PARTICLE BEAMS IN THE SOLAR ATMOSPHERE: GENERAL OVERVIEW

(Invited Review)

D. B. MELROSE
School of Physics, University of Sydney, NSW 2006, Sydney, Australia

(Received 27 September, 1989, in revised form 7 May, 1990)

Abstract. An overview of particle beams in the solar atmosphere is separated into discussions of (i) current-carrying beams, (ii) current-neutralized electron beams, and (iii) ion beams. The Alfvén–Lawson limit on an electric current implies some severe limitations including the following: the current flowing into the corona cannot exceed about 10^{12} A; if the current density is near threshold for a current instability then the current must flow in thin layers; and, the primary electrons and ions cannot be accelerated simply by the particles falling down a parallel potential drop. Considerable progress has been made in understanding how electron beams in type III solar radio events propagate in a way that is consistent with the generation of Langmuir waves, but a completely consistent picture has not yet emerged. Such beams, and more importantly the electron beams that generate hard X-ray bursts require current neutralization; how the required return current is set up is still not entirely clear. There is direct evidence for ion beams with energies $\gtrsim 10$ MeV per nucleon from γ-ray line emission; there is no unambiguous evidence for ion beams of lower energy. A mechanism is suggested for bulk energization of electrons due to dissipation of a parallel current in solar flares. Some outstanding problems concerning particle beams are identified.

1. Introduction

For the purpose of this paper a 'particle beam' is defined as (a) a collection of particles, (b) with a mean velocity that is nonzero, and (c) which exhibits some property that cannot be explained purely in terms of single-particle dynamics.

Particle beams may be classified as electron beams, ion beams, or neutral beams. The most widely studied beams are of nonrelativistic electrons of several to several tens of electron volts. Such beams are known to be the cause of hard X-ray bursts, type III radio bursts and of several other classes of radio burst. There is some observational evidence for the presence of ion beams with energies $\gtrsim 30$ MeV per nucleon associated with solar flares, implied by γ-ray line emission produced when the ions impact on the denser regions of the solar atmosphere. However, the evidence is specifically for precipitating ions, and it is not clear that they form a beam or beams in that condition (c) above may not be satisfied. There is no evidence for ion beams with energies lower than the threshold for γ-ray line emission, but this may be due to the poor signatures for such beams. Similarly, there is no clear evidence for neutral beams or jets in the solar atmosphere – mass flows, such as in spicules and coronal mass ejecta, are not normally classified as beams. Thus the main interest in beams concerns nonrelativistic electron beams and nonrelativistic ion beams. An important question in connection with electron beams concerns whether or not *current neutralization* occurs, that is, whether or not a

Solar Physics **130:** 3–18, 1990.

return current flows. Thus three types of particle beam are of interest: electric currents, current-neutralized electron beams, and ion beams.

Aspects of beams that are of interest are (i) energization or acceleration of the particles, (ii) escape of the particles from the acceleration region to form a beam, (iii) propagation of the beam, and (iv) the dissipation or destruction of the beam. The main emphases have been placed on the propagation of beams, including the effects of various instabilities, and on the dissipation of beams, including the consequences of the energy transfer involved. These emphases are reflected in the discussion here.

Electric currents and problems associated with them are discussed in Section 2, electron beams are discussed in Section 3, and ion beams are discussed in Section 4. The energization of electrons (so-called 'bulk energization') due to current dissipation is discussed in Section 5. Some outstanding problems are identified in Section 6.

2. Electric Currents

Alfvén (1939) pointed out that galactic cosmic rays propagating from a distant source towards the Earth constitute a current. He considered a cylinder of radius r_0 carrying a current I, and noted the form of the self-magnetic field: the field at r_0 is $B_0 = \mu_0 I/2\pi r_0$ (SI units are used here). The radius of curvature of the particles in the beam is $\rho = \gamma m v/qB$, where m is the mass, q is the charge, $v = \beta c$ is the speed, and γ the Lorentz factor of each particle. For $\rho \approx r_0$ the particles have figure-of-eight type orbits and for $\rho \lesssim r_0$ the orbit in the self field prevents the particles propagating in the direction of the beam, so that such a beam cannot exist. The relation $\rho \lesssim r_0$ implies a maximum current that can flow, and this current is independent of r_0. Independently Lawson (1957) noted the same limitation on the current, and pointed out that the result follows directly from Equation (12) of the classic paper by Bennett (1934) on the self-pinching of currents. The Alfvén–Lawson limit on the current for electrons is

$$I_{\mathrm{A}} = \frac{2\pi m_e \gamma v}{e\mu_0} = 1.7 \times 10^4\, \beta\gamma \quad \mathrm{A}\,. \tag{1}$$

All currents of interest in the solar corona greatly exceed the Alfvén–Lawson limit. For example observations of the vector magnetic field at the photosphere imply a current flowing through the photosphere in an active region of order 10^{11}–10^{12} A (e.g., Moreton and Severny, 1968). Another example is for the $\gtrsim 20$ keV electrons that precipitate at a rate that can exceed $10^{36}\ \mathrm{s}^{-1}$, as implied by data on hard X-ray bursts; such precipitating electrons constitute a current that can exceed 10^{17} A, compared with $I_{\mathrm{A}} \approx 10^3$ A.

Currents in excess of the Alfvén–Lawson limit can flow only under two conditions:

(i) If there is an ambient magnetic field whose strength exceeds that of the self magnetic field, then the orbits of the particles remain approximate spirals in the ambient field rather than the figure-of-eight orbits in the self field.

(ii) If there is a medium present, the ambient particles may set up a *return current* such that the local current density is always small. This situation is referred to as *current neutralization*. The self-magnetic field of a neutralized current is unimportant.

In this section the first of these possibilities is discussed, that is, the currents are assumed to be unneutralized.

Returning to Alfvén's (1939) model, the condition for an ambient magnetic field to allow a current I to flow in a cylinder of radius r_0 is $B > B_0$, that is

$$B \gtrsim \frac{\mu_0 I}{2\pi r_0} . \tag{2}$$

One may interpret (2) as implying a limit on the current I that can flow inside a cylinder of given radius r_0 for a given ambient magnetic field B. In an active region one might have $r_0 = 2 \times 10^6$ m and $B = 0.15$ T, implying that I is restricted to $\lesssim 2 \times 10^{12}$ A.

The limit of $I \lesssim 10^{12}$ A on the current flowing into the corona implies a severe constraint on models for solar flares. Models that strongly violate this constraint must be rejected. In particular the version of the loop model discussed by Spicer (1981) that involves only Joule dissipation (that is, no anomalous conductivity) and the photospheric dynamo model of Kan, Akasofu, and Lee (1983) are not acceptable in their existing forms for this reason.

The limit (2) applies to all currents, and so implies a further constraint on models for solar flares that invoke filamentation of the current. It is widely believed that any large-scale current I flows in filaments or sheets, and it is essential to make this assumption to account for the energy release in solar flares (e.g., Melrose and McClymont, 1987). There is a limit on the current density implied by the threshold for an appropriate current instability, and many theories appeal to local current densities at this threshold. For example, for the ion sound instability the limiting current density is, to within a factor of order unity, $n_e e v_s$ where n_e is the electron number density and v_s is the ion sound speed. The inequality (2) implies a limit on the thickness of the filament or sheet in which such a current flows. For a current density $J = n_e e v_s$ in a cylinder, the radius of the cylinder is restricted to $r_0 \lesssim B/\mu_0 n_e e v_s$ (e.g., Chiuderi, 1983). The implied thickness is inversely proportional to the electron number density, and for parameters of relevance to solar flares the thickness is restricted to a range of about a meter in denser regions and about a kilometer in less dense regions. Thus the need for anomalous conductivity to allow adequate dissipation in solar flares coupled with the current limitation imply that the basic energy release must occur in very thin layers in the solar atmosphere.

3. Electron Beams

There are two direct signatures of electron beams in the solar atmosphere: radio bursts that drift rapidly in frequency, and hard X-ray bursts. For some phenomena, notably type III bursts, there is also direct evidence from *in situ* observations in the interplanetary medium.

3.1. EVIDENCE FOR ELECTRON BEAMS IN THE SOLAR CORONA

The first evidence for electron beams in the solar corona came from the initial observations of meter-wave radio burst with a dynamic spectrograph. Wild (1950) suggested that type III bursts must be due to a disturbance propagating outward through the corona at a speed between 2×10^4 and 10^5 km s^{-1}. That the disturbance is a beam of electrons was widely believed. This was confirmed by *in situ* measurements by spacecraft of type III events in the solar wind (e.g., the review by Lin, 1985). Besides type III bursts there are several other types of burst that indicate the presence of electron beams. Amongst the clearest examples are

(i) the 'herringbone structure' in type II bursts (e.g., the review by Nelson and Melrose, 1985) and the seemingly associated 'SA events' in the interplanetary medium (Cane *et al.*, 1981), and

(ii) drift-pair bursts (Roberts, 1958), and S-bursts (Ellis, 1969).

In addition it is widely believed that type I bursts are due to beams of electrons.

Early evidence on hard X-rays from the Sun was indirect (from ionospheric disturbances), and the first direct evidence came from balloon observations in the early 1960s, and later from spacecraft data (e.g., the review by Kane, 1974). Data on hard X-rays led to a picture of the energy release in solar flares (e.g., Wild, Smerd, and Weiss, 1963) involving two phases of particle acceleration. (The picture of two phases is now regarded as an oversimplification.) The first phase was assumed to involve acceleration of the $\gtrsim 20$ keV electrons that produce both the type III bursts and the hard X-ray bursts, with the former due to upward propagating electron beams and the latter due to downward propagating electron beams. Data on electrons in the interplanetary medium suggest that lower energy electrons (2–20 keV) are important in type III emission, e.g., the review by Lin (1985). These electrons could not escape through the denser regions of the solar corona, and so must have been accelerated much higher in the corona than the height where the primary flare energy release occurs. (The relation between type III events in the corona and in the interplanetary medium is unclear, due in part to the lack of data between about 2 and 20 MHz.) These type III beams are the electron beams of most past and present interest.

In some flares the rate of precipitation of electrons required to explain hard X-ray bursts is such that it is consistent with virtually all the energy that reaches the chromosphere being transported from an energy release site in the corona by the energetic electrons (e.g., de Jager *et al.*, 1987). It is now widely accepted that Hα, ultraviolet, and soft X-ray emissions in flares are due to secondary effects resulting from the impact of the hard X-ray emitting electrons on the denser regions of the solar atmosphere.

3.2. PROPAGATION OF TYPE III BEAMS

The basic ideas on how an electron beam generates type III radio emission were first formulated by Ginzburg and Zheleznyakow (1958). An essential ingredient in the theory is the generation of Langmuir waves via a streaming instability. A major difficulty with the theory was pointed out by Sturrock (1964). Sturrock estimated the distance the electron beam would propagate before losing effectively all its energy to Langmuir waves; he estimated that the instability would 'produce tremendous beam deceleration in only a few meters'. (Actually, with his numerical values he should have estimated several kilometers rather than several meters.) In contrast, the electron beams were then known to propagate through the corona and some beams are now known to propagate to beyond the orbits of the giant planets. The obvious dilemma had a major impact on subsequent theoretical work on type III bursts and is still not completely resolved today.

There have been two seemingly contradictory arguments on how Sturrock's dilemma may be avoided, and most surprisingly the observational evidence suggests that both may be correct. These arguments depend on several properties of the interaction between Langmuir waves and electrons. In a one-dimensional treatment (which is of wider validity than might be expected), Langmuir waves with a phase velocity v_ϕ interact with electrons with velocity $v = v_\phi$. This interaction causes the waves to grow (the 'instability') for $\mathrm{d}f(v)/\mathrm{d}v > 0$ and to be damped for $\mathrm{d}f(v)/\mathrm{d}v < 0$, with the growth rate proportional to $\mathrm{d}f(v)/\mathrm{d}v$. In an 'inhomogeneous' beam (that is, a beam of finite length) faster electrons outpace slower electrons, and this tends to increase $\mathrm{d}f(v)/\mathrm{d}v > 0$ near the front of the beam thereby favoring instability. This tendency is partially balanced by the back-reaction of the instability on the electrons, called *quasi-linear relaxation*, which tends to form a *plateau distribution* $\mathrm{d}f(v)/\mathrm{d}v = 0$.

One line of argument is that the (one-dimensional) distribution function $f(v)$ of the electrons in the beam adjusts to a form that allows the beam to propagate in such a way that the Langmuir waves generated by electrons at the front of the beam are re-absorbed by electrons at the back of the beam. This avoids the excessive energy loss by having the energy going into the Langmuir waves recirculated amongst the electrons rather than being lost entirely to the beam. An idealized analytic model that describes this effect (Ryutov and Sagdeev, 1970) was applied to the type III problem by Zaitsev, Mityakov, and Rapoport (1972), and numerical models were developed by Takakura and Shibahashi (1976) and Magelssen and Smith (1977). Other and more recent developments have been reviewed by Grognard (1985). Comparison of the observed electron distribution functions in type III events with the self-consistent distribution functions in numerical models for the evolution of 'inhomogeneous' beams (Grognard, 1984) suggests that the observed electron distributions are indeed determined by the interplay of the faster electrons which outpace slower electrons, and quasi-linear relaxation.

An assumption of the 'inhomogeneous' beam model is that the system is locally homogeneous. This assumption is inconsistent with the observed Langmuir waves which are inhomogeneous, appearing in intense isolated clumps (Gurnett and Anderson, 1977; Gurnett *et al.*, 1978; Lin *et al.*, 1981). It may seem surprising that quasi-linear theory is applicable at all. However, it can be shown (Melrose and Cramer, 1989) that under plausible conditions quasi-linear relaxation for a clumpy distribution of Langmuir waves has the same form as for a homogeneous distribution with an energy density equal to the average energy density of the clumps, and this allows relaxation of the assumption of local inhomogeneity. Thus it appears that the electron distribution function is determined as suggested in the 'inhomogeneous' beam model except in that the quasi-linear relaxation is due to a clumpy distribution of Langmuir waves.

The other argument on how Sturrock's dilemma might be overcome is to note that the observed parameters for type III beams in the interplanetary medium imply that the growth rate is so small that the beam can pass before the Langmuir waves have grown significantly (Melrose, 1974). Observation of type IIIb bursts, which have an envelope like a type III burst but no continuous type III emission, suggests the existence of type III beams that do not radiate significantly, presumably because they do not generate Langmuir waves. The suggestion that the beams may not generate Langmuir waves overcomes the difficulty of how the beam propagates but leaves the problem that there is then no type III emission. The observation that the Langmuir waves are clumpy provides some support for this model in that it implies that the Langmuir waves do not grow most of the time, presumably because the growth rate is close to the minimum that allows effective growth (e.g., Smith and Sime, 1979; Melrose, Dulk, and Cairns, 1986). The inclusion of scattering of Langmuir waves severely exacerbates the problem of accounting for the wave growth (Muschietti, Goldman, and Newman, 1985), and it is difficult to explain how any growth at all can occur. Indeed quite extreme assumptions are required to account for wave growth (Melrose and Goldman, 1987).

In summary, (i) the form of the observed electron spectra suggests that when the waves do grow, the effect of the electrons appears to be well described by one-dimensional quasi-linear theory, at least over times as long or longer than that required to measure the particle distribution, and (ii) the conditions for Langmuir waves to grow do not appear to be satisfied for type III events in the solar wind – some special assumptions are required to account even for the highly inhomogeneous growth implied by the observed clumpy distribution of the Langmuir waves.

3.3. HARD X-RAY GENERATING BEAMS

The first detailed observations of solar hard X-ray bursts (Frost, 1969) provided evidence on the energy spectra of the precipitating electrons (Brown, 1971). Early interest in the interpretation of hard X-ray bursts concerned whether the electron energy spectrum is thermal or nonthermal and whether the emission is due to thick-target or thin-target bremsstrahlung. It is now accepted that although the energy spectrum is not well determined by the X-ray data, there are events where the spectrum appears quasi-thermal and others where there are clearly nonthermal features, and that most hard X-rays are due to thick-target bremsstrahlung.

The energy in the downgoing electron beams that produce hard X-ray bursts is thought to provide the energy for Hα, EUV, and soft X-ray emission in flares. Most of the energy in the precipitating electrons goes into ablation of chromospheric matter, which rises to produce soft X-ray emission. The consistency of this picture was confirmed for a specific flare by de Jager and Švestka (1985) who compared the energy in > 25 keV precipitating electrons (from hard X-ray data) with the energy in upward moving gas, and found the two to be approximately equal (1×10^{24} J).

The downward propagating electron beams transport momentum as well as energy to the chromosphere. Momentum balance is provided by the heated chromospheric gas having both red-shifted (downgoing) and blue-shifted (upgoing) components (e.g., Zarro *et al.*, 1988). The evidence for both energy and momentum balance provides support for the ablation (or evaporation) model, and hence for the hypothesis that much of the energy released in flares goes into $\gtrsim 20$ keV electrons.

3.4. Instabilities due to downward propagating electron beams

The downward propagating electron beams are subject to various plasma instabilities. One particular instability involves Langmuir-type waves generated by the anomalous Doppler effect in a region where the electron-cyclotron frequency exceeds the plasma frequency (e.g., Lifshitz and Tomozov, 1974; Holman, Kundu, and Papadopoulos, 1982). As in the case of the Langmuir waves in type III bursts discussed above, it has been argued (Vlahos and Papadopoulos, 1979) that marginal stability for this instability is achieved. There can be an interplay between the streaming instability and the anomalous Doppler instability (Vlahos and Rowland, 1984). These and other possible instabilities generate waves that cannot escape directly from the plasma, and which may be loosely described as longitudinal waves. Plasma emission due to such longitudinal waves is a possible direct signature of such instabilities, possibly leading to a spike of microwave emission.

More generally, radio spikes (e.g., the review by Benz, 1986) are regarded as radio signatures of the precipitating electrons. The favored emission mechanism for these bursts is electron cyclotron maser emission (Holman, Eichler, and Kundu, 1980; Melrose and Dulk, 1982), which is a topic of active current interest. However, plasma emission mechanisms (e.g., Vlahos, Sharma, and Papadopoulos, 1983) cannot be ruled out. An important detail of the theory is the form of the free energy to drive the maser. Ideas on this free energy have been influenced by data on the precipitating electrons in the Earth's auroral zone that produce the auroral kilometric radiation through electron cyclotron maser emission. The earliest idea involves an upward directed loss cone feature in the reflected (upgoing) electrons, as suggested for the auroral kilometric radiation by Wu and Lee (1979). Other features of the electron distribution in the auroral zones have been identified as possible candidates for the source of free energy for the maser; some of the most interesting ideas have arisen from the VIKING data, cf. the review by A. Roux in this workshop.

The details of the generation and propagation of the electron beam are crucial to the detailed understanding of the way the maser is driven. However, the theory has other uncertainties when applied to the interpretation of radio spikes. An ongoing problem concerns the difficulty in accounting for the escape of radiation generated at the fundamental cyclotron frequency through the second harmonic absorption layer (Melrose and Dulk, 1982). Two new and different ideas on how this problem might be overcome have been proposed recently (McKean, Winglee, and Dulk, 1989; Robinson, 1989).

In summary, downward propagating electron beams may be subject to both electrostatic and electromagnetic instabilities. Electrostatic instabilities could cause the emission of radio spikes due to some form of plasma emission. The electromagnetic instability, which is electron cyclotron maser emission, is potentially a useful diagnostic. However, as yet the interpretation of radio spikes is inadequately understood for them to be used to infer detailed features of the propagation of the beams.

3.5. GENERATION OF A RETURN CURRENT

The upgoing, type III emitting electron beams and the downgoing, hard X-ray emitting electron beams both require return currents. The return current needs to be cospatial with the direct current so that the net current I does not exceed the Alfvén–Lawson limit or, alternatively, that I satisfies (2). Once the need for a return current is recognized, two questions arise. First, of what observational significance is the presence of a return current? Second, how is the return current set up?

The return current involves thermal electrons drifting in the opposite direction to the primary electron beam (number density n_b, speed v_b) such that the drift speed is

$$v_d = \frac{n_b}{n_e} v_b . \tag{3}$$

If this drift speed exceeds the threshold for a current-driven instability, then appropriate waves are generated, with the ion sound instability being the one most often considered. Suggested consequences of the reverse current generating ion sound waves include the following: (i) An enhanced form of plasma emission in type III bursts was proposed by Melrose (1970); the ion sound waves coalesce with Langmuir waves and scatter the Langmuir waves into the backward direction to produce enhanced forms of fundamental and second harmonic plasma emission, respectively. (ii) The ion sound turbulence causes anomalous electric conductivity leading to an enhanced form of thermal dissipation for hard X-ray generating beams (Hoyng, Brown, and van Beek, 1976; Brown and Melrose, 1977; Knight and Sturrock, 1977). (iii) The ion sound turbulence causes anomalous thermal conductivity in a thermal conduction front that limits the escape of energetic electrons from the region of primary energy release in a flare (Brown, Melrose, and Spicer, 1979). These and other effects associated with ion sound turbulence generated by a return current are possible only if the drift speed implied by (3) exceeds the ion sound speed.

The question of how the return current is set up was raised by Spicer and Sudan (1984), who argued that it is inductively driven, rather than electrostatically driven as early authors assumed. This question has been somewhat controversial, cf. however, the paper in this workshop by G. van den Oord, who shows that the 'inductive' and 'electrostatic' distinction has little meaning in a full treatment. However, the problem of setting up the return current should not be dismissed lightly. To highlight the difficulty (and exaggerate it somewhat) electrons precipitating at 10^{36} s^{-1} constitute a primary current of 10^{17} A, and if the net current is not to exceed $I_A \approx 10^3$ A then one requires current neutralization to one part in 10^{14} in all places at all times. The important point is that the way the return current is driven needs to be considered on both the scale size of the beam itself and also on the scale size of the smallest current that needs to be neutralized.

To explore how the return current is set up in detail requires a model for the acceleration of the electrons and for their escape from the acceleration region. One simple model has been explored in a simulation experiment by Winglee, Pritchett, and Dulk (1988a, b) who found that the direct and return currents are not cospatial on a microscopic scale. The implications of such detailed numerical modeling on a microscopic scale in the overall setting up of a return current on the scale of the electron beams of interest are unclear. Further analytic and numerical modeling is required to clarify the details of the physics of return currents on a global scale.

3.6. OTHER ENERGETIC ELECTRONS IN THE SOLAR CORONA

The electron beams discussed so far are associated with the mildly relativistic electrons accelerated in the impulsive phase of flares and in storms that produce type III emission. As mentioned, there are various other types of solar radio bursts that are thought to be associated with electron beams. The interpretation of these widens the contexts in which electron beams are produced. The herringbone structure in type II bursts and SA events imply that type III-like electron beams can be produced at shock fronts. Type I bursts, especially in view of the correlation with type III bursts in type I–III storms, imply the acceleration of electron beams in active regions, presumably associated with magnetic reconnection. Drift pair bursts, S-bursts and the zoo of decimetric bursts are further examples where electron beams are probably involved, but the implications are less clear.

All these electron beams involve first-phase-like electrons, that is, electrons with energies in the range, say, 2–20 keV. There is evidence for higher energy electrons, both from the observations of γ-rays from solar flares (Peterson and Winkler, 1959), which are attributed to bremsstrahlung by high energy (MeV) electrons, and from observations of relativistic electrons in solar cosmic rays. However, there is no evidence that such electrons form beams.

4. Ion Beams

The most direct signature of ion beams in the solar atmosphere comes from γ-ray lines (Chupp *et al.*, 1973, and the review by Hudson, 1985). The threshold ion energy for production of the lines is ≈ 30 MeV per nucleon. In those events where γ-ray lines are detected the total number of energetic ions produced in the flare is in the range 10^{31}–10^{33} (e.g., Ramaty and Murphy, 1987). An unexpected observational feature is that there is no significant time delay in the acceleration of these ions, that is, they appear to be accelerated on a time-scale $\lesssim 1$ s (Chupp, 1983) characteristic of the 'first phase', in contradiction to the older idea that ion acceleration is a second phase phenomenon (Wild, Smerd, and Weiss, 1963).

It has been suggested that the primary energy release in flares is into ion beams, rather than into electron beams as assumed above. Colgate (1978) favored ion beams on the grounds that the current associated with an electron beam could not propagate (cf. the remark on this suggestion in Section 5 however). More recently, Simnett (1986) presented similar arguments in favor of proton beams. While the suggestion that the primary energy release is into proton beams rather than electron beams is not widely supported, it does not appear to have been has refuted entirely convincingly. On the other hand, it has not been shown that proton beams can account for the wide variety of phenomena that can be explained in terms of electron beams.

Apart from γ-ray lines for ions with energies $\gtrsim 30$ MeV per nucleon, there are few signatures of ion beams in the corona. One possible signature of sub-MeV ion beams is in the ultraviolet, specifically the red wing of Lα. Existing observational evidence (Canfield and Cook, 1978) indicates only that the ratio of the ion to electron flux in flares is below the threshold for detection. The stability of such beams against the generation of Alfvén waves places limits on their ability to propagate (Tamres, Melrose, and Canfield, 1989).

5. Bulk Energization Due to Current Dissipation

It appears that the primary energy release in the impulsive phase of a flare occurs through current dissipation in the corona leading to bulk energization of electrons, with these electrons escaping from the acceleration region and forming electron beams that transport most of the energy released down to the chromosphere. *Bulk energization* may be defined as an acceleration mechanism in which the mean energy of effectively all particles in a localized volume increases by a factor 2–100, say. Neither the bulk energization nor the formation of beams is adequately understood.

5.1. NEUTRALIZED AND UNNEUTRALIZED CURRENTS

There are several relevant ways of classifying flare models according to the form of the current being dissipated. One classification is based on whether the current is flowing across (perpendicular current) or along (parallel current) the magnetic field lines, e.g., Spicer (1982). For example, magnetic reconnection may be attributed to the dissipation of a perpendicular current, and current interruption (e.g., at a double layer) to dissipation of a parallel current.

It is also helpful to introduce another classification of coronal current systems, depending on whether they are neutralized or unneutralized. Note first that the net current flowing into or leaving the corona must be zero (except on the capacitive time-scale, which is of the order of light propagation time across the circuit here). The current in a given flux tube is said to the *neutralized* if the net current at each footpoint is zero, and is said to be *unneutralized* if there is a net current from one footpoint to the other. Dissipation of a perpendicular current in a flare is appropriate only for a neutralized current in a single flux tube or for unneutralized, oppositely directed currents in two interacting flux tubes. Observations of the vector magnetic field seem to favor unneutralized current systems (e.g., Hagyard, 1989). Observational evidence on flares associated with interacting flux tubes, which correspond to two bipolar regions (Machado *et al.*, 1988), does not seem to support oppositely directed currents playing an important role. It seems reasonable to conclude that these arguments favor dissipation of a parallel unneutralized current.

Nevertheless let us first consider bulk energization due to the dissipation of a perpendicular current. The most familiar example of such dissipation is in a current sheet (e.g., Vasyliunas, 1975). The energy released goes partly into heat and partly into the kinetic energy of plasma escaping along the separatrix at about the Alfvén speed, e.g., the magnetospheric observations reported by Lin *et al.* (1977). It is not clear how such energy release could lead to bulk energization in the form believed to occur in flares. In particular the kinetic energy in the jets of plasma squirted out the separatrices is predominantly in the ions and not in the electrons. This kinetic energy needs to be converted into random electron motion to account for bulk energization.

5.2. THERMALIZATION OF WEAK DOUBLE LAYERS

Dissipation of a parallel current may be described in terms of a circuit model. The flaring flux tube is regarded as an electric circuit carrying a current I, with resistance R_c and with a parallel potential drop $\Phi = IR_c$ across it. The power dissipated in the flare is then identified as $P = I\Phi$. With $I = 10^{12}$ A, to produce the power released in a large flare, say $P = 10^{22}$ W, requires $\Phi = 10^{10}$ V. In the model of Alfvén and Carlqvist (1967) this appears in a single large double layer. A more plausible model involves a large number of weak double layers (Khan, 1989). The implied coronal resistance $R_c = 10^{-2}$ ohm may then be attributed to anomalous ion sound resistivity associated with the weak double layers. It is tempting to attribute acceleration in either of these double layer models to particles simply falling down a parallel potential drop. However, this simple idea is unacceptable as the basis for a model of bulk energization.

The reason follows from an argument presented by Spicer (1983) and also by Holman (1985). Acceleration by a parallel potential drop leads to a beam of electrons propagating in one direction or a beam of ions propagating in the opposite direction, both of which involve a current in the latter direction. There is an important restriction on this mechanism in that the net current cannot change. An initial current of $I = 10^{12}$ A corresponds to a net flow of charge carriers at 10^{31} s^{-1}, and this number cannot change significantly as a result of the acceleration. (The argument is that this number can change only on the inductive time-scale, which is of the same order as the duration of the flare, so that the change cannot be by a factor of many orders of magnitude.) Hence, the total number of particles accelerated cannot exceed about 10^{31} s^{-1}, and this is negligible in comparison with the estimated 10^{36} s^{-1} in precipitating electrons. It follows that the acceleration processes for the primary electron and ions in flares cannot be due to particles falling down a parallel potential drop. It might be remarked that this appears to undermine one of Colgate's (1978) reasons for postulating that the energy release goes into ions rather than electrons.

A possible mechanism that involves weak double layers and avoids this difficulty is the following. Bulk energization may be attributed to the individual double layers forming by extracting the necessary potential energy from the directed energy in the current and randomizing this energy as they beak up. Energy flows from the current system into the double layer as the double layer forms. Each weak double layer has a relatively short lifetime. Statistically, the number of double layers remains constant as the dissipation proceeds, with the rates of formation and break up of individual double layers being in balance. The randomizing process in the break up of the weak double layers is associated with the ion sound turbulence that is needed to maintain the charge separation. The potential energy associated with the charge separation in the double layer is converted effectively into heat through the dissipation of the ion sound turbulence. This process might be called *thermalization* of the potential energy due to the continual formation and break up of weak double layers.

5.3. FORMATION OF BEAMS

Data on the spikes in the energy release in flares indicate that bulk energization occurs over a substantial volume (linear dimensions ≈ 300 km) in each spike (de Jager *et al.*, 1987). Bulk energization presumably leads to electron beams when the hot electrons propagate out of the region in which they are accelerated. How these electron beams set up the return current that enables them to do this is not clear. This problem requires further investigation. A related problem is how some of the electrons find their way onto open field lines to escape and form type III beams. It has been suggested that such escaping electrons might be due to a secondary acceleration process resulting from the absorption of electron–cyclotron maser emission (Sprangle and Vlahos, 1983). A model for the escape of the type III emitting electrons from the same regions as the hard X-ray emitting electrons is desirable.

6. Outstanding Problems

As mentioned in the Introduction, there are four aspects of beams that are of interest: acceleration of particles, formation of beams, propagation of beams and dissipation of beams. None of these aspects is adequately understood.

6.1. ACCELERATION OF PARTICLES

The term ‘acceleration’ of particles is used with the following three different meaning:

Bulk energization implies that all the particles in a localized region have their mean energy increased by a significant factor.

Formation of a suprathermal tail implies that a small fraction of the particles become separated from the main body of particles in velocity space to form a high-speed tail.

Acceleration of a ‘seed’ population implies further acceleration of suprathermal particles to higher energies.

Of these the least understood is bulk energization, which is, however, widely accepted as the primary energy release mechanism in solar flares (and also in type I storms).

Progress in understanding bulk energization requires further theoretical work. Bulk energization describes any enhanced form of collisionless dissipation that is collisionlike in converting other forms of energy essentially into heat, with greatly enhanced heating in localized regions. Such enhanced dissipation may be attributed to anomalous transport coefficients. Anomalous electric conductivity or resistivity is appropriate when the energy is supplied by a current. 'Magnetic reconnection' is associated with dissipation of a current in a sheet, and more generally of a perpendicular current. Dissipation of a parallel current is conventionally attributed to double layers, but at least in its simplest form this does not lead to bulk energization. A process called 'thermalization of weak double layers' is suggested above as a possible bulk energization process due to dissipation of a parallel current. Further formulation and analysis of models for bulk energization are desirable.

On the observational side, the type of data that may help in the understanding of bulk energization is likely to come from three areas: observation of bulk energization in the laboratory, *in situ* data on bulk energization in space plasmas, and high resolution data on energy release events in the solar atmosphere. The highest time resolution possible in microwaves and hard X-rays is required in order to identify the smallest scale on which energy release and bulk energization occurs.

Of particular importance in identifying the processes involved in the primary energy release in flares is much higher resolution of the vector magnetic field. Available data indicate a close relation between the current flowing in a flux tube and the energy release in a flare kernel (e.g., Lin and Gaizauskas, 1987; Machado *et al.*, 1988; Hagyard, 1988). From a theoretical viewpoint, the spatial and temporal structures of the electric current in a flaring flux tube are of central importance in understanding the details of the energy release. With higher resolution of the current one could hope to relate the size of the current channels to the localized regions of energy release inferred from other high resolution data (e.g., Sturrock *et al.*, 1984; de Jager *et al.*, 1987).

6.2. FORMATION OF BEAMS

Electron beams in solar flares form when electrons escape from the region or regions where the primary energy release occurs. However, the details of how the beams form have received little attention. Uncertainties remain as to how the return current is set up in detail (Spicer and Sudan, 1984; Brown and Bingham, 1984). In part this controversy may be attributed to inadequate modeling of the escape of the electrons from the primary energy release region. For example, even such a basic question as whether bulk energization and beam formation are to be treated as simultaneous or sequential processes does not appear to have been addressed.

Realistic modeling of the formation of beams requires data that identify the basic structure of the beams. The importance of high-resolution data cannot be overemphasized.

6.3. PROPAGATION OF BEAMS

The understanding of how streaming and other instabilities develop is the central theoretical problem in the interpretation of nonthermal radio emission from the Sun. The most widely studied instability is that for Langmuir waves in type III beams.

Although considerable progress has been made in our understanding of how type III beams propagate through the solar corona and the solar wind, the details of the instability that generates the Langmuir waves have not been tested realistically against the electron data. To do so requires much higher time resolution in the measurement of the particle distribution function. Specifically, the electron distribution function must be measured on a time-scale shorter than the estimated growth time for the instability in order to identify the features in the distribution function that drive the instability. A similar situation occurs with radio spike bursts that are attributed to electron-cyclotron maser emission by downward propagating electron beams. In place of *in situ* data, one needs high time and space resolution of the radio emission to make realistic progress in modeling the instability.

There are other types of radio burst that are probably signatures of electron beams. It is desirable to pursue further modeling of type I bursts, of fine structures in decimetric bursts, and of less familiar radio bursts with fine structure such as drift pair bursts and S-bursts. Many of the fine structures are so specific that it seems that quite specific properties of either the beam or of the ambient medium need to be invoked. Satisfactory interpretation of radio bursts with fine structure is likely to add significantly to our understanding of the propagation of electron beams in the corona.

6.4. Dissipation of beams

The dissipation of downward propagating electron beams, and possibly of ion beams, is important in understanding the wide variety of secondary phenomena associated with solar flares. The possible role of instabilities involving either the direct current or the return current is an area where some progress has been made but which is far from being well understood.

In conclusion, major progress in the understanding of particles beams in the solar atmosphere is likely to result from higher resolution observations, especially of the vector magnetic field, of the electron distribution in type III events in the solar wind, of hard X-ray bursts, and of radio spike bursts.

References

Alfvén, H.: 1939, *Phys. Rev.* **55**, 425.

Alfvén, H. and Carlqvist, P.: 1967, *Solar Phys.* **1**, 220.

Bennett, W. H.: 1934, *Phys. Rev.* **45**, 890.

Benz, A. O.: 1986, *Solar Phys.* **104**, 99.

Brown, J. C.: 1971, *Solar Phys.* **18**, 489.

Brown, J. C.: 1985, *Plasma Phys. Contr. Fusion* **27**, 1359.

Brown, J. C. and Bingham, R.: 1984, *Astron. Astrophys.* **131**, L11.

Brown, J. C. and Melrose, D. B.: 1977, *Solar Phys.* **52**, 117.

Brown, J. C., Melrose, D. B., and Spicer, D. S.: 1979, *Astrophys. J.* **228**, 592.

Cane, H. V., Stone, R. G., Fainberg, J., Stewart, R. T., Steinberg, J. L., and Hoang, S.: 1981, *Geophys. Res. Letters* **8**, 1285.

Canfield, R. C. and Cook, J. W.: 1978, *Astrophys. J.* **225**, 650.

Chiuderi, C.: 1983, in J. O. Stenflo (ed.), *Solar and Stellar Magnetic Fields: Origins and Coronal Effects*, D. Reidel Publ. Co., Dordrecht, Holland, p. 113.

Chupp, E. L.: 1983, *Solar Phys.* **86**, 383.

Chupp, E. L., Forest, D. J., Higbie, P. R., Suri, A. N., Tsai, C., and Dunphy, P. P.: 1973, *Nature* **241**, 333.

Colgate, S. A.: 1978, *Astrophys. J.* **221**, 690.

De Jager, C. and Švestka, Z.: 1985, *Solar Phys.* **100**, 435.

De Jager, C., Kuijpers, J., Correia, E., and Kaufmann, P.: 1987, *Solar Phys.* **110**, 317.

Ellis, G. R. A.: 1969, *Australian J. Phys.* **22**, 177.

Frost, K. J.: 1969, *Astrophys. J.* **158**, L159.

Ginzburg, V. L. and Zheleznyakov, V. V.: 1958, *Soviet Astron. AJ* **2**, 653.

Grognard, R. J.-M.: 1984, *Solar Phys.* **94**, 165.

Grognard, R. J.-M.: 1985, in D. J. McLean and N. R. Labrum (eds.), *Solar Radiophysics*, Cambridge University Press, Cambridge, p. 253.

Gurnett, D. A. and Anderson, R. R.: 1977, *J. Geophys. Res.* **82**, 632.

Gurnett, D. A., Anderson, R. R., Scarf, F. L., and Kurth, W. S.: 1978, *J. Geophys. Res.* **83**, 4147.

Hagyard, M. J.: 1988, *Solar Phys.* **115**, 107.

Holman, G. D.: 1985, *Astrophys. J.* **293**, 584.

Holman, G. D., Eichler, D., and Kundu, M. R.: 1980, in M. R. Kundu and T. E. Gergely (eds.), *Radio Physics of the Sun*, D. Reidel Publ. Co., Dordrecht, Holland, p. 457.

Holman, G. D., Kundu, M. R., and Papadopoulos, K.: 1982, *Astrophys. J.* **257**, 354.

Hoyng, P., Brown, J. C., and van Beek, H. F.: 1976, *Solar Phys.* **48**, 197.

Hudson, H. S.: 1985, *Solar Phys.* **100**, 515.

Kan, J. R., Akasofu, S.-I., and Lee, L. C.: 1983, *Solar Phys.* **84**, 153.

Kane, S. R.: 1974, in G. Newkirk Jr. (ed.) *Coronal Disturbances*, D. Reidel Publ. Co., Dordrecht, Holland, p. 105.

Khan, J. I.: 1989, *Proc. Astron. Soc. Australia* **8**, 29.

Knight, J. W. and Sturrock, P. A.: 1977, *Astrophys. J.* **218**, 306.

Lawson, J. D.: 1957, *J. Electr. Contr.* **3**, 587.

Lifshitz, M. A. and Tomozov, V. N.: 1974, *Soviet Astron. AJ* **18**, 331.

Lin, R. P.: 1985, *Solar Phys.* **100**, 537.

Lin, Y. and Gaizauskas, V.: 1987, *Solar Phys.* **109**, 81.

Lin, R. P., Anderson, K. A., McCoy, J. E., and Russell, C. T.: 1977, *J. Geophys. Res.* **82**, 2761.

Lin, R. P., Potter, D. W., Gurnett, D. A., and Scarf, F. L.: 1981, *Astrophys. J.* **251**, 364.

Machado, M. E., Moore, R. L., Hernandez, A. M., Rovira, M. G., Hagyard, M. J., and Smith, J. B., Jr.: 1988, *Astrophys. J.* **326**, 425.

Magelssen, G. R. and Smith, D. F.: 1977, *Solar Phys.* **55**, 211.

McKean, M. E., Winglee, R. M., and Dulk, G. A.: 1989, *Solar Phys.* **122**, 53.

Melrose, D. B.: 1970, *Australian J. Phys.* **23**, 871.

Melrose, D. B.: 1974, *Solar Phys.* **38**, 205.

Melrose, D. B. and Cramer, N. F.: 1989, *Solar Phys.* **123**, 343.

Melrose, D. B. and Dulk, G. A.: 1982, *Astrophys. J.* **259**, 884.

Melrose, D. B. and Goldman, M. V.: 1987, *Solar Phys.* **107**, 329.

Melrose, D. B. and McClymont, A. N.: 1987, *Solar Phys.* **113**, 241.

Melrose, D. B., Dulk, G. A., and Cairns, I. H.: 1986, *Astron. Astrophys.* **163**, 229.

Moreton, G. E. and Severny, A. B.: 1968, *Solar Phys.* **3**, 282.

Muschietti, L., Goldman, M. V., and Newman, D. L.: 1985, *Solar Phys.* **96**, 181.

Nelson, G. J. and Melrose, D. B.: 1985, in D. J. McLean and N. R. Labrum (eds.), *Solar Radiophysics*, Cambridge University Press, Cambridge, p. 333.

Peterson, L. E. and Winkler, J. R.: 1959, *J. Geophys. Res.* **64**, 697.

Ramaty, R. and Murphy, R. J.: 1987, *Space Sci. Rev.* **45**, 213.

Roberts, J. A.: 1958, *Australian J. Phys.* **12**, 327.

Robinson, P. A.: 1989, *Astrophys. J.* **341**, L99.

Ryutov, D. D. and Sagdeev, R. Z.: 1970, *Soviet Phys. JETP* **31**, 396.

Simnett, G. M.: 1986, *Solar Phys.* **106**, 165.

Smith, D. F. and Sime, D.: 1979, *Astrophys. J.* **233**, 998.

Spicer, D. S.: 1981, *Solar Phys.* **70**, 115.

Spicer, D. S.: 1983, *Adv. Space Res.* **2**, 135.

Spicer, D. S. and Sudan, R. N.: 1984, *Astrophys. J.* **280**, 448.

Sprangle, P. and Vlahos, L.: 1983, *Astrophys. J.* **273**, L95.

Sturrock, P. A.: 1964, in W. N. Hess (ed.), *Physics of Solar Flares*, AAS–NASA Symp. NASA SP-50, Washington D.C., p. 357.

Sturrock, P. A., Kaufmann, P., Moore, R. L., and Smith, D. F.: 1984, *Solar Phys.* **94**, 341.

Takakura, T. and Shibahashi, H.: 1976, *Solar Phys.* **46**, 323.

Tamres, D. H., Melrose, D. B., and Canfield, R. C.: 1989, *Astrophys. J.* **342**, 576.

Vasyliunas, V. M.: 1975, *Rev. Geophys. Space Phys.* **13**, 303.

Vlahos, L. and Papadopoulos, K.: 1979, *Astrophys. J.* **233**, 717.

Vlahos, L. and Rowland, H. K.: 1984, *Astron. Astrophys.* **139**, 263.

Vlahos, L., Sharma, R. R., and Papadopoulos, K.: 1983, *Astrophys. J.* **275**, 374.

Wild, J. P.: 1950, *Australian J. Sci. Res.* **A3**, 541.

Wild, J. P., Smerd, S. F., and Weiss, A. A.: 1963, *Ann. Rev. Astron. Astrophys.* **1**, 291.

Winglee, R. M., Pritchett, P. L., and Dulk, G. A.: 1988a, *Astrophys. J.* **327**, 968.

Winglee, R. M., Pritchett, P. L., and Dulk, G. A.: 1988b, *Astrophys. J.* **329**, 440.

Wu, C. S. and Lee, L. C.: 1979, *Astrophys. J.* **230**, 621.

Zaitsev, V. V., Mityakov, N. A., and Rapoport, V. O.: 1972, *Solar Phys.* **24**, 444.

Zarro, D. M., Canfield, R. C., Strong, K. T., and Metcalf, T. R.: 1988, *Astrophys. J.* **324**, 582.