Advances in Plasma Astrophysics
Proceedings IAU Symposium No. 274, 2010
A. Bonanno, E. de Gouveia Dal Pino & A.G. Kosovichev, eds.

doi:10.1017/S174392131100706X

Electromagnetic emission by subsequent processes L→L'+S and L+L'→T

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Abstract. Using a 2.5-D electromagnetic particle-in-cell (PIC) model, very early stages of a generation of the electromagnetic emission produced by a monochromatic Langmuir wave are studied. It is found that the electromagnetic emission, which is dominant on the harmonic of the plasma frequency, starts to be generated in a very small region of k-vectors. Later on the k-vectors of this emission are scattered around a 'circle' (in our 2-D case), given by the relations for the L+L'→T process. Analytical analysis of two subsequent processes L→L'+S a L+L'→T confirms these results.

Keywords. waves, radiation mechanisms: general, Sun: radio radiation

1. Introduction

In astrophysical plasmas the Langmuir waves are easily generated (Benz 1993). But Langmuir waves are local waves and distant observers can obtain an information about them only after their transformation to electromagnetic ones. Several processes were proposed for this transformation, e.g.: $L \rightarrow T \pm S$ and $L + L' \rightarrow T$ (Melrose 1980). Details of these processes were studied by e.g. Robinson(1997), Bárta & Karlický (2000), and Willes *et al.* (1996). Furthermore, there are papers which studied this transformation numerically, usually after a generation of Langmuir waves by the two-stream instability (Sakai & Nagasuki 2007, Yu & Guangli 2008). In the present paper, using the PIC model, we study very early stages of this transformation.

2. Numerical modelling

We use a 2.5-D relativistic electromagnetic PIC code. The system size is $L_x = 1024\Delta$ and $L_y = 1024\Delta$, where Δ is a grid size. The electron-proton plasma with the proton-electron mass ratio m_p/m_e=1836 is considered. In each numerical cell we initiated 200 electrons and 200 protons. The electron thermal velocity was taken to be the same in the whole numerical box as $\mathrm{v}_T = 0.06\ c$, where c is the speed of light. The Debye length is $\lambda_D = 0.6\ \Delta$. The initial magnetic field in the system is zero. Then we initiated a monochromatic Langmuir wave with the electric field oriented along the x-coordinate ($\boldsymbol{E} \equiv (\mathrm{E}_x, 0, 0)$) with the k-vector corresponding to $k = 0.125$ (expressed in the ratio to $1/\lambda_D$), and with the electrostatic field energy $E_L/\mathrm{W}_T = 0.029$, where W_T is the thermal plasma energy. Computations were made for 40 plasma periods. Here, we present only the results for the magnetic field component B_z, which represents the electromagnetic waves in the system. In Fig. 1 (left) the $k_x - \omega$ dispersion diagram of the B_z component, computed in the time interval 0-32.6 plasma periods, is shown. As seen here the electromagnetic emission is generated on the plasma frequency and its harmonic. The emission on the harmonic frequency is stronger, see Fig. 1 (right). For this reason we concentrate

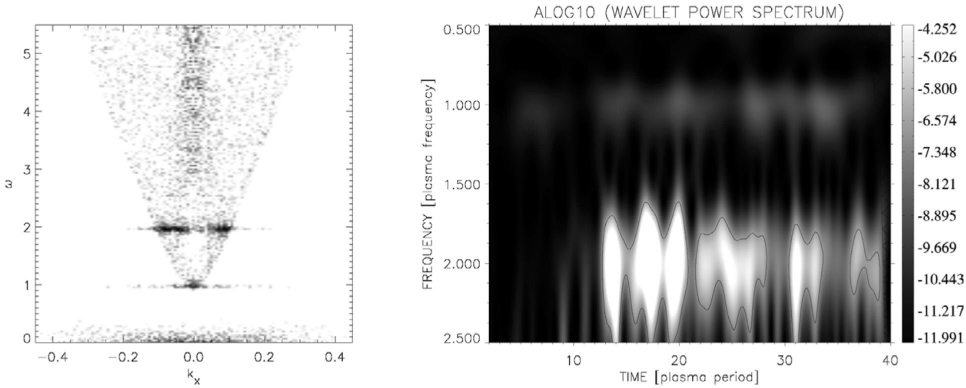

Figure 1. Left: The $k_x - \omega$ dispersion diagram obtained by the 2D Fourier transform of the magnetic field components B_z. The frequency is expressed in the ratio to the plasma frequency. Right: The wavelet spectrum of the B_z.

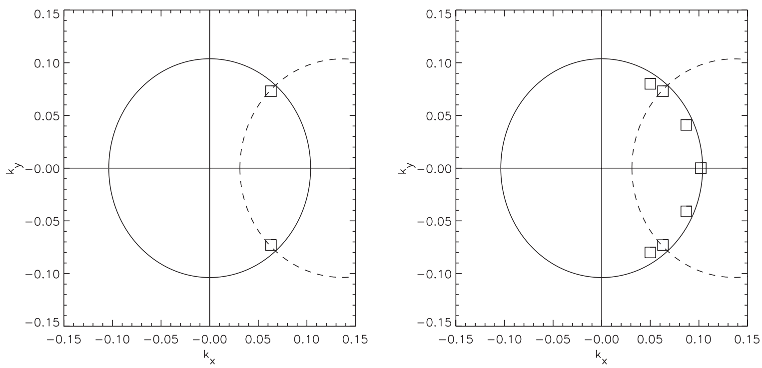

Figure 2. The $k_x - k_y$ diagram of the enhanced energy density (squares) of the B_z component at the time 12.7 (left part) and 14.3 (right part) plasma periods, respectively. Full circle corresponds to the relation (3.4) and dashed circle to the relations (3.5 and 3.6).

our attention only to a formation of this harmonic electromagnetic emission. We wanted to know how this emission is formed in the k-vector space. We recognized that the first k-vectors corresponding to the harmonic emission appeared at 12.7 plasma periods in the very small region around $\boldsymbol{k} = (0.063,\ 0.073)$, see the square in Fig. 2 (left). Then the k-vectors of this emission started to be scattered around a 'circle', see the squares in Fig. 2 (right) at the time 14.3 plasma periods.

3. Analytical analysis of the L→L'+S and L+L'→T processes

Starting from resonant conditions and dispersion relations for the decay process, after some algebraic manipulations, we can write:

$$|\boldsymbol{K}| = 2k_0\cos(\phi) - 2/3v_s \tag{3.1}$$
$$K_x = |\boldsymbol{K}|\cos(\phi), \tag{3.2}$$
$$K_y = |\boldsymbol{K}|\sin(\phi), \tag{3.3}$$

where $\boldsymbol{k_0} = (k_0, 0)$ and $\boldsymbol{K}$ are the normalized k-vectors of the pumping Langmuir and ion-sound waves, and v_s is the constant proportional to the sound speed.

https://doi.org/10.1017/S174392131100706X Published online by Cambridge University Press

On the other hand, for the k-vector of the electromagnetic wave (T) (on the harmonic frequency), generated by the coalescence L+L'→T we derived:

$$(c/v_T)^2(k_{Tx}^2 + k_{Ty}^2) = 3 \quad (3.4)$$

which is the equation of circle with the center in the point (0,0) and the radius $v_T/c\sqrt{3}$. Now, assuming that the coalescence process includes the mother Langmuir and daughter waves from the parametric decay, then we can write:

$$k_{Tx}^{ML+DL} = 2k_0 - K_x, \quad (3.5)$$

$$k_{Ty}^{ML+DL} = -K_y, \quad (3.6)$$

where components of $\boldsymbol{K}$ are expressed by (3.2) and (3.3). ML and DL mean the mother and daughter Langmuir wave. Thus, when we consider the T-wave (on harmonic frequency) as a result of the coalescence of the mother Langmuir wave with daughter Langmuir ones (1-order in the cascading process) then the k-vectors of this T-wave have to correspond to the crossing point of curves given by the relations (3.5), (3.6), and (3.4), see the 'circles' in Fig. 2. Comparing the 'circles' with locations of the squares computed in PIC model, we can see a good agreement between numerical and analytical results. We also determined the angle between the k-vectors of the mother Langmuir wave and the electromagnetic one corresponding to the crossing point of the 'circles' in Figs. 2. In our case this angle is 49 degrees. It increases with the increase of the k_0 vector of the mother Langmuir wave.

4. Conclusions

Both the numerical modelling and analytical analysis show that the first k-vectors of the harmonic electromagnetic emission are generated in the vicinity of the crossing point of two 'circles' given by two subsequent resonant wave processes L→L'+S and L+L'→T. In the following times the k-vector of this emission is scattered around the full 'circle' given by the coalescence process L+L'→T. The angle of the k-vector of the first electromagnetic plasmon with that of the mother Langmuir wave increase with the v_{ph}/c decrease. It changes from 37 degrees for $v_{ph}/c = 0.7$ to 66 degrees for $v_{ph}/c = 0.1$. Thus, in the interval of beam velocities ($v_{beam} \approx v_{ph}$) considered for type III bursts in the corona, this angle deviates from that ($\sim$ 90 degree) considered in the so called head-on approximation of the coalescence process (Melrose 1980). It was found that in very early phases (for parameters considered here), the electromagnetic emission on the harmonic frequency is stronger than that on the fundamental frequency.

Acknowledgements

This research was supported by the grants 300030701 and 300030804 (GA AS CR), 205/07/1100 (GA CR) and the Centre for Theoretical Astrophysics, Prague.

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