PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Energetic Particle Production in Flares [and Discussion]

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Energetic particle production in flares

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Bursts of energetic ions and electrons are frequently seen in interplanetary space and it is beyond doubt that the majority originate at or near the Sun. Many events are correlated with major solar flares and it is customary to associate such flares with energetic particle production. Possible acceleration mechanisms are presented, and we argue that the particle production occurs following magnetic reconnection relatively high in the corona; the bulk of the energy goes into the ionic, rather than the electronic, component. The principal characteristics of energetic solar particle events are reviewed briefly. In small events only a modest amount of energy is deposited below the transition zone, thereby producing a minimal Hα response. In large events, as the bulk of the energy is carried by protons of less than 1 MeV, only during the impulsive phase is a significant amount of energy deposited below the transition zone. Later in the event, chromospheric ablation enhances the coronal density, inhibiting further energy deposition in the chromosphere. A model is outlined whereby acceleration of the electrons responsible for the impulsive hard X-ray burst occurs in the chromosphere as a result of the interaction of the primary ions. Observations supporting this hypothesis are discussed.

1. Introduction

One of the outstanding problems in solar physics is the way in which ions and electrons are accelerated at the time of solar flares. Theorists have been prolific in applying well-known physical laws to a multitude of conceivable situations involving tenuous magnetized plasmas in which some kind of dramatic instability is induced, to produce accelerated particles. The mechanisms for ions are direct electric field acceleration, stochastic acceleration or shock acceleration, although there is clearly overlap between the latter two processes, both of which involve the Fermi principle. These mechanisms can also operate on electrons, but they become less effective as the electrons become relativistic.

The first application of Fermi's acceleration concept to flares was by Parker (1957), who attempted to account for the relativistic protons from the 23 February 1956 flare. It was realized that the flare energy did not come upwards out of the photosphere, as the latter was subject to too small a change to have released so much energy. The source is almost certainly magnetic energy released by reconnecting fields in the corona, and current sheets must play an important role in the acceleration. There is no shortage of mechanisms for accelerating particles extremely rapidly in this situation. In an early review Wentzel (1964) supposed that for a large flare the storage volume could have dimensions 10^5 km $\times$ 10^5 km $\times$ 10^4 km thick.

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Table 1

proponent	mechanism	goal
Parker (1957)	stochastic Fermi acceleration	relativistic protons
Wentzel (1964)	?	energetic protons
Brown (1971)	?	> 25 keV electrons
Colgate (1978)	?	> 4 MeV protons
Simnett (1986)	shock acceleration	10^2–10^3 keV protons
Martens (1988)	direct E-field acceleration	> 200 keV protons

Extracting energy efficiently from such a large volume is difficult conceptually and it may require a larger volume with a corresponding reduction in efficiency. The new insights we have gained by studying coronal mass ejections over the last decade are also leading us in this direction.

The global energy balance is crucial to flare models. Brown (1971) showed that the demands of the impulsive hard X-rays burst were so large that instead of concentrating on ion acceleration, as Parker and Wentzel had done, it was more appropriate to focus on the electrons. After all, mildly relativistic electrons were required during the impulsive phase to produce the hard X-ray burst, and also to produce the type III radio bursts sometimes seen around the same time. Electron acceleration on its own was a potential difficulty. However, current sheets may become unstable in the reconnection region and generate Langmuir (longitudinal electrostatic) waves. Hoyng *et al.* (1980) showed that Langmuir wave turbulence could accelerate electrons impulsively to *ca.* 50 keV. The energetic protons were only needed later, and it became attractive to treat particle acceleration as a two-stage process where electrons were accelerated first, and the energy released as they interacted in the chromosphere generated coronal shocks which accelerated, sometimes, relativistic ions. Colgate (1978) argued against this, and while not offering a real solution to the problem of producing hard X-rays, concluded that a more likely energy carrier was a beam of greater than 4 MeV protons which generated hard X-rays by thermal bremsstrahlung due to local heating. Simnett (1986) claimed that 4 MeV was too high, and that plasma heating and mass motions during the impulsive phase required the bulk of the energy to be in 10^2–10^3 keV protons. A significant advance was made by Martens (1988), who realized that the acceleration mechanism proposed by Speiser (1965) was ideally suited to produce the neutralized ion–electron beam advocated by Simnett (1986).

Table 1 gives representative milestones in the history of flare particle production theory. For protons, the emphasis has gradually shifted to lower energies. For electrons, it has been clear for two decades that the critical energy is above *ca.* 20 keV. The community is still very divided over the electron/proton question; it is intended that this paper should clarify the issue. In §2 we outline our concept for primary energetic particle production; §3 reconciles the observations of energetic particles in space with this concept; §4 reviews key observations which support this; §5 discusses the energy budget; and §6 indicates how the electrons which produce the hard X-rays might be accelerated, as secondaries via the interaction of the primary protons in the chromosphere.

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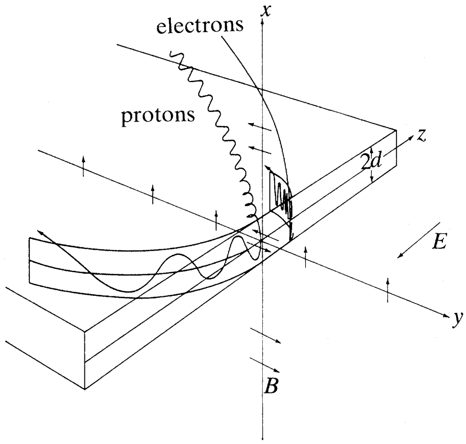

Figure 1. An illustration of particle acceleration in a current sheet of thickness $2d$. The magnetic field, which is predominantly in the y direction, reverses across the sheet. There is an electric field in the $-z$ direction which accelerates charged particles. There is a small magnetic component B_p perpendicular to the sheet. Protons and electrons that enter the sheet oscillate about the sheet and are accelerated in opposite directions; but they are turned the same way by B_p. When they are turned through 90° they are ejected (after Speiser (1965)).

2. The proposed concept

Coronal magnetic fields are rooted in the photosphere and are driven by photospheric motions. Active regions represent 'focal' points for high coronal field lines such that energetic particles accelerated high in the corona are guided to specific areas of the chromosphere. Many, if not most, of the field lines associated with active regions form low-lying closed loops extending less than a few 10^4 km into the corona. It is these loops that become highly visible during flares as they fill up with hot plasma ablated from the chromosphere. They play an insignificant part in accelerating energetic particles.

Returning to the 'invisible' high (*ca.* $2\,R_\odot$) coronal field lines, there is quasi-continuous reconnection occurring, resulting in the acceleration of charged particles. Ion acceleration has been reviewed by Simnett (1991), who favoured a direct electric field acceleration. The mechanism first proposed by Speiser (1965) is particularly attractive as it predicts acceleration of both electrons and ions, which are ejected from the current sheet as a beam, directed along the principal magnetic field; it is illustrated schematically in figure 1 (see caption). The process favours protons over electrons, as electrons are ejected sooner that protons and therefore spend less time in the accelerating field. The maximum proton energy is a function of the lateral dimension of the current sheet and the size of the perpendicular magnetic field. Martens (1988) suggests that variations in B_p can easily produce the observed spectra of solar protons. An alternative concept, which is somewhat harder to evaluate, is the explosive coalescence model of Sakai *et al.* (1987), which also involves direct electric field acceleration. It also favours protons over electrons.

Coronal reconnection proceeds as a series of small, local readjustments which then create more energetic, metastable configurations, which may in turn reconnect, producing progressively larger energy releases. Particle acceleration is synonymous with reconnection, but its extent depends on the parameters of the current sheet thereby produced. We suppose that small events accelerate protons to only modest

Table 2. *Transition zone column-density ((a) an active region atmosphere and (b) and (c) two model flare atmospheres)*

transition zone column-density (cm^{-2})	mass-column-density of hydrogen ($g\ cm^{-2}$)	threshold proton energy for penetration
(*a*) 3.4×10^{19}	5.7×10^{-5}	225 keV
(*b*) 1.5×10^{20}	2.5×10^{-4}	510 keV
(*c*) 1.6×10^{21}	2.5×10^{-3}	1.85 MeV

Table 3. *Range/energy values for protons in a coronal loop*

mean number density (cm^{-3})	looptop height (cm)	mass column density traversed $M/(g\ cm^{-2})$	proton energy for range M
4×10^{8}	5×10^{9}	2.1×10^{-5}	130 keV
	10^{10}	4.2×10^{-5}	190 keV
2×10^{9}	5×10^{9}	1×10^{-4}	310 keV
	10^{10}	2×10^{-4}	460 keV

energies, for example, less than 10 MeV, which is consistent with observations of solar protons outside identified flares.

Proton acceleration by the Speiser mechanism will have the following effects.

1. The protons are initially strongly field-aligned, such that the majority of the more energetic components will reach the 'focal' point in the chromosphere, where they will dump their energy. The normal result of this influx of energy is local heating and it will promote an Hα brightening, the size of which will depend on the total energy involved. As discussed in §6, if the energy density in the beam exceeds a threshold, energetic electrons, sufficient to produce the impulsive hard X-ray burst which accompanies many flares, can be accelerated in the chromosphere. Depending on the coronal density above the transition zone, some protons may be scattered out of the loss cone and will be reflected back into the corona. Table 2 gives the column density above the transition zone for three model atmospheres; the equivalent thickness of hydrogen; and the threshold proton energy for penetration. The thresholds are in the region of the predicted output of the accelerator, so that modest variations in either the accelerator or the atmospheric density can alter the observed outcome dramatically.

2. Although the accelerated protons are strongly field-aligned, there will be distribution of pitch angles such that a fraction is trapped in the closed coronal field. However, for energies *ca*. 1 MeV, the lifetime of such protons against collision losses is very limited even at coronal densities. Table 3 gives typical examples. If the mean number density in the coronal loop is $4 \times 10^{15}\ m^{-3}$ and the looptop is at 10^{8} m above the photosphere ($1R_{\odot} \equiv 7 \times 10^{8}$ m), then the mass-column traversed is $4.2 \times 10^{-3}\ kg\ m^{-2}$, equivalent to the range of a proton of 190 keV. The lifetime of a proton with this initial energy would be about one minute. We have assumed that a trapped proton travels twice the minimum distance along an assumed semicircular field line in going between mirror points. Scattering is therefore a significant effect, and a 500 keV proton under these conditions cannot survive for more than five reflections. Thus the energy that does not get dumped in the chromosphere will merely heat the corona, and this may account for its high temperature. Pressure

build-up via heating may also be the destabilizing trigger for coronal mass ejections (Simnett & Harrison 1985).

3. Some particles will be scattered on to open magnetic field lines; it is these particles which form the quasi-continuous emission from the Sun.

3. Particle observations in space

We have argued that primary energetic particle production at the time of solar flares is comprised mainly of ions or protons, and that the electronic component is insignificant. The proposed energy spectrum is of the form shown in figure 2, which is intended to represent the output from a current sheet following an application of Speiser's (1965) mechanism. The upper energy cut-off is a consequence of the lateral dimension of the coronal current sheet; the power law region reflects variations in the perpendicular field B_p across the current sheet; and the flattening below 100 keV represents a low energy cutoff (Martens 1988), merely extended as a flat spectrum to avoid a major discontinuity. Spectral variations are produced by changes in the dimensions of the current sheet, which affect the high energy cut-off changes in B_p. We suggest that all accelerated spectra may be represented by the general form shown in the hatched portion of figure 2. This is broadly consistent with particle observations in space. A spectral flattening is often observed below *ca.* 100 keV. At higher energies the spectrum frequently obeys a power law in kinetic energy. In a moderate event the spectral index γ is generally in the region -3 to -5 up to the highest observable energies. Here the differential energy spectrum is portrayed as $(\mathrm{d}J/\mathrm{d}E) = E^{\gamma}$. Some large events, such as 3 June 1982, have flat spectra, varying as $E^{-1.2}$, although this is not a general property of observed spectra from large events; that seen at 1 AU† from the 4 August 1972 event varied as E^{-4}.

Electron observations are difficult to compare with those of protons, as propagation effects may dominate the relative sizes of the observed fluxes, especially at low energies. For well-connected events Ramaty *et al.* (1980) showed that above a few MeV the proton:electron ratio was typically 10^2–10^3. The spectra of electron events in interplanetary space show no cut-off down to 2 keV (Potter 1981), which was the detection limit.

Propagation effects may distort the observed spectrum from the accelerated spectrum, and the best estimate of the latter comes from observing the velocity dependence of the arrival of the prompt particles. Only the most energetic particles (above *ca.* 500 MeV) represent the true source, and even they may undergo propagation effects. The observed spectrum late in the event, say at the time of the 10 MeV maximum, contains a combination of: those protons released promptly and diffusing in the interplanetary medium; those diffusing in the corona and gradually escaping, albeit after energy losses; and those accelerated by an outward-propagating shock wave. We know from direct observations that the spectrum of the latter particles is very steep, with a power-law index γ of typically -5 (Datlowe 1972). It is a very difficult problem assessing the exact form of the accelerated spectrum, but that shown in figure 2 is a strong contender. Coronal shocks and propagation effects, coupled with velocity dispersion, modify the observed spectrum to give the variety of spectral forms reported over the last three decades.

We have rejected particle acceleration by magnetohydrodynamic (MHD) shocks as the dominant process involved with primary acceleration. Shock acceleration to

† 1 AU ≈ 149600×10^6 m.

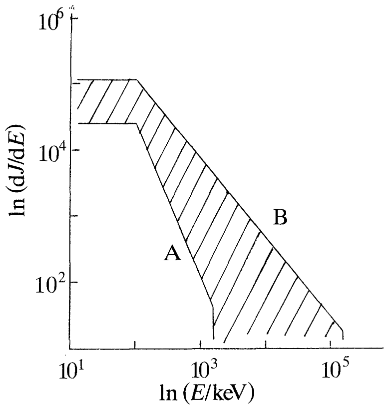

Figure 2. The form of accelerated proton spectrum we believe is compatible both with observations in space and with particle acceleration in a coronal current sheet. Any spectrum within the hatched portion is allowed. Spectrum A would represent that typically accelerated in a small, but frequent, event, while B would represent the output at the time of a major flare.

relativistic energies was in vogue when particle production was believed to be a two-stage process. Recall de Jager's (1969) opinion that the first stage was a rapid, possibly inductively driven, acceleration to modest energies (*ca.* 100 keV); while the second stage occurred some 10–20 minutes later and was a more gradual acceleration of the remnants of the first stage to relativistic energies via flare-generated coronal shocks. It was argued that the type II radio burst supported this view. However, we now know that coronal shocks do not accelerate relativistic particles. In a comprehensive study, Kahler (1982) showed that 20 MeV protons are not produced to any significant degree in shocks that give type II bursts. *In situ* measurements of particles associated with strong interplanetary shocks show that only rarely does the proton energy exceed a few tens of MeV, or the electron energy exceed 20 keV. Furthermore, Van Nes (1984) showed that *ca.* 48% of shocks do not accelerate protons at all, at the MeV level, by the time they reach 1 AU. We also know (Forrest & Chupp 1983) that in some, possibly all, gamma ray events, relativistic protons are present at the onset of the impulsive phase. Therefore we maintain that as a general rule ion acceleration occurs at the time of the primary magnetic reconnection, when the highest-energy ions are produced. In very large events, where proton energies greatly exceed 1 GeV, it is reasonable to suppose that relativistic electrons, with energies up to 50–100 MeV, are also accelerated, and these are occasionally observed. But most flares, and hard X-ray bursts, are not accompanied by such electrons in significant quantities.

4. Key observations that constrain particle acceleration models

There are observations which either directly or indirectly can help decide whether ions or electrons transfer the bulk of the energy from the coronal magnetic field to the chromospheric plasma in a typical impulsive hard X-ray event. For simplicity we adopt the premise that the same basic acceleration mechanism operates for all flares. Differences between flares are a function only of the magnitude and timescale of the energy release. the accelerated spectrum, the atmospheric density and the topology of the magnetic field.

Table 4

phenomenon	reference
onset of chromospheric ablation with respect to the impulsive hard X-ray burst	Antonucci *et al.* 1982
unpredictability of the occurrence of hard X-rays from the timing of the soft X-rays	Feldman *et al.* 1982
impact linear polarization in Hα	Hénoux *et al.* 1990
relative timing between correlated X-ray and microwave fine structures	Cornell *et al.* 1984
absence of metric radio emission during many major flares	Simnett & Benz 1986
correlation between X-ray and UV continuum brightenings	Orwig & Woodgate 1986
transition line (UV) brightenings in the absence of hard X-rays	Cheng *et al.* 1984, 1985
relative timing of white light and gamma ray emissions	Ryan *et al.* 1983
spikes with simultaneous (1 s) emission from 46 keV to 40 MeV	Kane *et al.* 1986
soft X-ray brightenings at the onset of coronal mass ejections	Simnett & Harrison 1985
fragmentation of decimetric radio emission	Benz 1985

Table 4 lists phenomena which provide important boundary conditions for flare models; references are included. The majority of these were discussed by Simnett (1986, 1991) and Simnett & Haines (1991). It is beyond the scope of this paper to repeat all their arguments and we pick a sample to discuss briefly. Chromospheric ablation may begin before the onset of the hard X-ray burst. It can be shown in large events that the upflowing, heated material must come from the chromosphere. Before electrons can heat this material they must simultaneously radiate via bremsstrahlung; for electrons that, despite scattering, have enough energy to penetrate below the transition zone, a significant amount of this radiation is in hard X-rays. Therefore if the hard X-rays are not seen by the time of the onset of the chromospheric ablation, non-thermal electrons are not responsible for the energy transfer. As the bulk of the soft X-ray-emitting plasma is derived from this ablated material, the unpredictability of the occurrence of the hard X-ray burst from the timing of the soft X-ray light curve supports the same argument.

The most direct evidence for low-energy ions in the solar atmosphere has been provided by Hénoux *et al.* (1990). They have shown that the linear polarization they observed in the Hα line was most likely produced by low-energy proton bombardment, where the protons had an initial minimum energy in the corona of *ca.* 200 keV. Where hard X-ray observations were available, there was no emission during the period the polarization was observed; the polarization was, however, detected on the rising portion of weak soft X-ray events. The conclusion is that the energy in the protons produces the hot X-ray-emitting plasma in addition to the *Hα* polarization.

The time structures of hard X-ray and microwave intensities are often highly correlated. Originally the correlated fluctuations were believed to be simultaneous, but as the temporal and spatial resolution improved two things became evident: (*a*) the microwaves were slightly delayed from the X-rays (by *ca.* 10^{-1} s); (*b*) the microwaves came from near the apex of low-altitude, but coronal, 'flare' loops, whereas the X-rays came from the footpoints of these loops. The delay is in the wrong sense if electron acceleration is in the corona within the loop, as the microwave burst should build up within a few gyroperiods, whereas the X-rays will not be produced until the electrons have propagated to the footpoints. The delay is in the correct sense if electron acceleration is in the chromosphere and this is an important consequence of the Simnett & Haines (1991) model for hard X-ray production, which we discuss in §6. Another important feature of the radio emission is the complete absence of metric radio activity during *ca.* 15% of major flares (Simnett & Benz 1986), and the delay of type III radio emission from the onset of the hard X-ray burst of more than 60 s in 43% of gamma ray flares. This effectively precludes intense coronal electron beams as an energy transport mechanism in these flares.

5. The energy budget

The potential problem with the flare-energy budget has been known since the 1970s. If the hard X-ray burst is produced by a power-law distribution of electrons, a cut-off must be invoked below *ca.* 25 keV to avoid exceeding the estimated total energy budget for many flares. As there is no evidence for such a cut-off, either from observations or from arguments based on the acceleration mechanism, this is a severe problem. Extending an E^{-4} differential number spectrum from 25 keV to 2.5 keV adds two orders of magnitude to the energy budget. Furthermore, Smith (1979) has reviewed comprehensively possible electron acceleration mechanisms and he has concluded that not more than 10% of the energy released via magnetic reconnection could go into non-thermal electrons. Therefore, if electrons are the main energy carrier the energy budget would be exceeded by at least three orders of magnitude, notwithstanding the energy in the ions. These may be present to relativistic energies at the onset of the impulsive phase (Forrest & Chupp 1983); they may be present at *ca.* 200 keV without electrons of comparable energy (Hénoux *et al.* 1990); and most theoretical acceleration mechanisms accelerate ions rather than electrons, on an energy basis.

6. The production of hard X-rays

Our discussion would be quite academic if one of the characteristic features of the impulsive phase of large flares, namely the rapidly varying hard X-ray burst, could not be accounted for. Until recently this was a major obstacle to the non-thermal proton hypothesis for flares. However, Simnett & Haines (1991) have developed a one-dimensional model whereby the energetic electrons are all secondaries, accelerated in the chromosphere via the interaction of a primary proton beam, which is neutralized by accompanying electrons of the same velocity. Figure 3 illustrates the basic concept, whereby the process starts with a neutralized beam of ions (p) and electrons (e), produced in the corona and propagating collisionlessly downwards towards the chromosphere. Upon reaching the density discontinuity at the transition zone the beam electrons scatter, while the ions continue. The concept is easiest to understand if monoenergetic protons are invoked, although in reality a complete spectrum is needed.

Simnett & Haines developed their model in three parts. First is a steady-state model of the interaction layer at the surface of the chromosphere, where the beam electrons are scattered and a self-consistent electric field Φ is set up which slows down the beam protons. Normally cold background chromospheric electrons e_c will neutralize Φ. However, if the beam flux is high enough the resistivity of the chromospheric plasma will be too high for neutralization to occur, and the only other supply of electrons is of those in the beam itself. There is consequently runaway acceleration of these beam electrons e_b, and the second part of the model is a kinetic

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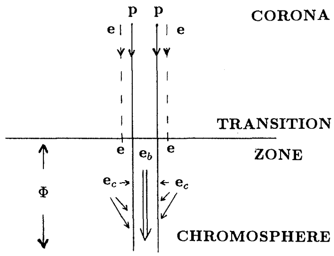

Figure 3. The concept of the development of an electric potential below the transition zone which may lead to runaway electron acceleration (see text).

description of this process. The third part of the model is the effect of partial current neutralization by the background chromospheric plasma if its resistivity is below a critical value. The key result is the relation between the plasma current density, J_{pl}, and the current density of runaway beam electrons, J_{b}, given by

$$J_{\mathrm{pl}}/J_{\mathrm{b}} = 7.89\,(m_{\mathrm{i}}/m_{\mathrm{e}})^{\frac{3}{2}}\,(2eT_{\mathrm{p}}/m_{\mathrm{i}}\,v^2)^{\frac{3}{2}}\,\lambda_{\mathrm{ei}}\,n_{\mathrm{ipl}}/\lambda_{\mathrm{p}}\,n_{\mathrm{b}} = R, \tag{1}$$

where m_{p}, m_{e} are the proton and electron masses, respectively, T_{p} is the ambient plasma temperature, v is the beam velocity, n_{b} is the number density in the beam, n_{ipl} is the ion density of the background plasma, λ_{ei} is the Coulomb logarithm and $\lambda_{\mathrm{p}} = 23 - \ln\,(n_{\mathrm{e}}^{\frac{1}{2}}\,T_{\mathrm{e}}^{-\frac{3}{2}})$. Apart from constants the denominator is the beam energy flux. If $T_{\mathrm{p}} = 1$ eV, $n_{\mathrm{ipl}} = 10^{18}\ \mathrm{m}^{-3}$ and the beam proton energy is 1 MeV, this gives an energy flux $> 10^{13}\ \mathrm{J\ m^{-2}\ s^{-1}}$ for the runaway condition $R < 1$ to be established.

To achieve a high energy flux, the beam may fragment into many dense filaments, each of which may produce runaway electron acceleration to some characteristic energy, which may vary in different filaments. Evidence for fragmentation has been given by Benz (1985), who argued from metric/decimetric radio observations that the impulsive phase of some flares (at least) consisted of tens of thousands of elementary spikes. This may occur in most flares, but it could be normally unobservable due to resolution limitations. Fragmentation of a hypothetical electron beam is difficult to visualize due to scattering; fragmentation of an intense proton beam is more plausible. A complete treatment of the problem is extremely complex, as both the energy and spatial distributions of the incoming ions must be taken into account; also the global electron distribution is a summation of those present in all filaments. The non-thermal X-ray burst comes from interactions of these electrons in the chromosphere. Equation (1) shows that electron acceleration may be turned on and off extremely rapidly simply by changes to the beam energy flux, which may in turn relate to the hypothetical filamentation process, or by a change in the local plasma temperature. Thus rapid fluctuations in the hard X-ray burst are naturally explained.

Note that the impulsive hard X-rays are produced predominantly by non-thermal electron bremsstrahlung. There is a natural high-temperature thermal component as the majority of the beam energy is dissipated as heat, regardless of whether runaway electrons are produced.

7. Summary

We have taken a global view of particle acceleration including the observations in space, possible acceleration processes, and the way the accelerated particles interact in the solar atmosphere. These three factors cannot be considered independently. It has been shown that protons must be considered as the dominant output from magnetic reconnection from an energetics viewpoint. Only then does the energy budget even start to become reasonable. Even so, the problem with the energy budget does not go away, but it is greatly alleviated as the electrons are secondary to the ions and the electron energy is mainly at high energies. The supply of coronal particles is difficult to achieve, but as the energy per particle may now be typically 500 keV (for protons) against 25 keV (for electrons), the problem has again been alleviated (by a factor of *ca.* 20). The momentum deposited in the chromosphere by the protons is considerable; however, there are frequently red-shifts seen in the Hα line at the onset of flares (Ichimoto & Kurokawa 1984). Our mechanism for hard X-ray production is one that we believe is possible, and it does not appeal to exotic processes, or to a 'black box'. There may well be other, more plausible ways of producing hard X-ray bursts from a proton beam where the bulk of the energy is in the 10^2–10^3 keV region.

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Discussion

E. R. Priest (*The University, St Andrews, U.K.*). I feel that you have dismissed the possibility of shock acceleration too quickly, since there are many other types of shock or scenarios where they are produced, in addition to the blast wave giving a type II radio burst. For example, shocks both slow-mode and fast-mode are associated with the reconnection process, and three-dimensional reconnection throughout a sheared structure may give rise to many small shocks which Vlahos has suggested as efficient accelerators.

G. M. Simnett. I dismissed shock acceleration on observational, rather than theoretical grounds. It is attractive to advocate one dominant mechanism rather than two or more different mechanisms, to account for energetic particle production. As, observationally, shocks in the solar atmosphere and inner heliosphere do not appear to accelerate protons above about 20 MeV, I have rejected shock acceleration as the primary mechanism in flares. It undoubtedly occurs at some level, as you have indicated, and in so far as it goes it could be efficient; but not to relativistic energies.

A. G. Emslie (*The University of Alabama, U.S.A.*). I do not understand the physics of your neutral beam model. One can neglect the plasma current J_p only if $n_b \gg 10^{-3}$ of the *chromospheric* density, i.e. $n_b \gg 10^{10}$ cm^{-3}. This number is comparable with the ambient coronal density and raises the questions of (i) supply (the corona would be emptied in a loop transit time *ca.* 1 s); (ii) momentum (the mass flux $n_b m_p v_b$ requires a large 'piston' in the acceleration region with no allowance for the 'recoil', and (iii) energy (the energy flux $n_b v_b E$ is approximately 50 times *larger* for 1 MeV protons than it is for 20 keV electrons, also with $n_b v_b = 10^{18}$: this places intolerable demands on the acceleration mechanism). Therefore, I cannot see a beam density large enough for J_p to be neglected ever occurring, and consequently I do not see how hard X-rays could ever be produced in your model.

G. M. Simnett and M. G. Haines. (i) There will still be some runaways if $n_b \sim 10^{-3}$ n_p, with the parameters chosen in our paper. This question of supply depends on the volume of the corona taking part. The energy transferred to the chromosphere may well be limited by the amount of matter available to transport it. The coronal density in the reconnection region is not very well known. (ii) The coronal mass ejection, which starts before the impulsive hard X-ray burst, could be the recoil. (iii) The energy demands on the acceleration mechanism are in fact lower if the protons are the primary energy carriers. The energetic electrons are all secondary and have a natural low-energy cut-off. This is discussed in the paper.