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Letter to the Editor

Instability of beam-driven return currents in the deep chromosphere of solar flares

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Abstract.
It is shown that, contrary to previous thinking, the return current driven by a thick target flare beam may be unstable to ion sound wave generation in the deep chromosphere, particularly for intense hard beams and early in the flare. This is so despite the strong collisional attenuation of the beam and the high plasma density in the chromosphere because the low ionisation there results in a high drift velocity of the few free electrons available to carry the return current. The resulting ion acoustic wave generation will enhance local beam heating and affect diagnostics through the presence of enhanced microscopic and return current electric fields.

Key words: Sun:flares –electron beams –return currents

1. Introduction

The potential importance for flare beam transport of the electric field set up to drive a beam-neutralising return current against the finite plasma resistivity was first noted by Hoyng (1975), Hoyng et al. (1976), Brown and Melrose (1977) and Knight and Sturrock (1977) and discussed in greater detail by Emslie (1980,1981) and Brown and Hayward (1980) among others. An important limiting factor in beam propagation is that intense enough beams drive a return current faster than the critical drift speed for electrostatic wave generation. These waves enhance the resistivity and hence Ohmic energy losses of the beam to plasma heating and may even act to limit the maximum possible beam flux to the wave generation threshold value (e.g. Brown and Melrose (1977)). In these analyses it has been assumed that if the return current is subcritical at the injection site it will remain so thereafter because collisions reduce the beam flux with depth and the atmospheric density rises much faster than the thermal speed falls (apart from across the transition region) - cf Emslie (1981). In this Letter we draw attention to the fact that this assumption can be invalid when allowance is made for the fall in the free electron density available to carry the return current in the weakly ionised low chromosphere. We consider only the case of an electron beam but essentially the same considerations apply to a proton beam.

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2. Collisional beam propagation

As a first approximation we assume the beam distribution with depth to be collision dominated and use the resulting beam current variation with depth to assess the self-consistency of the assumption in terms of return current stability. We adopt a power law spectrum at injection of flux spectral index δ and total flux $F_1(cm^{-2}s^{-1})$ above cut-off energy E_1, and zero pitch angle. Allowing for Coulomb scattering and energy losses, following Brown's (1972) treatment gives for the beam current at column density $N(cm^{-2})$ from the injection site

$$j_b(N) = \begin{cases} F_1 e & N \leq N_1 \\ F_1 e \left(\frac{N}{N_1}\right)^{(1-\delta)/2} & N > N_1 \end{cases} \quad (1)$$

where $N_1 = E_1^2/3K$ and the constant $K = 2\pi e^4 \Lambda$ in the Coulomb cross-section K/E^2 has been assumed independent of N. In practice the Coulomb logarithm Λ will decline from its ionised hydrogen value Λ_{ee} of around 20 near the hot injection site to its neutral hydrogen value $\Lambda_{eH} = \Lambda_{ee}/2.6$ in the deep atmosphere (Brown 1973, Emslie 1978). For simplicity we will consider the limiting cases of $\Lambda = \Lambda_{ee}$ everywhere and $\Lambda = \Lambda_{eH}$ everywhere with the latter more relevant to the weakly ionised layers of interest here.

Beam current neutralisation then requires a plasma electron drift current density $j_p = n_e e v_D = j_b$ at speed v_D where n_e is the electron density given by $n_e = n(x + x_M)$ with n the total (neutral and ionised) hydrogen density, x the degree of hydrogen ionisation, and x_M the correction for metallic electrons which we take as 10^{-4}. Ion-sound waves and their generation by a drift current in a weakly ionised plasma with neutral collisions have been discussed by Mikhailovskii (1974, p.126) among others and the key parameter is the ratio of v_D to the ion sound speed $v_{is} = (kT_e/m_i)^{1/2}$. Equating j_p to j_b given by (1) yields for this ratio, $R = v_D/v_{is}$

$$R(N) = \frac{v_D}{v_{is}} = \frac{F_1}{n(N)(x(N)+x_M)(kT_e(N)/m_i)^{1/2}} \times \begin{cases} 1 & N \leq N_1 \\ \left(\frac{N}{N_1}\right)^{(1-\delta)/2} & N > N_1 \end{cases} \quad (2)$$

Mikhailovskii gives the criterion $R \geq 1$ for ion sound wave growth for cold ions but not the dependence of the criterion on

T_e/T_i. Since we are concerned here only with checking whether instability may arise because of the low free electron density we will take the criterion $R \geq 1$ as of the right order of magnitude.

3. Target atmosphere distribution

The importance of return current dissipation and possible instability depend on conditions in the target atmosphere, being greatest when the atmosphere is coolest and least dense, such as at the start of the flare. Here we consider the value of $R(N)$ for the values of $n(N)$, $T(N)$, $x(N)$ in a variety of atmospheres ranging from the quiet sun (QS) and active region (AR) models of Basri et al. (1979) to the flare models, 1, 2 and 3 of Machado and Linsky (1980). For the coronal region we have followed the procedure of Emslie (1981) and extrapolated across a constant pressure transition zone to an isothermal corona, using $n(N) = \frac{P_c-(N-N_c)m_H g}{2kT_0}$, where P_c and N_c are the pressure and column density of the transition zone respectively, and T_0 is the temperature of our isothermal corona which we take to be 10^6K for the quiet sun, 3×10^6K for the active region plage, 2×10^6K for active region bright points and 1.5, 2 and 4×10^7K for flare models 1, 2 and 3 respectively. Figs. 1, 2, 3 and 4 show the run of R and $x + x_m$ with N, the column density, found from these published models by translating geometric height into column density N where necessary.

We have computed $R(N)$ from (2) for these models for electron fluxes $F_1 = 10^{17} cm^{-2} s^{-1}$ and $F_1 = 1.5 \times 10^{17} cm^{-2} s^{-1}$ above $E_c = 25$ keV based on the total injection rate required for a large hard x-ray burst (Hoyng et al. 1976) spread over an area of $10^{18} cm^2$. Results are shown in Figs. 1, 2, 3 and 5, for spectral index $\delta = 4$, and in Fig. 4 for $\delta = 3$.

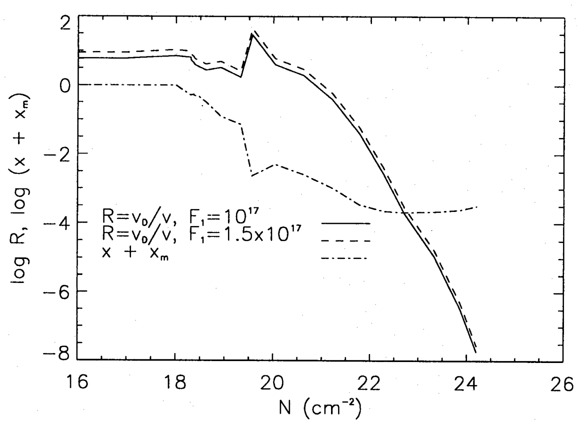

Fig. 1. Variation of R and degree of total ionization with column density,N, for quiet sun model, Basri et al. model C. $\Lambda = \Lambda_{eH}$ and $F_1 = 1.5 \times 10^{17}, 10^{17} cm^{-2} s^{-1}$, $\delta = 4$.

4. Discussion and conclusions

We see from Figs. 3 and 4 that the best candidate for instability for the models, fluxes and spectral indices considered, is the Basri P model of the active region plage, i.e. for a relatively cool atmosphere relevant to flare onset, as anticipated above. For both limiting cases of Λ and F_1 considered we find that, v_D is consistently less than v_{is} on injection but grows with decreasing ionization as N increases until the stability criterion

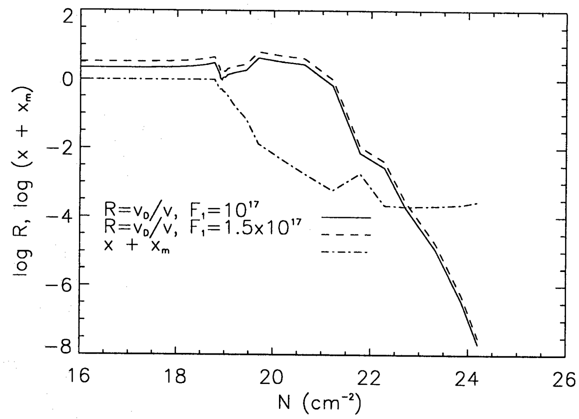

Fig. 2. Variation of R and degree of total ionization with column density, N, for active region bright point model, Basri et al. model BP. $\Lambda = \Lambda_{eH}$ and $F_1 = 1.5 \times 10^{17}, 10^{17} cm^{-2} s^{-1}$, $\delta = 4$.

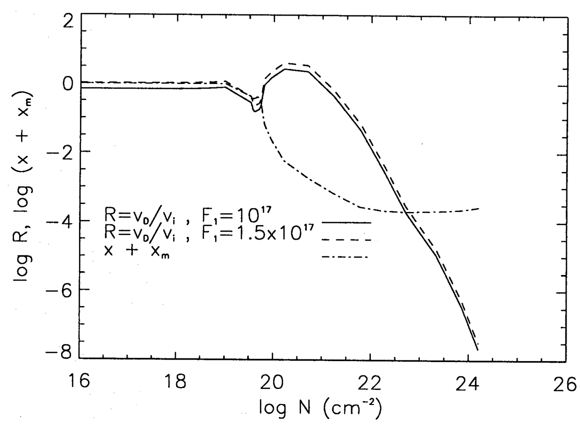

Fig. 3. Variation of R and degree of total ionization with column density,N, for active region plage model, Basri et al. model P. $\Lambda = \Lambda_{eH}$ and $F_1 = 1.5 \times 10^{17}, 10^{17} cm^{-2} s^{-1}$, $\delta = 4$.

is exceeded over a very substantial range of N. Here we show only the results for $\Lambda = \Lambda_{eH}$, the more relevant value in the deep chromosphere

A similar analysis applied to Basri et al. quiet sun model C, Fig. 1, seems to indicate that the drift velocity even at the relatively low initial fluxes considered here, will always exceed the ion sound speed throughout the corona. This would lead to rapid disintegration of the beam, or coronal heating leading to stabilization.

From Fig. 2 we can see that the results obtained for active region model BP seem to imply that beam stability through the corona in this model atmosphere would require a slightly lower initial flux than those considered here - for such a lower beam flux the stability criterion would be somewhat exceeded in the chromosphere.

Figure 5 shows the results obtained when considering beam propagation through Machado and Linsky's flare model atmosphere, importance 1. The coronal drift velocity is well below the ion sound speed for the conditions considered, since

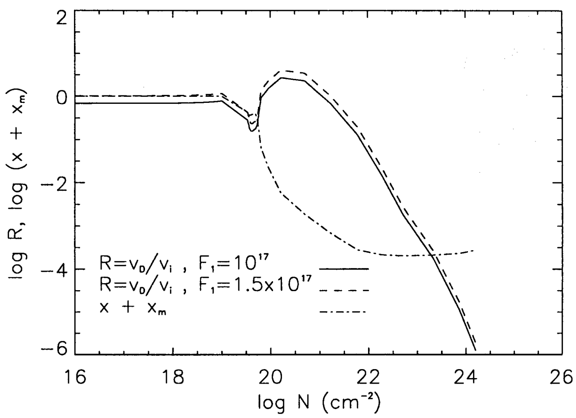

Fig. 4. Variation of R and degree of total ionization with column density, N, for active region plage model, Basri et al. model P. $\Lambda = \Lambda_{eH}$ and $F_1 = 1.5 \times 10^{17}, 10^{17} cm^{-2} s^{-1}$, $\delta = 3$.

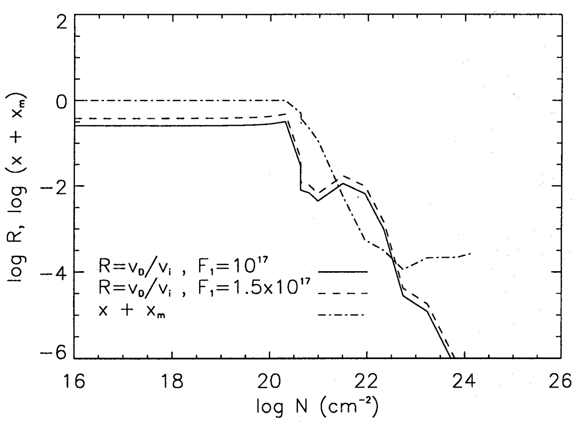

Fig. 5. Variation of R and degree of total ionization with column density, N, for flare model importance 1, Machado and Linsky. $\Lambda = \Lambda_{eH}$ and $F_1 = 1.5 \times 10^{17}, 10^{17} cm^{-2} s^{-1}$, $\delta = 4$.

the corona is hot. We can see that after the initial decline of the ratio, R, it begins to rise again to a small peak at $N \simeq 5 \times 10^{22} cm^{-2}$, but, for the stability criterion to be exceeded at this level would require a very large initial electron flux to compensate for the reduction in chromospheric beam flux caused by the large densities in this model. This would produce a corresponding increase in R throughout the corona, leading to beam disintegration before such a level was reached. Results obtained using the same beam parameters for models of importances 2 and 3 are similar.

These results are summarized in Table 1, where the range of flux and column density for which the beam-return current system is unstable to ion-acoustic wave generation is indicated. In all of those cases shown the beam is stable throughout the corona and, since this does not occur with a corresponding instability in the chromosphere for Machado et al.'s flare model this is not listed. In the cases of the Basri C and BP models the fluxes required to maintain stability through the corona are very low; we show these primarily for completeness.

Table 1. The range of column densities over which $R(N) > 1$ for a variety of F_1 in the models Basri C, BP and P. All of these fluxes are stable throughout the corona. Since stability in the corona with instability in the chromosphere cannot be achieved for the flare model importance 1 this is not shown.

Model	Flux ($cm^{-2}s^{-1}$)	Range of N where $R(N) > 1$
BP	2.4×10^{16}	$4.833 - 4.93 \times 10^{19}$
	$2.5 - 2.6 \times 10^{16}$	$4.833 - 5.0 \times 10^{19}$
	$2.7 - 2.8 \times 10^{16}$	$4.833 - 5.5 \times 10^{19}$
	$2.9 - 3.0 \times 10^{16}$	$4.833 - 6.0 \times 10^{19}$
	3.1×10^{16}	$4.833 \times 10^{19} - 1.45 \times 10^{20}$
	$3.2 - 3.5 \times 10^{16}$	$4.833 \times 10^{19} - 1.6 \times 10^{20}$
	3.6×10^{16}	$4.833 \times 10^{19} - 1.8 \times 10^{20}$
	$3.7 - 4.4 \times 10^{16}$	$4.833 \times 10^{19} - 4.23 \times 10^{20}$
P	$3.7 - 1.3 \times 10^{16}$	$1.63 - 1.634 \times 10^{20}$
	3.8×10^{16}	$1.63 - 1.67 \times 10^{20}$
	$3.9 - 4.0 \times 10^{16}$	$1.62 - 1.7 \times 10^{20}$
	4.1×10^{16}	$1.60 - 1.8 \times 10^{20}$
	4.2×10^{16}	$1.59 - 1.8 \times 10^{20}$
	4.3×10^{16}	$1.58 - 1.8 \times 10^{20}$
	$4.4 - 6.6 \times 10^{16}$	$1.63 - 5.004 \times 10^{20}$
	$6.7 \times 10^{16} - 1.0 \times 10^{17}$	$8.98 \times 10^{19} - 5.004 \times 10^{20}$
	$1.1 - 1.3 \times 1017$	$6.42 \times 10^{19} - 5.004 \times 10^{20}$
C	$4 - 5 \times 10^{15}$	$3.2 - 3.71 \times 10^{19}$
	$6 \times 10^{15} - 1.3 \times 10^{16}$	$2.5 - 4 \times 10^{19}$
	$9 \times 10^{15} - 1.3 \times 10^{16}$	$2.5 - 6 \times 10^{19}$
	$1.2 - 1.3 \times 10^{16}$	$2.5 - 7 \times 10^{19}$

It appears from this preliminary analysis that the low ionization in the chromosphere could provide a high enough drift velocity of those electrons free to carry the return current, sufficient to excite ion acoustic wave generation. This will, however, only occur for a limited set of conditions, particularly those in a 'cool' initial atmosphere affected by sudden beam onset. The onset of ion-acoustic waves will result in an increase in the effective collision frequency, ν_{eff}, and hence in the development of anomalous resistivity. When this occurs several effects are possible. Firstly, there may be rapid electron heating causing an increase of the value of v_{is} which will in turn reduce the value of $R(N)$. In this case the instability will switch off and the resistivity will return toward a classical value. Secondly, the increased heating associated with anomalous resistivity may lead to increased collisional ionization of the ambient plasma. In this case $x(N) + x_m$ will increase, $R(N)$ will correspondingly decrease, and again the instability will tend to switch off. However, if the resistivity remains anomalous on a sufficiently long timescale then we will find that the beam is strongly decelerated over a very short distance. The reason for this strong deceleration is that the electric field of the return current will increase, since $E = \eta J_p = \eta J_b$, and it is this increased electric field which decelerates the beam.

Anomalous resistivity increases the rate of Ohmic return current dissipation and the timescale on which the beam is stopped is given by $\tau_{stop} = (n_p/n_b)2/\nu_{eff}$ seconds (van den Oord, 1990). The beam is then stopped over a distance $v_b \tau_{stop} \simeq 30\beta(n_p/n_b)$ cm. At the point where this occurs there will be significant energy deposition enhancement in the atmosphere.

Abourdarham and Hénoux (1985) showed that white-light flare continuum emission can be produced as a result of heating caused by electron bombardment in the chromosphere. For an electron flux with a low energy cut-off at 80 keV they calculated that an energy flux of $2.5 \times 10^{10} erg cm^{-2} s^{-1}$ is required to produce the observed emission. If we consider the model atmosphere P of Basri et al. (1979) then we can see that a beam of 80 keV electrons would be stopped by the deceleration described above in a distance of $\sim 9 \times 10^6$ cm. For this model $R(N) > 1$ over a range of column depths $\sim 6 \times 10^{19} - 5 \times 10^{20}$. Therefore, it is likely that there will then be significant energy deposition in the layers of the atmosphere where anomalous resistivity dominates, possibly capable of producing whitelight continuum emission.

The ratio of return current to beam collisional heating rates at a depth N is given by

$$\frac{P_{RC}}{P_{coll}} = \alpha \times \frac{\left[\frac{7.26\times10^{-9}x}{T^{3/2}} ln\left[\frac{3}{2e^3}\left(\frac{k_B^3 T^3}{\pi n}\right)^{1/2}\right] + A\right] F_b^2 e^2}{\pi e^4 n\gamma(\delta-2)B(\delta/2, \frac{2}{4+\beta})\mathcal{F}_1\left[\frac{(2+\beta/2)\gamma K N}{E_1^2}\right]^{-\delta/2}} \quad (3)$$

where α is the factor by which the resistivity is enhanced over the collisional value, $A = \frac{7.6\times10^{-18}(1-x)T^{1/2}}{x}$, $\beta = \frac{2x\Lambda_{ee}+(1-x)(\Lambda''-\Lambda_{eH})}{\Lambda_{eH}+x(\Lambda_{ee}-\Lambda eH)}$, for an electron beam, $\Lambda'' = ln\left[\frac{1}{\alpha}\left(\frac{m}{m_e}\right)\left(\frac{v}{c}\right)\right]$ (Emslie, 1978) and $\gamma = m/m_e[x\Lambda_{ee} + (1-x)\Lambda_{eH}]$. For the fluxes used in Fig. 3 and at N values near the peak in R, this ratio is about $0.05\times\alpha$. Thus, if the resistivity is enhanced by wave generation by a factor $\alpha > 20$, then return current heating will dominate in this part of the chromosphere.

Finally we emphasise that we have only addressed the question of whether R may exceed unity in the chromosphere for coronally stable return currents and not what will happen when it does. This is a complicated and neglected issue - cf. Duijveman et al. (1981) and Cromwell et al. (1988). Qualitatively, as soon as the drift threshold is exceeded, η will rise, causing E to rise sharply and decelerate the beam, depositing energy by Ohmic dissipation of the return current at rates which may be well above beam collisions. This heating will raise the plasma temperature and ionisation and tend to turn the instability off. Based on Duijveman et al. (1981) and Cromwell et al. (1988) we would speculate that in practise the system will evolve through a series of marginally stable states with enhanced η and potentially important diagnostic signatures, which may include burst-like enhancements in XUV lines due to a lack of equilibrium between the electron temperature and ion ionization states and line broadening associated with the wave level. Detailed work in this area will be necessary to qauntify the process and relate it to data.

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