

## THEORETICAL STUDIES ON RAPID FLUCTUATIONS IN SOLAR FLARES

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Abstract

Rapid fluctuations in the emission of solar bursts may have many different origins e.g. the acceleration process can have a pulsating structure, the propagation of energetic electrons and ions can be interrupted from plasma instabilities and finally the electromagnetic radiation produced by the interaction of electrostatic and electromagnetic waves may have a pulsating behavior in time. In two separate studies (Vlahos, Sharma, and Papadopoulos, 1983; Vlahos and Rowland, 1984) we analysed the conditions for rapid fluctuations in solar flare driven emission.

1. Time evolution of a beam-plasma system

A possible interpretation of the solar hard X-ray bursts is that a relatively large flux of non-thermal electrons accelerated near the energy release site of a solar flare, stream along the magnetic field lines toward the chromosphere. The interaction of the non-thermal electrons with the ions in the upper chromosphere produces, via collisional Bremsstrahlung, photons with energies from 20 Kev to several Mev. The energetic electrons are unstable to the growth of plasma waves. In the linear regime, plasma waves with phase velocity  $\omega_e/k_b < v_b$  will grow with a rate

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$$\gamma_L = \frac{n_b}{n_0} (v_b/\Delta v_b)^2 \omega_e \cos^2 \varphi \quad (1)$$

where  $v_b$  is the beam velocity,  $\omega_e$  is the plasma frequency,  $n_b$ ,  $n_0$  are the beam and ambient densities,  $\Delta v_b$  is the beam spread around the beam velocity and  $\varphi$  the angle between the wave vector and the external magnetic field. As the beam driven waves reach a threshold value e.g.  $W_{th}/n_0 T_e = [v_e/v_b]^2$  the dispersion characteristics of the medium change dramatically and lead to the formation of solitons. The long wavelength high frequency waves are localised in space, producing soliton type formations in the wave energy and cavities in the ion density. The local ion density is proportional to the plasma wave energy (Papadopoulos, 1975) e.g.

$$\frac{\delta n}{n_0} = \frac{1}{[W_1^1/(2n_0 T_e)]} \quad (2)$$

where  $W_1^1$  is the energy density of the beam excited waves. The localization in space of the plasma waves causes a fast transfer of wave energy out of resonance with the beam electrons and into resonance with the low energy tail of the Maxwellian distribution. The rate with which the waves are transferred away from resonance with the beam is

$$\gamma_{NL} = (m/M)^{1/2} \{W_1^1/n_0 T_e\}^{1/2} \omega_e \quad (3)$$

for  $(W_1^1/n_0 T_e) > (v_e/v_b)^2$ . The net result from the soliton formation is: (1) the transfer of energy from the beam driven waves to non-resonant plasma waves ( $W_2^1$ ) with low phase velocity and (2) the excitation of ion-density fluctuations. As long as  $(W_2^1/n_0 T_e) = \delta n/n_0$  the ion fluctuations are undamped. The non-linear frequency shift, due to  $W_2^1$ , for the low frequency waves is  $-kc_s$ , so we obtain an essentially stationary non-linear ion perturbation. When  $W_2^1$  is absorbed by Landau damping on the electrons, this non-linear frequency shift disappears, and the ion fluctuations are converted to normal linear modes (ion acoustic waves) of the plasma and can

then damped.

The evolution of a beam-plasma system then follows three stages: (1) the linear growth of beam driven waves with rate  $\gamma_L$ . (2) Once the wave energy passes a threshold value, discussed above, a fast transfer of plasma waves to lower phase velocity waves occurs. (3) Ion density cavities are also formed once  $(W_1^1/n_0 T_e)$  is above  $(v_e/v_b)^2$ . When  $W_2^1 < W_s$  the non-resonant waves cannot support the cavitons and the "cavitons radiate" ion density fluctuations. The ion density fluctuations scatter the high frequency waves to lower phase velocities with a rate

$$\alpha_{NL} = (W_s/n_0 T_e)(\lambda_s/\lambda_{De})^2 \omega_e \quad (4)$$

where  $\lambda_s = 10\lambda_D$  and  $\lambda_{De}$  is the electron Debye length. The time dependent evolution of the beam driven waves can also be described by the following phenomenological system of rate equations

$$\frac{dW_1^1}{dt} = \gamma_L W_1^1 - \gamma_{NL} W_2^1 \theta(W_1^1 - W_2^1) - \alpha_{NL} W_1^1 \theta(W_s - W_2^1) \quad (5)$$

$$\frac{dW_2^1}{dt} = \gamma_{NL} W_2^1 \theta(W_1^1 - W_{th}) - \nu_L W_2^1 - \alpha_{NL} W_2^1 \theta(W_s - W_2^1) \quad (6)$$

$$\frac{dW_s}{dt} = \gamma_{NL} W_2^1 \theta(W_1^1 - W_{th}) - \nu_1 W_s \theta(W_s - W_2^1) \quad (7)$$

where  $\nu_L$  is the damping of the Langmuir waves in the tail,  $\nu_1$  is the damping of the ion density fluctuations and  $\theta$  is a step function (see more discussion on eqs(5)-(7) in Vlahos and Rowland, 1984). We solved eqs(5)-(7) numerically and the results are plotted in Fig.(1).

## 2. Stochastic three wave interaction

Electron beams, formed during the impulsive acceleration phase of a flare, stream continuously toward the chromosphere. Since the magnetic field increases slowly in the direction of propagation a fraction of the beam electrons precipitate while the remainder became part of the stably

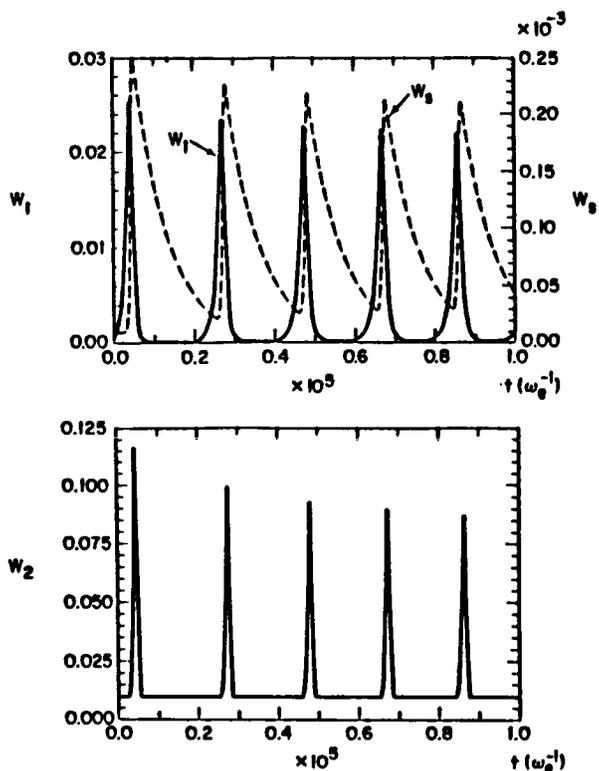


Figure 1: The rate equations are solved numerically using  $n_b/n_0=10^{-2}$ ,  $W_1^1(t=0)=5 \times 10^{-5}$ ,  $W_2^1(t=0)=W_s(t=0)=10^{-5}$ ,  $v_b/v_e=10$ . (a) The temporal evolution of the resonant high frequency waves and the acoustic wave (b) the temporal evolution of the non-resonant waves. The individual pulse have a duration  $\approx \mu\text{sec}$  to  $\text{msec}$ , dependig on the beam strength.

trapped component. For a plasma with cyclotron frequency ( $\Omega_e$ ) larger than the plasma frequency ( $\omega_e$ ), the presence of the beam can amplify waves in both , lower and upper hubrid brances. The beam exited electrostatic waves are convectivly amplified and propagate toward the cutoff region where their energy piles up in a narrow wave packet with bandwith  $\delta\omega_{UH}$ .

Coherent upconversion of the beam amplified electrostatic waves to electromagnetic waves produce an intrinsically stochastic emission component. For a coherent interaction we average the basic three wave coupling equations over space, retaining however their dynamic character. We thus have a zero-dimension but dynamic model. The energy input is steady and represents the rate at which electrostatic waves convert into the interaction volume. The three wave equations for the real amplitude( $\alpha_j$ ) and phase are

$$\frac{d\alpha_1}{dt} = \gamma_1 \alpha_1 - \Lambda_1 \alpha_2 \alpha_3 \cos \phi \quad (8)$$

$$\frac{d\alpha_2}{dt} = \gamma_2 \alpha_2 - \Lambda_1 \alpha_3 \alpha_1 \cos \phi \quad (9)$$

$$\frac{d\alpha_3}{dt} = \gamma_3 \alpha_3 + \Lambda_2 \alpha_1 \alpha_2 \cos \phi \quad (10)$$

$$\frac{d\phi}{dt} = -\delta\omega_{UH} + (\Lambda_2 \alpha_1 \alpha_2 / \alpha_3 - \Lambda_1 \alpha_1 \alpha_3 / \alpha_2 - \Lambda_1 \alpha_2 \alpha_3 / \alpha_1) \sin \phi \quad (11)$$

where  $\Lambda_1, \Lambda_2$  are the coupling coefficients and  $\gamma_j$  are the linear growth (or damping) of the wave.

The evolution of the electromagnetic wave is shown in Fig.(2).

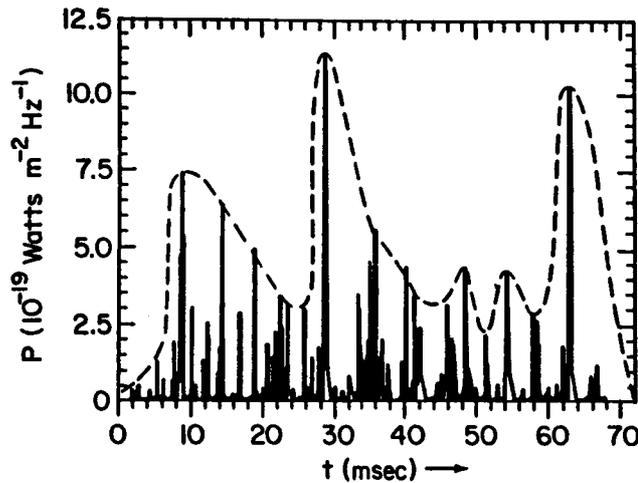


Figure 2: The time evolution of the electromagnetic wave resulting from the dynamic interaction of two electrostatic waves near the cutoff region. The individual pulses have a duration  $< 1$  msec. The dotted line represents the response of an instrument with resolution  $> 10$  msec.

## References

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