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Energetic Particles in Solar Flares: Theory and Diagnostics [and Discussion]

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Energetic particles in solar flares: theory and diagnostics

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Recent progress and future prospects in diagnostics of energetic electrons and ions in the flares are reviewed, together with the roles they play in the flare as a whole. Most of the discussion centres on hard X-ray and gamma-ray and thermal plasma emission data, rather than on radio sources.

Since *Solar Maximum Mission* and *Hinotori* there has been major progress in all areas of flare electron diagnostics. Electron spectra are now recoverable with some precision, electrons with energies above 10 MeV are known to be highly anisotropic, and indications are available of the spatial distribution of electrons at 20 keV. Timescales of electron acceleration are now known to be shorter than 0.1 s. Energetic electrons are believed to carry much of the flare power.

Ion diagnostics are more limited. For greater than 1 MeV ions the flux, spectrum and acceleration timescale are now quite well known. Low energy ions are hard to diagnose but have been invoked as a flare heating mechanism alternative to electron beams. The problems with beam heating models are discussed with special attention to the problems of the low energy proton model and its only direct diagnostic, Hα impact polarization.

Finally, theoretical problems associated with return currents and with accelerator requirements are discussed and attention is drawn to the possible importance of entropy as well as energy considerations.

1. Introduction

Energetic ions and electrons have long been known as products of flares both by direct detection in space and by their radiation signatures at the Sun. On the basis of magnetic dissipation models (see, for example, Priest 1991) this is not surprising since annihilation of a field B over a volume of dimension L sufficient to yield total energy

$$\epsilon = B^2L^3/2\mu_0$$

over time t there should be an induced voltage

$$V = BL^2/t = 2\times10^{11}\ \mathrm{V}\,[\epsilon/(10^{25}\ \mathrm{J})\,(L/10^7\ \mathrm{m})/(t/10^2\ \mathrm{s})]$$

which is above the highest solar cosmic ray energy observed. However, details of how sufficient particles are accelerated quickly enough, and with the observed spectrum, remain unclear since the problem involves particle kinetics and microscopic plasma processes as well as the magneto hydrodynamics (MHD) of the primary energy release process to which it must be intimately related. For a lucid exposition of this field the reader is referred to Heyvaerts (1981), and also to Melrose (1980), MacKinnon (1986) and Vlahos (1990). It is my inexpert impression that there have been no major

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breakthroughs in the past decade and here I will touch on only one facet of particle acceleration theory (§4). Primarily I will discuss recent progress and future prospects in the fields of particle diagnostics (§2) and energy transport (§3), which have received close attention recently, one reason being that particles may play a role in the transport of primary energy release through the flare volume. The highest energy particles have the further practical importance as a hazard in space to man and equipment, a ROSAT computer being a recent likely victim of such damage.

Ideally the particle diagnostic problem is that of determining the electron and ion velocity $\boldsymbol{v}$ distribution functions $f_{\mathrm{e,i}}(\boldsymbol{r}, \boldsymbol{v}, t)$ at each position $\boldsymbol{r}$ and time t, these two functions characterizing essentially all particle properties and processes of interest. Since remote observations always integrate along the line of sight and since transverse resolution is unlikely to better 100 km – about 10^7 Debye lengths and 10^4 ion-gyro radii – we can at best deal with spatial averages of $f_{\mathrm{e,i}}$ over much larger scales than those of microscopic plasma processes, though smaller than those of macroscopic field geometry. These latter scales can be an important clue to the reconnection mode operating, and to particle transport processes. Interplanetary particle measurements, which I will not describe here, are subject to the opposite problem of yielding spot measurements of $f_{\mathrm{e,i}}$ but not the large-scale distribution.

2. Electron and ion diagnostics

(a) *Electron diagnostics*

Remote diagnostics of particles always involve modelling assumptions about the radiation process through which the desired f is convoluted to produce the observed photon intensity (and polarization) as a function of position, time and frequency. The predominant radiation processes for energetic electrons (greater than 30 keV) are electron–ion bremsstrahlung at hard X-ray frequencies, gyrosynchrotron radiation at centimetric frequencies, and coherent plasma processes at metric frequencies.

Radio diagnostics

Coherent plasma radiation processes excited by charged particle beams or pulses are potentially very important signatures of the particle and plasma distributions. For instance, it has recently been shown (Roelof & Pick 1990) that metric Type III bursts occur in filamentary coronal density structures, possibly indicating preferential beam propagation or wave generation in these channels. On the other hand, the theoretical level of waves generated and their conversion rate to radiation are extremely uncertain and the particle fluxes involved are (probably) very small in terms of flare energetics. For the same reason, however, the very high electron fluxes required by some models of hard X-ray bursts would produce unobserved huge radio fluxes unless their generation is suppressed by beam decollimation or plasma stratification (see, for example, McClements 1987). Metric burst imaging and frequency drift reveal the propagation of electrons through the corona. Time variations in metric fluxes reveal timescales down to milliseconds.

Gyrosynchrotron emission is attributed to mildly relativistic electrons in the coronal B-field, burst spectra indicating fields of $(5–50)\times10^{-3}$ T. Interferometric (e.g. VLA) data give the highest current resolution of the electron spatial distribution, though only for those electrons in plasma tenuous enough ($n < 10^{19}\ \mathrm{m}^{-3}$) for centimetric waves to propagate. Such images reveal cases of loop ‘footpoint’ emission from mirroring electrons and cases of loop top trapping of electrons (Hurford 1989), similar to results in hard X-rays, based on field geometry obtained from soft X-ray images or field extrapolation models. To some degree, therefore, the centimetric diagnostic can be regarded as complementary to the hard X-ray one, extending it to higher energies.

Hard X-ray diagnostics

(i) *Electron flux.* Curiously, the most ambiguous aspect of electron diagnosis from hard X-rays is that of the electron flux (zeroth moment of $f_e(\boldsymbol{v})$) because the conversion factor is very model dependent. The radiation mechanism involves close (*ca.* 10^{-14} m) Coulomb encounters of electrons with ions whereas the great bulk of electron collisions are long range (*ca.* Debye lengths of 10 mm) ones. Unless the overall $f_e(\boldsymbol{v})$ is very close to maxwellian, most of the energetic electron energy goes into heating the plasma rather than radiation, in the ratio of the energy loss cross sections, viz about 10^5 (Brown 1971). Furthermore, even if $f_e(\boldsymbol{v}, \boldsymbol{r})$ starts as locally maxwellian, the steep temperature gradients required to match the spatially integrated bremsstrahlung spectrum (Brown 1975) result in reversion to a beam-like situation as hot electrons stream into cold plasma, unless bottled up magnetically or by wave generation (Brown *et al.* 1979). Under anything other than these rather restrictive conditions the energetic electron power required to explain a hard X-ray burst flux is comparable with the total impulsive flare power (Brown 1971). Such a situation is very demanding on the electron acceleration or heating mechanism in the primary energy release process (cf. §4). Such fluxes are also close to the limit set by return current instability (Brown & Melrose 1977). On the other hand the rapid transport of energy through the flare volume has proven attractive (though not yet convincing, cf. §3) in trying to explain the impulsive phase heating of the X-ray ultraviolet (XUV) and optical flare plasmas, as discussed by others (Simnett 1991).

(ii) *Electron spectra.* Because of the steep spectra involved, the energy content of the non-thermal component is very sensitive to the energy above which $f_e(\boldsymbol{v})$ ceases to be maxwellian. Aside from the complication of spatial averaging, any prospect of detecting this transition spectrometrically has been made difficult by the low resolution (*ca.* 30%) and count rates of most spectrometers and by the smearing effect of the bremsstrahlung cross-section of $f_e(\boldsymbol{v})$. The former problems have been overcome by the advent of large area Ge detectors (Lin & Schwartz 1987) currently being flown from Antarctica. The latter problem is intrinsic and inescapable but minimized by good spectrometry and sound inversion techniques (Craig & Brown 1986). Thus, while *Solar Maximum Mission* (*SMM*) spectrometry could not possibly distinguish between non-thermal and anisothermal $f_e(\boldsymbol{v})$, or determine the presence of bumps in the speed distribution ($f'_e(v) > 0$), both of these tests are now possible (Brown & Emslie 1988; Emslie *et al.* 1989; Brown *et al.* 1991*a*; Lin 1991) though they require measurement of derivatives of the photon spectral index variation with energy. (Note that, contrary to common impressions, plasma wave generation does not suppress features with $f'_e(v) > 0$, only those with $f'_e(\boldsymbol{v}) > 0$, which condition also depends on the angular distribution.) Thus recent progress in spectrometry has led us to a point where it is now possible, following Brown's (1971) analytic treatment, to *derive* electron spectra numerically by smoothed/stabilized data inversion techniques (Thompson *et al.* 1991), rather than just fit to crude models, though data noise still limits the analysis to finding only major features in $f_e(\boldsymbol{v})$. Figure 1 shows an example of such an inversion of data from Lin & Schwartz (1987) by Thompson

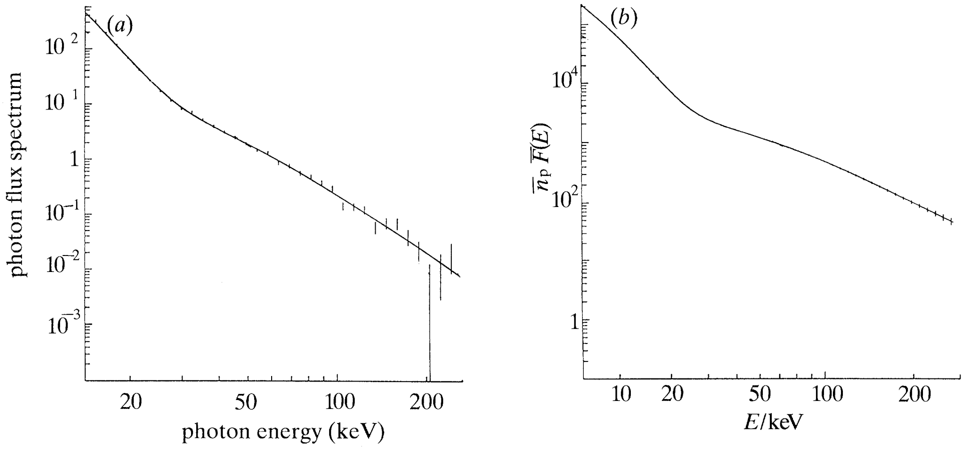

Figure 1. Example of the results of an optimized stabilized inversion (Thompson *et al.* 1991) to derive a mean source electron energy spectrum (*a*) from a bremsstrahlung photon spectrum (*b*) from Lin & Schwartz (1982).

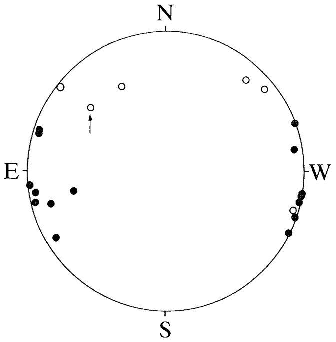

Figure 2. Distribution of greater than 20 MeV continuum flares on the solar disc showing the emission to be highly anisotropic (from Rieger *et al.* 1983).

et al. (1991). This improvement in spectral diagnostic capability means that some factors affecting the photon spectrum, somewhat forgotten recently, should be reconsidered; notably partial plasma ionisation (Brown 1973) and solar albedo (Tomblin 1972).

(iii) *Electron anisotropy*. In analysing spectra, the effect of X-ray directivity is usually ignored: this is equivalent to assuming that $f_e(\boldsymbol{v})$ is fairly isotropic. This approximation is quite well justified at low energies by the important stereoscopic (Kane *et al.* 1988) and statistical (Vestrand *et al.* 1987) results that X-ray directivity is not large up to several 100 keV. At greater than 10 MeV, however, the distribution of bursts on the solar disc (Rieger *et al.* 1983) (see figure 2) shows $f_e(\boldsymbol{v})$ to be highly anisotropic with electrons moving nearly horizontally in the emission region. Theoretical modelling (MacKinnon & Brown 1989, 1990; Miller & Ramaty 1990) shows this to result mainly from propagation processes, rather than from $f_e(\boldsymbol{v})$ at acceleration, the data yielding important constraints on the plasma density and field distribution where the electrons are near mirroring.

(iv) *Hard X-ray source geometry*. The spatial distribution of hard X-rays in two dimensions was imaged for the first time by *SMM* (Hoyng *et al.* 1981), and by *Hinotori*

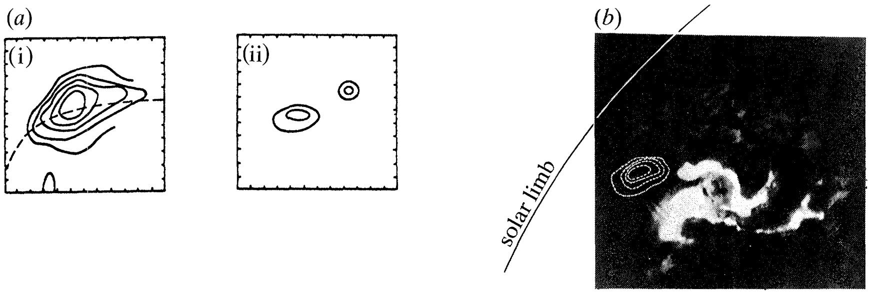

Figure 3. Images of greater than 20 keV hard X-ray flares showing (*a*) footpoints seen by *SMM* (from Hoyng *et al.* 1981) ((i) 3.5–8 keV, (ii) 16–30 keV) and (*b*) coronal emission seen by *Hinotori* (from Tsuneta *et al.* 1984).

(Tsuneta *et al.* 1984). Because the energies are rather low (less than 30 keV) there are ambiguities of interpretation between beam, trap and thermal emissions (MacKinnon *et al.* 1985; Machado *et al.* 1985). Subject to this proviso, the data indicate cases where the emission is concentrated near loop footpoints, as expected in beam models (Brown & McClymont 1976) and others where it is at loop summits as expected in trap and confined thermal models (see figure 3). Consistent results are found at high energies by stereo/occultation results (Kane 1983) and centimetric data (see, for example, Hurford 1982). Results of direct imaging at higher X-ray energies by *Solar-A* are eagerly awaited.

(v) *Hard X-ray time variations.* On longish timescales (greater than 1 s) some events show energy dependent delays between impulsive features. These have been interpreted as the energy dependence of collision times of electrons in a coronal trap (see, for example, Brown 1972; Bai & Ramaty 1979; Vilmer *et al.* 1986) but could also be a direct reflection of a dynamic acceleration function injecting electrons into a dense target (Brown 1971). On very short timescales there are occasional features present down to 10 ms but with a frequency close to Poisson noise expectation, with Fourier noise analysis showing however that real timescales down to 100 ms are certainly present (Loran *et al.* 1985). Given that electron propagation smears out bremsstrahlung features, still shorter times must characterize $f_e(\boldsymbol{v})$ at acceleration. This must tightly constrain parameters at acceleration sites. For example in a model where all the electrons in a spike come from the plasma in the original site volume, the site must be large and dense enough to provide 10^{35} electrons in 100 ms but must have an Alfvén crossing time shorter than this and be able to sustain a stable return current. Combining these constraints would require each acceleration site to have $n \approx 10^{16}\ \mathrm{m}^{-3}$ and size ≈ 3000 km for $B = 0.03$ T.

(*b*) *Ion diagnostics*

High-energy ions (greater than 1 MeV)

Direct confirmation of the presence of ions of greater than 1 MeV at the flare site came with the *Skylab* ATM detection of flare gamma-ray lines (Chupp *et al.* 1973) and these have been studied extensively from *SMM* and *Hinotori* data (see Chupp 1984; Rieger 1990) at much higher resolution and sensitivity. Analysis yields information on the ion flux spectrum and time variations and on the atmospheric nuclear abundances, free from the complication of knowing the population equilibrium in atomic line diagnostics. Details of the methodology and results have been reviewed by Ramaty & Murphy (1987) and references therein. No direct spatial information is available on gamma-ray sources though the very high densities needed to produce the neutron capture line and other considerations seem consistent with a downward proton beam geometry. These protons may also contribute to the very high energy continuum through pion production and decay. Because the ions involved are non-relativistic there is no direct information on the anisotropy of $f_i(\boldsymbol{v})$. Time variations of the gamma ray flux show that ions of many MeV must be accelerated in seconds.

Protons of greater than 40 MeV have also been invoked as a source of hard X-rays at greater than 20 keV through collisions with ambient electrons (Boldt & Serlemitsos 1969; Heristchi 1986). Emslie & Brown (1987) applied this idea to *SMM* data and conclude that the proton flux needed to produce the hard X-rays was in excess of the simultaneous gamma-ray line requirement by several orders. This conclusion has been challenged strongly by Heristchi (1986) but without achieving much support thus far. Apart from the gamma-ray line problem, the model has other difficulties (Brown *et al*. 1989) not least that a vertical beam of 40 MeV protons would produce the hard X-rays below the photosphere while large pitch angle protons would stop higher in the atmosphere too slowly for hard X-ray fine time structure.

Low-energy ions (*less than* 1 MeV)

MacKinnon (1990) has pointed out that ions of less than 1 MeV can produce gamma-ray lines at greater than 1 MeV by radiative capture processes though detection of these lines will require larger area detectors than currently available. Ions of still lower energy are also hard to diagnose. One possibility is non-thermal ionization effects and the production of continuum brightenings/darkenings (white/black-light flares, Hénoux *et al*. 1989), though these effects are probably the same for electrons and ions. A second is non-thermal (Doppler-shifted) lines, such as Lα, from energetic hydrogen atoms (Orrall & Zirker 1976; Canfield & Chang 1985) or He$^{\rm II}$ ions (Peter *et al*. 1990) resulting from charge exchange between ambient atoms and non-thermal ions moving at approximately orbital electron speeds. A third is non-thermal excitation of ambient atom transitions with energies *ca*. m_e/m_i × the ion energy (so that the ion speed is in resonance with the orbital electrons); in particular the production of polarized Hα by anisotropic proton or electron impact (Hénoux *et al*. 1990). The main problem of detection of these non-thermal lines is the large thermal background line intensity. However, in the case of the second of these diagnostics, the line polarization should aid its detection.

Observations of polarized Hα from a flare region have been reported and their interpretation in terms of proton and electron impact discussed by Hénoux *et al*. (1990). Since the polarization data take many minutes of integration time it is hard at this stage to be sure the phenomenon is impulsive, as expected for beam impacts, but Hénoux *et al*. (1990) suggest that proton impact is the most plausible mechanism. Among issues needing to be addressed for this diagnostic are the following.

1. The argument that the polarization direction favours slow particles, and hence protons, since slow electrons isotropize, depends on the assumptions of vertical particle motion and a vertical field. Field convergence may invalidate this argument through field inclination and mirroring of fast electrons.

2. More work is needed on how the contribution to impact polarization varies along the particle path; although the impact cross section falls at higher energies, so also do the competing Coulomb losses. In addition, thus far only impact excitations

from level 1 have been considered whereas level 2 can be more important (Fletcher & Brown 1991).

3. As discussed more fully in §3, the slow speed and short range of the slow protons which produce impact polarization poses problems with the power requirements of the heated thermal plasma. The lack of convincing ion diagnostics in the 20–1000 keV range is unfortunate since there is a vogue to invoke these 'invisible' particles as a panacea (see §3).

3. Particle heating of the thermal flare

There is an enormous literature (see Woodgate & Kundu 1987) on the modelling of flare heating and hydrodynamics driven by non-thermal particles, usually electrons. This topic is being addressed by several other authors in this volume and I will confine myself to giving my view of the status of some of the more contentious issues, which I have reviewed more completely elsewhere (Brown 1986; Brown *et al.* 1989).

Despite the progress made in modelling from the multi-band *SMM*, *Hinotori* and coordinated data, information on beam fluxes and areas, etc., has remained uncertain or ambiguous in the case of electrons and almost non-existent in the case of ions. The modelling of the optical and XUV flare plasma response (heating, motion, evaporation, etc.) to particles responsible for the simultaneous non-thermal bursts can therefore be described at best as showing rough consistency. For example, although there are cases of hard X-ray footpoints roughly coincident with impulsive optical brightenings, and for which modelling based on the whole hard X-ray flux gives Hα line profiles compatible with observations (Canfield *et al.* 1984), the modelling assumes that all the (non-imaged) hard X-ray flux comes from the footpoint area which does not agree with comparisons of the imaged and non-imaged hard X-ray data themselves (MacKinnon *et al.* 1986). Another discrepancy is that a thick-target electron beam should drive chromospheric evaporation with a larger blue shift than observations permit (Peng Li *et al.* 1989). To get around this it has been suggested that most of the electrons may be coronally confined. It is to be hoped that *Solar-A* will permit more precise definition of the spatial and temporal distribution of all the important data for such model testing.

Feldman (1991) has strongly challenged the beam heating model on several grounds. First, that the evaporated XUV material ought to show chromospheric abundances rather than coronal (this objection applying to any evaporative model) and secondly, that in many events there is no resemblance between the hard X-ray light curve and the time derivative of the XUV emission which the non-thermal electrons are supposed to be heating (see Feldman 1991). Proper comparisons of this kind, of course, require full modelling, taking account of instrument response, of bremsstrahlung emissivity, and of varying temperature and density distributions, rather than just comparing raw light curves. Such comparisons must be a high priority for *Solar-A* data analysis.

With regard to electron versus proton heating, the virtual absence of reliable proton diagnostics means that protons of convenient properties can be invoked more or less at will without risk of observational contradiction. However, while 'absence of evidence is not evidence of absence' neither is it evidence of presence! Until low energy proton diagnostics are improved, the electron–proton heating controversy has to rest largely on questions of the theoretical viability of the proton model, most of which remain untouched by the proton advocates, though electron models have been subjected to such tests for almost 20 years. Among these I see the following as particularly important.

1. Is there any proton injection spectrum which creates the right distribution of thermal emission with 'height' in the atmosphere? Very high energy protons (greater than 40 MeV) lose their energy too deep, while very low energy ones are stopped in the corona (cf. Brown *et al*. 1989). Since a power-law spectrum of electrons above 30 keV or so gives about the right heating distribution, one would expect protons with the bulk of their energy deposited at the same depth as 30 keV electrons – viz protons of about 1 MeV injection energy – to be what is needed. Such protons will stop in the chromosphere producing impact Hα polarization from the ambient neutrals as they pass through the 10–10^3 eV range. This of course means that the energy flux needed at injection is about 30 times that delivered to the Hα impact region.

Also, the mean free path of 10–10^3 eV protons in the chromosphere is very short, viz about $L = 5\times10^{21}\mathrm{m}/n(\mathrm{m}^{-3})$ which is only 100 m if one believes that the impact polarization occurs in the thermal Hα forming layers where $n \approx 10^{19}$ m^{-3}. Consequently, the total number of atoms available in an impact polarization source of area $S = 10^{14}\times S_{14}\,\mathrm{m}^2$ is $N = SnL = 5\times10^{35}S_{14}$. If q is the proportion of these atoms in the third level times the fraction of spontaneous transitions which are polarized, then the maximum impact polarized Hα line luminosity possible is, regardless of the proton flux driving it,

$$P_\alpha = NqA_{32}\,\epsilon_\alpha \sim 10^{25}qS_{14}\ \mathrm{W},$$

where A_{32} is the Einstein coefficient and ϵ_α is the energy of an Hα photon. This sets a lower limit to q for any observed P_α and hence on the necessary proton flux. The corresponding proton energy flux at injection is very sensitive to the model atmosphere they have to traverse, in some estimates quite modest and in others impossibly large (Hénoux *et al*. 1990; Fletcher & Brown 1991). Clearly these models require a lot of refinement.

2. Are slow protons capable of producing sufficiently impulsive behaviour in the heated plasma? Proton speeds of 4×10^6 m s$^{-1}\times(\mathrm{E}/100\ \mathrm{keV})^{\frac{1}{2}}$ are no higher than the Alfvén speed which has generally been ruled out as too slow to synchronize spatially separated impulsive emissions, taking several seconds to traverse even a small loop.

3. What are the electrodynamic properties of the required proton beam? Are they theoretically possible and do they obviate any problems in electron beam models? Delivery of a specified energy flux by a proton beam of, say, 30 keV implies exactly the same beam current density as delivery of the same flux by electrons of the same energy so that any electrodynamic problems with the latter also blight the former.

4. How does a low-energy proton beam generate hard X-rays? Two proposals have been offered. One (Simnett & Strong 1984) is that the protons heat the plasma to produce thermal bremsstrahlung. This has not been quantified: what needs checking is whether any proton distribution consistent with other data can produce plasma of large enough temperature and emission measure to fit the hard X-ray data. These two requirements act in opposite senses, the higher the density and volume of the heated plasma the higher is the emission measure but the lower is the temperature. Secondly, Simnett & Haines (1990) have proposed a mechanism whereby a low-energy proton beam, somehow carrying neutralizing electrons at the same speed (see §4) accelerates a flux of non-thermal electrons with power and particle energy comparable to that of the proton beam. It is far from clear, to me at

least, how a proton beam can accelerate electrons of velocities faster (by $(m_p/m_e)^{1/2}$) than the protons. But in any case the proton beam now acts as a further intermediary to create an electron beam with all the alleged problems that proton beams were invoked to resolve.

4. Theoretical considerations

(*a*) *Return currents*

Unless the particle flux is almost perfectly isotropic, the beam power required to heat a flare, or to produce a hard X-ray burst non-thermally, enormously exceed the Alfvén–Lawson limit. Such a beam can propagate in a plasma by creating an electric field which drives a neutralizing return current. There are, however, some continuing areas of confusion concerning beam driven return currents in flares, in particular the following.

1. Some authors still confuse return currents and current closure. The latter refers to the route by which the charge borne by a current returns to its starting point. In the case of a drift current the 'return' branch of the current closure need not be co-spatial with the 'forward' branch but could just be closure round a subphotospheric loop for example. In the case of a high density beam current, however, the beam current must be co-spatially neutralized down to small size scales (cf. Winglee *et al.* 1991) if the beam self magnetic field is not to destroy the beam.

2. There has been controversy over whether a beam return current is driven electrostatically (Brown & Bingham 1984) or inductively (Spicer & Sudan 1984). The most thorough discussion of this problem is given by van den Oord (1990) whose essential conclusion is that the controversy is semantic rather than physical. When the electric field is resolved into curl-free (electrostatic) and divergence-free (inductive) components with use of a suitable gauge, their longitudinal components turn out to be almost exactly equal and opposite so, in the only mathematically meaningful sense, the effects are comparable. However, when the two are combined the small uncancelled field, which is physically important in driving the return current, is associated with a beam head charge (i.e. is 'electrostatic') for a large distance – the collisional mean free path – behind the beam head, but behind that becomes predominantly associated with the diffusively growing beam magnetic field (i.e. 'inductive'). Unfortunately this analysis has obvious application only for the case of a rigid beam. When beam deceleration, which takes place over about a mean free path, is considered it is still not clear that the beam/return-current system is not close to the quasisteady electrostatic situation conjectured originally by Knight & Sturrock (1977). The real flare situation is further complicated by the likely small-scale filamentation of the system (Winglee *et al.* 1991).

3. There seems to be an impression that proton beams do not require a return current since the protons need only carry neutralizing electrons with them. This is quite false. First, the beam neutralising electron current is a return current just as for an electron beam but in the opposite direction. Secondly, the protons do not drag electrons on a one to one basis at the proton speed. Rather the electric field generated by the proton beam drags all the denser plasma electrons to form a slow moving return drift current, again just as for an electron beam. (This is obvious from the van den Oord (1990) analysis with the beam charge reversed in sign.) What does propagate with the protons is the phase speed of the return current excitation front in the plasma electrons.

4. What has not been considered to date is the fact that the electric field generated by the beam (electron or proton) will quickly also accelerate ambient protons to participate in the return current drift but it is easy to show that the effect of this is to only to slightly reduce the electric field by a factor $\sigma_e/(\sigma_e+\sigma_p)$ where $\sigma_{e,p}$ are the electron and ion conductivities.

(b) *Energy and entropy considerations*

Without any consideration of specific mechanisms, interesting conclusions can be drawn regarding particle heating/acceleration from energy and entropy considerations. If primary energy release is from a field B in a plasma of density n, the mean energy released per particle is

$$E = B^2/(2\mu_0 n) = 30 \text{ keV} \times (B/10^{-2}\text{ T})^2/(n/10^{16}\text{ m}^{-3}).$$

On energy grounds it is therefore quite plausible that the first result of reconnection is a population of particles of mean energy 30 keV which subsequently heats a larger plasma volume.

As pointed out by Brown & Smith (1980), however, there could be an important entropy difference between a situation where these particles form a hot maxwellian $f_e(\boldsymbol{v})$ at $kT = 30$ keV and one where some of the energy goes into a fraction of accelerated tail particles. It has now been shown by Brown *et al.* (1991*a*) that in the case where these particles form a bump of width ΔE in the tail of the distribution that the total entropy of the final system becomes arbitrarily small as ΔE tends to zero. This must mean that any finite initial field energy implies an upper bound on the monochromicity of any accelerated particles its annihilation produces. It is hoped that further analysis will reveal similar entropic bounds on the total energy of accelerated particles and hence constrain all models of the role of energetic particles in flares.

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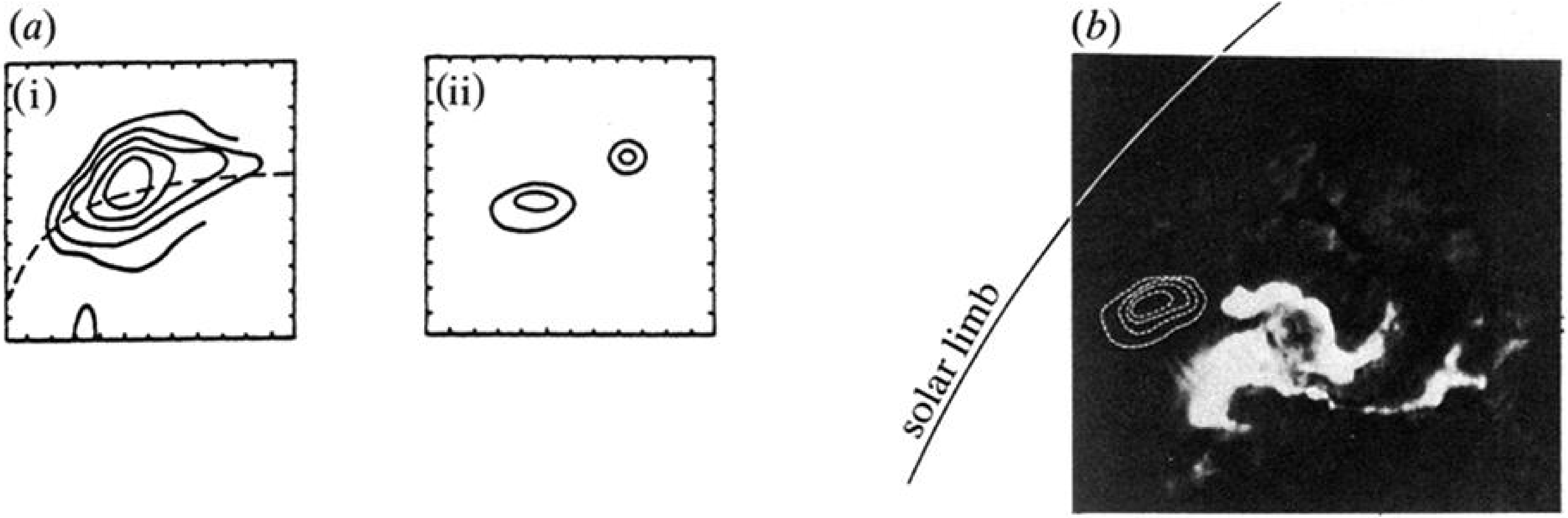
Discussion

A. G. EMSLIE (*University of Alabama, U.S.A.*). In the connection of electrons versus proton beams, it is worth pointing out that the velocity of a 100 keV proton (and consequently its accompanying electron 'beam') is much smaller than the thermal velocity of the ambient electrons. It seems appropriate, both in connection with this specific point, and also in general, to ask you to clarify the working definition of 'beam' that you are using throughout.

J. C. BROWN. A 'beam' has a distribution function $f(\boldsymbol{v})$ with $\overline{v_{11}^2} \gg \overline{v_1^2}$. (The terminology is also used loosely by flare researchers for non-thermal populations undergoing 'streaming', even if the streaming speed is only comparable with the speed of Larmor motion about the field.) This definition is independent of the ambient plasma parameters. A 100 keV proton has about five times the speed of a chromospheric electron. The 'accompanying' electrons have a much lower speed and form a plasma drift current rather than a beam, unless injected with the protons.



igure 3. Images of greater than 20 keV hard X-ray flares showing (*a*) footpoints seen by *SMM* rom Hoyng *et al*. 1981) ((i) 3.5–8 keV, (ii) 16–30 keV) and (*b*) coronal emission seen by *Hinotori* rom Tsuneta *et al*. 1984).