PARTICLE ACCELERATION IN SOLAR FLARES

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Abstract. Particle acceleration during solar flares is a complex process where the main 'actors' (Direct (D.C.) or turbulent electric fields) are hidden from us. It is easy to construct a successful particle accelertion model if we are allowed to impose on the flaring region arbitrary conditions (e.g., strength and scale length of the D.C. or turbulent electric fields), but then we have not solved the acceleration problem; we have simply re-defined it. We outline in this review three recent observations which indicate that the following physical processes may happen during solar flares: (1) Release of energy in a large number of microflares; (2) short time-scales; (3) small length scales; and (4) coherent radiation and acceleration sources. We propose that these new findings force us to reformulate the acceleration process inside a flaring active region assuming that a large number of reconnection sites will burst almost simultaneously. All the well-known acceleration mechanisms (electric fields, turbulent fields, shock waves, etc.) reviewed briefly here, can be used in a statistical model where each particle is gaining energy through its interaction with many small reconnection sites.

1. Introduction

Particle acceleration (ions, electrons, and nuclei) is an essential part of the 'flare problem'. The other parts of the 'flare problem' are: (1) global structure of the active region and energy storage, (2) energy release (3) interaction of energized plasma with ambient plasma, (4) reaction of the atmosphere, and (5) radiation signatures. All these parts of the 'flare problem' are in fact one complex problem that is very hard to split into independent pieces. On the other hand solving the global problem is a task that goes beyond our instrumental and theoretical capabilities today.

Numerical simulations that are currently very popular 'suffer' from the fact that several aspects of the flare problem demand global MHD modeling (lengths $\geq 10^9$ cm and time-scales $\geq (L/V_{\mathrm{A}})$ s); others require 'kinetic' modeling ($L \approx c/\omega_{pe} \ll 1$ km, $\tau \approx$ many $(\omega_{pe}^{-1}, \Omega_e^{-1}) \ll 1$ s). The 'global modeling' imposes dynamic boundary conditions on the 'kinetic' part and the 'kinetic' modeling determines characteristic parameters (e.g., resistivity) for the global modeling. The comments made above are well known but in practice we ignore them and continue our work on the global or local level imposing artificial boundary or local conditions.

The physical process that control particle acceleration lie on the interface of the global and local phenomena. Several theoretical attempts made so far emphasize the global or the local aspect of the acceleration process. Let us mention a few characteristic examples. A number of articles have proposed a D.C. electric field as a possible mechanism for electron acceleration in solar flares (e.g., De Jager, 1986, and references therein). The strength of the electric field is estimated from the linear evolution of the

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tearing mode (no temporal or spatial dependence is considered). However, it is well known that the appearance of the electric field inside the plasma, as well as its temporal and spatial structure depends critically on the boundary conditions.

Another example of this approach is the acceleration of ions by MHD turbulence (Fermi acceleration) or shock waves. In this work a serious effort is made to match the spectrum of the observed data with the spectrum of the accelerated particles, but little attention is placed on the mechanism that excites the turbulence or drives the shocks (Forman, Ramaty, and Zweibel, 1985); Ramaty and Murphy, 1987, and references therein).

As a final example, consider the 'localized hot spots' or 'conduction fronts'. We have used these concepts for so long, almost a decade, even developing radiation models, but we know so little on the physics of their origin, stability and evolution (but see recent numerical simulation by Winglee, Pritchett, and Dulk, 1988).

A large number of review articles have appeared recently on particle acceleration in solar flares (Heyvaerts, 1981; Chupp, 1984; Vlahos *et al.*, 1986; De Jager, 1986; Forman, Ramaty, and Zweibel, 1985; Ramaty and Murphy, 1987; Sakai and Ohsawa, 1987; Scholer, 1988). These articles review the observed data and the mechanisms that can accelerate charged particles, but they omit the process of fitting to the existing data or the connection to the global energy release processes in solar flares.

In this review we will follow a different approach. First we will discuss a few *key* observational results, which seem to indicate a need for a new thinking on our research in particle acceleration. We will review a number of new theoretical ideas that indicates that the corona is probably full of small magnetic tubes (fibers). The acceleration mechanisms proposed so far will be reviewed *briefly* in Section 4. Finally in Section 5 we will discuss a new acceleration mechanism proposed especially for a fibrous corona and we will close our review with a summary of the current research.

2. Recent Observational Results

A detailed review of the recent observational results related to particle acceleration and recorded by the SMM or Hinotori satellites during the 1980 solar maximum was presented elsewhere (see Vlahos *et al.*, 1986). We will outline below three characteristic observations that, in our opinion, suggest the need for a new way of thinking on particle acceleration and transport in solar flares.

(1) The U.C. Berkeley balloon flight of June 27, 1980 was the first to observe the Sun with high-energy resolution (≤ 1 keV) and sensitivity in the energy range ≥ 20 keV (Lin *et al.*, 1983). They discovered the phenomenon of solar hard X-rays microflares which have peak fluxes $\simeq 10$–100 times less than the normal flares. These bursts occurred one every five minutes on average through the 141 min of solar observations. Although they are associated with small increases in soft X-rays, their spectra are best fit by power-laws which can extend up to ≥ 70 keV. These microflares are thus probably nonthermal in origin. The integral number of events varies roughly inversely with X-ray intensity (Figure 1), so that many more bursts may be occurring with peak fluxes below the limit

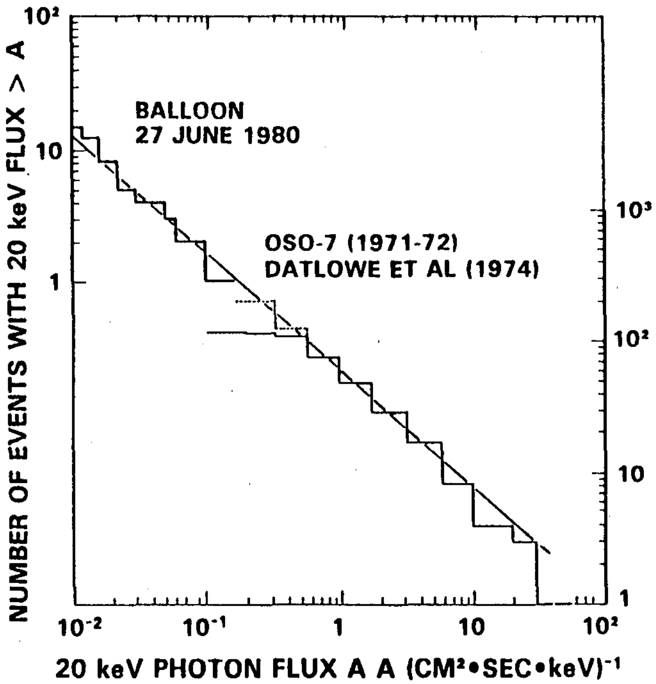

Fig. 1. The distribution of integral number of events versus peak 20 keV photon flux for the solar hard X-ray microflares observed in the balloon flight of June 27, 1980. Als shown for comparison is the distribution of solar flare X-ray bursts reported by Datlowe *et al.* (1974). The distributions have been arbitrarily moved vertically to show that their slopes are approximately the same (from Lin *et al.*, 1983).

of sensitivity. There is also some indication that these bursts may be made up of spikes of $\simeq 1$ s duration (Figure 2). Perhaps these are real 'elementary' bursts, a factor 10^2–10^3 smaller than the elementary flare bursts reported by De Jager and De Jonge (1978). Kaufmann *et al.* (1985) reached a similar conclusion regarding such 'microbursts' in the microwave domain. These hard X-ray 'microflares' and the 'microbursts' indicate the impulsive electron acceleration to above 20 keV energy is very common and may be the primary transient energy release mode in the solar corona.

(2) Spikes of duration less than 100 ms are well known in the 200–3000 MHz band. At meter wave lengths some have been reported near the starting frequency of type III bursts (Benz, Zlobec, and Jaeggi, 1982) at decimeter wave lengths as a part of type IV events (Droge, 1977) and at centimeter wave lengths superimposed on a gradual event (Slottje, 1978). In an analysis of 600 short decimetric events (excluding type IV's), Benz, Aschwanden, and Wiehl (1984) have found 36 events consisting only of spikes. An example of the data is presented in Figure 3 together with a hard X-ray time profile and a blow-up of some single spikes. Benz (1985) analyzed these data and reached the conclusion that the groups of spikes are always associated with groups of metric type III bursts. The spikes tend to occur in the early phase of the type III groups and predomi-

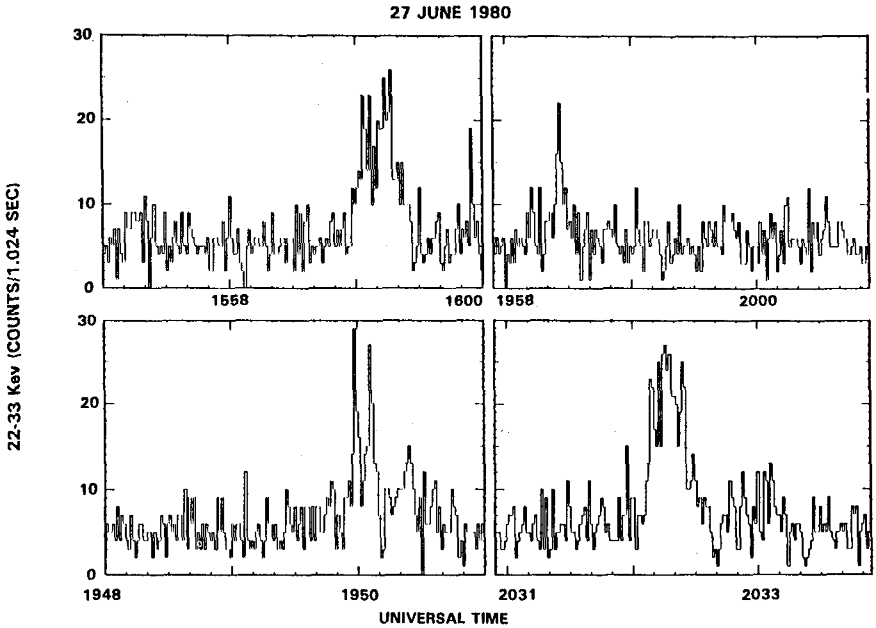

Fig. 2. The four largest hard X-ray microflares are shown here at 1.024 s resolution (from Lin *et al.*, 1983).

nantly in the rising phase of hard X-rays. The half-power duration of the spikes is less than 100 ms, the time resolution of the instrument used. The spectrum of the spikes has been recorded and the typical half power widths are 3–10 MHz at 500 MHz. This puts a severe constraint on the spectral width of the radio emission and, therefore, on the generation mechanism. Assuming a locally homogeneous corona with a magnetic field scale length of 10 000 km, the source size in the direction of the field gradient must be equal to or less than 100 km. This is less than the limit imposed by time variations. Assuming this dimension for the lateral extent of the source, the lower limit of the brightness temperature is as high as 10^{15} K. The high brightness temperature of short duration (1–100 ms) spikes observed during the impulsive phase of some flares indicates that a *coherent radiation mechanism* is responsible.

(3) Observation of the time dependence of the gamma-ray fluxes from solar flares provided a great deal of information on the acceleration and interaction of the energetic particles. These time dependencies are determined by the temporal structure of the acceleration process, by the lag, due to propagation and trapping, between the acceleration and the interaction of the particles, and by the delay between the interaction of the particles and the emission of photons. Bremsstrahlung and most nuclear line emission are produced essentially instantaneously at the time of the interaction of the particles and, therefore, serve as the best tracers of the time dependencies of the acceleration and interaction processes. Timing studies based on these radiations define the total duration of particle interaction in flares, as well as the overall temporal structure of the emission.

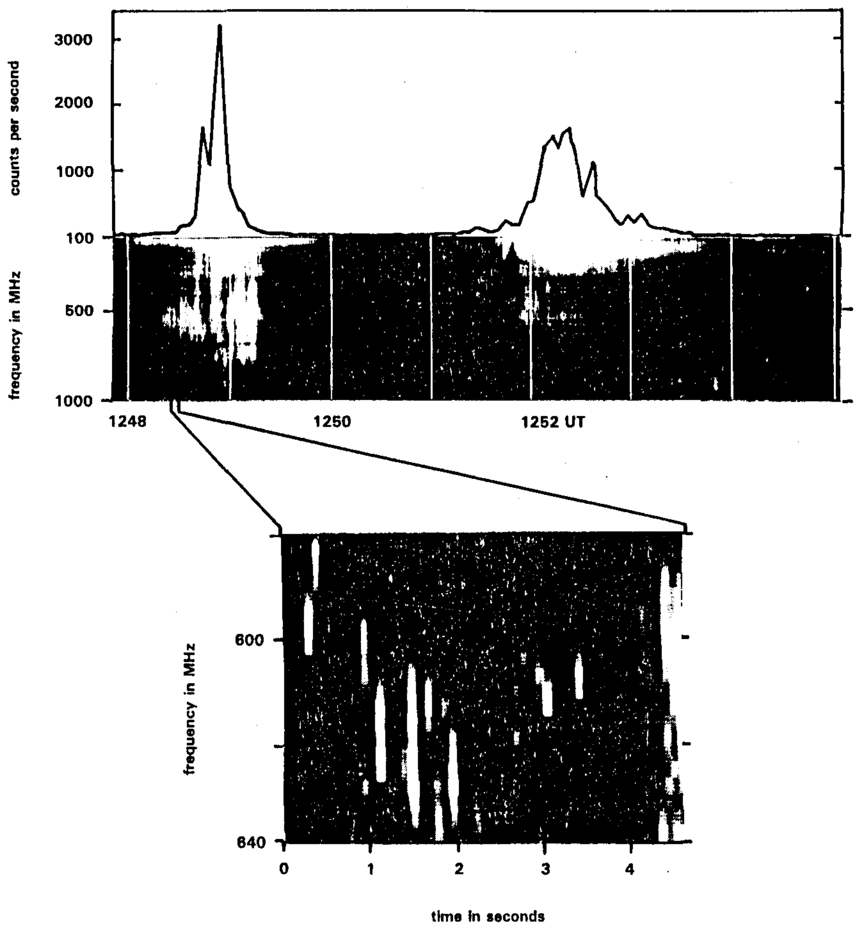

Fig. 3. *Top*: Composed figure showing hard X-ray counts (> 30 keV, observed by HXRBS on board the Solar Maximum Mission) vs time, of the double flare of August 31, 1980 and radio spectrogram registered by the analog spectrograph at Bleien (Zürich). The spectrogram shows type III bursts at low frequency having starting frequency in correlation with the X-ray flux and spike activity above 300 MHz. *Bottom*: Blow-up of a small fraction of spectrogram produced from data of the digital spectrometer at Bleien (Zürich). The blow-up shows single spikes which are resolved in frequency (from Benz, 1985).

But of particular interest is the temporal relationship between the fluxes in the various energy channels, as these data provide information on the relationship between ion and electron acceleration. The gamma-ray spectrometer γ-ray observations > 0.3 MeV indicates a range of total flare duration from $\simeq$ 10 s to over 1000 s. The total emission in the majority of these events consists of at least a few emission pulses. These separate emission pulses can be as short as $\simeq$ 10 s and as long as 100 s. It is important to note that in a few events there are no delays detected between the emission in 40–120 keV and 10–25 MeV (Figure 4). Another aspect of the timing studies is the relationship between the starting times of the fluxes in different energy channels. Forrest and Chupp

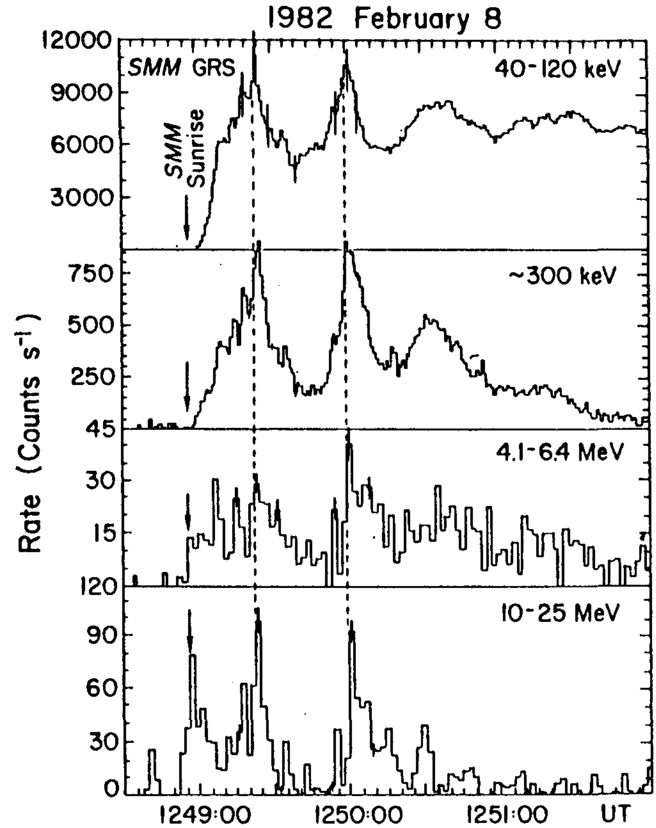

Fig. 4. The observed time histories in 4 energy bands for a gamma-ray flare (from Chupp, 1984).

(1983) have studied this relationship for the 40–65 keV flux and the 4.1–6.4 MeV flux in two impulsive flares. They found that the starting time, defined as the time when flux above background was first detected, was the same in each energy band within ± 2 s for the smaller flare and ± 0.8 s for the larger flare, in spite the fact that these flares show evidence for a delay in the maximum of the fluxes of the same two energy bands.

The observations outlined above uncovered the presence of (1) very short time-scales, (2) small scale lengths, (3) large number of explosive phenomena, and (4) intense coherent radiation sources. We propose in this review that these observations are important new findings that should redirect our work on particle acceleration in solar flares.

3. A Model for the Fibrous Corona

Let us accept the idea proposed initially by Parker (1972) that the footpoints of the bipolar fields are subject to random shuffling and mixing, then tangential discontinuities

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(current sheets) are formed and the amplitude of each discontinuity increases with the passage of time. Eventually a point is reached where rapid reconnection of the magnetic field across the individual discontinuities destroys them as fast as they are created by the motions of the footpoints. We expect the bipolar fields above the surface of the Sun to be filled with small scale reconnection events, i.e., filled with nanoflares, microflares, or flares depending on the rate and total energy released. The spontaneous formation of tangential discontinuities is a peculiar consequence of the static equilibrium properties of the magnetic field imbedded in a infinitely conduction fluid. The discontinuities arise when the field is subjected to continuous but complex deformation, so that the magnetic lines of force are wound and wrapped about each other in complicated patterns (see discussion and references in Parker, 1988; Moffat, 1987; Low and Wolfson, 1988).

In this review we will assume that the active region is full of small (characteristic radius < 10–100 km) magnetic fibers randomly moving with a characteristic velocity $v \simeq 0.5$ km s^{-1}. Nanoflares continuously heat the corona but under certain circumstances a large number of dissipation sites are present, increasing the total energy release by thousands or hundreds of thousands times, we will call this a 'flare' (see Figure 5). We propose that acceleration and transport should be re-examined in such an environment. In the next section we will briefly review the physics of the well known acceleration mechanisms and in Section 5 we will use many of these acceleration mechanisms inside a fibrous corona.

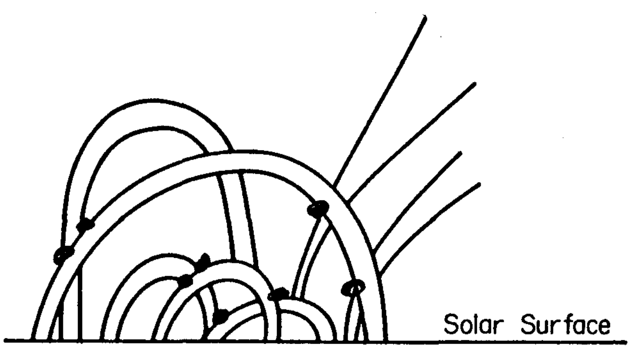

Fig. 5. A catastrophic interaction of thousands of reconnection layers.

4. Main Acceleration Process

The general concepts of particle acceleration is illustrated by discussing briefly the three generic types of particle acceleration. (a) Coherent acceleration, (b) Fermi (or stochastic) acceleration, (c) shock wave acceleration. We will review briefly the main conclusions from these acceleration processes below.

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4.1. Coherent acceleration

Coherent acceleration can be the result of a D.C. electric field (when the acceleration time is shorter than the time of change of the E-field), or a narrow-band electromagnetic wave. We will discuss these two physical processes separately.

The origin and strength of the electric field in solar flares is not well known. There are at least two possible ways that an electric field will appear in solar flares (i) magnetic reconnection or (ii) double layers.

There have been several attempts (Van Hoven, 1979; Smith, 1980; Heyvaerts, 1981) to estimate the electric field produced by the resistive tearing mode instability but the results disagree. The principal reason for the lack of agreement is that the induced E-field depends critically on the small scale structure of the magnetic field and the transport properties of the instability as it nears the point of saturation, and such nonlinear behavior is poorly known. There are two distinct mechanisms available in a reconnecting field, for accelerating particles, (a) the electric field $\mathbf{E}_0 = \eta J_0 \mathbf{e}_z$ (where η is the resistivity and J_0 is the current) in the tearing layer itself and (b) the $\mathbf{E} = -\mathbf{v} \times \mathbf{B}$ due to the flow velocity $\mathbf{v}$ outside the resistive layer which converts magnetic flux into the tearing layer. The strength of these fields is still an open question. The answer depends sensitively on the time development of the field structure at the reconnection point, which (in turn) depends on the local resistivity and on the external boundary conditions. A number of articles have calculated the detailed changes of local reconnection due to radiation losses and thermal conduction (Steinolfson and Van Hoven, 1984; Van Hoven, Tachi, and Steinoffson, 1984). Bulanov (1986) estimated the E-field from the rapid changes in a magnetic field structure in the course of the breaking of a current sheet, which gives rise to an induced electric field, $E \simeq (V_A/c)B$, where V_A is the Alfvén velocity, c is the speed of light. An *approximate estimate* of the dimensions of the current sheet is given and then the maximum energy gain by the particles and their spectrum is calculated (assuming conservation of particle flux in phase space). Depending on the structure of the magnetic field near the reversal the energy spectrum can be a *power-law or exponential form*. Buchner and Zeleny (1986) and Martin (1986) discussed the stochastization of orbits near the magnetic field reversal and studied the role of this stochastization to the reconnection efficiency and particle acceleration.

All these recent attempts are important steps towards our understanding of particle acceleration near the reconnection sheet, but as we mentioned above, depends so critically on the magnetic structure, the boundary conditions and the time evolution of the resistive instability. Thus we feel that it is not yet easy to construct detailed models based on this acceleration mechanism for solar flares.

Double layers were initially proposed almost twenty years ago by Alfvén and Carlqvist (1967). They assumed that in a current flowing through a plasma, a density depression may rise while the induction of the total circuit is large enough for the current to be maintained. A D.C. electric field must appear to adjust the velocity of the electron flow in such a way that the current density remains constant, $en(x)v(x) = J$. We can easily estimate the potential drop and the energy gained by the particles. It is possible to show

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rigorously the existence of self consistent solutions of the Vlasov equations able to sustain large potential drops, and able to accelerate electrons and ions to high energies (Block, 1978; Hubbard and Joyce, 1979). More informations for Double layers can be found in Smith (1983). Double layers too need a careful understanding of the large-scale structure circuits in solar flares, as well as the local conditions at the point that the circuit breaks down. Although it is an open question whether double layers are good candidates for particle acceleration, the whole subject should be re-examined for a fibrous corona since the conditions for double-layer formation are easier to achieve inside the fiber due to the stronger current localization.

The presence of an electric field inside the plasma (independent of its origin) is a subject that needs careful study. It is well-known that if the electric field is less than the Dreicer field, a small fraction of electrons $(n_r/n_0) \cong 0.5 \exp(-E_{\rm D}/2E)$, where n_r is the number of density of the runaway particles, n_0 is the ambient density, and $E_{\rm D}$ is the Dreicer field, will run away. In the absence of a magnetic field (or if $\omega_{pe} \gg \Omega_e$) the energy gained by the runaway particles will be limited only by the scale length of the potential drop. In the presence of a magnetic field the scenario of the runaway particles changes since the electrons can excite an instability (the anomalous Doppler resonance instability) which scatters the electrons perpendicular to the magnetic field direction. The final result is that the tail will be isotropized and eventually thermalized. Moghaddam-Taaheri *et al.* (1985) and Moghaddam-Taaheri and Vlahos (1987) studied the evolution of the runaway tail as a function of electric field and found that for $E_\parallel < 0.2\, E_{\rm D}$ the anomalous Doppler resonance scattering is weak and the tail is possible to be accelerated to very high energies.

If the electric field exceeds the $E_{\rm D}$ inside the plasma the whole distribution will runaway and drive currents. Depending on the details of the ambient plasma parameters a number of current driven instabilities can be excited (see Heyvaerts, 1981, for a catalog of the potential instabilities and the necessary conditions for their excitation). Spicer (1983) and Holman (1985) have discussed the difficulties that arise when we attempt to accelerate all the necessary electrons for a hard X-ray burst from a single potential drop inside the flaring plasma.

We discussed earlier the discovery of intense narrow-band, highly polarized microwave spikes and their excellent correlation to X-rays and type III bursts. These observations have been interpreted as the signature of unstable loss-cone type electron distributions, formed inside a flaring magnetic loop (Holman, Kundu, and Eichler, 1983; Melrose and Dulk, 1982; Sharma, Vlahos, and Papadopoulos, 1982; Vlahos, Sharma, and Papadopoulos, 1983). Sprangle and Vlahos (1983) and Karimabadi *et al.* (1987) studied the interaction of coherent electromagnetic waves with the ambient plasma. It is well known that the relativistic cyclotron frequency and the wave phase change in such a way that the resonance between the electrons and the wave is maintained in a uniform magnetic field (Kolomenskii and Lebedev, 1963; Roberts and Buchsbaum, 1964) and the particles gain energy continuously. Karimabadi *et al.* (1987) extended those calculations to oblique em waves and showed that the fundamental and second harmonic will accelerate electrons to high energies and the acceleration is virtually unchanged when a wave with finite bandwidth is considered.

4.2. Fermi or (stochastic) acceleration

Stochastic acceleration of particles in turbulent fields is defined as the process that causes particles to change their energy in a random manner with many increases and decreases that lead finally to acceleration. Stochastic acceleration of ions or nuclei can result from Alfvén waves with wave lengths of the order of particle gyroradius. Alfvén waves will propagate parallel and antiparallel to the magnetic field directions. Electrons can also be accelerated stochastically by lower hybrid waves (Lampe and Papadopoulos, 1987; Benz and Smith, 1987). Formally stochastic acceleration is described as the solution of the diffusion equation in momentum space:

$$\frac{\partial f}{\partial t} = \frac{1}{p^2} \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial f}{\partial p} ,$$

where D_{pp} is the diffusion coefficient in the momentum space. The diffusion coefficient can be estimated from the wave spectrum. The solution of the diffusion equation for the particle distribution (Tverskoi, 1967) can be expressed in terms of modified Bessel functions for $E \ll mc^2$ (non-relativistic protons) or an exponential for $E \ll mc^2$ (a case relevant to electrons). Acceleration takes place only when the particles move with velocities equal or larger than the Alfvén velocity (the velocity of the moving scatterers). Assuming that the particles stay inside the acceleration volume for a finite time T, a series of characteristic spectra will be formed for the accelerated particles and can be used for fitting the observed data (Ramaty and Murphy, 1987, and references therein).

Melrose (1983) has demonstrated that magnetoacoustic turbulence with frequency $\omega \approx 30\ \mathrm{s}^{-1}$ can accelerate ions from 100 keV to 30 Mev in ≈ 2 s if $(\delta B/B)^2 \approx 0.1$. Ambrosiano *et al.* (1989) followed particle inside a *turbulent reconnecting magnetic field* and found that particles are accelerated to very high energies. This turbulent neutral point mechanism includes both coherent and stochastic components of acceleration. Turbulence appears to influence the acceleration in several ways: it enhances the reconnection electric field while producing a stochastic electric field that gives rise to momentum diffusion; it also produces magnetic irregularities that trap test particles in the D.C. strong reconnection electric fields for times comparable to the magnetofluid characteristic time.

The main problem with stochastic acceleration in solar flares is that very little is known on the processes that generate the turbulent spectra used in the diffusion equation.

4.3. Shock wave acceleration

The theory of particle acceleration in shock waves combines coherent and stochastic elements. If we assume that there is no wave activity upstream and downstream of the shock then the main acceleration mechanism is the drift of ions and electrons along the $E = -V_s \times B$ field, where B is the value of the magnetic field and V_s is the upstream flow velocity as it is measured by an stationary on the shock frame. The shock frame is the frame moving with the shock discontinuity. Examples of ion motion in the shock

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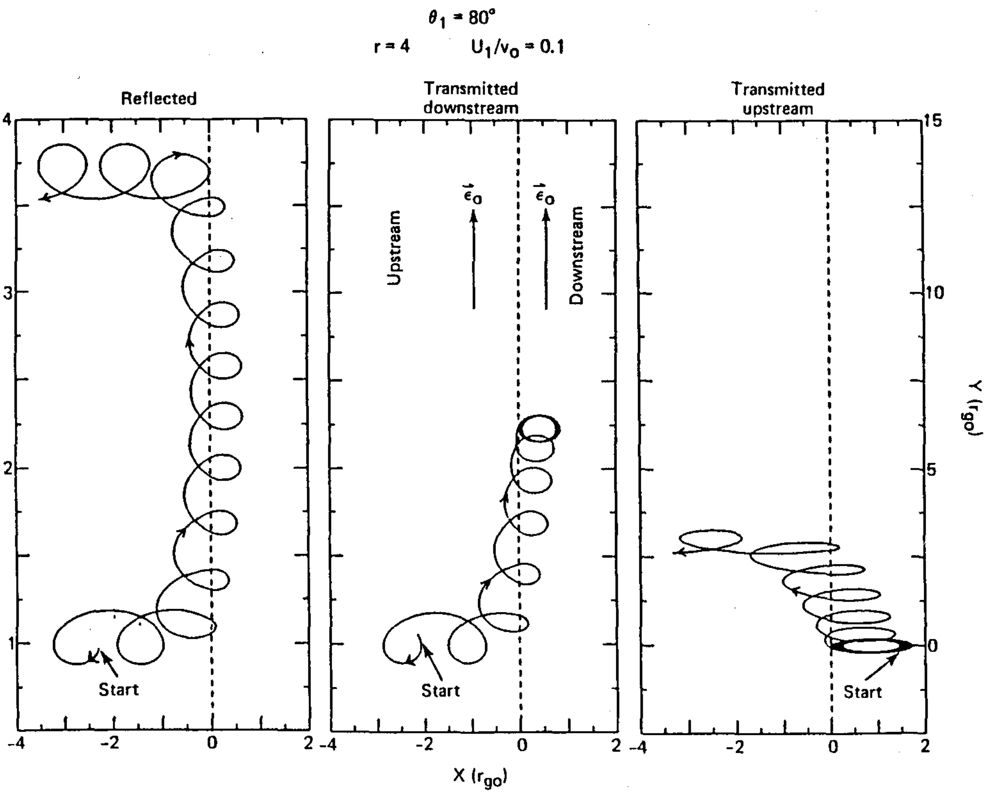

Fig. 6. Sample particle trajectories in shock frame at quasi-perpendicular shock with $\theta_1 = 80°$ (Decker, 1989).

frame are shown in Figure 6. It is obvious that when $V_s \parallel B$ (parallel shock) the electric field approaches zero and drift acceleration is not important.

If the upstream and downstream plasma is turbulent, then ions and electrons are scattered. If we view the picture in the shock frame and assume that $V_s \parallel B$, then an energetic particle crossing the shock from upstream will be scattered back upstream since the randomly moving turbulence upstream have now a systematic velocity (the downstream fluid velocity) away from the shock. This scattering will change the energy (ε) of particle the by $(V_2/c)\varepsilon$ (V_2 is the downstream fluid velocity). The particle will then move backward cross the shock again and propagate upstream gaining $(V_1/c)\varepsilon$ (V_1 is the upstream fluid velocity), the total energy gain is $(\frac{3}{4})V_s\varepsilon$ if the upstream velocity is V_s and the downstream for a strong shock $(\frac{1}{4})V_s$. In other words the parallel shock organized the upstream and downstream turbulence such that the rate of energy is the first-order power of the turbulent velocity. This is in contrast with the stochastic acceleration which is proportional to the second-order power in V_s.

Shock wave acceleration includes elements of coherent and stohastic acceleration processes. This coupling of coherent and stochastic processes is more pronounced in oblique shocks (see Decker and Vlahos, 1986; Decker, 1989). Oblique shocks have $E \neq 0$ in the shock transition and turbulence scatter particles back and forth (see Figure 7).

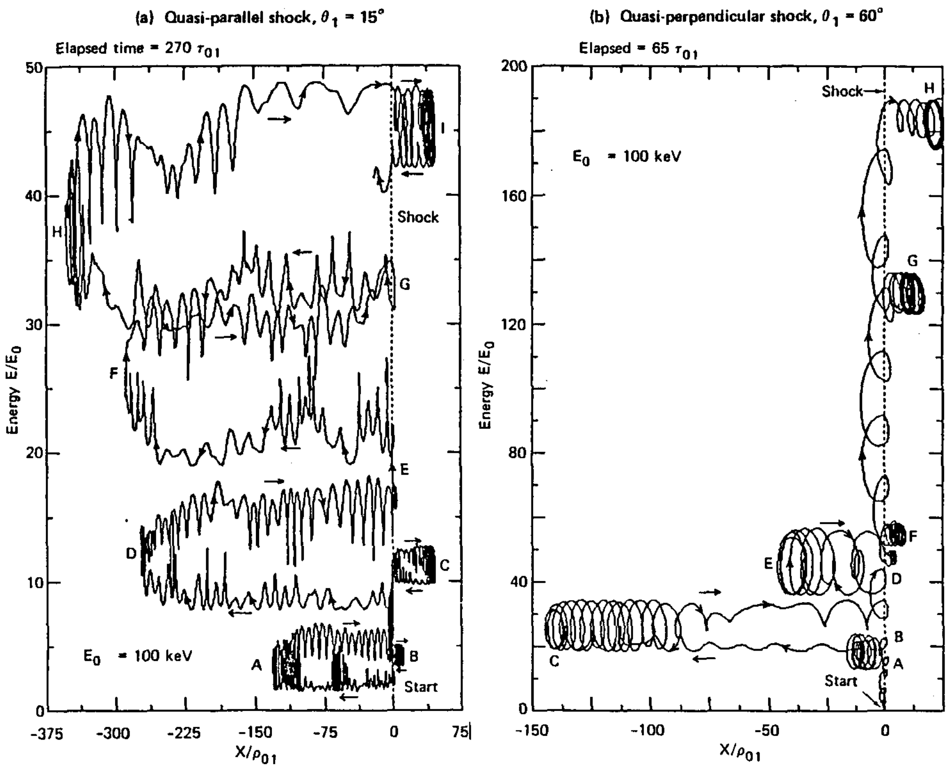

Fig. 7. (a) Sample particle orbit showing multiple shock encounters at a quasi-parallel ($\theta_1 = 15°$) shock. Shown is the energy E/E_0 (E_0 = 100 keV) versus particle's x-coordinate in shock frame. Elapse time is 270 upstream gyroperiods. (b) Sample particle orbit at a quasi-perpendicular ($\theta_1 = 60°$) shock. Elapsed time is 65 upstream gyroperiods (from Decker and Vlahos, 1986).

Shock wave acceleration in solar flares have been used extensively (see Ramaty and Murphy, 1987) since it is possible to accelerate electrons and ions quickly and form the observed spectrum assuming that we know how to form shock waves and turbulence with the 'correct' characteristics (wave energy, wave spectrum, etc.). In solar flares shock waves have been associated with acceleration of particle in the upper corona since they were related to metric and decametric type II bursts.

In Section 6, acceleration in solar flares proceeds in coherent, stochastic or mixed mode inside reconnecting sheets, shock waves or double layers. Although here is an abundance of ideas on particle acceleration, none of them is sitting on firm ground yet. For this reason a number of flare models appeared recently using extensively 'black boxes' in places where we sunspect that particle acceleration is possible.

5. Acceleration in a Fibrous Corona

Assuming that an active region is a collection of small fibers then a 'flare' is the sudden release of energy in many small regions inside the energy release volume. We will show below that in that environment the coherent and stochastic elements of particle acceleration take another interesting twist.

Let us start with the assumption that inside an active region many sudden releases of energy appear almost simultaneously in many different spots (Figure 5). We also assume that the released energy is going primarily into heating.

Cargill, Goodrich, and Vlahos (1988) studied numerically the evolution of such a 'hot spot'. They used a hybrid numerical code (Winske, 1985) to follow the evolution of heated plasma. They found that once $\beta = 8\pi p/B^2$ exceeds unity a shock wave is formed moving away from the hot spot (Figure 8). The shock is formed in time scales $\ll 1$ s. Initially the formation of quasi-perpendicular shocks was studied, but recently Cargill (1989) extended these calculations in the formation of parallel shock waves. The formation time for parallel shocks is longer ($\simeq 100\ \Omega_i^{-1}$) but still much less than one second.

The formation of a large number of shock waves inside the active region initiates a number of important processes. (a) Each shock wave can be an efficient and fast accelerator (see Decker and Vlahos, 1987, and references therein). (b) Once a particle escapes from each shock, it is possible to continue gaining energy from a neighboring shock. Electrons and ions have now a 'mean-free path' for their interaction with a large number of shock waves (Toptyghin, 1980).

Even if the shock-particle interaction is coherent (e.g., shock drift) the N-shocks-particle interactions are stochastic. The important difference between this processes and the classical Fermi acceleration is the fact that the shock-particle interaction is much more efficient than wave-particle interaction. (c) Shock waves interact among themselves (Cargill *et al.*, 1986; Cargill and Goodrich, 1987) and the result from their interaction is strong heating and acceleration of a small number of particles. Colliding shocks depart from their collision point with less energy and after many collisions will disappear.

Adding the two effects together, even if we start with localized 'heating' the N-shocks-particle interaction and the shock-shock interactions will heat and/or accelerate particles in a large volume.

Depending on the mean-free path for shock-particle or shock-shock collisions the energy release volume will end up as a large 'hot spot' (if shock-shock collisions are the dominate process) or 'a hot spot with a large number of accelerated particles' (if the N-shock-particle interactions are the dominant process). Thus we conclude, thermal or non-thermal flares can be produced in such environment, depending on the ratio of the characteristic mean-free paths mention above.

In summary heating, jets of fluid plasma and acceleration of a few electrons around the reconnecting sheet are coupled with the global heating and acceleration through the formation of many of shock waves. We feel that this approach, dictated by the

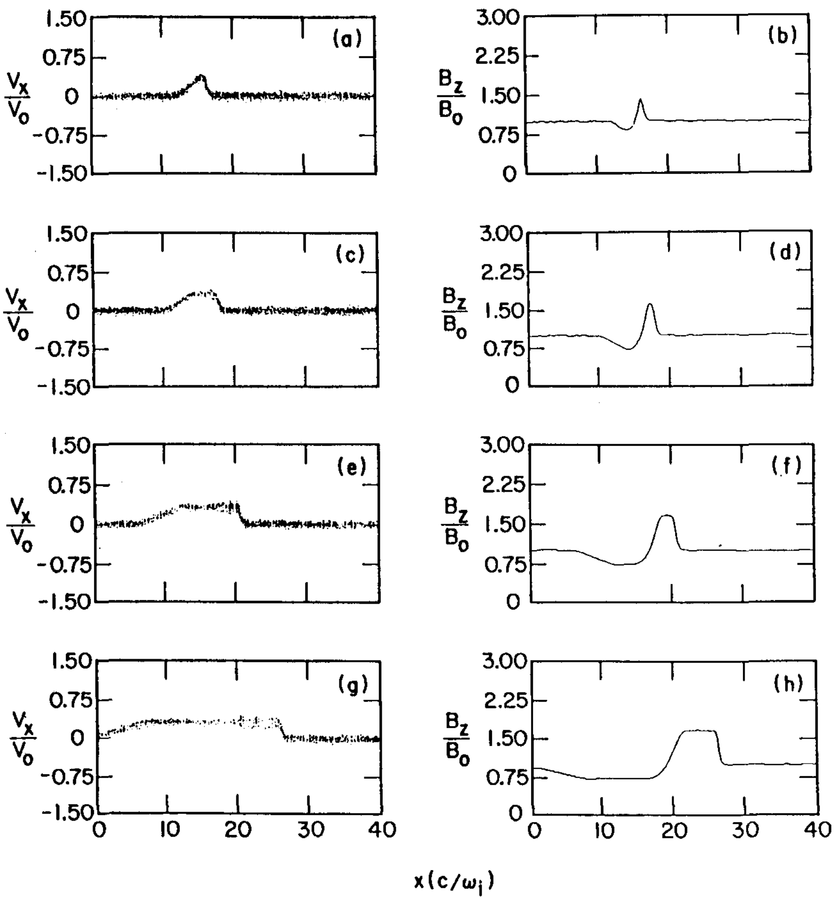

Fig. 8. The formation of a perpendicular shock due to a hot electron plasma. (8a, c, e, g) are (v_x, x) phase space at $t = 0.9$, 1.8, 3.6, and 7.2 Ω_i^{-1}, respectively. (8b, d, f, h) is the magnetic field at the same times. The velocities in the phase space plots are normalized to v_0, the lengths to an ion inertial length (c/ω_i) of the initial plasma and the magnetic field to its initial value. In this case, v_0 is defined as $v_0^2 = 2kT_e/m_i$ (from Cargill, Goodrich, and Vlahos, 1988).

observational data (hard X-rays, microflares, microwave spikes, and fast acceleration of ions) and the current theoretical understanding of the evolution of active regions combine almost all the elements of particle acceleration processes mentioned in Section 4 but places them in different environment; the fibrous corona.

6. Summary

When computer companies start the development of a large software program (a new compiler or a new word processor) they split the construction of this program in tenths or sometimes hundreds of smaller jobs. When these partial jobs are finished they put them together in order to complete the initial software. Sometimes the problems rising during the final welding of all these individual efforts are as big as the construction of the initial program without splitting it. We have almost reached such a state in solar physics. Many different pieces of information processed locally, or developed as local models, are in fact part of the same global problem. Our effort to piece together models for energy release, acceleration, transport, radiation, etc., at present looks as difficult as the problem we initially started to work on. In my opinion it is important to realize that we are not going to make any real progress without a strategy that connects the analysis made of the local parts of this admittedly fundamental, but extremely hard problem, with the global problem.

Our main conclusions in this review are:

(1) Observations suggest that microbursts are possibly a fundamental process in solar flares.

(2) We have evidence for generation of coherent electromagnetic radiation in solar flares.

(3) We have evidence that particles are accelerated to all energies almost simultaneously.

(4) Global modeling of the solar active region suggest that bipolar fields above the surface of the Sun are filled with small scale reconnection events.

(5) A number of mechanisms exist that can accelerate electrons, ions or nuclei to high energies. The main problems are: how these mechanisms are connected to the energy release process and how they will accelerate the number of particles that are necessary.

(6) We have proposed that new observational and theoretical work demand now a different approach in solar flare physics. We must start deemphasizing the single loop model, or the huge single reconnection sheet model, etc., and move on to statistical ensembles for large numbers of energy releases and acceleration sites. We feel that a step in that direction is the proposal that N-shocks-particle and shock-shock interactions discussed briefly in this review. Although these statistical models have not been tested yet by observations, much information collected during the last solar maximum may prove helpful on this count.

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References

Alfvén, H. and Carlqvist, P.: 1967, *Solar Phys.* **1**, 220.
Ambrosiano, J. J. Matthaeus, D., Goldstein, M. L., and Plante, D. R.: 1989, *J. Geophys. Res.* (in press).
Benz, A. O.: 1985, *Solar Phys.* **96**, 357.

Benz, A. O. and Smith, D.: 1987, *Solar Phys.* **107**, 299.
Benz, A. O., Zlobec, P., and Jaeggi, M.: 1982, *Astron. Astrophys.* **109**, 305.
Benz, A. O., Ashwanden, M. J., and Wiehl, J. J.: 1984, *Decimetric Radio Emission During Solar Flares*, Kunming Workshop Proceedings.
Block, L. P.: 1978, *Astrophys. Space Sci.* **55**, 59.
Buchner, J. and Zeleny, L. M.: 1986, *Proceedings of the Joint Varena–Abastumani International school and Workshop on 'Plasma Astrophysics'*, ESA SP-251, p. 195.
Bulanov, S. V.: 1986, *Proceedings of the Joint Varena–Abastumani International School and Workshop on 'Plasma Astrophysics'*, ESA SP-251, p. 185.
Cargill, P. J.: 1989, *J. Geophys. Res.* (submitted).
Cargill, P. J. and Goodrich, C. C.: 1987, *Phys. Fluids* **30**, 2504.
Cargill, P. J., Goodrich, C. C., and Vlahos, L.: 1988, *Astron. Astrophys.* **189**, 254.
Chupp, E. L.: 1984, *Ann. Rev. Astron. Astrophys.* **22**, 359.
Datlowe, D. W., Elcan, M. J., and Hudson, H. S.: 1974, *Solar Phys.* **39**, 127.
Decker, R. B.: 1989, *Space Sci Rev.* (in press).
Decker, R. D. and Vlahos, L.: 1986, *Astrophys. J.* **306**, 710.
De Jager, C.: 1986, *Space Sci. Rev.* **44**, 43.
De Jager and De Jonge, G.: 1978, *Solar Phys.* **58**, 127.
Droge, F.: 1977, *Astron. Astrophys.* **57**, 285.
Forrest, D. J. and Chupp, E. L.: 1983, *Nature* **305**, 291.
Forman, M. A., Ramaty, R., and Zweibel, E. G.: 1985, in P. A. Sturrock (ed.), *The Physics of the Sun*, D. Reidel Publ. Co., Dordrecht, Holland, p. 249.
Heyvaerts, J.: 1981, in E. R. Priest (ed.), 'Particle Acceleration in Solar Flares', *Solar Flare Magnetohydrodynamics*, Gordon and Breach, New York, p. 429.
Holman, G.: 1985, *Astrophys. J.* **293**, 584.
Holman, G., Kundu, M. R., and Eichler: 1983, in M. R. Kundu and T. E. Gergely (eds.), 'Radio Physics of the Sun', *IAU Symp.* **86**, 457.
Hubbard, R. F. and Joyce, C.: 1979, *J. Geophys. Res.* **84**, 4297.
Karimabadi, H., Menyuk, C. R., Sprangle, P., and Vlahos, L.: 1987, *Astrophys. J.* **316**, 462.
Kolomenskii, A. A. and Lebedev, A. N.: 1963, *Soviet Phys. Dokl.* **7**, 745.
Kaufmann, P. *et al.*: 1985, *Solar Phys.* **95**, 155.
Lampe, M. and Papadopoulos, K.: 1977, *Astrophys. J.* **212**, 886.
Lin, R. P., Schwartz, R. A., Kane, S. R., Pelling, R. M., and Harley, K. C.: 1983, *Astrophys. J.* **251**, L109.
Low, B. C. and Wolfson, R.: 1988, *Astrophys. J.* **324**, 574.
Martin, R. F.: 1986, *J. Geophys. Res.* **91**, 11985.
Melrose, D. B.: 1983, *Solar Phys.* **89**, 149.
Melrose, D. B. and Dulk, G. A.: 1982, *Astrophys. J.* **259**, 844.
Moffat, H. K., 1987, in G. Comte-Bellot and J. Mathieu (eds.), *Advances in Turbulence*, Springer-Verlag, p. 240.
Moghaddam-Taaheri, E. and Vlahos, L.: 1987, *Phys. Fluids* **30**, 3155.
Moghaddam-Taaheri, E., Vlahos, L., Rowland, H. L., and Papadopoulos, K.: 1985, *Phys. Fluids* **28**, 3034.
Parker, E.: 1972, *Astrophys. J.* **174**, 499.
Parker, E.: 1988, *Astrophys. J.* **330**, 474.
Ramaty, R and Murphy, R. J.: 1987, *Space Sci. Rev.* **45**, 213.
Roberts, C. S. and Buchsbaum, S. J.: 1964, *Phys. Rev.* **A135**, 381.
Sakai, Y. and Ohsawa, J.: 1987, *Space Sci. Rev.* **46**, 113.
Sharma, R. R., Vlahos, L., and Papadopoulos, K.: 1982, *Astron. Astrophys.* **112**, 377.
Scholer, M.: 1988, in O. Havnes *et al.* (eds.), *Activity in Cool Star Envelopes*, D. Reidel Publ. Co., Dordrecht, Holland, p. 195.
Slottje, C.: 1978, *Nature* **275**, 520.
Smith, D. F.: 1980, *Solar Phys.* **66**, 135.
Smith, R., 1983, in M. R. Kundu and G. Holman (eds.), 'Unstable Current Systems and Instabilities in Astrophysics', *IAU Symp.* **107**, 113.
Spicer, D. S.: 1983, *Adv. Space Res.* **2**, 135.
Sprangle and Vlahos, L.: 1983, *Astrophys. J.* **273**, L95.
Steinolfson, R. S. and Van Hoven, G.: 1984, *Astrophys. J.* **276**, 391.

Toptyghin, I. N.: 1980, *Space Sci Rev.* **26**, 157.
Tverskoi, B. A.: 1967, *Soviet Phys. JEPT* **25**, 317.
Van Hoven, G.: 1979, *Astrophys. J.* **232**, 572.
Van Hoven, G, Tachi, T., and Steinolfson, R. S.: 1984, *Astrophys. J.* **280**, 391.
Vlahos, L., Sharma, R. R., and Papadopoulos, K.: 1983, *Astrophys. J.* **275**, 374.
Vlahos, L. *et al.*: 1986, *Energetic Phenomena on the Sun*, NASA CP-2439, p. 2–1.
Winglee, R. M., Pritchett, P. L., and Dulk, G. A.: 1988, *Astrophys. J.* **327**, 968.