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PROMPT ACCELERATION OF $\gtrsim$30 MeV PER NUCLEON IONS IN SOLAR FLARES

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Abstract. Observation of prompt γ-rays in solar flares requires that ions be accelerated to > 30 MeV nucl^{-1} in $\lesssim 2$ s. A model for prompt acceleration is developed. The energy release is assumed to occur in a flaring loop with the energy release region being $\lesssim 10^4$ km in dimensions and with an Alfvén speed $v_A \simeq 3 \times 10^3$ km s^{-1}. The acceleration is assumed to occur in two steps. The second-step acceleration from $\simeq \varepsilon_T = \frac{1}{2} m_p v_A^2$ nucl^{-1} to $\gtrsim 30$ MeV nucl^{-1} is attributed to stochastic acceleration by hydromagnetic turbulence which is found to be fast enough under conditions which are not extreme. Main emphasis is placed on the first step, called preacceleration, to $\varepsilon_T \simeq 100$ keV nucl^{-1}. Preacceleration mechanisms which involve accelerating a small fraction of ions from the tail of a Maxwellian distribution are unacceptable because they would lead to enormous abundance anomalies. Preacceleration is attributed either to localized heating of ions to $\simeq 10^9$ K or to acceleration by potential electric fields. The latter mechanism is favoured and some theoretical ideas are outlined based on observations of reconnection in the Earth's magnetotail. Whether energetic ions are prompt, delayed or unobservable depends only on the rate at which the stochastic acceleration proceeds. The second-step acceleration of electrons, invoked to account for a harder microwave component, is predicted to be slower by a factor $\simeq 3$ than for $\simeq 30$ MeV nucl^{-1} ions.

1. Introduction

It has long been recognized that flare-associated particle acceleration on the Sun occurs in two phases (Wild *et al.*, 1963; de Jager, 1969). In the first phase up to $\simeq 10^{36}$ electrons are accelerated to $\lesssim 100$ keV in $\lesssim 1$ s. The acceleration is attributed to microturbulent fields (ion sound and Langmuir turbulence) which supposedly results in both a bulk energization of electrons and in the formation of a power-law tail to the electron energy spectrum (e.g. Ramaty *et al.*, 1980; Brown and Smith, 1980). In the second phase energetic ions and $\gtrsim 1$ MeV electrons are produced on a timescale $\gtrsim 10^2$ s. The acceleration is attributed to Fermi acceleration by hydromagnetic waves or to shock-wave acceleration, both of which are thought to be effective only for ions with speed $v > v_A$ and electrons with speed $v > 43 v_A$, where v_A is the Alfvén speed (Melrose, 1974; Achterberg and Norman, 1980). The observation of γ-ray lines in flares (Chupp *et al.*, 1973) implies the presence of ions with $\gtrsim 30$ MeV nucl^{-1} (Wang and Ramaty, 1974; Ramaty *et al.*, 1975, 1979). Until recently it was thought that these ions and the associated γ-rays were a second phase phenomenon. However, improved sensitivity and time resolution ($\simeq 2$ s) has shown that the γ-rays can sometimes appear within a few seconds of the flash phase of a flare (Chupp *et al.*, 1981; Chupp, 1982). In a particular flare (03 : 12 UT of 1980, June 7) the γ-rays showed a quasi-periodicity which correlated closely with quasi-periodicity in both microwave bursts and hard X-ray bursts, the correlation being slightly better with the former (Forrest *et al.*, 1981). Independent evidence for prompt acceleration of ions comes from ground level cosmic-ray events

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(GLE's) (Cliver *et al.*, 1982). Both the GLE data and the γ-ray data (Willett *et al.*, 1982) show that the acceleration of ions is not always prompt, but may be delayed from the flash phase by 10 to 100 s. Nevertheless these observations require revision of the older concept of second-phase acceleration, which was based at least in part on evidence for acceleration by type II shock waves well separated from the energy-release process both in space and time.

A convenient distinction is between second-phase and second-step acceleration. This distinction was drawn by Bai and Ramaty (1979) in connection with the interpretation of hard X-ray bursts. They argued that a delay which increases with increasing energy is due to electrons with $\varepsilon \gg 100$ keV being accelerated by a second-step process which occurs in the same region as the first-step (or first-phase) mechanism. The two steps start essentially simultaneously, with the second-step mechanism having an injection threshold; this requires that the first-step process act as a preacceleration stage for it. Bai (1982) suggested that the prompt acceleration of ions to $\gtrsim 30$ MeV nucl^{-1} is another manifestation of second-step acceleration; this idea is accepted here.

The second-step acceleration mechanism presumably involves either stochastic acceleration by hydromagnetic waves or acceleration by shock waves. (It is argued below that the latter is unlikely.) Both these require that the ions be efficiently scattered and hence have energies $\varepsilon > \varepsilon_T$ where $\varepsilon_T = \frac{1}{2} m_p v_{\mathrm{A}}^2$ may be interpreted as the threshold energy for electrons or as the threshold energy per nucleon for ions. The first-step acceleration must produce particles with $\varepsilon > \varepsilon_T$ before second-step acceleration can proceed. For ions it is convenient to refer to the first-step as 'preacceleration'.

Here the prompt acceleration of ions to $\varepsilon \gtrsim 30$ MeV nucl^{-1} is discussed with particular emphasis on the preacceleration stage. The model for the acceleration region is outlined in Section 2, where it is argued that ε_T is about 0.1 MeV nucl^{-1}. It is suggested in Section 3 that the conditions required for acceleration from ε_T to $\gtrsim 30$ MeV nucl^{-1} in $\lesssim 2$ s by hydromagnetic turbulence can be satisfied without invoking implausible parameters. The major difficulty is then in accounting for preacceleration to $> \varepsilon_T$. It is shown in Section 4 that preacceleration mechanisms which involve accelerating a small fraction of all ions from the tail of a Maxwellian distribution lead to enormous abundance anomalies. It is suggested that acceptable preacceleration mechanisms must accelerate essentially all the ions in localized regions to $> \varepsilon_T$. Two possible types of such preacceleration are discussed in Section 5; one is 'bulk energization' of the ions, as is widely assumed for electrons, and the other is acceleration by electric fields with potentials $\Phi > \varepsilon_T / e$. Some questions concerning the acceleration of electrons and ions are discussed in Section 6.

2. The Model

The model envisaged here for the acceleration region is a widely accepted one for a flaring region (e.g. Kahler *et al.*, 1980). The energy release is confined to a region near the top of a magnetic loop or arcade. The linear dimension of this region is $\lesssim 10^4$ km (e.g. Cheng and Widing, 1975; Ohki *et al.*, 1982; Marsh and Hurford, 1982). Typical parameters are $B = 500$ G and $n_e = 10^{11}$ cm^{-3}. With these parameters the Alfvén speed is $v_A = 3 \times 10^3$ km s^{-1}, and the energy threshold is $\varepsilon_T = 0.1$ MeV.

As pointed out by Lin (1982) the distance over which a shock wave can propagate on the prompt acceleration timescale is less than the dimensions of the energy release region. It follows that the second-step acceleration necessarily occurs is the same region as the first-step acceleration. In addition it seems unlikely that the acceleration can be due to a type II like shock because this could form only on a timescale or order the Alfvén propagation time across the region.

The energy release is attributed to magnetic reconnection, as envisaged by Spicer (1977), or to current interruption (Alfvén and Corlqvist, 1967) in the form discussed by Spicer (1981). Locally the dissipation of magnetic energy occurs in regions whose dimensions are small. The actual linear dimension, L say, is important in the following discussion of second-step acceleration because the localized heating should result in a spectrum of magnetoacoustic turbulence with wavenumber $k \simeq 1/L$ and frequencies $\omega_T = kv_A \simeq v_A/L$. Spicer (1977) estimated $L \simeq 100$ km, which with $v_A = 3000$ km s^{-1} gives $\omega_T \simeq 30$ s^{-1}, i.e. $\omega_T/2\pi \simeq 5$ Hz. There is direct evidence for pulsations in hard X-rays in flares at a rate 1 to 5 Hz (Kiplinger *et al.*, 1982), and correlated pulsations in hard X-ray and microwaves at 3 to 4 Hz have been reported in one flare (Takakura *et al.*, 1983). These correspond to angular frequencies $\omega_T \simeq 30$ s^{-1}, and hence if interpreted as magnetoacoustic waves they would correspond to scale lengths $\simeq 100$ km similar to those predicted by Spicer (1981).

3. Prompt Second-Step Acceleration

The suggestion that second-step acceleration to $\gtrsim 30$ MeV nucl^{-1} in $\lesssim 2$ s can occur under conditions which do not seem extreme is based on the following estimates.

In the flaring region one expects hydromagnetic (actually magnetoacoustic) turbulence with scale lengths typical of the dimensions of the reconnection regions and with relative amplitudes $\delta B/B$ approaching unity. In the presence of such turbulence acceleration can be described in terms of diffusion in energy space, as shown by Kulsrud and Ferrari (1971), cf. also Kulsrud (1979) and Melrose (1980, p. 74). It might be remarked that Kulsrud and Ferrari (1971) assumed: (a) isotropic turbulence whereas only the magnetoacoustic component contributes (Achterberg, 1981); (b) small amplitudes $\delta B/B \ll 1$, but a similar result was obtained by Tverskoi (1967) without this assumption; and (c) a phenomenological scattering frequency whereas the scattering frequency may be determined self-consistently (Melrose, 1974). None of these assumptions is particularly restrictive. The resulting acceleration rate for nonrelativistic particles is

$$\frac{1}{\varepsilon}\frac{d\varepsilon}{dt} = 2\pi\omega_T \frac{v_A}{v}\left(\frac{\delta B}{B}\right)^2 . \tag{3.1}$$

The slowest acceleration is at the highest speed. A 30 MeV nucl^{-1} ion has $v \simeq c/4$ and the acceleration time to this speed is

$$t_{30\,\mathrm{MeV}} \simeq \left[4\pi\omega_T \frac{v_\mathrm{A}}{c}\left(\frac{\delta B}{B}\right)^2\right]^{-1}. \tag{3.2}$$

For $v_\mathrm{A} = 3 \times 10^3$ km s^{-1} and $\omega_T = 30$ s^{-1}, one has $t_{30\,\mathrm{MeV}} = 2$ s for $(\delta B/B)^2 \simeq 10^{-1}$. These requirements do not seem extreme.

Here we have considered only acceleration through a Fermi-type process by hydromagnetic turbulence. Other possible forms of second-step acceleration are acceleration by shock waves and cyclotron acceleration. Although acceleration by shock waves is favoured by second-phase acceleration (Achterberg and Norman, 1980) it is difficult to see how shocks could form on the short time scales available in the present situation. The large scale hydromagnetic turbulence may well subsequently evolve into weak shocks, but this can occur only after propagation over many wavelengths which would take several seconds or so with the parameters adopted here. Cuclotron acceleration can be quite efficient (Barbosa, 1979) but only for relatively large wavenumbers; this seems to require evolution of the magnetic turbulence e.g. through the development of a turbulent cascade (Bicknell and Melrose, 1982).

It may be concluded that the main difficulty in understanding the prompt acceleration of ions is not the efficiency of Fermi-type acceleration but the requirement that the ions be preaccelerated to $> \varepsilon_T$. Let us now discuss possible preacceleration mechanisms starting with some older ideas which involve building up a distribution of suprathermal ions by drawing ions out of the tail of a thermal distribution in velocity space.

4. Preacceleration from a Maxwellian Tail

A seemingly plausible class of preacceleration mechanisms for ions involves drawing a small fraction of the ions out of the tail of a Maxwellian distribution to much higher speeds. These processes may either occur impulsively, in the sense that collisions have no time to replenish the depleted Maxwellian tail, or continuously, with collisions generating the flux to higher speeds in an attempt to maintain the Maxwellian tail (Gurevich, 1960). In this section three possible preacceleration mechanisms of this form are discussed. They are Landau damping, continuous tail replenishment and runaway acceleration. It is argued that in all cases the relative abundances of the accelerated ions should differ from those of the unaccelerated ions by large factors, contrary to observations.

The plasma is assumed to consist of electrons (e) and various species (i) of ions including protons (p). Let species i have mass $m_i = A_i m_p$, charge $q_i = Z_i e$, number density n_i, temperature T_i, and thermal speed $V_i = (T_i/m_i)^{1/2}$. It is convenient to normalize all speeds to the thermal speed of protons, and to write

$$u_i = \frac{V_i}{V_p} = \left(\frac{T_i}{A_i T_p}\right)^{1/2} \tag{4.1}$$

for the normalized thermal speed of species i.

A. LANDAU DAMPING

Suppose preacceleration is due to the Landau damping of waves with phase speed $v_\phi \gg V_p$, and that the acceleration occurs on a timescale much shorter than the collision timescale for ions with speed $v > v_\phi$. (If the condition $v_\phi \gg V_p$ were not satisfied the waves could resonate with thermal protons and would be heavily damped.) The only ions accelerated are those with $v > v_\phi$. The fraction η_i of such ions of species i is

$$\eta_i = \left(\frac{\pi}{2}\right)^{1/2} \int_{v_\phi}^{\infty} \frac{\mathrm{d}v\, v^2}{V_i^3} e^{-v^2/2V_i^2}$$
$$\simeq \left(\frac{\pi}{2}\right)^{1/2} \frac{u_\phi}{u_i} e^{-u_\phi^2/2u_i^2} \tag{4.2}$$

for $u_\phi = v_\phi / V_p \gg u_i$. Hence the fraction of species i accelerated is related to the fraction of protons accelerated by

$$\eta_i = \frac{1}{u_i}\left(u_\phi \sqrt{\frac{\pi}{2}}\right)^{1-1/u_i^2} \eta_p^{1/u_i^2} \tag{4.3}$$

with $1/u_i^2 = A_i T_p / T_i$.

B. COLLISIONAL REPLENISHMENT OF A DEPLETED MAXWELLIAN TAIL

An ion of species i has Coulomb interactions with ions of the same species, ions of other species and with electrons. For $v \ll V_e$ the effect of electrons can be neglected, and for $v \gg$ all V_i we may define a basic collision frequency for species i by

$$\nu_i = \frac{Z_i^2}{A_i^2 V_i^5} \frac{4\pi Z_j^2 e^4 n_j V_j^2}{A_j^2 m_p^2} \ln \Lambda, \tag{4.4}$$

where $\ln \Lambda$ is the Coulomb logarithm and where the sum is over all ionic species. The effective collision frequency for an ion of species i is then

$$\nu_i(v) = \nu_i \left(\frac{V_i}{v}\right)^3. \tag{4.5}$$

A variety of processes including Landau damping and gyromagnetic absorption can lead to a diffusion of particles in momentum space. Such diffusion tends to deplete a Maxwellian tail by causing a net diffusion to higher energy. The rate at which collisions feed ions into the region $v \gtrsim 3V_i$ to replenish the tail is determined primarily by the rate of collisions at the speed where the collisional rate $\nu_i(v)$ is equal to the rate of diffusion. A theory was developed by Gurevich (1960), and applied to acceleration of ions by Melrose (1968).

Briefly, suppose the acceleration process is described by a diffusion equation of the form

$$\frac{\partial f_i(v)}{\partial t} = \frac{1}{v^2} \frac{\partial}{\partial v} \left\{ v^2 D_i(v) \frac{\partial f_i(v)}{\partial v} \right\} , \tag{4.6}$$

where $f_i(v)$ is the distribution function for species i and $D_i(v)$ is the diffusion coefficient. Then Gurevich's (1960) method implies an average relative rate of production of accelerated ions of species i due to a balance between the diffusion to higher v implied by (4.6) and the collisional slowing down. This rate is given by

$$\frac{1}{n_i} \frac{\mathrm{d}n_i}{\mathrm{d}t} = \nu_i \exp \left[- \int_0^\infty \frac{\mathrm{d}u\, u}{1 + u^3\, d_i(u)} \right] , \tag{4.7}$$

with

$$d_i(u) = \frac{D_i(uV_i)}{\nu_i V_i^2} . \tag{4.8}$$

In general $D_i(v)$ depends on Z_i and A_i, and (4.7) with (4.5) and (4.8) leads to an exponential dependence on some function of Z_i, A_i, and T_i.

C. RUNAWAY ACCELERATION

Runaway of electrons in a parallel electric field is well known and may be treated by Gurevich's method, e.g. Lebedev (1965), Kulsrud *et al.* (1973). The runaway process has been invoked in connection with solar flares, when the 'collisions' may be due to scattering off microturbulent fields (Houghton, 1975; Norman and Smith, 1978). Here the only point we wish to make is that runaway acceleration of ions would be a strongly species-dependent process. To this end it suffices to note that the ions which run away correspond to those with $v > v_{ri}$, where v_{ri} is determined by (cf. Norman and Smith, 1978)

$$\nu_i \left(\frac{v_{ri}}{V_i} \right)^{-3} = \frac{Z_i}{A_i} \frac{eE_\parallel}{m_p} , \tag{4.9}$$

where $E_\parallel$ is the parallel electric field and where (4.5) has been used. The fraction of accelerated ions of different species is then proportional to $\exp[-v_{ri}^2/2V_i^2]$ which again gives an exponential dependence on a function of Z_i, A_i, and T_i.

D. DISCUSSION

A characteristic feature of acceleration from the tail of a Maxwellian distribution is that the relative abundance of the accelerated ions differs from that of the unaccelerated ions by a very large factor. For example, suppose that the acceleration is due to Landau damping, that all the ionic species have the same temperature and that a fraction η_p of the protons are accelerated. Then according to (4.3) fractions $\eta_p^{A_i}$ of other ionic species are acceleration. Specifically if 1% of the protons are accelerated only 10^{-8} of the ^{4}He ions are accelerated. With the other processes discussed above the dependence are different but are similarly extreme. Another possible mechanism which has not been discussed above is gyroresonant absorption. This is also highly species selective, and this selectivity is the basis for a theory for preferential acceleration of ^{3}He (Fisk, 1978). Other forms of gyromagnetic absorption, e.g. involving the magnetic beach effect (Stix, 1962, p. 44) or ion-ion hybrid resonances (e.g. Stix, 1975; Perkins, 1977) are also highly species selective.

It is well known that solar energetic ions exhibit a rich variety of abundance anomalies, and there are specific theories to account for these in terms of specific acceleration or preacceleration mechanisms (e.g. Fisk, 1978; Mullan and Levine, 1981; Möbius *et al.*, 1982). However, it should be emphasized that the average abundances of solar energetic ions are not extremely different from normal solar abundances, and that under some conditions the abundances are essentially normal (e.g. Price, 1973; Sakurai, 1975; Fan *et al.*, 1975). Preacceleration mechanisms which are as species selective as those above are unacceptable as general mechanisms.

5. Efficient Preacceleration in Localized Regions

The extremely high species selectivity of acceleration from a Maxwellian tail seems to rule it out as an acceptable preacceleration mechanism in the present context. The alternative is that preacceleration occurs in localized regions and leads to a fraction of all the ions exceeding the threshold energy ε_T in these regions. There are then two obvious possibilities. First, the threshold condition may be satisfied by thermal ions in localized regions, due to the ions being locally heated to $KT \gtrsim \varepsilon_T$ or due to ε_T being locally depressed to $\varepsilon_T \lesssim KT$. Second, all the ions in localized regions may be accelerated by an electric field to $> \varepsilon_T$. Both possibilities are discussed here.

Mullan and Levine (1981) have explored a particular preacceleration mechanism in detail. They assumed a low Alfvén speed (400 to 500 km s^{-1}) and argued that the threshold condition could then be satisfied for ions with several times the ambient thermal energy (corresponding to $T = 1$ to 2×10^6 K). Such a low Alfvén speed may exist high in the corona but not at the heights where the energy release is thought to occur. Thus the first possibility above requires that the ions be heated locally to a temperature $\simeq 10^9$ K, corresponding to a thermal energy $\simeq 100$ keV, for $\varepsilon_T \simeq 100$ keV nucl^{-1}.

A. Rapid local ion heating

The idea that first-phase acceleration of electrons in solar flares is equivalent to a 'bulk energization' has become widely accepted (e.g. Ramaty *et al.*, 1980). With a thermal interpretation of the impulsive hard X-ray bursts electron temperatures up to 10^9 K are required. If the ions are heated to the same temperature as the electrons, then the energy threshold condition $\varepsilon > \varepsilon_T$ could be satisfied for ions only a few times the thermal energy.

Relatively little attention has been paid to the possible bulk energization of ions. An exception is the investigation by Duijveman *et al.* (1981) who discussed rapid heating in localized regions of current dissipation. They found that the ratio of the electron to ion temperatures can remain close to unity only under specific conditions, and that for most of the cases studied T_e/T_i becomes quite large. For say $T_e/T_i = 6$ and $T_e = 5 \times 10^8$ K, their results leave the ion temperature at a value $T_i \simeq 10^8$ K which is too low for present purposes.

Ideas on bulk energization have yet to be fully explored, and the specific question of the rapid heating of ions requires further investigation.

B. Acceleration by parallel electric fields

The simplest way to accelerate particles to $> \varepsilon_T$ is by an electric field with a potential drop $\Phi > \varepsilon_T/e$ along the magnetic field. Such potential drops may occur in potential double layers, as has been discussed in connection with solar flares by Alfvén and Carlqvist (1967), Smith and Priest (1972), Block (1978), and Spicer (1981), amongst others. A potential double layer involves a potential drop $\Phi \gg KT/e$ and so it leads naturally to the formation of streams of energetic electrons and ions.

Whether or not double layers are likely to be important in solar flares is unclear (Spicer, 1981; Spicer and Brown, 1981). Here we favour preacceleration during reconnection, as discussed below. However let us remark that quite large potential drops are possible in principle due to relative motions in the flaring region. The maximum potential Φ can be estimated using a formula for a homopolar generator:

$$\Phi \simeq \frac{\Phi_{\mathrm{mag}}}{Tc}, \tag{5.1}$$

where Φ_{mag} is the magnetic flux enclosed in a cylinder and T is the period of rotation of the cylinder. With a magnetic field of 500 G, a cylinder of radius 100 km and a period of 0.3 s (corresponding to a relative fluid motion of 30 km s^{-1}), (5.1) implies $\Phi \simeq 5 \times 10^9$ V. In practice the geometry is likely to be much less favourable than (5.1) implies, and this estimate of Φ is almost certainly an overestimate. Nevertheless $\Phi \gg \varepsilon_T/e \simeq 10^5$ V should be present in a flaring region.

Such potential differences are not along magnetic field lines and so it is by no means clear that they can lead to double layers. They can become available for acceleration of particles during reconnection when two field lines at different potentials reconnect.

C. Acceleration during reconnection

This leads us to the suggestion that the most favourable preacceleration mechanism is one associated directly with reconnection. Evidence in support of this suggestion comes from observations of reconnection in the Earth's magnetotail.

Lin *et al.* (1977) interpreted data observed from a spacecraft in lunar orbit in terms of reconnection at an X-type neutral sheet. They estimated the magnetic inflow rate and the outflow rate of energetic particles along the separatrix and found approximate energy balance. They suggested that the energetic particles produced in the merging process are the source of the hot plasma in the plasma sheet. The velocities of the outflowing plasma were sometimes of order v_{A}, implying the presence of potential differences $\simeq \varepsilon_T/e$.

Sarris and Axford (1979) discussed related observations of impulsive bursts of protons in the magnetotail. Their data involved high energy resolution and allowed them to estimate the location of the source of the protons by interpreting a spatial dependence of the bursts at different energies (from 0.3 MeV to 1.0 MeV) in terms of time-of-flight differences. They concluded that during the magnetic reconnection potentials of order 1 MV became available for acceleration of the protons.

Further insight into the acceleration process follows from the following simple argument. Suppose the potential Φ is across a region of thickness d orthogonal to **B**. Then the electric drift causes the plasma to flow at a speed

$$v = \frac{c\Phi}{\mathrm{d}B} . \tag{5.2}$$

Now let us identify this flow as that of the outgoing ions. The thickness of the flow region is about a gyrodiameter (Lin *et al.*, 1977), i.e.

$$d \simeq \frac{2v}{\Omega_i} . \tag{5.3}$$

Then (5.2) and (5.3) imply

$$e\Phi \simeq \tfrac{1}{2} m_i v^2 .$$

The result (5.4), which is seemingly obvious, depends explicitly on the thickness of the region of ion outflow being given by (5.3). For the parameters chosen here ($n_e = 10^{11}$ cm^{-3} is the only relevant one) this corresponds to $d \simeq 10^2$ cm for $v = v_{\mathrm{A}}$. A very large number of such reconnecting regions is required to account for the energy release in a flare. Even assuming each region is $\simeq 10^7$ cm in lateral extent, one would require $> 10^8$ such regions in a large flare. This is compatible with the reconnecting regions being $\lesssim 1\%$ of the linear dimensions of the overall source, i.e. 100 km compared with 10^4 km.

It might be remarked that Brown *et al.* (1980) have argued that the hard X-ray component can be due to a distribution of many small impulsively-heated kernels. Their kernels are larger than our localized reconnection regions, which could not be resolved using currently available instruments.

The estimate (5.1) is based on a global argument while (5.4) is based on a local argument. From the global viewpoint one has no reason to expect the potential Φ to develop across a single reconnecting region rather than across many such regions. The timescale for tearing instabilities is much shorter than the observed timescales in flares, and hence the system must be a driven one rather an unloading one in Akasofu's (1981) terminology. This suggests that the potential drop across individual reconnecting regions should adjust to a value determined by local rather than by global constraints. From the local viewpoint one expects $\Phi \lesssim \varepsilon_T/e$ because an energy $e\Phi \simeq \varepsilon_T$ per ion corresponds to the magnetic free energy per ion and the available free energy cannot exceed this.

D. SUMMARY

In summary, it is envisaged that reconnection occurs in many localized regions each of which produces jets of outflowing ions, as observed in the terrestrial magnetotail (Lin *et al.*, 1977; Sarris and Axford, 1979; Andrews *et al.*, 1981). Some of these jets have $v > v_A$ and can provide ions, with normal solar abundances, for acceleration by the second-step mechanism. A substantial fraction of all the ions in the flaring region must pass through reconnecting regions. Based on theoretical work, Spicer and Brown (1981) suggested that about 10% of the magnetic energy released goes into ion flows, with the remaining 90% going into heat. This suggests that a maximum of 10% of the ions can be accelerated to $v \simeq v_A$. However the actual fraction preaccelerated to $v > v_A$ is uncertain and could be much less than 10%.

6. Discussion

The observations relating to prompt acceleration of energetic ions and their interpretation raises a number of questions including the following:

(i) What is the relation between electron and ion acceleration?

(ii) Why is the acceleration sometimes prompt and sometimes delayed?

(iii) It appears that promptly accelerated ions do not escape from the Sun (Chambon *et al.*, 1981; von Rosenvinge *et al.*, 1981; Pesses *et al.*, 1981), why not?

(iv) What is the relation between second-step acceleration and second phase acceleration?

We comment on each of these questions.

(i) *Electron Acceleration*

The viewpoint adopted here is that of Bai and Ramaty (1979) and Bai (1982): prompt acceleration occurs in two steps for both electrons and ions. However it does not follow that the two steps are the same for electrons and for ions.

The data on prompt electrons come from microwave and hard X-ray bursts. The data imply the presence of two components (Crannell *et al.*, 1978; Marsh *et al.*, 1981), one of which may be thermal and the other nonthermal (Dulk and Dennis, 1982). It seems that the harder component can be delayed by $\simeq 15$ s from the $\lesssim 100$ keV component (Bai and Ramaty, 1979). This suggests that the second-step acceleration of electrons may be somewhat slower than the second-step acceleration of ions.

The second-step mechanism of acceleration by hydromagnetic turbulence invoked in Section 3 leads to a natural explanation for somewhat slower second-step acceleration of electrons than of ions. Suppose that the first-step mechanism produces ions and electrons of similar energies $> \varepsilon_T$ so that the rate of acceleration depends only on the second step. Then according to (3.1) the acceleration of the electrons is slower than that of the ions due to the dependence on $1/v$. An acceleration time of 15 s for a 350 keV electron (Bai and Ramaty, 1979) would correspond to an acceleration time of 3 s of a 30 MeV nucl^{-1} ion. These relative timescales tend to support the suggestion that the first-step and second-step accelerations of electrons and ions are similar and that the second-step mechanism is of the form discussed in Section 3.

(ii) *Delayed Energetic Ions*

Delayed acceleration of energetic ions must be attributed to a slow acceleration from ε_T to $\gtrsim 30$ MeV nucl^{-1} at least with the assumptions made here. The preacceleration is related directly to the flaring process itself and must be prompt. A likely explanation is that in delayed events the relative amplitude $\delta B/B$ of the turbulence in (3.1) is weaker than in prompt events. On the basis of the comments made under (i) one would then expect no hard component of the electrons in events with delayed energetic ions.

(iii) *Escape of Prompt Ions*

There is no obvious reason why prompt ions should not escape into the interplanetary medium; whenever energetic electrons escape one would expect co-accelerated ions also to escape. It has been estimated that electrons escape from only $\simeq 20\%$ of sources in which they are accelerated (Kane, 1981), and that then only $\simeq 10^{-3}$ of the accelerated electrons escape (Lin and Hudson, 1976). In view of the low occurrence rate of flares producing prompt γ-rays and of this low probability of escape, it may be that the (anticipated) rare events in which energetic ions escape have yet to be detected or identified.

(iv) *Second-Step versus Second-Phase Acceleration*

It is not clear what relation if any there is between second-step acceleration and second-phase acceleration. The distinguishing criteria assumed here are that second-step acceleration occurs in the flaring regions and that second-phase acceleration occurs higher in the corona in association with a type II event.

Recently Lin *et al.* (1982) showed that flares fall into two classes. One class produces only electrons $\lesssim 100$ keV and the other class produces, in addition to such electrons, a higher-energy electron component and energetic ions. In other words, one class of flare produces only first-phase particles and the other class produces both first-phase and second-phase particles. The second-phase acceration is clearly defined only for electrons which produce type II and other meter-wave bursts and an extended microwave burst; their acceleration is attributed to the type II shock wave. The data on GLE's (Cliver *et al.*, 1982) imply that the ions escape near the maximum of the microwave burst. There seems no evidence that there is a distinct second-phase, as opposed to second-step acceleration of the ions. The simplest interpretation is that the ions are accelerated in the flaring region and that their association with type II events and other 'second-phase' phenomena is indirect, e.g. due to the shock wave facilitating the escape of the energetic particles.

With the ideas discussed here, the class of flares which lead to only first-phase phenomena would be interpreted in terms of the second-step mechanism being too slow to produce observable effects. Flares which exhibit delayed γ-rays, i.e. with delayed second-step acceleration of ions, should be intermediate between the two classes of flare.

7. Conclusions

The observation of prompt γ-rays and their interpretation in terms of prompt acceleration of ions to > 30 MeV nucl^{-1} requires some revision of existing ideas on first and second phase acceleration. In particular the first phase must involve ions as well as electrons, and at least in the prompt events a further acceleration must occur in the energy release region, evidently before there is time for a type II shock wave to form. A useful alternative classification is to acceleration in two steps, as suggested by Bai and Ramaty (1979) and Bai (1982). The first and second steps both occur in the energy release region on a prompt timescale in prompt events. The term 'second phase' may then be restricted to phenomena which are associated with the passage of a type II shock wave and hence which may be well separated from the energy release region in both time and space.

Of the two steps of acceleration for the ions the first step, called preacceleration here, is the more difficult to interpret. (It seems that stochastic acceleration to > 30 MeV nucl^{-1} by hydromagnetic turbulence could occur under conditions which are not extreme.) The preacceleration mechanism is required to accelerate ions to an energy $> \frac{1}{2}m_i v_{\mathrm{A}}^2$ where resonant scattering is efficient and hence where stochastic acceleration becomes operative. One class of mechanisms involve acceleration of a small fraction of the ions from a Maxwellian tail; such acceleration is excluded on the grounds that it would lead to enormous abundance anomalies contrary to observation. Acceptable mechanism involves accelerating a substantial fraction of all species of ions in localized regions (or coordinate space). It is possible that the preacceleration mechanism is simply a 'bulk energization' for the ions, as is widely assumed for the electrons. However it seems likely that bulk energization leads to an ion temperature considerably lower than the electron temperature (Duijveman *et al.*, 1981) and hence would not constitute an acceptable preacceleration mechanism.

The idea favoured here is that reconnection leads to ion jets, as has been observed in the Earth's magnetotail (Lin *et al.*, 1977; Sarris and Axford, 1979; Andrews *et al.*, 1981). The acceleration of ions to $v \gtrsim v_{\mathrm{A}}$ (and hence $\varepsilon \gtrsim \varepsilon_T$) is then seen as an integral part of the energy release process itself. For those particles with $\varepsilon > \varepsilon_T$ stochastic acceleration could proceed, and whether the energetic ions are prompt, delayed or unobservable then depends only on the rate at which the stochastic mechanism operates.

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