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# PLASMA TURBULENCE AND IMPULSIVE UV LINE EMISSION IN SOLAR FLARES

**John C. Brown**

Department of Astronomy
University of Glasgow
G12 8QW, Scotland

ABSTRACT

Observations show that hard X-ray burst and UV lines rise and fall simultaneously on time scales of seconds. Hydrodynamic simulations of beam-heated atmospheres, based on collisional transport, however, produce only a gradual fall in UV emission, when the beam flux falls, due to the long time scale of conductive relaxation. It is suggested that this discrepancy might be explained by onset of plasma turbulence driven by the strong heat flux or by the beam return current going unstable. Such turbulence greatly reduces electrical ($\sigma$) and thermal ($\kappa$) conductivities. Fall in $\sigma$ reduces the hard X-ray flux by enhanced ohmic dissipation of the return current, while fall in $\kappa$ may cause the UV line to fall by reducing the transition region thickness.

## 1 Introduction

Simultaneous SMM data in hard X-ray and UV lines exhibit synchronism of both rise and fall of impulsive spikes down to time scales of order of seconds. The driving mechanism for both is believed to be a thick target electron beam. However, numerical simulation of the atmospheric response to such a beam (Mariska and Poland, 1985) does not reproduce synchronous fall in the two emissions. In such simulations, UV line emission rises because of the direct heating effect of the beam and because of the increased conductive flux in the transition region driven by beam heating of the corona (cf Section 2). Though the direct heating turns off with the beam, the fall in the enhancement due to conduction is gradual because the corona acts as a heat reservoir.

This paper gives a very preliminary discussion of how onset of beam generated plasma turbulence might modify the simulation results through anomalous transport effects.

## 2 Line Formation in the Flare Transition Region

An injected electron beam dominates flare atmosphere heating in the corona and in the low chromosphere, where the temperature gradient is rather small, while in the upper chromosphere and transition region, after a brief initial transient, the steep temperature gradient results in energy transport being dominated by thermal conduction (driven by the coronal beam heating) - e.g. Shmeleva and Syrovatskii (1973) and subsequent authors. In a quasi-steady transition region there is negligible direct beam heating, because of the small column mass, and essentially constant conductive flux down to the temperature ($\simeq 10^5$K) where radiative losses become stable and maximal, and where densities become high enough for conductive deposition to be radiated away. Furthermore, because of the small column mass, the transition region can be adequately described as having spatially uniform pressure.

For a conductive energy flux F emanating from the corona, the thermal structure of the transition region is then described by

$$\kappa(T) \frac{dT}{dz} = F \qquad (1)$$

where $\kappa(T)$ is the thermal conductivity at temperature T, at geometric depth z. Since the bulk of the energy of a beam is deposited in the corona, F is essentially the energy flux of the beam.

An optically thin collisionally excited transition region line of wavelength $\lambda$, with emissivity $n^2 f_\lambda(T)$ (erg cm$^{-3}$s$^{-1}$) at plasma density n, temperature T, will have a total luminosity per unit area

$$I_\lambda = \int_Z n^2(z)\, f_\lambda\, (T(z))\, dz \qquad (2)$$

where n is determined by the constant pressure condition $nT = n_o T_o$ where $n_o$ is the atmospheric density at the upper chromospheric level where the bolometric radiative loss curve maximises at temperature $T_o$ ($\simeq 10^5$K). $n_o$ will, of course, depend on the magnitude of F, the higher value associated with a flare pushing the base of the transition region deeper in the atmosphere to the depth where $n_o$ is high enough to radiate off the input. For lines formed in the upper transition region ($T \gtrsim 10^5$K), (2) then becomes

$$I_\lambda = n_o{}^2 T_o{}^2 \int_Z \frac{f_\lambda(T)}{T^2}\, dz \qquad (3).$$

As a first approximation, a typical line may be approximated as being formed over a fixed interval $\Delta T$ centred on the peak temperature T of line formation and (3) can be approximated, using (1), as

$$I_\lambda = n_o{}^2 T_o{}^2 \int_T \frac{f_\lambda(T)}{T^2} \frac{dT}{F/\kappa(T)} = \left\{ \frac{T_o{}^2}{T^2} f_\lambda(T)\Delta T \right\} \frac{n_o{}^2 \kappa(T)}{F} \qquad (4)$$

where $\kappa(T)$ is a mean value of $\kappa$ over $\Delta T$ approximated by its value at line peak T.

It follows that <u>if $\kappa(T)$ remains of the same form</u>, $I_\lambda$ is determined by

$n_o^2/F$. Increase in F alone during a flare would result in a decrease in $I_\lambda$ due to the transition region becoming thinner. However, as already noted, increase in F also results in increase in $n_o$ and steady state numerical simulations (Emslie, 1985) show that the rise in $n_o$ more than offsets the decrease in $\Delta Z = \kappa(T)\Delta T/F$ and the nett result is a rise in UV flux $I_\lambda$ accompanying an increase in thick target hard X-ray flux due to the increased F. Time dependent simulations (Mariska and Poland, 1985) confirm this and show that the rise is closely synchronous but that when F falls, the thermal conduction relaxation time is too long for $I_\lambda$ to track F. All of these calculations, however, assume that $\kappa(T)$ retains the same form throughout and in particular neglect the consequences of onset of anomalous transport processes.

## 3 Effect of Onset of Plasma Turbulence on Transition Region Lines

### 3.1 Qualitative Description

Suppose that instead of assuming the beam flux F to peak at the observed peak of a radiation spike, while transport is still classical, we suppose that during its rise F exceeds a threshold for anomalous transport effects to set in. This may be due to one or more of three processes: two-stream instability of the beam itself, resulting in Langmuir wave generation (e.g. Emslie and Smith 1983; McClements et al 1985 - this Workshop); drift current instability of the beam driven return current resulting in generation of electrostatic (ion-cyclotron, ion-acoustic) waves (e.g. Hoyng et al 1977; Cromwell et al 1985, Holman 1985 - this Workshop); heat flux instability resulting in electrostatic wave generation by the currents associated with steep thermal gradients (Mannheimer 1977, Brown et al 1979, Smith and Lilliequist 1979). Here we will concentrate our attention on the last two processes as it is these which will directly affect thermal and electrical conductivities.

When such plasma waves appear, the effective electron collision frequency will increase, resulting in a fall in both electrical ($\sigma$) and thermal ($\kappa$) conductivities. Decrease in $\sigma$ will increase the electric field required to drive the return current, reducing beam electron lifetimes, and consequently the X-ray bremsstrahlung from the beam. Decrease in $\kappa$, on the other hand, will result in a decrease in the transition region thickness (1) and consequently in $I_\lambda$ provided $n_o$ does not rise enough to offset this factor. The extent to which $n_o$ will eventually rise for a given change in $\kappa$ will have to be determined by a steady state numerical calculation (cf Machado and Emslie 1979). For the moment we will assume that $n_o$ is determined mainly by the input flux F rather than by details of $\kappa(T)$ and that the $\kappa$ factor in $I_\lambda$ overwhelms the $n_o^2$ factor. Likewise, the time scale on which the transition region thins will have to be found by time dependent numerical simulation. We note, however, that a change in structure purely due to a change in coronal heating when F changes will take roughly the time of propagation of a thermal front along the coronal loop length. On the other hand, re-adjustment of the transition zone structure due to an in situ change of $\kappa$ (typically in a few plasma periods) will occur in the much shorter time needed for a thermal front to cross the transition region.

## 3.2 Conditions for Onset of Anomalous Transport in the Flare Transition Region

If beam electrons are injected into the transition region at a total rate $\mathcal{F}(s^{-1})$ over an area A then the condition for return current instability can be written

$$n\left(\frac{kT_e}{m_e}\right)^{1/2} f(T_e/T_i) < \mathcal{F}/A \qquad (5)$$

where f declines from about unity as $T_e/T_i$ increases from unity (e.g. Hoyng et al 1977, Brown and Hayward 1981).

On the other hand, the heat flux $F = E\,\mathcal{F}/A$ is likely to drive wave generation if it significantly exceeds the saturated value $\sim \frac{1}{6}n\left(\frac{kT_e}{m_e}\right)^{1/2}kT$ or roughly

$$n\left(\frac{kT_e}{m_e}\right)^{1/2}\frac{kT_e}{E} \lesssim \mathcal{F}/A \qquad (6)$$

where E is the mean energy of beam electrons.

From (5) and (6) we see that which effect sets in first depends on the value of f compared to $kT_e/E$. With $E \gtrsim 10\,\mathrm{KeV}$ and $kT_e \lesssim 6.5\,\mathrm{KeV}$ for the transition region, it seems almost certain that heat flux instability will set in first except for very high $T_e/T_i$ values and near the top of the transition zone. (Noting the condition $nT_e$ = constant we see that the left side of (5) varies as $T_e^{-1/2} f(T_e/T_i)$ which increases with depth in the atmosphere whereas the left side of (6) varies as $T_e^{1/2}$ and so decreases with depth - i.e. the heat flux is most unstable at low $T_e$.) In absolute numerical terms, the separate criteria are as follows.

### Heat Flux Instability

If the transition region pressure is $P(\mathrm{dyne\ cm^{-2}}) = 10^2 P_2 \simeq nkT_e$ and with $T = 10^6 T_6(\mathrm{K})$, $\mathcal{F} = 10^{36}\mathcal{F}_{36}(s^{-1})$, $A = 10^{18}A_{18}(\mathrm{cm}^2)$ and $E = 10E_1(\mathrm{KeV})$ then (6) becomes

$$\frac{\mathcal{F}_{36}E_1}{A_{18}} \gtrsim 2.3P_2T_6^{1/2} \qquad (7).$$

Thus for typical flare transition region pressures $P_2 \simeq 0.3-3$ (e.g. Machado et al 1979) and temperatures $T_6 \simeq 1$ and with the electron beam parameters $\mathcal{F}_{36} \simeq E_1 \simeq 1$ typical of large hard X-ray bursts, heat flux instability in the transition zone is likely if the injection area $A \lesssim 4 \times 10^{17}\mathrm{cm}^2$ which is very possible.

Return Current Instability

With the same notation and $f = 0.1\, f_{-1}$, (5) becomes

$$\frac{\mathcal{F}_{36}}{A_{18}} \gtrsim 27\, P_2 f_{-1} \quad (8).$$

This condition will be satisfied only if f is particularly small, due to large $T_e/T_i$, or if the injection area A is << $10^{18} cm^2$, for typical flare transition region pressures. It is more readily satisfied in the corona, where P is smaller (and $\mathcal{F}$ larger), and so may contribute strongly there to beam deceleration, and hence to the fall in bremsstrahlung from the beam.

3.3 Quantitative Effect of Plasma Turbulence in the Transition Region

Both the electrical ($\sigma$) and thermal ($\kappa$) conductivities are determined by the effective collision frequency $\nu_{eff}$ of the electrons, viz

$$\kappa \simeq 6 \times 10^{11} n_{10} T_6/\nu_{eff} \quad \mathrm{erg\,cm^{-1}\,s^{-1}\,K^{-1}} \quad (9)$$

and

$$\sigma \simeq 2 \times 10^{18} n_{10}/\nu_{eff} \quad \mathrm{s^{-1}} \quad (10)$$

where $n_{10} = \frac{n}{10^{10}}$ .

In the classical regime $\nu_{eff} = \nu_{coll}$ given by

$$\nu_{coll} = 7 \times 10^2 \; n_{10}/T_6^{3/2} \quad (11)$$

whereas in the presence of (e.g. ion-acoustic) waves of energy density W, $\nu_{eff}$ becomes of order

$$\nu_{eff} = \nu_{pe}\left(\frac{W}{nKT}\right) = 10^9 n_{10}^{1/2}\left(\frac{W}{nKT}\right) \quad (12)$$

where $\nu_{pe}$ is the plasma frequency. Thus the classical and anomalous transport coefficients become

$$\kappa_{class} = 10^9 T_6^{5/2} \quad (13a)$$

$$\kappa_{AN} = 6 \times 10^2 n_{10}^{1/2} T_6 \Big/ \left(\frac{W}{nKT}\right) \quad (13b)$$

and

$$\sigma_{class} = 3 \times 10^{15} T_6^{3/2} \quad (14a)$$

$$\sigma_{AN} = 2 \times 10^9 n_{10}^{1/2} \Big/ \left(\frac{W}{nKT}\right) \quad (14b).$$

If then, during a UV/HXR burst, waves are generated by either return current or heat flux instability, at wave onset the thermal conductivity and hence the transition region scale thickness will fall by a factor (Equation

(1))

$$\frac{\Delta Z_{AN}}{\Delta Z_{class}} = \frac{\kappa_{AN}}{\kappa_{class}} \simeq 6 \times 10^{-7} n_{10}^{1/2} T_6^{-3/2} / \left(\frac{W}{nKT}\right) \qquad (15).$$

The actual value of W/nKT depends on how the waves are driven. Simulations of return current instability (Cromwell et al 1985 - these proceedings) lead to values of W/nKT as high as $10^{-3}$ at saturation and around $10^{-5}$ in marginal stability. In the more relevant case of heat flux instability, Brown et al (1979) found that in the case of extreme temperature gradients, unstable generation of ion sound waves led to $W/nKT \simeq (m_e/m_p)^{1/2} \simeq 1/43$ for which (15) gives

$$\frac{\Delta K_{AN}}{\Delta K_{class}} \simeq 2 \times 10^{-4} P_2^{1/2} / T_6^{2}$$

Consequently, neglecting any compensating factor due to increase of $P_o$, Equations (4) and (16) show that a small increase in F past a critical threshold can result in a reduction in UV line strength by several orders of magnitude. Furthermore, we expect this decrease to be very fast - roughly the time it takes for F to rise above the instability threshold across the temperature domain of formation of the line concerned.

Whether wave generation is driven by heat flux or return current instability , its effect on $\sigma$ will act on the electron beam in two ways. Firstly, it will increase the electric field driving the return current and so decelerate the beam in the region of its propagation. Secondly, and more speculatively, it may feed back on the region of acceleration of the beam and interfere with beam production (Brown and Melrose 1977). To see the consequences of the first effect on the HXRB, we can compare the thick target bremsstrahlung yield in the case of collisional losses only (the usual thick target case - Brown 1971) with that when strong return current losses dominate. In each case the bremsstrahlung photon yield at energy $\varepsilon$ from an electron of initial energy $E_o$ is roughly $\nu = nQ_B v\tau$ where $Q_B$ is the bremsstrahlung cross section (appropriately averaged over electron energies between $\varepsilon$ and $E_o$), v is the electron velocity and $\tau$ is stopping lifetime. In the classical (collisional case) $\tau = E_o^2 / 2\pi e^4 \Lambda n v$ and so

$$\nu_{class}^{Brems} \simeq \frac{Q_B E_o^{2}}{2\pi e^4 \Lambda} \quad \text{(photons per electron)} \qquad (17).$$

In the case of return current losses dominating (e.g. Brown and Hayward 1981) $\tau = m_e v_o/(ej/\sigma) = \sigma A E_o / e^2 \mathcal{F} v_o$ so that the photon yield is

$$\nu_{AN}^{Brems} \simeq nQ_B \sigma_{AN} A E_o / e^2 \mathcal{F} \qquad (18).$$

Taking the ratio of (18) to (17) substituting, for $\sigma_{AN}$ from (14b) and inserting numerical values then gives

$$\left(\frac{\nu_{AN}}{\nu_{class}}\right)_{Brems} \simeq 3 \times 10^{-8} \frac{n_{10}^{3/2} A_{18}}{\mathcal{F}_{36} E_1} \Big/ \left(\frac{W}{nKT}\right) \qquad (19)$$

which even with W/nKT as small as $10^{-4}$ implies a fall in thick target bremsstrahlung yield of over 3 orders of magnitude, effectively switching off the hard X-ray production entirely.

## 4 Conclusions

In summary, when the electron beam flux in a beam heated flare becomes large enough for onset of wave generation either directly by the beam return current, or via production of heat flux beyond saturation, we expect an immediate reduction in both hard X-ray burst intensity (due to anomalous return current dissipation) and simultaneously in the emission of UV lines from the transition region (due to reduction in its thickness by anomalous thermal conductivity). The exact magnitude and time scales of this effect require further investigation by numerical simulation, hopefully as a sequel to this Workshop. In particular, the effect of reducing $\kappa$ on the transition region pressure (i.e. $n_o$) and its effect on the above conclusions is the topic of Workshop related collaborations.

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