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STATISTICS OF LANGMUIR WAVES ASSOCIATED WITH TYPE III SOLAR RADIO BURSTS

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Abstract. Sixteen years of radio, waves and particles data recorded by the Wind spacecraft are examined searching for type III solar radio bursts observed *in situ*. Applying rigorous criteria, a data set of 36 high-quality events is selected. With such a numerous data set, which is statistically representative of the studied phenomenon, it is possible to constrain observationally and with a better confidence the type III generation models. For each of the events, the precise shape of the Langmuir wave power distribution observed in the spectral domain is determined. These observed distributions are modeled by a Pearson system of probability distributions. It is shown that the probability distributions of the logarithm of the Langmuir waves power spectral density belong to three "main" types of Pearson's probability distributions: type I, IV and VI. In addition, the effects of the instrumental integration time of the Wind radio receivers on the observed Langmuir wave power distributions is modelled. The results imply that it is not possible to conclude definitively, that the distribution of the Langmuir waves energy in the real temporal domain is lognormal, as it is predicted in some theories as the Stochastic Growth Theory by Robinson, 1992.

1. INTRODUCTION

The fact is that the Sun blows away a wind, made of material particles, whose importance is highly considerable since the whole Solar System is immersed in, and all planetary environments are shaped by it. For the space plasma physicists and astronomers, the solar wind is a challenging wide field to explore and to find a number of stunning surprises and extreme conditions which are virtually impossible to simulate in the laboratory. The only stellar wind that can be studied in detail is from the Sun, our nearest star. Thanks to the huge amount of measurements collected by ground based and space missions during the last few decades, we are closer to understanding of some natural phenomena, keeping in mind that Nature always turns out to be more astonishing than we had imagined. And yet, from the first ideas about the existence of the solar wind to the present epoch, its intrinsic nature and origin have motivated, and still motivates, much debate.

Research in this doctoral dissertation explores only a part of the puzzle. Beginning with an energetic electron beam, without going into the mechanism of its formation, we shall track it along the solar magnetic field lines indirectly observing the type III solar radio bursts – its inevitable signature in radio spectrum. The type III radio bursts are created by a conversion of electrostatic Langmuir waves into electromagnetic radiation. Along the entire trajectory, electron beam generates locally Langmuir waves in an interaction with the particles of surrounding, much slower, solar wind. But, we are able to record these waves only accidentally, rarely – that is, when the satellite is just on the path of the electron beam, so the instruments can measure products of the interaction, i.e. Langmuir waves. In particular, as the main subject, we investigate here in details this intermediate gradient of that complicated space interplay. By using well established mathematical and statistical methods we have extracted and derived parameters of Langmuir waves energy probability distribution. Expecting to verify some existing theories, the results, on the contrary, led us to a conclusion that the conversion processes from an electron beam through the Langmuir wave to the type III radio bursts are more complex than it was anticipated and incorporated in existing models.

2. LANGMUIR WAVES

In situ observations of extremely bursty waves with widely varying electric fields are quite common in space physics. Examples include Langmuir waves seen in type II and III solar radio sources, the Earth's foreshock, Langmuir, beam, and z-mode waves in polar cap and auroral regions of the magnetosphere, and electromagnetic ion cyclotron and mirror-mode waves in the magnetosheath. Fields can rapidly fluctuate by orders of magnitude leading to extremely broad probability distributions of field strength. Herein, we discus the physical meaning of a probability distribution that could stand behind the observed electric field pattern and one of the theoretical approaches, namely the Stochastic Growth Theory.

For this study the used measurements are obtained by means of four different experiments onboard the Wind spacecraft, a laboratory for long-term solar wind measurements, launched on November 1, 1994. The Wind spacecraft is placed in the solar wind, often near the L_1 Lagrangian point about 200 Earth radii in the sunward direction from the Earth. The radio and electric field observations that we analyze, and that are the main focuss of this work, have been obtained by the WAVES experiment (Bougeret et al, 1995). On this instrument the locally generated Langmuir waves are recorded by both the Time Domain Sampler (TDS) module, which captures short waveform snapshots of the waves' electric field; and by the Thermal Noise Receiver (TNR), which performs onboard spectra of the electric fluctuations in a large frequency domain including the local plasma frequency, f_{p}. While the TDS transmits to the ground, due to telemetry allocation issues, only a small part of the Langmuir waves' snapshots that are observed (generally the most intense ones), the TNR records them in the spectral domain and transmits them continuously. The TNR is a double multi-channel receiver covering the frequency range from 4 kHz to 256 kHz in 5 logarithmically-spaced frequency bands. Each band covers 2 octaves with one octave overlap. Each of these bands is divided into either 32 or 16 logarithmically-spaced channels. TNR provides rapid measurements of the plasma electric field fluctuations. In the radio domain, where the electromagnetic type III bursts are observed, we use data from the RAD1 and RAD2 radio receivers. The RAD1 frequency range, from 20 to 1 040 kHz, is divided into 256 linearly spaced channels of 3 kHz bandwidth each. The frequency range of the RAD2 radio receiver, from 1 075 to 13 825 kHz, is divided in the same number of channels as RAD1, but with 20 kHz bandwidth. For the selection of a sample event we use, in addition to the WAVES data: (1) one minute averaged measurements of the interplanetary magnetic field vector in GSE (Geocentric Solar Ecliptic) cartesian coordinates from the Magnetic Field Investigation (MFI), Lepping et al, 1995; (2) full three-dimensional distribution of suprathermal electrons recorded by the three-dimensional Plasma and Energetic Particle (3DP) Investigation, Lin et al, 1995; (3) solar wind data from the Solar Wind Experiment (SWE), Ogilvie et al, 1995, which provides three-dimensional velocity, density and temperature of the solar wind protons. All these measurements, taken simultaneously by the four experiments, allow us to perform a qualitative analysis and selection of the events of interest.

The selection procedure was performed very carefully and thoroughly in two phases. The first phase of the selection was a purely visual recognition of the events. In the second phase, proceeding with additional criteria, inadequate events selected in the first phase were eliminated.

Type III solar radio bursts are easily recognizable on dynamical spectra plots. They are intense and have fast, nearly vertical, frequency drifts from higher to lower frequencies. Looking at dynamical spectra we can see sometimes a lot of type III bursts, but only rarely do the generating electrons pass over the spacecraft so that we can observe the Langmuir waves directly, *in situ*. Locally generated Langmuir waves can be recognized as intense narrowband emissions around plasma frequency, f_p. The increase in electrostatic energy around f_p that persists on dynamical spectra throughout the day varying between approximately 10 and 40 kHz (the typical variation range for f_p at $\approx$ AU) is due to the quasi thermal noise observed *in situ*, Meyer-Vernet and Perche, 1989. For the selection we look for times when very sharp intensity increases around the plasma frequency occur at approximately the same time when a type III burst is observed to reach frequencies close to f_p.

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 choice. 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 first order ordinary 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.

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. the 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, and entirely determine the type of the Pearson distribution system through one parameter, κ, defined as:

$$\kappa = \frac{\beta_1(\beta_2+3)^2}{4(2\beta_1-3\beta_1-6)(4\beta_2-3\beta_1)}. \tag{3}$$

For $\kappa < 0$, $0 < \kappa < 1$ and $\kappa > 1$, the distributions are called type I, type IV and type VI, respectively. These three cases are known as "the main types" because they occupy areas in the (β_1, β_2) space, contrary to the other types which are represented by lines or points. Type III ($\kappa = \pm\infty$) lies on the boundary between type I and type VI. Type V ($\kappa = 1$) lies on the boundary between type IV and type VI. If $\kappa = 1$, an additional condition is needed for the classification. The distribution is classified as type II if $\beta_1 = 0$ and $\beta_2 < 3$, type VII if $\beta_1 = 0$ and $\beta_2 > 3$, and as a normal, also known as type XI, if $\beta_1 = 0$ and $\beta_2 = 3$.

When the type of the Pearson distribution is specified, all parameters (three or four, depending on the type) of the distribution can be determined from the mean, variance, skewness and kurtosis, i.e. from the first four moments.

3. RESULTS

Up to now, only a few studied cases of *in situ* type III bursts have been reported in the literature. The intent of this research was to examine statistically in details the basic and general characteristics of Langmuir waves associated with type III solar radio bursts and electron beams responsible for their generation, all observed *in situ* simultaneously. Thus, we have built an extensive set of type III events detected *in situ* by the Wind spacecraft over 16 years of observations. For each event, all the three of the Langmuir waves, the associated energetic electrons and the type III radio bursts are present. This is the first time that such an exhaustive data set is built, which can be used for further statistical analysis.

For each of the 36 events from our set we have constructed accurate Langmuir waves power distributions by previously correctly removing the background. A Pearson type I distribution seemed to be the best choice to fit the distribution of the logarithm of the electric field power provided at TNR's output. It has to be noted that the obtained Pearson distributions are characterized by an asymmetry in the direction of large electric field powers, a result in qualitative agreement with the one obtained by Bale et al (1997) in the terrestrial electron foreshock. In order to explore the meaning and the possibility of a physical exploitation of these electric field probability distributions, we examined the effect of the TNR instrumental transfer function and integration time on a Langmuir wave field which is known to be composed of short duration wave packets. Numerical simulations reproducing the response of TNR to various types of input Langmuir waves power distributions and for different wave packet frequency rates are performed. By comparing the amplitudes of variations of the simulated output distributions with those derived from Wind observations, we can conclude that the best agreement between simulations and observations is achieved when:

1. the shape of the input probability distributions is rather Pearson I or lognormal, but not a power law which should be definitively excluded;

2. the wave packets rate (λ) lies between 0.1 and 1;
3. the maximum value of the input wave packet amplitudes is about $5 \times 10^{-3}\,\mathrm{V\,m^{-1}}$.

A consequence of the nature of the Langmuir wave packet field and of the simulations is the fact that the power in output of the TNR is actually smaller than the "instantaneous" power in the wave packets. By examining the maxima of the input Langmuir waves power in the case of lognormal or Pearson distributions with the maxima of the Wind TNR output distributions, it appears that there is an overall normalization factor of about 100 that should be applied to the Wind data in order to retrieve the actual Langmuir waves power.

In further examination we have found preliminary relations between the Langmuir waves power, the electron beam fluxes, the energies and the densities. By using additional selection criteria, we extracted 19 events from the data set of 36 events used in previous analysis, taking those where an increase of electron fluxes was detected by 3DP instrument.

1. We found a strong linear dependence between logarithms of electron energies and their fluxes. The value of power-law index was found to be -2.47 ± 0.06. This result is in good agreement with the results obtained by Krucker et al (2009) for a statistical survey of the spectral shapes of 62 solar impulsive electron events detected within 1 to 300 keV, not necessarily accompanied by type III radio bursts, and Lin et al (1982) for nine events seen within 10 keV to 10 MeV almost all accompanied by type III radio bursts.

2. For variations of the Langmuir waves power as a function of the energy of the beam electrons, the Langmuir waves power is clearly an increasing function of electron energy within the range $\sim$ 2 to 7 keV. Above this energy, Langmuir waves power is presenting a "plateau" staying constant with energy increase. This experimental result is in quite good agreement with the simulations by Reid and Kontar (2012). The detailed comparison of our observational findings with their simulations will be the subject of a future work.

3. The next aspect of the relations between Langmuir waves power and energetic electrons examined in this research, was the relation between the normalized Langmuir waves power and the electron beam number density (n_b). The rate at which the Langmuir waves are generated (inverse of the quasilinear relaxation time) is roughly proportional to the electron beam number density $\tau_\mathrm{QL}^{-1} \propto n_\mathrm{b}(\sqrt{n_\mathrm{e}})^{-1}$. We have observed the proportionality up to a value of 10^{-10} for this ratio, where it reaches a maximum and then decreases. But, the expected dependence has not been found. Several reasons can be the cause for not obtaining the expected functional dependence. This result may be biased by instrumental effects, so it needs further consideration.

4. The relation between electromagnetic radiation in type III radio bursts and electrostatic radiation of Langmuir waves was tested for the type III radiation at the first harmonic of the plasma frequency, $2f_\mathrm{p}$. A rather not too strong linear dependence (in logarithmic scale) with slope of 0.45 and correlation coefficient 0.6 is found, but we consider it good enough, taking into account that the

background in type III radiation was not removed. This is the first observational statistical evidence of the proportionality between the electromagnetic radiation in type III radio bursts at $2f_\mathrm{p}$ and the electrostatic radiation of Langmuir waves ($P_{2f_\mathrm{p}} \propto P_\mathrm{LW}$).

These statistical results, obtained directly from the measurements, can be used as a reliable direction guidance for theoretical work, in understanding limitations of existing instruments and in construction of instruments for future missions, as well as in numerical simulations, comparison with solar flares X-ray, γ-ray, ground based radio, optical measurements etc. Additionally, this work is indirectly related to the acceleration of solar energetic electrons: the electron beams are source of electromagnetic emission, therefore the radio bursts can be used to track the escaping electrons from the Sun into the interplanetary medium. Furthermore, they provide a possibility to investigate the acceleration of electrons during a non-linear stage of the beam-plasma instability to the energies greater than the energies at which they were injected.

The research work on the data set of 36 high-quality events, selected for the research, is far from being exhausted. There is a plenty of room for the continuation of the investigation and improvements. For example, it is necessary to refine the analysis already done in many aspects; to understand the instrumental effects on the electron beam number density; to find the relation between the total power of Langmuir waves and total power of type III radio bursts; to improve the density model of interplanetary medium, and much more.

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