COLLISIONLESS EFFECTS ON BEAM-RETURN CURRENT SYSTEMS IN SOLAR FLARES

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ABSTRACT

A large fraction of the electrons which are accelerated during the impulsive phase of solar flares stream towards the chromosphere and are unstable to the growth of plasma waves. The linear and non-linear evolution of plasma waves as a function of time is analyzed with the use of a set of rate equations that follow in time the non-linearly coupled system of plasma waves-ion fluctuations. The non-thermal tail formed during the stabilization of the precipitated electrons can stabilize the Anomalous Doppler Resonance instability and prevent the isotropization of the energetic electrons. The precipitating electrons modify the way the return current is carried by the background plasma. In particular, the return current is not carried by the bulk of the electrons but by a small number of high velocity electrons. For beam/plasma densities $\gtrsim 10^{-3}$, this can reduce the effects of collisions and heating by the return current. For higher density beams where the return current could be unstable to current driven instabilities, the effects of strong turbulence anomalous resistivity is shown to prevent the appearance of such instabilities. Our main conclusion is that the beam-return current system is interconnected and how the return current is carried is determined by the beam generated strong turbulence.

1. Introduction

The intensity of non-thermal electrons, with energies between 10-200 keV, which is necessary to explain the observed x-ray emission in these energies is relatively high e.g. $F_b \simeq 10^{36}$ electrons/s (Hoyng et al. 1976). Assuming an area for the emitting source $\cong 10^{18}$ cm^2 and an average speed for the precipitating electron $v_b \simeq 10^{10}$ cm/sec one concludes that the density of the precipitating electrons is $n_b \simeq 10^8$ cm^{-3}. The plasma density in the low corona lies between $10^9 < n_o < 10^{11}$ cm^{-3} which leads us to conclude that $10^{-3} < n_b/n_o < 10^{-1}$. The consequences of such a large flux of non-thermal electrons streaming towards the chromosphere have up to now been discussed as two separate

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problems. The beam stabilization was addressed by Lifshitz and Tomozov (1974) and Vlahos and Papadopoulos (1979). The role of the return current on the other hand was addressed assuming that the beam was stable and the velocity of the "bulk" return current was estimated from the relation $v_r = (n_b/n_o)\, v_b$ (see Hoyng et al. 1978, Brown and Hayward (1982) and references therein). Vlahos and Rowland (1983) and Rowland and Vlahos (1983) suggest that the presence of a linearly unstable beam effects the way the return current is carried and the beam/return current must be viewed as one unified system.

2. Beam stabilization and strong turbulence effects

The dispersive characteristics of the plasma are modified dramatically when the beam generated waves W_r exceed a threshold value $(W_{th}/n_oT_e) \gtrsim (k_o\lambda_D)^2$, where T_e is the ambient temperature, k_o is the wave number of the beam driven waves ($k_o \sim \omega_e/v_b$), ω_e is the plasma frequency and λ_{De} is the electron Debye length). It is easy to show that for $n_b/n_o \gtrsim 10^{-5}$ the quasilinear saturation level of beam driven waves is above the threshold for strong turbulence. In other words, the beam generated waves will start forming solitons and reduce the wavelength of the beam driven plasma waves once $W_r > W_{th}$. The reduction of the wavelength of the unstable waves has several important consequences: (a) the waves that are non-resonant with the beam (W_{nr}) have small phase velocity ($\omega_e/k_{nr} \simeq (2\text{-}3)v_e$) and are damped in the tail of the thermal distribution. As a result of the interaction of the non-resonant, low phase velocity waves with the tail of the thermal distribution low energy non-thermal tails with energies around 5 ~ 10 keV will be formed. (b) The formation of solitons is coupled with the ions and forms ion cavities that are strongly coupled with the soliton pulses. Cavitons play an important stabilizing role in the newly arriving electron beams. A detailed analytical and numerical discussion of these processes has now been published and we refer the reader to the original papers and the references therein for further study (see Papadopoulos 1975 and Rowland 1980). The problem of beam-plasma interactions described above differs from the related work in type III bursts in two important ways. (1) the plasma is strongly magnetized ($\omega_p/\Omega_e \lesssim 1$, where Ω_e is the gyrofrequency) and (2) the beam density is much stronger $(n_b/n_o) \gtrsim 10^{-4} - 10^{-1}$. Both factors suggest that the system is one-dimensional and solitons collapsed from two-dimensional evolution will not be important (see Rowland, Lyon and Papadopoulos 1981). A system of rate equations for the regime that is described above is given below (see Vlahos and Rowland for detail discussion).

$$\frac{dW_r}{dt} = \gamma_L W_r - \gamma_{NL} W_{nr}\, \theta(W_r - W_{th}) - a_{NL} W_r \tag{1}$$

$$\frac{dW_{nr}}{dt} = \gamma_{NL} W_{nr} - \gamma_d W_{nr} - a_{NL} W_{nr}\, \theta(W_s - W_2) \tag{2}$$

$$\frac{dW_s}{dt} = \gamma_{NL} W_{nr} - \nu_s W_s\, \theta(W_s - W_2) \tag{3}$$

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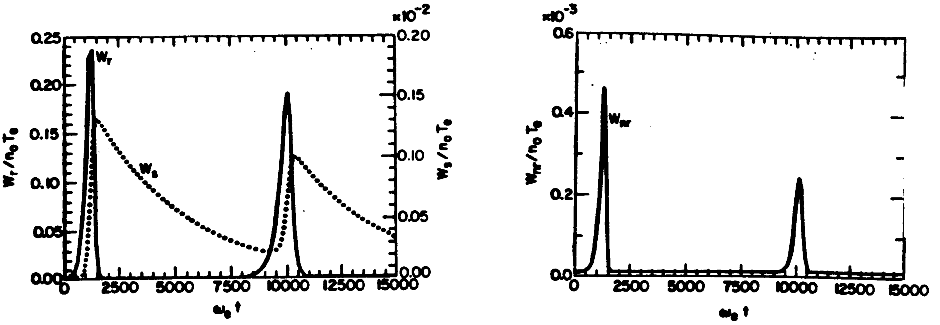

Fig. 1. Solution of the rate eq. (1)-(3)

where W_s is the ion wave energy, γ_L is the linear growth rate, γ_{NL} is the rate that the resonant waves are transferred to low phase velocities, γ_d is the Landau damping of the non-resonant waves in the tail of the thermal distribution, $\theta(x)$ is the step function, a_{NL} is the scattering of the high frequency waves from the ion density fluctuations ν_s is the damping of the ion density fluctuations. Solving the system eqs. (1)-(3) we found that the system of waves is pulsating periodically as it is shown in Fig. 1. Rowland (1980) demonstrated this behavior in fully kinetic, Vlasov simulations.

The main conclusion from our study of the beam-plasma interaction can be summaried as follows (Vlahos and Rowland, 1983):

a. The beam losess a few percent of its initial energy to maintain the pulsations shown in Fig. 1. The beam losses are minimized because the ion acoustic waves stabilize the beam between pulses.

b. The energy lost from the beam does not heat the bulk of the electrons but forms 5-10 keV non-thermal tails.

c. If $n_b/n_o > 10^{-2}$, strong turbulence does not prevent the initial quasilinear relaxation. However, since $W_r >> W_{th}$, strong turbulence effects still appear (non-thermal tails, solitons, cavitons, strong low frequency turbulence etc.). In particular, the high levels of low frequency turbulence will again decouple the beam from the plasma and later arriving beam electrons will lose little energy in the volume.

d. By increasing the Landau damping, the non-thermal tails can prevent the pitch angle of the beam particles by the anomalous Doppler resonance. Similarly the enhanced low frequency turbulence by increasing the scattering of the high frequency waves to lower phase velocities will increase the damping and quench this instability. Thus the particles that propagate along the field lines will suffer little cross field scattering and subsequent trapping on the coronal part of the loop.

3. Collisionless effects on the return current

The presence of beam excited solitons plays an important role on the return current. Low velocity electrons in the bulk of the distribution are trapped between solitons (Rowland et al. 1981). Only particles with velocity $\gtrsim$ (2-3) v_e can freely escape. A result of the trapping of the bulk of the ambient distribution is that the return current will be carried by fewer and thus more energetic electrons that are not trapped between solitons. The exact number of the electrons that will carry the return current and their final velocity depends upon the strength of the precipitating beam and the rise time of the beam acceleration process. We found (Rowland and Vlahos 1983) that

a. For weak beams $(n_b/n_o) < 10^{-3}$ and a slow rise time (a few secs) the return current is carried by particles that suffer several collisions before escaping from the loop. In this case the return current collisional heating estimated by several authors (see Brown and Hayward 1982) is modified in two important ways; (1) only a few percent of the ambient electrons carry the return current and (2) their average velocity is $\simeq$ (2-3) v_e.

b. For strong beams $n_b/n_o \gtrsim 10^{-3}$ and a fast rise time the return current is carried by a few collisionless electrons that obtain relatively high speed (4-6) v_e before escaping from the loop.

c. Because the return current is carried by superthermal electrons and the bulk of the plasma remains stationary, current driven instabilities (ion cyclotron, ion acoustic, etc.) will not appear even with very strong beams $(n_b/n_o > 10^{-2})$.

In summary we conclude that the beam-return current is a highly interactive system that must be discussed in a unified way. A first attempt in this direction is made recently by Vlahos and Rowland (1983) and Rowland and Vlahos (1983).

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DISCUSSION

Ionson: In what way do you and Spicer disagree?

Vlahos: The analysis presented by Spicer was based on two assumptions (a) the precipitating electrons were confined in a flux tube with 10 km diameter and (b) the beam (which was assumed stable) drives inductively a return current which is unstable. Using weak turbulence theory he estimated the anomalous resistivity and the decay of the return current. As I described, above the beam goes unstable first and the presence of solitons inhibits the bulk of the electrons from carrying the current; thus we concluded that the return current driven instabilities are out of the question. The assumption that weak-turbulence theory is valid is highly questionable because of the presence of strong parallel magnetic fields. Last, but not least, I would like to point out that if the area that carries the beam is (10 km)^2, the beam density has to be $n_b \sim 10^{12}$ cm^{-3} to explain the x-ray observations. Furthermore, if one assumes that the loop is filled with small tubes, still the problem is not solved, since you have to explain the interaction of the tubes, the density of beam electrons in each tube, etc. I honestly do not see why one has to assume such a filamentation of the precipitating beams. I know of no observation that supports such a claim and we know very little about the acceleration of these electrons to argue that such a filamentation really happens.

Spicer: I stated that the beam radius was determined by the acceleration region, not by the X-ray observations.

Also, how can you claim the inductive electric field associated with the decay of the return current only causes minimal beam losses if Rowland's code doesn't have Faraday's Equation in it?

Vlahos: The role of the beam driven inductive electric field was used in our analysis (see Rowland and Vlahos) to estimate the number of particles that are accelerated in the tail to neutralize the current carried by the precipitating electrons. From the simulations one can determine the strength of the inductive electric field and the amount of energy required to drive the needed return current. From this, one can find the beam energy loss.

Guillory: Similar relaxation-oscillation behavior, and effects due to cavitons and concomitant field spikes, were discussed in an astrophysical context (jets in galactic nuclei) by Rose et al. at the recent AAS meeting and are contained in a recently sumitted paper (Ap.J.).

D. Smith: When you combine this with the decay of return current a la Lee and Sudan, what will happen?

Vlahos: The decay of the current will take as much as 10^{12} secs. The reason being that we use a radius for the current carrying flux tube $R_L \simeq 10^8$-10^9 cm and that the bulk of the plasma is stable. The return current is carried from the tail and suffers only Coulomb collisions, thus the Spitzer conductivity is a good approximation when the collison rate is calculated using only the small number of high velocity electrons. Taking these two factors into account you can show that the decay time for the return current will be $\tau \simeq \tau_c\ (R_L^2/\lambda_e^2) \simeq 10^{12}$ sec! (where τ_c the collision time, $\lambda_e = c/\omega_e$, c is the speed of light and ω_e is the plasma frequency).