffer vertical buoyant forces. When popping up in the atmosphere they create short lived X ray bright point, which are seen on figure 7, by their interaction with the ambient fields, or perhaps by their own internal dynamics.

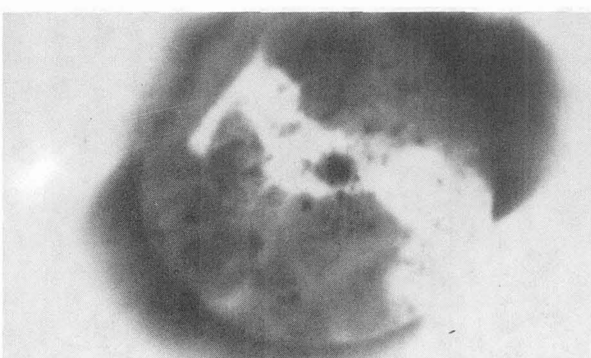


Fig. 7. — Negative of an X ray picture of the solar corona showing X ray bright points (black dots).

A more dramatic energy release event is the solar flare which instead of being a very local energy release in a rather quiet environment occurs in an active region. Obviously the energetics of a solar flare cannot be accounted for only on the basis of the energy of the emerging magnetic field. The event releases some 10^{32} ergs in some 100 to 1 000 s depending on the importance of the event. An $H\alpha$ photograph of a flare at its full development is shown in figure 8.

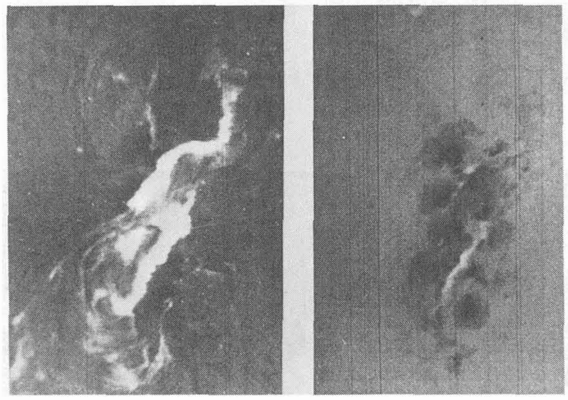


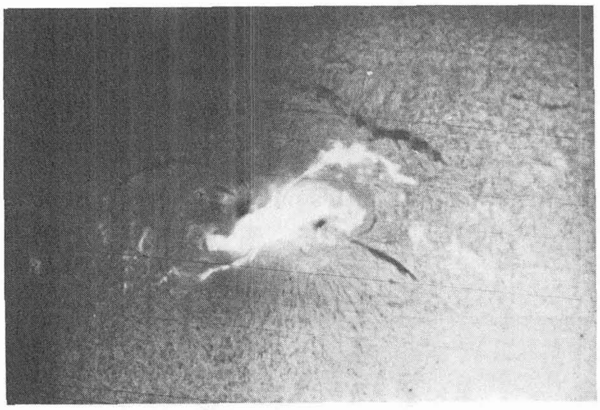
Fig. 8. — A fully developed two ribbon solar flare as it appears in $H\alpha$ light (left) and in white light (right). The fact that white light emission is detectable is rare and characteristic of very large events only.

We can sketch the observable manifestations of a flare as follows :

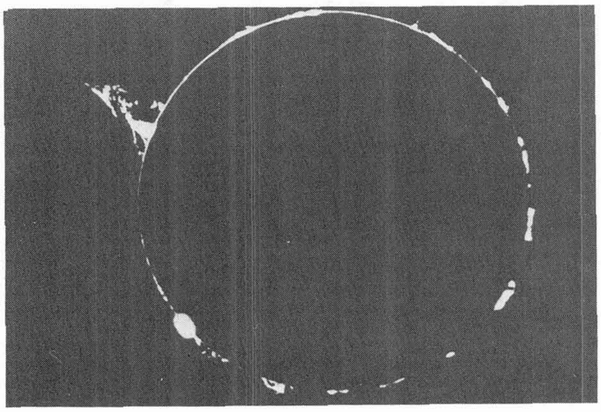
1) The phenomenon occurs always very chose to a line where the photospheric magnetic polarity reverses, let us call this the inversion line, in an active region or very near.

2) The phenomenon proper is preceded by a preflare phase during which the energy to be liberated into *radiated* forms is stored in the region. This build up phase does not need to last more than some hours.

3) An active region filament is often present, which maps almost exactly the inversion line. Prominences, or filaments (Fig. 9) are an important object of the solar corona which I have not yet had the opportunity to describe. It is so to speak cloud like matter at chronospheric conditions hanging up high in the corona and certainly prevented from just free falling by Lorentz forces. Filaments may exist outside active regions hanging at heightes of 40 000 km above the surface (they are called quiescent prominences) as well as inside active regions ; in the latter case their height does not exceed some 7 000 km. The object has the form of a thin thing hanging vertically over a height much larger than the scale height of a 10^4 K plasma (which would be very small). This means that the filament must be supported at each point in its body by Lorentz forces if it is a structure in magnetohydrostatic equilibrium which it seems to be. No really satisfactory model of filament equi-



a)



b)

Fig. 9. — a) A flare is shown here together with several active region filaments (dark ribbons) ($H\alpha$ photograph). b) A quiescent prominence is shown here suffering an upward motion, and will soon disappear (upper left). This is a coronograph $H\alpha$ photograph in which the bright sun is artificially hidden.

librium and energy balance exist at present, though on a global scale the problem may be looked at as a 2D MHD equilibrium problem which I shall describe below. It has been established at Meudon Observatory (Martes *et al.*) by a confrontation of magnetic map and velocity map that the flare are most likely to occur in cases when a shear flow exist on the photosphere in the vicinity of the magnetic inversion line. This has been interpreted as a necessary condition for energy storage, and this idea has been substantially supported by an approximate calculation of the amount of magnetic energy stored in the corona as a result of current driven there (Tanaka, Nakagawa) by the deplacement of the feet, of field lines which are obliged to follow the photospheric motions, the latter being an energy reservoir of the process. The magnetic field in the corona which is unobservable directly, had been extrapolated from photospheric data on the basis of a constant α ($\alpha = \mathfrak{J}/B$) force free approximation. The value of α has been chosen to match the general direction of field lines, as observed from the $H\alpha$ pictures. It has been shown that the stored magnetic energy calculated that way increased steadily up to the moment of the flare, but was smaller just after. Moreover, the quantitative value of this decrease was found to be compatible with the sum of the observed emissions produced by the flare in various forms (light, X rays, EUV, energetic particles, mass motions). Solar physicists, are then quite confident that the liberated energy was actually stored in the form of magnetic energy in a coronal current system. Because the β of the coronal plasma is low, the magnetic structure is very likely to be force free, except perhaps in the vicinity of possibly existing current sheets, or in the filament which is so often found to underline the line of inversion of the magnetic polarity and, as we just noted, must be sustained by Lorentz forces.

The flare itself begins abruptly by an impulsive phase which may be a short as several seconds. At that time the most conspicuous phenomenon is the emission of a spiky burst of hard X rays, in the energy band between, say, 20 keV and 100 keV, radio emission of cm and m wavelengths are also observed. Almost simultaneously bright small regions (flare knots) appear in, the chromosphere as seen, in particular, in the $H\alpha$ line. This illumination is due to energy precipitating in or conduced to the photosphere. It will subsequently broaden on time scale of several minutes. This is the flash phase. In flares of some importance the illumination takes the form of two parallel ribbons (Fig. 8) and it has been shown recently, thanks to soft X ray observations that these ribbons are bridged by soft X ray emitting loops. In large event a typical radio emission at meter wavelength occurs, which is the signature of a shock wave. The system of hot loops and bright $H\alpha$ ribbons then persist for some time, typically one hour, while the ribbons separation systematically and slowly increases. At a late stage of the process these loops become progressively cooler and, become eventually visible in $H\alpha$ as a system of so-called post flare loops, such as shown here on the limb $H\alpha$ picture (Fig. 10).

In a small number of cases, one has observed a gamma ray emission. Actually the γ ray emission is

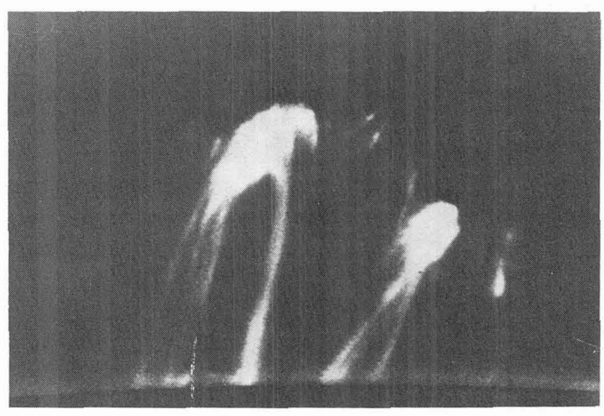


Fig. 10. — Post flare loops. $H\alpha$ picture taken near the limb of the sun.

associated with very large event only and a suitable detailed spectrum has been observed in only one case; the observed spectrum consists of a continuum emission, which can be explained by bremsstrahlung from high energy electrons, and a few number of lines. The high intensity line at 2.2 MeV results from neutron capture by protons to give deuterium nuclei. In some flares expanding mass motions are observed high in the corona, in white light photographs (coronal transcients), though such motions are also often associated with non flaring events. Long after the flare (due to propagation conditions in the interplanetary space), high energy electrons are observed on space crafts as well as energetic protons and cosmic ray nuclei.

The problems posed to the theorist can then be stated as follows :

1) To understand the preflare stable configuration and the reason of its destabilization or at least its evolution prior to flare.

2) To pin point the mechanism which gives rise to the impulsive liberation of energy.

3) To understand why this energy is so distributed in the various observable forms, in particular, how the 25-100 keV electrons which are responsible of the impulsive manifestations during the very first seconds are accelerated.

4) To modelize the main phase continuous dissipation process.

5) To explain the acceleration of higher energy electrons (1 MeV to 10 MeV) and of high energy protons and nuclei (10-100 MeV, sometimes more).

It is impossible to review in detail all these aspects; therefore we shall consider some interesting or better observed aspects and in particular problems related to build up and impulsive phase triggering. As I explained a bit earlier, the magnetic configuration in the preflare state is a current carrying plasma. Some authors have a long time advocated that the electric currents in the corona should form a large current sheet, and the flare would be due to an impulsive dynamic reconnection process in this sheet (Syrovatskii). It is difficult however to conceive how such a sheet current system could grow to such a large extent as to contain the energy for the flare without tearing quite early of suffering the interchange instability (Uchida, Sakurai). If current concentrations in a sheet-like structure occur at all, one now thinks that they would appear on a more local scale. Probably more likely is the idea that the current system is just almost everywhere present in the flare region. We can then have two different looks at it : one can consider its global arrangement, which I think is the relevant way to analyse it as far as magnetic storage and global stability is concerned, while the other way is to look at its more detailed local configuration, and fine structure a point of view which is on the other hand of primary importance if one is interested in flare triggering.

A suitable analysis of the first problem can be done by taking advantage of the fact that, as suggested by the two ribbon structure observed in many flares and the elongated form of the filament, a 2D approximation to the global magnetic structure, ignoring variation of quantities in the direction parallel to the line of inversion of the magnetic polarity would not be too bad an approximation. In that case the magnetic configuration is well defined by the z component of the magnetic field, B say, and the z component of the vector potential, A say. Both these quantities are functions of x and y. One can write the magnetic field as :

$$\mathbf{B} = \frac{\partial A}{\partial y}\mathbf{e}_x - \frac{\partial A}{\partial x}\mathbf{e}_y + B\mathbf{e}_z .$$

In that case $A(x, y) = $ constant represents the projection on the xy plane of lines of forces

$$\mathbf{J} = \frac{1}{\mu_0}\left(\frac{\partial B}{\partial y}\mathbf{e}_x - \frac{\partial B}{\partial x}\mathbf{e}_y - \Delta A\mathbf{e}_z\right)$$

$$\mathbf{J} \wedge \mathbf{B} = \frac{-1}{\mu_0}\left(\left(B\frac{\partial B}{\partial x} + \Delta A\frac{\partial A}{\partial x}\right)\mathbf{e}_x + \right.$$
$$\left. + \left(B\frac{\partial B}{\partial y} + \Delta A\frac{\partial A}{\partial y}\right)\mathbf{e}_y + \left(\frac{\partial B}{\partial x}\frac{\partial A}{\partial y} - \frac{\partial B}{\partial y}\frac{\partial A}{\partial x}\right)\mathbf{e}_z\right) .$$

One can easily show that the force balance equation :

$$\mathbf{j} \wedge \mathbf{B} = \nabla p + \rho g\mathbf{e}_y$$

and the 2D translational symmetry, imply that the z component of the Lorentz force vanish, which (look at his expression) mean that B is constant along a line of force, or :

$$B(x, y) = B(A(x, y)) = B(A) .$$

The pressure p, which is a priori a function of (x, y) can be looked at as a function of altitude y and line of force parameter A :

$$p(x, y) = p(A(x, y), y) = p(A, y) .$$

With this in mind, we can write the x and y component of force balance as an hydrostatic equation of equilibrium :

$$\frac{\partial p}{\partial y} = -\frac{\mu}{\mathfrak{R}}\frac{p}{T(A, y)}$$

which expresses equilibrium along a line of force, and we obtain also, on the other hand, an equation for the shape of lines of forces :

$$-\Delta A = \frac{\partial}{\partial A}\left(\frac{B^2(A)}{2\mu_0} + p(A, y)\right) .$$

The equation for the pressure can be integrated only if we know the temperature distribution along the line of force. The latter, especially if a prominence is involved in the magnetohydrostatic equilibrium of interest can only be obtained as a result of a very complicated energy balance which is self consistently coupled to the magnetohydrostatics problem that we try to solve by means of such effect as the pattern of mechanical energy flow in the structure, heat conduction. Up to now studies of prominence equilibrium have only used crude approximations like T = constant (!) and the existence of field along the direction of symmetry has largely be ignored though observations definitely show that it is present and large.

Another interesting approximation is to take advantage of the fact that the β of the plasma is small, and to solve for the force free case, the equation :

$$- \Delta A = \frac{\mathrm{d}}{\mathrm{d}A} \frac{B^2(A)}{2\mu_0} = \varphi(A)$$

where now B_z is non zero.

We need however to prescribe $B^2(A)$ for this non linear elliptic equation to be written in closed form. This function, at least for those values of A taken on the boundary, in that case the X axis, may be prescribed once one knows the displacement of the footpoints of line $A(x, y) = a$ one with respect to the other. The relevant relation is

$$B(a) = l(a) \left(\int_{-x(a)}^{+x(a)} \frac{\mathrm{d}x'}{(\partial A/\partial x')_{A(x',y')=a}} \right)^{-1} .$$

It seems perfectly justified to assume that the energy build up proceeds through a series of equilibria. In full, the problem is to solve the coupled set of equations above for a series of time dependent functions $l(A, t)$ where t would enter as a mere parameter. This programm has not yet been completed because of the intricate relation between $B(A)$, $l(A)$ and $A(x, y)$. Authors have preferred to take a look at a schematization of this problem in which we skip the relation which relates $B(a)$ and $l(a)$ and consider that the function $\varphi(A, t)$ is given be :

$$\varphi(A, t) = \lambda(t) F(A)$$

(Low, Jockers, Birn *et al.*, Heyvaerts *et al.*), where the stretching parameter $\lambda(t)$ varies from 0 (potential configuration) to progressively larger values of λ. One can show that, stating the problem in this form amount to prescribe the vertical current driven by the boundary (the photosphere or here the X axis) into the domain of study.

The corresponding shear $l(a)$ can be deduced afterwards if one wishes, but due to the crude simplifications exerted before, it has no reason to be a monotonous function of λ nor to be regular, as one could have wished. Nevertheless some general interesting results can be obtained. We have been able (Heyvaerts *et al.*, 1978) to prove mathematically the following results for the solution of :

$$- \Delta A = \lambda F(A)$$

in $(\mathbb{R} \times \mathbb{R}^+)$ with boundary conditions $A(x, 0) = g(x)$ on the x axis, subject to the reasonable conditions that $F(A)$ be regular and finite, vanishes except for A in a certain bounded interval, and vanishes sufficiently rapidly near $A = 0$ which is the boundary value $A(\pm \infty, 0)$. The semi infinite character of the domain mathematically acts as a singularity of the operator. It seems to be a feature of essential significance.

1) The potential configuration found for $\lambda = 0$ can be followed by continuity up to some finite value λ^* of the stretching parameter.

2) Whatever λ be, however, there exist at least one solution with an asymptotically open topology. This is schematically shown in figure 11.

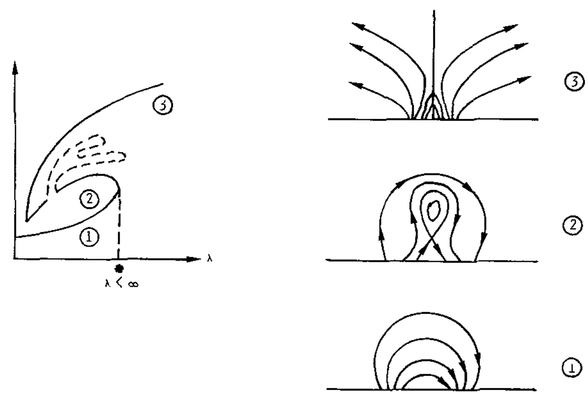


Fig. 11. — Schematic properties of the 2 dimension MHD equilibria obtained by growing the current delivered by the boundary in proportion to $\sqrt{\lambda}$ (see text).

The catastrophy behaviour of the potential like solution had been recognized earlier for special cases either by solving analytically for one case (Low, Birn *et al.*), either from semi qualitative argument and numerical study of special cases (Jockers). The universality of this behaviour is now established as well as the existence of an open topology solution, a new result, which had been suspected from earlier work, by Barnes and Sturrock.

The ideal MHD stability of the lower branch solution against 3D perturbations has been established in full generality (Birn, 1978) as well as partial results concerning dissipative stability.

Nothing general is known concerning other (intermediate solutions) which may well exist. Work is in progress on this question.

It does not seem impossible at all that the structure could be driven by continuous stretching to the catastrophy point where a dynamical evolution will necessarily take place, due to the lack of neighbouring equilibrium. A conjecture is that the structure would be blown open towards the « top » open solution ; if a filament is involved in the structure this would appear as a sudden disappearance as often observed. Another conjecture would be that it jump on some intermediary equilibrium state, involving a change of topology which could be achieved only through a dissipative process. As a phenomenological model some authors (Kopp *et al.*) propose that the trigger of the flare be actually the MHD blowing up of the global magnetic configuration, which later will reconnect to a normal, that is to a closed topology, type of configuration only then giving rise to dissipative phenomena, particle acceleration...

Although this might sometimes be so, observations also indicate that in some instances the flare is triggered by the emergence of small regions of some polarity imbedded into larger regions of the opposite polarity. Besides it is known from X ray observations that the very first soft X ray brightenings sometimes occur in tiny compact structures which look like loops. The problem of finding a *local* trigger mechanism and a way of spreading the dissipative process to the rest of the structure then arises for explaining these events. The main requirement is to get a very impulsive process, working on a time scale of a few seconds and able to produce the hard X ray emission which we observe, the latter is the hard X ray emission which we observe. The latter is the signature of the presence of fast electrons in the 100 keV range in the flaring region. The number of electrons needed to give rise to the observed radiation depends however to some extent on the conditions of production of these X rays, a problem on which we come back soon. Some models have now been examined with some detail in the litterature, though it has not yet been possible, by far, to reach a definite conclusion. A large number of them have dealt with the possibility of reaching a state of microturbulence in the current carrying system, or reaching high values of the electric field, of the order of the Dreicer field (Coppi Friedland, Heyvaerts and Priest, Heyvaerts and Kuperus). All these models as well as the double layer model proposed by Alfvén face the same difficulty : it is extremely difficult to find oneself in conditions such that the necessary thresholds be reached. Reaching the Buneman threshold in a plasma with $n = 10^{11}$ cm^{-3} and $T = 10^{6}$ K implies a current density of 64 000 A m^{-2} which corresponds to a field gradient of 1 000 G m^{-1}. Sheet like current concentrations or extreme degrees of the filamentation would then be required. Observations nevertheless, as we shall see later point to extreme current densities ! I cannot enter here into the details of specific mechanisms which have been imagined to achieve this situation. In brief, I would summarize that switching the resistivity regime in a current sheet, reconnecting or not, to a microturbulent state is feasible in special conditions (Heyvaerts, Priest, Tur and Priest). A flare model based on the idea that the primary energy release is due to such a transition has been proposed. It has been shown that a small number of particles can be accelerated as a result of the sudden energy conversion that result from this change of resistivity regime. Another idea is that the very primary release of energy be not due to micro-instabilities but instead to the rapid development of a tearing instability in some suitable structure of the region, for example a single current-carrying loop. The situation actually realized cannot be inferred from the observations because these structures should be at the limit or even smaller than the resolution of telescopes and magnetographs.

The tearing instability in a loop can only be a viable theory if the structure can be maintained stable prior to the impulsive phase while still containing an adequate amount of free energy. It should also be proved that the release time scale, once instability has started can be short enough. Concerning the first point, Spicer (1976) has established that this requirement implies that a compact low lying loop must be considered.

The time scale requirement if we take as a typical growth time the geometrical mean of Alfvén and resistive time scale :

$$\tau = \sqrt{\tau_A \tau_R}$$

has been long considered to be a fairly severe constraint. First estimations led Spicer to conclude that the mechanism was only viable if the structure contained rather concentrated current sheets with a thickness of some 80 m only. Moreover, it was known some tearing modes appear to reduce their growth at rather low levels. However, here, we should keep in mind several aspects of the question, in particular the fact that growth rates tend to be larger than those applicable to a plane sheet when other geometries are considered, that some types of tearing modes continue to exponentiate during their non linear development, and that the dependance of the growth rate on the parameter S, which may be very large, may differ substantially from the $(\tau_A \tau_R)^{1/2}$ formula. To get an idea of the importance of these effects let us consider the growth time for three different cases of tearing modes ; according to respectively :

$$\tau = (\tau_A \tau_R)^{1/2} = \tau_R S^{-1/2}$$

and the extreme cases of slow tearing modes

$$\tau_{\text{slow tearing}} = \tau_R^{3/5} \tau_A^{2/5} = \tau_R S^{-2/5}$$

and of a very fast, $m = 1$, double tearing mode, which according to Spicer (1978) has a growth time :

$$\tau_{DTM} = \tau_R^{1/4} \tau_A^{3/4} = \tau_R S^{-3/4} .$$

For parameters appropriate to our problem, we have

$$\tau_R = \mu_0 \sigma a^2 = 10^6 \left(\frac{T^\circ}{10^6}\right)^{3/2} a_{\text{km}}^2$$

$$S = 2.18 \times 10^9 a_{\text{km}} \left(\frac{B}{100\ \text{G}}\right) \left(\frac{T^\circ}{10^6}\right)^{3/2} \left(\frac{10^{16}}{n\ (\text{m}^{-3})}\right)^{1/2} .$$

Let us consider a standard case $B = 100$ G, $T = 10^6$ K, $N = 10^{16}$ m^{-3} but two different scales for the current carrying region, $a = 10$ km and $a = 100$ km.

	$a = 10$ km	$a = 100$ km
	—	—
τ_R	10^8 s	10^{10} s
τ	$10^{2.85}$ s	$10^{4.35}$ s
τ_{STM}	$10^{3.88}$ s	$10^{5.5}$ s
τ_{DTM}	2 s	33 s

It is seen that, whereas the slow types of tearing modes are, even with these rather small characteristic sizes, far too slow as compared to the impulsive phase characteristic times, a considerable factor can be gainted if so called fast tearing modes are involved, and that non linear saturation may not be a serious limitation. It remains of course to justify that one is really in that situation. Refering to a numerical calculation by Schnack and Killeen, Spicer (1978) argues that a bit less than 5 % of the total magnetic energy may be released in 14 Alfven travel times in the form of heat, which of course represents a fairly high rate of energy release, in the case of double tearing modes and that this could rapidly raise the plasma to a very high temperature, given approximatively ignoring any losses by say

$$nkT = 0.9 \times 5/100 \times B^2/2\,\mu_0 \,.$$

This allows to reach 2×10^7 K for 100 G, or 2×10^9 K for a release in 1 000 G field. In the latter case the mean energy per particle is high enough to be of the order of what is required to produce the hard X rays thermally. One difficulty in the present state of this theory is of course that one does not really understand yet why the structure should *wait* finding itself in such a very unstable state before it starts to tear. Moreover, though the sheet thickness implied is by far not as small as the ones implied by the micro-instability phenomena it is still quite smaller than the typical size of the cross section of such a loop, which may be estimated to some thousand kilometers, so that a specific theory is also required to explain how such current concentrations may arise. An analysis of thermal instabilities applicable to a coronal plasma heated by a mechanical energy flux, as well as by Joule heating and which cools by radiation and conduction has been made in the litterature (Heyvaerts, 1974; Spicer, 1976). A linear analysis indicates that currents could be concentrated as a result of what is essentially an overheating instability in certain conditions of initial temperature. However, the growth times are fairly long, of the order of several hours. This is barely compatible with the preflare time scale but this rate may be larger if an even modest factor of enhancement of the resistivity can be explained, or perhaps does this rate accelerates in the non linear stage. The degree to which currents can become concentrated is not yet precisely known.

Let us now assume that we have been able to find a mechanism which dumps the required energy at the required rate into the electrons of some finite small region in some loop. How will these particles behave, and will it then be possible to explain the observed radiations ? It seems that this aspect of the question, which is a better posed problem, and which may be subject to some observational tests has met with a larger degree of sucess.

The point starts by a consideration of the hard X ray impulsive burst, for which it has been soon recognized that the most likely emission mechanism was bremsstrahlung. It has been first thought that the source should simply be pictured as an acceleration region high in the corona, providing fast particles travelling down and bombarding the denser parts of the solar atmosphere. However, once the required flux of electrons could be estimated from the observations (Hoyng *et al.*); it was realized that this simple model was not tenable because it would involve a flux of 10^{36} electrons.s^{-1} dumped in the chromosphere, and a total number of accelerated electrons as high as 10^{37}-10^{38} which is just the order of magnitude of the total electron content of a flaring flux tube. This directed flow of electrons constitute a beam passing through a plasma, between the acceleration region and photosphere. It will not only become unstable to plasma waves but create an enormous magnetic field. In fact the electric current represented by the downwards flowing fast particles will be compensated by a return current driven in the background plasma. This return current, if the beam is too strong, will itself turn microunstable and the beam will stop, because it loses all its energy driving this excessively damped current. Only ion acoustic instability has been studied up to now in this context, but I think that results concerning the electrostatic ion cyclotron instability should appear soon. The simple downward flow of energetic particles to the chromosphere may then just not be possible. Actually this is fortunate, because the embarassingly high number of electrons required can be traced back to the fact that X ray radiative losses of these particles in a cold plasma is 10^{-5} times smaller than collisional losses on cold electrons. Bombarding a cold gas with energetic electrons is an intrinsically inefficient way of emitting X rays. A more efficient source would be one in which the electrons would be more or less thermal at temperature 15 keV say. Collision losses would be reduced to zero, but of course, one must in this case take care of conduction and expansion losses that the hot region must suffer. The conduction losses can be cut down by just the same beam return current instability mentioned above because the hot electrons which sustain the heat flow act as the beam we were speaking of before and induce also a return current. It then appears possible thanks to this process to understand the bottling up of a large part of the energetic electron population in the coronal regions, and its more effective ability to emit X rays. However, the « corks » of turbulence are not completely opaque for the fastest electrons which leak out, driving in the exterior medium a beam-plasma instability. The beam may be strong, but according to Papadopoulos and Vlahos it can be stabilized by the transfer of waves to low phase velocities as a result of the ponderomotive force once the Langmuir turbulence has reached the threshold level for the modulational instability to set in. The resulting ion clumping according to C. Norman and B. Smith will produce a state of enhanced resistivity, which will be an ideal way of spreading of the dissipative process to a larger volume of the flaring region, while, however, the stabilized beam will be able to reach down to the chromosphere and produce there impact effects which are actually observed in the form of flare knots.

I would like now to finish this talk by explaining how a peculiarity of solar cosmic ray nuclei which has been for some time quite a puzzle finally turns out to give us interesting clues concerning the conditions in the preflare plasma.

The acceleration of high energy nuclei is an interesting aspect of the flare mechanism. This acceleration occurs only in a restricted number of flares. The proton acceleration seems well correlated with type II radio emission which is, I recall, considered to be the signature of a shock wave travelling in the corona. It is not known at present whether this shock is responsible of the particle acceleration or whether both effect are different consequences of a common cause. It seems however that nuclei and proton acceleration originate from a different, somewhat delayed, mechanism than the electrons energized in the impulsive phase (Bai, Ramaty). This point is still quite controversial, though a fair evidence of this can be obtained from a timing of γ ray line emission at 2.2 MeV.

The acceleration mechanism proposed thus far for these particles has been second order Fermi acceleration by *weak* long wave MHD turbulence (Melrose). Other processes could perhaps be operative too. It suffices for my purpose to mention that these mechanisms have an injection threshold. For 2d order Fermi acceleration, the momentum of the particle must be larger than $M_i v_a$. It has appeared rather puzzling for some time that a number of small flares, or even events not reported as qualified flares at all exhibited a strong anomaly of the isotopic abundance of helium in the accelerated ion population. Normally

$$\mathrm{He}^3/\mathrm{He}^4 \simeq 10^{-3} \quad \text{while} \quad \mathrm{He}^4/\mathrm{H} \simeq 10^{-1}\,.$$

Events have been reported in which the cosmic ray population exhibit :

$$\mathrm{He}^3/\mathrm{He}^4 \simeq 1\,; \quad 10^3 \text{ larger than normal!}$$

It is interesting to report that we can now reasonably think that a solution to this puzzle has been found; this explanation rests on the demonstration that in certain conditions, the plasma which will be later exposed to the acceleration mechanism could be preheated by an electrostatic ion cyclotron turbulence in such a way that He^3 and some charge states of heavier ions be preferentially preheated. The point is as follows : assume that as a result of some unspecified conditions an electrostatic ion cyclotron instability is driven by some current. In a pure hydrogen plasma, these waves would all have frequencies above the ion gyrofrequency but if a noticeable amount of helium is present in the coronal gas they could also be excited above the ionized He^4 gyrofrequency. It is then possible, according to the excitation conditions, to have waves above $\Omega(\mathrm{He}_2^4) = \Omega_i/2$. Now, it is remarkable that He^3 is the only neutron poor isotope susceptible to be present in reasonable amounts in the solar plasma. Its gyrofrequency lies between $\Omega(\mathrm{He}_2^4)$ and Ω_i. Fisk, the author of this theory determined the optimal conditions for which waves in the vicinity of $\Omega(\mathrm{He}_2^3)$ are first driven unstable. He found this to occur for :

$$\mathrm{Te}/\mathrm{Ti} \simeq 5 \qquad \mathrm{He}/\mathrm{H} \sim 0.2, 0.3\,.$$

This is an abundance of helium larger than normal but not ruled out by any observation. It is expected, and it can be calculated that the rate of heating of He^3 exceeds in these conditions that of other abundant ions, thus making He^3 ions more likely to be injected in the acceleration mechanism, which will convert them into solar cosmic rays. Heavier ions can be also preferentially preheated by this turbulence by means of a second harmonic resonance. Of course, the ions preferentially heated are those whose second harmonic of the gyrofrequency is not much different than $\Omega(\mathrm{He}_2^3)$. This is the case of C, O, Fe ions in the following charge states :

$$^{12}\mathrm{C}^4,\ ^{16}\mathrm{O}^5,\ ^{56}\mathrm{Fe}^{17}\,.$$

It is especially significant that very recently, Gloeckler has observed that these charge states of these ions are overabundant in He^3 rich event, confirming the theory (Fisk). This success lends a great deal of support to the idea that ion cyclotron waves, are, in small flares, driven unstable somewhere. As the threshold for the instability is very high, as we remarked already earlier, the unstable current could be found in a rather thin current sheet or in the unstable return current driven in the sort of conduction front described earlier. Future observations will hopefully decide between these two possibilities by testing wherever possible whether the modest amount of electrons accelerated in these special events can or cannot drive an anomalous thermal conduction front.

As a conclusion, one can say that the solar flares encompass much of the most exciting aspects of present day plasma physics. This may be one of the reasons for which they are still ill understood, the other being the fact that the amount of data obtained is both exceedingly abundant on some aspects but nevertheless inexistent on such crucial points as microstructures, state of turbulence... As a result theories produced up to now cannot reach the high degree of sophistication and confidence involved in such fields as magnetospheric or laboratory physics. This review has been oriented to a presentation of the most recent trends of research, though other ideas only rapidly alluded to here may have more to do with the phenomenon than we use to believe in our present state of understanding.

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