Proceedings of the VIII Serbian-Bulgarian Astronomical Conference (VIII SBAC)
Leskovac, Serbia, May 8-12, 2012,
Editors: M. S. Dimitrijević and M. K. Tsvetkov
Publ. Astron. Soc. "Rudjer Bošković" No 12, 2013, 367-373

LANGMUIR WAVES, TYPE III RADIO BURSTS AND IMPULSIVE ELECTRON EVENTS

SONJA VIDOJEVIC[1,2], ARNAUD ZASLAVSKY[1], MILAN MAKSIMOVIC[1], SÄM KRUCKER[3], MILAN DRAZIC[2], OLGA ATANACKOVIC[2]

[1]*LESIA–Observatoire de Paris, CNRS, UPMC Univ. Paris 06, Univ. Paris-Diderot, France*
[2]*Faculty of Mathematics, University of Belgrade, Serbia*
[3]*Space Sciences Laboratory, University of California, Berkeley, USA*
E-mail: sonja.vidojevic@obspm.fr, sonja@matf.bg.ac.rs, arnaud.zaslavsky@obspm.fr, milan.maksimovic@obspm.fr, krucker@ssl.berkeley.edu, mdrazic@matf.bg.ac.rs, olga@matf.bg.ac.rs

Abstract. It is known that interplanetary electron beams ejected from the sun are unstable in the solar wind and that they generate Langmuir waves (electrostatic) and electromagnetic waves (type III bursts). For the present statistical analysis we used radio observations in a range of 4 - 256 kHz from WAVES experiment onboard WIND spacecraft. A subset of 36 events, with Langmuir waves and type III radio bursts occurring at the same time, was selected. After background was removed, the remaining power spectral density is modeled by Pearson's system of probability distributions (type I, type IV and type VI). A relation in form of power-law between the power of Langmuir waves, the energy and the flux of the electrons in the impulsive electron events corresponding to the occurrence of the Langmuir waves is preliminary examined. We found a strong power-law dependence between electron fluxes and energies (power-law index γ equals 2.47 ± 0.06). The consequence of this fact is that the estimated parameters are highly unstable in numerical sense, thus the proposed model can be simplified, instead of two variables, it can be represented with only one: flux or energy.

1. INTRODUCTION

Localy generated Langmuir waves (electrostatic) and electromagnetic radio waves by the propagating of an electron beam in a surrounding plasma are some of the basic problems in plasma physics. Understanding of the conversion mechanisms by which electron beam produces Langmuir waves and radio waves is of essential importance to explain some of strong radiations in plasma astrophysics such as radio jets in active galactic nuclei, pulsars and neutron stars, or solar radio bursts. Unfortunately, for the distant objects *in situ* measurements are available only for radio emission and, sometimes, indirect measurements for the source - electron beam. Unique opportunity to study complete conversion processes, with simultaneously observed energetic electrons and associated Langmuir and radio waves in the regions where these radio waves are generated (*in situ*), we have only for the solar radio bursts thanks to the numerous solar space missions in last few decades.

Energetic electron beams, ejected and accelerated from the sun by some violent processes - usually flares or coronal mass ejections, interact with interplanetary plasma to produce Langmuir waves and radio emissions called type III radio bursts (e.g. Lin 1985). The main characteristic of solar type III radio bursts is a fast negative frequency drift in very wide range of frequencies, from few kHz to hundreds of MHz. As the electron beam travels away from the sun along magnetic field lines, the density of surrounding plasma descries, so consequently the frequency of type III bursts decrease in time, $f_p = 9\sqrt{n_e}$ (n_e is the electron number density in m^3, f_p in kHz). Langmuir waves and energetic electron events measured in situ have been directly associated with type III solar radio bursts and well-documented by many authors (e.g. Lin 1970, Frank and Gurnett 1972, Gurnett and Anderson 1977, Ergun et al. 1998).

Here, we present preliminary statistical analysis of electron beam and Langmuir waves associated with type III radio bursts. Firstly, after the background was removed, the remaining power of Langmuir waves is modeled by Pearson's system of probability distributions. It is found that the distributions belong to the three main Pearson's types: I, IV and VI. Secondly, a relation between the power of Langmuir waves, the energy and the flux of the electrons in the impulsive electron events corresponding to the occurrence of the Langmuir waves was analyzed.

The measurements obtained by the experiments onboard Wind spacecraft are used in this study. Wind spacecraft is a laboratory for long-term solar wind measurements launched on November 1, 1994 (Harten and Clark, 1995). The radio and electric field observations used, are obtained by the WAVES experiment (Bougeret et al. 1995). The locally generated Langmuir waves are recorded by the Thermal Noise Receiver (TNR, part of WAVES experiment), which provides measurements of the plasma electric field fluctuations in frequency domain from 4 kHz to 256 kHz in 5 logarithmically-spaced frequency bands including the local plasma frequency. The second used experiment is 3-D Plasma and Energetic Particle (3DP) Investigation (Lin et al. 1995) that provides the full three-dimensional distribution of suprathermal electrons. For the impulsive electron events the data detected with the electrostatic analyzers (EESAs) from $\sim$ 0.2 keV to $\sim$ 27 keV in 15 energy channels were used. The electron energy flux spectra are produced by summation over angular bins - - omnidirectional flux. The energetic electron events are easily recognizable by its velocity dispersion, with faster electrons arriving earlier, as expected if the electrons of all energies are simultaneously accelerated at the the same point and travel the same distance along the interplanetary field to reach the spacecraft. A subset of 36 events, with Langmuir waves and type III bursts occurring at the same time, was selected.

2. DATA ANALYSIS AND RESULTS

When dealing with empirical data with significant skewness and kurtosis, the normal distribution is not the best choice for modeling. The four parameter Pearson's system of distributions is a better to use. It represents a wide class of distributions with a wide variety of shapes and thus, provides more accurate representations of the observed data. On the other hand, it includes, as special cases, some well known distributions (normal, beta, gamma, Student's t-distribution etc.). Karl Pearson (1895) defined this distribution system by the following ordinary first order differential equation for the probability density function $p(x)$:

$$-\frac{p'(x)}{p(x)} = \frac{b_0 + b_1 x}{c_0 + c_1 x + c_2 x^2} \tag{1}$$

where b_0, b_1, c_0, c_1 and c_2 are five real parameters. After normalizing the fraction with any of them, only four independent parameters remain. The form of the solution of this differential equation depends on the value of these parameters, resulting in several distribution types.

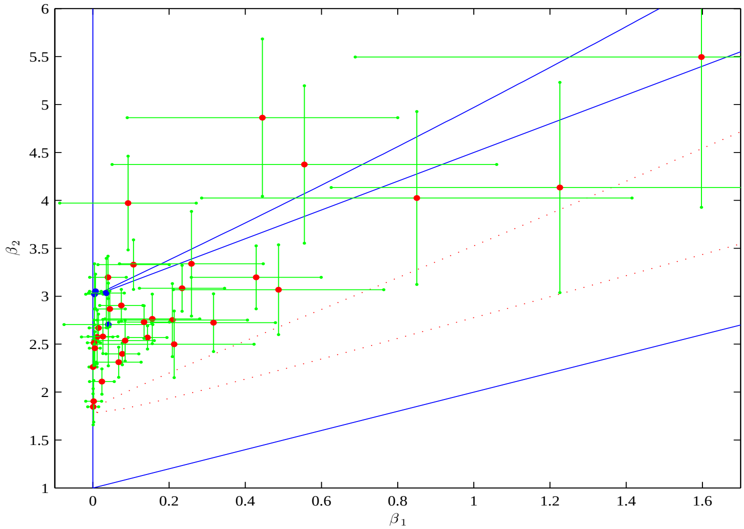

Figure 1: Beta plane. Out of the 36 events: 31 belong to Pearson's type I, 1 to type VI and 5 to type IV probability distribution. Most of the events are close to normal distribution – $(\beta_1, \beta_2) = (0, 3)$, but only for 4 (blue points) their error ellipses encompass the point of normal distribution (see electronic version).

The classification of distributions in the Pearson system is entirely determined by the first moment (mean–μ_1) and the next three central moments (variance–μ_2, skewness–μ_3 and kurtosis–μ_4). Pearson proposed two dimensionless parameters, i.e. two moment ratios associated with the square of the skewness (β_1) and kurtosis (β_2):

$$\beta_1 = \frac{\mu_3^2}{\mu_2^3}, \quad \beta_2 = \frac{\mu_4}{\mu_2^2}. \tag{2}$$

These two parameters characterize the asymmetry and the peakedness of the distribution, respectively. They entirely determine the type of the Pearson distribution system. We have shown that the probability distributions of the power spectral density of the Langmuir waves belong to the three main types of Pearson's probability distributions: type I, type IV and type VI (see positions of all 36 events in (β_1, β_2) plane in Fig. 1).

Next step was to extract those events where impulsive electron events can be seen at the same time as Langmuir waves. Several additional criteria had to be satisfied: (1) a clear velocity dispersion; (2) high enough signal-to-noise ratio; (3) a clear separation from surrounding events to avoid multiple events. The analysis of data detected with the electrostatic analyzers (EESAs) showed that these conditions are satisfied for 19 out of 36 previously selected events. We have analyzed a relation between power of Langmuir waves, the energy and the flux of the electrons. As a model, we proposed:

$$P_{\rm LW} = a\, n_{\rm ch}^{\alpha}\, E_{\rm ch}^{\beta}. \tag{3}$$

In order to perform planned analysis, three dimensional points were created ($E_{\rm ch}$, $n_{\rm ch}, P_{\rm LW}$). $E_{\rm ch}$ is energy of particular channel of EESA instrument in [keV], $n_{\rm ch}$ is electron flux in [cm^{2}s sr eV]$^{-1}$ integrated over time interval of 12 minutes centered at electron flux maximum and $P_{\rm LW}$ is corresponding power of Langmuir waves in [V^{2}m^{-2}] integrated over the same time interval as the electron flux. Numerical integration is performed using trapezium method in both cases. The time interval of 12 minutes was chosen empirically to avoid overlapping in Langmuir waves power series and, on the other hand, to get rough approximation of electron beam flux (fair enough for a preliminary analysis) measured by particular channel. It turns out that energetic electron fluxes can be seen only in first 8 most energetic EESAs channels that spawn electron energies from about 2 to 27 keV. This fact indicates that the energies of electrons responsible for Langmuir waves emission are in range [2,27] keV. The average over all 19 events is 13.2 keV. In the Fig. 2 three-dimensional plot of the averaged variables is presented. As it can be seen, the strong linear dependence between logarithms of $E_{\rm ch}$ and $n_{\rm ch}$ in form:

$$n_{\rm ch} = bE_{\rm ch}^{\gamma}. \tag{4}$$

exists. The value of power-law index, γ, was found to be -2.47 ± 0.06. Because of this strong dependence between $n_{\rm ch}$ and $E_{\rm ch}$, which has the same form (power-law) as the model proposed (Eq. 3), the model given in the form $P_{\rm LW} = P_{\rm LW}(n_{\rm ch}, E_{\rm ch})$ (Eq. 3) has an infinite number of solutions. The smaller mean square errors of the fitting by Eq. (4) result in larger estimated errors for a, α and β in the model Eq. (3).

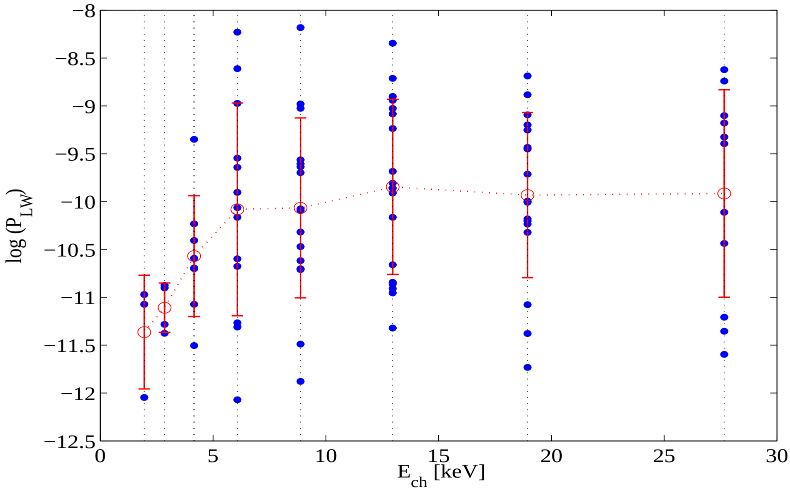

Figure 2: Relation between the logarithm of Langmuir waves power, P_{LW}, and the energies of electrons, E_{ch}. The blue points represent the integrals of Langmuir waves spectral density over the same time interval (12 min) as for the corresponding impulsive electron event fluxes, n_{ch} (see Fig. 3 for n_{ch}). Open red circles are means of Langmuir waves power at particular electron energies. The error bars are calculated as 1σ standard deviation (see electronic version).

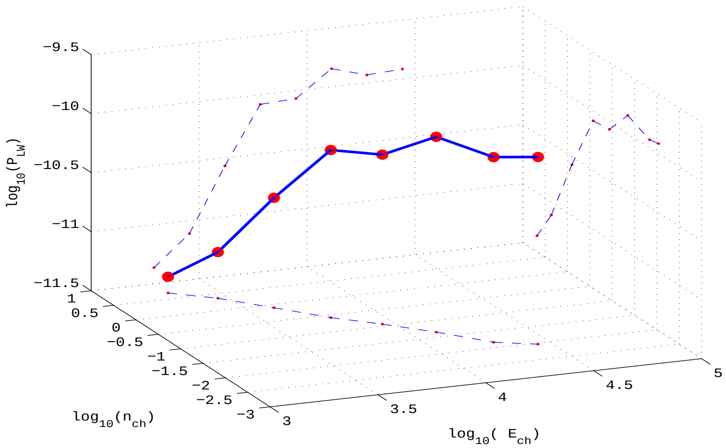

Figure 3: Spatial curve (solid line) represents the relation between logarithms of averaged Langmuir waves power, the electron energies and the averaged electron fluxes. The dashed lines are orthogonal projections of the spatial curve onto the coordinate planes. Note the projection onto horizontal plane – it can be fitted very good with logarithm of Eq. (4), i.e. with a linear model. For the projections onto vertical planes it can be seen that power-law is satisfied only partially (for lower electron energies) and then, the Langmuir waves power is flattened.

3. CONCLUSIONS

We have shown that for 36 events of intense locally formed Langmuir waves associated with type III radio bursts, the probability distributions of the power of these waves in spectral domain belong to the three main types of Pearson's probability distributions: type I, type IV and type VI. The similar result was obtained by Krasnoselskikh et al. (2007) for the Langmuir waves within the Earth's electron foreshock. Principal properties of the events' distributions (skewnes and kurtosis) are summarized in beta plane, Fig. 1. The χ^2 goodness of fit test shows that the Pearson's probability distributions fit the data better than normal for all of the considered events. This is in contradiction with Stochastic Growth Theory proposed by Robinson (1992) which assumes log-normal distribution (or normal in logarithmic scale) for the Langmuir waves. Investigation of possible reasons of this disagreement is not within the scope of this study – further work is needed.

The power of Langmuir waves produced by the energetic electron beam can not be modeled in form of Eq. (3) by both, the flux and the energy of electrons, because of the strong power-law dependence between them. The power-law index is found to be 2.47 ± 0.06. This result is comparable to the result recently obtained by Krucker et al. (2009) and earlier by Lin et al. (1982). The dependence between power of Langmuir waves and either the energy or either the flux, does not satisfied power-law. The partial power-law exist until the electron energy reaches approximately 10-13 keV when the saturation arises. The similar is for the dependence between power of Langmuir waves and the electron flux: the saturation starts at about 0.1 $(\mathrm{cm^2 sr\, s\, eV})^{-1}$. A more detailed analysis is needed for an explanation of this saturation which is scope for the future study.

References

Bougeret, J., et al.: 1995, Waves: The Radio and Plasma Wave Investigation on the Wind Spacecraft, *Space Science Reviews*, **71**, 231–263.

Ergun, R. E. et al.: 1998, Wind Spacecraft Observations of Solar Impulsive Electron Events Associated with Solar Type III Radio Bursts, *Astrophysical Journal*, **503**, 435.

Frank, L. A. and Gurnett, D. A.: 1972, Direct Observations of Low-Energy Solar Electrons Associated with a Type III Solar Radio Burst, *Solar Physics*, **27**, 446.

Gurnett, D. A. and Anderson, R. R.: 1977, Plasma wave electric fields in the solar wind - Initial results from HELIOS 1, *Journal of Geophysical Research*, **82**, 632.

Harten, R. and Clark, K.: 1995, The Design Features of the GGS Wind and Polar Spacecraft, *Space Science Reviews*, **71**, 23.

Krasnoselskikh, V. V., Lobzin, V. V., Musatenko, K., Soucek, J., Pickett, J. S. and Cairns, I. H.: 2007, Beam-plasma interaction in randomly inhomogeneous plasmas and statistical properties of small-amplitude Langmuir waves in the solar wind and electron foreshock, *Journal of Geophysical Research (Space Physics)*, **112**, 10109. Krucker, S. Oakley, P. H. and Lin, R. P.: 2009, Spectra of Solar Impulsive Electron Events Observed Near Earth, *Astrophysical Journal*, **691**, 806.

Lin, R. P.: 1970, The Emission and Propagation of 40 keV Solar Flare Electrons. I: The Relationship of 40 keV Electron to Energetic Proton and Relativistic Electron Emission by the Sun, *Solar Physics*, **12**, 266.

Lin, R. P.: 1985, Energetic solar electrons in the interplanetary medium,*Solar Physics*, **100**, 537.

Lin, R. P., Mewaldt, R. A. and Van Hollebeke, M. A. I.: 1982, The energy spectrum of 20 keV-20 MeV electrons accelerated in large solar flares, *Astrophysical Journal*, **253**, 946.

Lin, R. P. et al.: 1995, A Three-Dimensional Plasma and Energetic Particle Investigation for the Wind Spacecraft, *Space Science Reviews*, **71**, 125.

Pearson, K.: 1895, Contributions to the Mathematical Theory of Evolution. II. Skew Variation in Homogeneous Material, *Philosophical Transactions of the Royal Society of London*, **186**, 343.

Robinson, P. A.: 1992, Clumpy Langmuir waves in type III radio sources, *Solar Physics*, **139**, 147.