SPATIAL FRAGMENTATION OF SOLAR FLARE PLASMA
AND BEAMS

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Abstract. The observational and theoretical arguments for spatial fragmentation of the bulk of the thermal and non-thermal components of solar flare plasma are summarised. Observational aspects considered include XUV filling factors, EUV centre to limb variations, and \(H\alpha\) impact polarisation. Theoretical points addressed are the high flare inductance and beam/return current closure at the acceleration site.

A high degree of beam/plasma filamentation implies strong transverse temperature gradients so that cross-field conduction must be included in energy transport modelling. Preliminary results are described for a simple two-component model.

Key words: flares, solar – beams – fragmentation

1. Introduction

Here we use the term ‘fragmented’ in the sense of extensive spatial inhomogeneity of the bulk of flare plasma (while flare energy dissipation must involve thin structures, these do not necessarily permeate the bulk of the plasma). In other papers herein considerable evidence is given for type III bursts occurring in various fragmented channels but the plasma and beams involved probably comprise only a small fraction of the flare volume and energy. We will therefore consider XUV and optical flare emission whose sources constitute the bulk of the flare plasma, and hard X-ray (HXR) emission whose source electrons carry a large fraction of the flare non-thermal energy. One issue is whether these data lend support to a ‘top-down’ fragmentation with energy release driven by large scale factors, or a ‘bottom-up’ one in which the bulk release is the cumulative sum of many small events.

2. Observational Evidence of Plasma and Beam Fragmentation

The spatial scale on which fragmentation is anticipated is far below possible telescope resolution but fragmentation can be inferred indirectly from spectropolarimetric and anisotropy data, combined with larger scale images.

First, XUV resonance lines yield the hot plasma emission measure \(EM = \int_V n^2 dV\), while forbidden line ratios yield a mean spectrometric density \(<n>\) and telescope images yield the total volume \(V\). An important fact is that the observed filling factor \(EM/(<n>^2V)\) is always \(\ll 1\). This implies that the hot XUV plasma volume is highly inhomogeneous in temperature (see

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eg, Doschek, Al'meaky et al. and references therein). This may explain why hot (XUV) and cool (optical) loops are sometimes observed to be almost cospatial in large scale images.

Second, a more model dependent conclusion can be drawn from the observation of Donnelly and Kane (1978) that the ratio of EUV to HXR flare flux declines with heliocentric distance. Since the HXR and EUV flare light curves are closely synchronised, an electron beam heated model seems appropriate but, according to these authors, can only be reconciled with centre-to-limb data in a 'trench' model, in which the beam is fragmented, the EUV being generated only in local 'trenches' in the surrounding atmospheric structure.

Third, Fletcher and Brown (1993) have pointed out that the observed polarisation of flare H{\alpha} lasts too long and is too extensive to be due to impulsive phase electron or proton beam impacts. They find, however, that a viable model is highly fragmented impact excitation by evaporative hot plasma upflow at its interface with cool plasma at its boundaries.

3. **Theoretical Arguments for Intense (HXR) Beam Fragmentation**

Beam models of HXR bursts (Brown, 1971) essentially yield a value for the quantity

$$\mathcal{F} = \int_S \int_V f_e(v, r)|v| d^3v dS$$

where $f_e(v)$ is the electron velocity distribution function, and $S$ is the area across the beam. For a large flare $\mathcal{F} \approx 10^{36}s^{-1}$ (Hoyng et al., 1976). If $f_e(v)$ is strongly collimated in a single direction then $|v| \approx v$ and the resulting beam current is $I_b \approx e\mathcal{F} \approx 10^{17}$A. Such a 'naked' beam is impossible, not least because it would have a magnetic self-energy vastly in excess of the flare magnetic energy which created it, which corresponds to a flare region drift current $I_d < 10^{13}$A for reasonable fields $\mathbf{B}$. The need to 'reduce' the net beam current far below $e\mathcal{F}$ suggests that the beam system must be fragmented, for at least three reasons.

1. The high inductance of a flare region permits no significant change in the total current from $I_d$ during a flare, energy dissipation only being possible through a spatial redistribution of $\mathbf{j}$ (cf. Melrose 1993). One way to reconcile this with the large value of $e\mathcal{F}$ is that $\mathcal{F}$ comprise a large number of ($\approx I_b/I_d \approx 10^4$) counterstreaming beams.

2. If flare onset arises because $\mathbf{j}$ reaches a critical value $j_c(n_c, T)$, one can estimate from coronal densities and temperatures the largest possible area occupied by $\mathbf{j} = j_c$ before the resulting $\mathbf{B}$ becomes unreasonably large. The need for sufficient total magnetic energy then gives an esti-
mate for the total number of such current filaments required (Melrose, 1993).

3. If one considers only beam propagation, problem 1 is eliminated by a coplanar plasma return current (Knight and Sturrock, 1977). However, the electric field generated by the beam, to drive the return current, is opposite to that accelerating the beam. In a lab experiment the plasma current returns charge to the accelerator cathode via the grid anode (J. D. Lawson (1984)—private communication). Such elements are of course excluded in a flare and the only mechanism proposed for current closure (Winglee et al., 1991) is for the beam and return current to be not coplanar but filamented on the scale of an ion-gyro radius.

All three of these arguments appear to require that the numerous elements of the fragmented flare current and beam distribution organise themselves with large scale coherence, pointing strongly to a ‘top-down’ rather than a ‘bottom-up’ process of energy release.

4. Energy Transport in a Filamented Beam Plasma Structure

The very extensive work (see eg, Kundu and Woodgate, 1986) which has been carried out on energy transport in beam heated flare plasma has concentrated solely on 1-D hydrodynamic treatments with the field acting solely as a rigid channel for longitudinal gas flow and heat conduction. In a highly filamented structure, however, cross-field gradients may be so large that cross-field thermal conduction must be considered. We present here preliminary results of a simple two-component filamented model we are developing, in which cross-field conduction is considered.

Consider a longitudinally short segment of a structure made up of a large number $N$ of cylindrical elements, each comprising an inner section of radius $\rho R$, with a mean electron density and temperature $n_1$, $T_1$, surrounded by an annulus of outer radius $R$ and parameters $n_2$, $T_2$. For simplicity, we take the inner region to be heated by thin target collisions of an electron beam of total rate $\mathcal{F}/N$ electrons s$^{-1}$, and electron energy $E$, and cooled by cross-field thermal conduction to the outer annulus, which is in turn cooled by radiative losses so that a steady state is achieved. $T_1$ is assumed high enough for conduction to far exceed radiation. Finally the system is closed by assuming constant gas pressure, $nT$. The two energy balance equations are then crudely

$$\frac{\Lambda e^4}{8\pi\epsilon_0 E} \frac{\mathcal{F}}{N} \approx 2\pi\rho R \kappa_{\perp}(B, n_1, T_1) \frac{T_1}{\rho R}$$

$$\approx \pi R^2 (1 - \rho^2) n_2^2 f_{\text{RAD}}(T_2)$$

where $f_{\text{RAD}}$ is the radiative loss function (Cox and Tucker, 1969) and (Rosenbluth and Kaufman, 1958) $\kappa_{\perp} \propto n^2/B^2 T^{1/2}$. We seek parameter regions
which allow self-consistent solutions in which $T_1$ is well above the peak in $f_{\text{RAD}}(T)$ while $T_2$ is below it, where we approximate

$$f_{\text{RAD}}(T) \approx (3.76 \times 10^{-28} \text{eV m}^3 \text{s}^{-1})(T/\text{K})^{2.3}.$$  

The adjustable input parameters are $B$, $\mathcal{F}$, $n_1$, $\rho$, $N$, $R$, with the ultimate intent being to constrain these so that: $T_1$, $T_2$ and the total emission measures $\pi \rho^2 R^2 n_1^2 N L$ and $\pi (1 - \rho^2) R^2 n_2^2 N L$ be compatible with XUV and optical data; and $\mathcal{F}$ be compatible with HXR data. In particular these five constraints should put bounds on the number $N$ of filaments involved.

A typical set of results for our preliminary calculations for $B = 0.01 \text{T}$, $\mathcal{F} = 10^{36} \text{s}^{-1}$, $E = 50 \text{keV}$, $N = 10^6$, $n_1 = 10^{16} \text{m}^{-3}$, and $\rho = 0.2$, is $T_1 = 1.1 \times 10^6 \text{K}$, $T_2 = 8.4 \times 10^3 \text{K}$, $n_2 = 1.3 \times 10^{18} \text{m}^{-3}$, $N \pi R^2 = 10^{14} \text{m}^2$.

5. Conclusions

There is strong theoretical and observational support for the idea that flare energy release and acceleration is highly fragmented, but a great deal of work is required to understand how such a structure is achieved and how it modifies flare energy transport.

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References