CONSIDERATION OF THE JOVIAN S-BURSTS AND NB-EMISSION BASED ON THE PARAMETRIC MODEL

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Abstract

The new mechanism for the formation of a fine structure in the dynamic spectra of the Jovian decametric radio emission is proposed. The main attention is paid to the formation of narrow-band (NB) emission and quasiperiodic trains of S-bursts. Our model is based on the effects of occurrence of the amplitude-frequency modulation and extension of the frequency spectrum of a signal during propagation of the radiation in a medium with time-varied parameters. It is shown that non-stationary disturbances of the planetary magnetic field and strong frequency dispersion of the plasma at frequencies close to the cutoff frequency of the extraordinary wave in the Jovian ionosphere can play a crucial role in the formation of NB emission and quasiperiodic trains of S-bursts. As a result of the numerical experiments, it was concluded that the amplitude-frequency characteristics of an initially continuous signal can drastically vary as functions of the form of the magnetic-field disturbance in the Jovian ionosphere. Structures similar to those observed in the real experiments, ranging from NB emission and quasiperiodic trains of S-bursts to more complex structures, arise in the dynamic spectrum.

1 Introduction

The Jovian decametric radio emission has regularly been observed almost each time the planet appeared in the radiotelescope's field of view since it was discovered in 1955 [Burke and Franklin]. The radiation consists of noise storms formed by strong sporadic bursts and observed in a range of frequency from a few megahertz to 39 MHz. On the basis of first observations, the decametric radio emission was divided into two types, the L (long)

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component and the S (short) component, differing in the scale of the time envelope. The L radiation represents a noise storm with typical time scales of up to several tens of seconds. The S-radiation, or S-bursts, which were observed for the first time by Kraus [1956], have significantly smaller time scales and last for up to tens of milliseconds during observation at a fixed frequency.

The fine structure of the dynamic spectra containing S-bursts is very diversified. The negative frequency drift, which is approximately proportional to the radiation frequency, $df/dt \propto f$, and a small frequency interval f occupied by the burst, $\Delta f/f \sim 10^{-2} - 10^{-1}$, are characteristic features of the S emission considered in our work. The pulses of such S emission often form quasiperiodic trains with one or several repetition frequencies in a range of about 2 to 400 kHz in the dynamic spectrum (see, for example, Flagg et al. [1976]; Krausche et al. [1976]; Riihimaa [1977], and also Carr and Reyes [1999] and references therein). An example of the dynamic spectrum with a train of S-bursts observed in July 6, 1999 (Kharkov, Ukraine) using radio telescopes UTR-2 (Ukrainian T-shape Radio telescope) is shown in Figure 1 [Litvinenko et al. 2004].

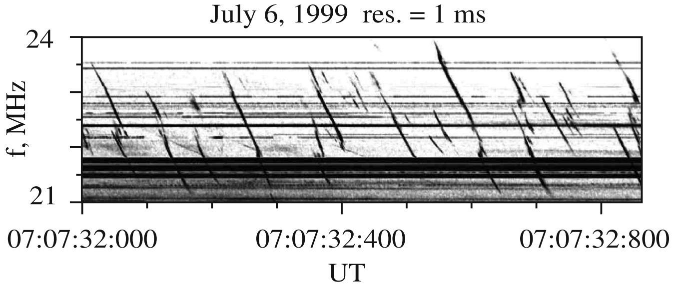

Figure 1: Dynamic spectrum with a train of S bursts.

In the dynamic spectra of the Jovian decametric emission, Riihimaa [1968, 1977, 1992] discovered one more type of radiation, which he named narrow-band L-emissions. Similar type of the emission was observed by Flagg et al. [1976]. Authors named the latter type of emission a narrow-band (NB) emission. These emissions are quasi-continuous and have a narrow frequency spectrum. A characteristic feature of the mentioned narrow-band emissions is that their dynamic spectrum is time-varied. Namely, fluctuations of the frequency of the emission band appear with the time and sometimes the narrow-band emission transforms into train of S-bursts, and vice versa, as the noise storm develops (Figure 2). It is important to mention that the transformation of the continuous emission into a train of S-bursts can be accompanied by a significant increase in the frequency range occupied by the emission (up to about 3 MHz), and the appearance of a frequency drift characteristic of S-bursts.

The generation of S emission has been studied in many papers (see Goldstein and Goertz, [1983]; Zarka, [1998], and references therein). These referenced authors mainly discussed different types of high-frequency plasma and electromagnetic instabilities capable of generating S-radiation and some of its features. These theories, for example, explain fairly well the origin of such properties of S-bursts as there are the high brightness temperature, the hollow-cone directivity pattern, the high-frequency cutoff of the radiation spectrum near the frequency 39.5 MHz, and the negative frequency drift, which, following Ellis

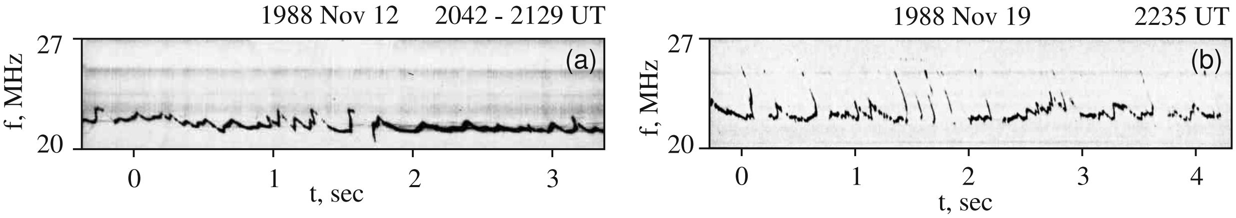

Figure 2: Dynamic spectra of the NB emission recorded (a) - in November 12, 1988 and (b) - in November 19, 1988. The figures are adapted from [Riihimaa, 1992]

[1965], is usually related to the adiabatic motion of the radiating electrons along the planetary magnetic field lines.

In the present paper, we consider a mechanism for the formation of quasiperiodic trains of Jovian decametric S-bursts. We pay attention to the crucial role of the non-stationary character of the medium in which the radiation propagates, namely, the Jovian ionosphere, and the dependences of the refractive index of the emitted waves on frequency (frequency dispersion of the medium).

2 Propagation of the Extraordinary Electromagnetic Wave in a Magnetized Plasma with Non-stationary Disturbances of the Magnetic Field

It's well known that the propagation of waves in a medium with non-stationary variations of parameters can be accompanied by the amplitude-frequency modulation of a signal and the broadening of its frequency spectrum. We assume that radio emission, which is initially quasimonochromatic, can be modulated by the variations of the refractive index of the plasma due to disturbances, of e.g. by intense MHD waves.

For a study of the spectrum transformation of the propagating wave, it is convenient to use the equations directly determining the variations $\omega(\vec{r},t)$, $\vec{k}(\vec{r},t)$. These equations can easily be obtained by using the geometric-optical approximation generalized to the case of non-stationary media [Ostrovskii and Stepanov, 1971; Stepanov, 1969]:

$$\frac{\partial \omega}{\partial t} + \left(\vec{V_{gr}}\nabla\right)\omega = -\omega\left(\frac{\partial n\omega}{\partial \omega}\right)^{-1}\frac{\partial n}{\partial t}\bigg|_{\omega,\vec{k}} \tag{1}$$

In equation (1) n is the refractive index of the medium, $\vec{V_{gr}}$ is the vector of the group velocity of the wave, ω and $\vec{k}$ are the frequency and the wave vector of the radiation. Variations in the frequency ω for a fixed group front are determined by the derivative of the refractive index with respect to time $\frac{\partial n}{\partial t}\big|_{\omega,\vec{k}}$, which characterizes the degree of nonstationarity of the medium.

Consider the theoretical possibility of the formation of S-bursts of the Jovian decametric radio emission as a result of propagation of the mentioned radiation in the ionosphere and lower magnetosphere of the planet. For this, we numerically solve the problem of propagation of the initially continuous S emission corresponding to the fast extraordinary wave with frequency close to the cutoff frequency in a plasma with parameters typical of the Jovian ionosphere and with non-stationary disturbance of the planetary magnetic field. For finding a solution to the system of equation (1) within the framework of the WKB approximation, one can use the method of characteristics.

Jovian decametric emission exhibits a high degree of linear polarization. For example, at frequency 20 MHz the average degree of linear polarization is about 0.87 for the emission from the Io-B source [Dulk et al., 1994]. The high degree of linear polarization can be realized under condition that the angle between radiation propagation and the planetary magnetic field in the source itself and in its close vicinity (in the region where the geometrical- optics approximation is valid) is more than 73°. [Shaposhnikov et al., 1997], i.e. the radiation propagates almost across the magnetic field of the planet. For a numerical solution of the problem, we assume for simplicity that the radiation propagates across the magnetic field. In this case, from (1) it can be obtained, that

$$\frac{dz}{dt} = c\frac{\left[\left(f^2 - f_L^2(z,t)\right)\left(f^2 - f_L^2(z,t)\right)\right]^{1/2}\left(f^2 - f_{UH}^2(z,t)\right)^{3/2}}{f\left(f^4 - 2f^2 f_{UH}^2(z,t) + f_{UH}^2(z,t)\left(f_L^2(z,t) + f_R^2(z,t)\right) - f_L^2(z,t) f_R^2(z,t)\right)} \tag{2}$$

$$\frac{df}{dt} = -\frac{\left(f^2 - f_L^2(z,t)\right)\left(f^2 - f_L^2(z,t)\right) f_{Be}^2(z,t)}{f\left(f^4 - 2f^2 f_{UH}^2(z,t) + f_{UH}^2(z,t)\left(f_L^2(z,t) + f_R^2(z,t)\right) - f_L^2(z,t) f_R^2(z,t)\right)} \frac{df_{Be}(z,t)}{dt} \tag{3}$$

In equations (2) and (3) $f_{UH} = \sqrt{f_{Be}^2 + f_{pe}^2}$ is the upper-hybrid resonance frequency, $f_R = \frac{1}{2}\left(\sqrt{f_{Be}^2 + 4f_{pe}^2} + f_{Be}\right)$ is the cutoff frequency of the fast extraordinary wave, $f_L = \frac{1}{2}\left(\sqrt{f_{Be}^2 + 4f_{pe}^2} - f_{Be}\right)$ is the cutoff frequency of the slow extraordinary wave, and f_{pe} and f_{Be} are the plasma frequency of electrons and the electron gyrofrequency, respectively; the ray coordinate z is reckoned across the undisturbed magnetic field $\vec{B}_0$.

Strong frequency dispersion can be expected only in the ionosphere of the planet. Outside the ionosphere, the refractive index of the extraordinary electromagnetic wave is close to unity almost independent on frequency. In a latter case, variation in the dynamic spectrum of the radiation due to dispersion turns out to be insignificant on the magnetospheric scale. Hence, following Zaitsev et al. [1986], we assumed that the source of S-bursts is located in the Jovian ionosphere, near the maximum of the ionospheric plasma, whereas the dynamic spectra of the radiation were calculated at the point corresponding to the point of the radiation output from the Jovian ionosphere.

According to the sounding data obtained using spacecrafts and Galileo orbiter, the electron density profile in the Jovian ionosphere depends on the time and place of measurements. Hinson et al. [1997] reported on the peak electron density $n_e \approx 10^5$ cm^{-3} located at the altitude $h_m \approx 900$ km with thickness $H \approx 200$ km in the evening sector, in the morning sector these parameters are $n_e \approx 2\times10^4$ cm^{-3}, $h_m \approx 2000$ km, and $H \approx 1000$ km. The directivity pattern of the Jovian decametric radiation source represents a hollow cone, which is magnetic field aligned and has an angular aperture $2\theta_s \approx 120^\circ - 150^\circ$ [Dulk, 1965; Shaposhnikov et al., 2000]. Assuming $\theta_s \approx 60^\circ$, we find that the ionospheric path length l_i ($l_i = H/\cos\theta_s$) of the decametric electromagnetic radiation for the above-mentioned parameters of the ionosphere is 400 km and 2000 km, respectively.

Let us first consider the case where the spatial distribution of the magnetic field disturbance is described by a uniform Gaussian function, whose amplitude is periodically varied in time with frequency Ω:

$$B(z,t) = B_0 \left(1 + \delta B \sin(\Omega t) exp\left(-\frac{(z-z_0)^2}{a^2}\right)\right) \tag{4}$$

Here, a is the characteristic spatial scale, δB is the maximum disturbance amplitude $\delta B << B_0$, and z_0 is the coordinate of the maximum of the magnetic field disturbance. The source is located at the point $z = z_s (z_s \leq z_0)$ and generates a narrowband ($\Delta f/f = 0.5\%$), linearly polarized wave at the frequency $f > f_R$, corresponding to the fast extraordinary mode and propagating along the z axis. The disturbance frequency was chosen equal to the pulse repetition frequency in quasiperiodic trains of S-bursts, and its typical values within the range of 2 Hz to 400 Hz [Carr and Reyes, 1999; Litvinenko et al., 2004]. The magnetic field $B_0 = 7$ G.

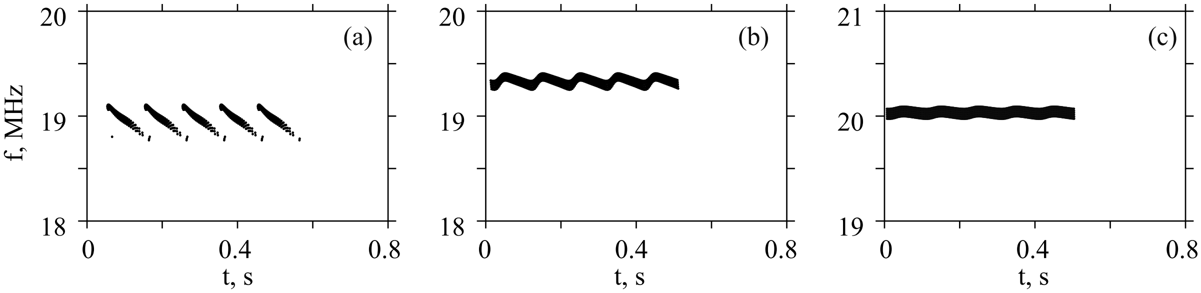

Figure 3: Examples of calculated dynamic spectra of decametric emission at the output of the Jovian ionosphere with $N_0 = 10^5$ cm^{-3} and $H = 1000$ km. Disturbances of the magnetic field along the wave propagation path is described by function (4) with $\Omega/2\pi = 10$ Hz, $\delta B/B = 0.02$, and $a = 100$ km. The dynamic spectra are constructed for the radiation generated at the frequencies a) $f = 1.02 f_R$, b) $f = 1.04 f_R$, c) $f = 1.08 f_R$.

The results obtained by numerical solution of the system of equations (2) and (3) for different values of the ratio f/f_R are presented in Fig. 3.

Propagation of a quasi-monochromatic signal through a non-stationary dispersive medium gives rise to the amplitude-frequency modulation of radiation, which results in that structures similar to those observed in the dynamic spectra of the Jovian decametric radio emission, including trains of narrow-band S-bursts (Figs. 3b), NB emission drifting over the frequency spectrum (Figs. 3a, 3b).

Numerical calculation of dynamic spectra of decametric emission for different values of the ratios $\delta B/B_0$, different values of the a are presented in our paper [Shaposhnikov, 2011].

3 Conclusion

It is shown that the time-frequency structure of the initially continuous radiation generated in the Jovian ionosphere at frequencies close to the cutoff frequency of the fast extraordinary wave and transmitted through the region with non-stationary magnetic field can vary dramatically. Depending on conditions in the radiation source and in its vicinity, different forms of the fine structure, ranging from NB emission and quasiperiodic trains of S-bursts to more complex ones, will be observed in the dynamic spectrum. If conditions in the source are time-varied, then such variations will be reflected in the dynamic spectrum as a time variation in the fine structure of the burst.

A necessary condition for the occurrence of quasiperiodic trains of S-bursts in the model we propose is that non-stationary disturbances of the planetary magnetic field are present in the Jovian ionosphere. The repetition periods of bursts in these trains correspond to characteristic time scales of the magnetic-field disturbances. The magnetic-field oscillations in the ionospheric Alfvén resonator can ensure the required disturbance. Our model of the formation of quasiperiodic trains of S-bursts and NB emission relates the magnetic-field oscillations in the ionospheric Alfvén resonator to the fine temporal structure of these bursts without imposing constraints on the source of emitting electrons, neither regarding the electron acceleration mechanism nor the localization of the acceleration region itself. In particular, the acceleration can occur in Io's ionosphere, as is supposed in Zaitsev et al. [2003], and this stipulates the correlation between the mentioned radiation and the position of Io in the orbit. Besides, the correlation can also be a consequence of excitation of the ionospheric Alfvén resonator by an Alfvén wave from Io.

Another necessary condition of the occurrence of quasiperiodic trains of radiation pulses in our model is that a sufficiently strong frequency dispersion of the ionospheric plasma is present for the waves which form this emission, i.e., the group velocity of these waves should significantly depend on frequency. Otherwise, the time-frequency structure of the radiation on its propagation path from the source to the observer will not undergo a notable variation (see Fig. 3 (c)). According to modern concepts, the Jovian decametric emission corresponds to the fast extraordinary waves. The group velocity of these waves strongly depends on the frequency near the cutoff. Hewitt and Melrose [1983] found that a loss-cone driven electron-cyclotron maser can effectively generate fast extraordinary waves near the cutoff frequency. They showed that the generation takes place over a wide range of angles in a very narrow frequency band. The spatial growth rate can be quite large due to the small group velocity. Note here that in this case the source of emission considered in present work can be above the planetary ionosphere. Another mechanism of generation of fast extraordinary electromagnetic waves near the cutoff frequency is proposed by Zaitsev et al. [1986] in the plasma model of the S-burst and NB emission generation. According to Zaitsev et al. [1986], plasma waves are generated in the Jovian ionosphere at frequencies near the upper-hybrid resonance, and then these waves are converted into fast extraordinary electromagnetic waves occupying a narrow frequency band closed to the cutoff frequency.

It should be stressed that the mechanism for the formation of the dynamic spectra proposed in this paper is not sensitive to the fine structure of initial emission before its propagation through dynamic Jovian ionosphere. Frequency transformation effect is parametric, but linear by its nature: the frequencies of sequential elements of the wave propagating in plasma with time-varying magnetic field are transformed independently. As a result, frequency modulation due to non-resonant parametric effects is not conflicting with other mechanisms for the fine structure formation (for example, the pulsing regime of plasma-wave conversion into electromagnetic radiation Zaitsev et al. [1986]), but additionally complicates the dynamic spectrum. In other words, non-resonant frequency modulation can transform the spectrum of the emission arising from any kind of instabilities and having any form of modulation before the entrance into the area with time-varying field. As a result, a complex fine structure with different time scales can appear in the dynamic spectrum of the Jovian decametric radio emission.

To finalize, we formulate the main conclusions concerning the formation of dynamic spectra containing S-bursts and NB emission. Propagation of radiation in the Jovian ionosphere with non-stationary variation in the magnetic field can give rise to an amplitude-frequency modulation of the decametric emission, which leads to a significant broadening and modification of its frequency spectrum. Depending on conditions in emission source and in its vicinity, different forms of the fine structure, ranging from NB emission and quasiperiodic trains of S-bursts to more complex ones, will be observed in the dynamic spectrum. It is important that the trains of bursts also arise in the case where continuous radiation is generated in the source. This allows the dynamic spectra containing S-bursts to be used for radioastronomical diagnostics of the Jovian ionosphere.

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