Parametric mechanism for the formation of Jovian millisecond radio bursts

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Received 19 August 2010; revised 3 December 2010; accepted 22 December 2010; published 3 March 2011.

[1] We develop a theory of formation of a fine structure in the dynamic spectra of the Jovian decametric radio emission. Main attention is paid to the formation of narrowband (NB) emission and quasiperiodic trains of short (*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 radiation in a medium with time-varied parameters. It is shown that nonstationary 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 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 a 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. Time variation in the conditions of generation and propagation of decametric radiation in the Jovian ionosphere is reflected in the dynamic spectrum as a time variation in the fine structure of the radiation. For example, a structure of the NB emission type is replaced by a quasiperiodic train of *S* bursts and vice versa.

Citation: Shaposhnikov, V. E., S. V. Korobkov, H. O. Rucker, A. V. Kostrov, M. E. Gushchin, and G. V. Litvinenko (2011), Parametric mechanism for the formation of Jovian millisecond radio bursts, *J. Geophys. Res.*, *116*, A03205, doi:10.1029/2010JA016041.

1. Introduction

[2] 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*, 1955]. The radiation consists of noise storms formed by strong sporadic bursts and observed in a range from a few Megahertz to 39 MHz. On the basis of first observations, the decametric radio emission was divided into two types, the long (*L*) component and the short (*S*) component, distribution by the scale of the time envelope. The *L* radiation represents a noise storm with typical time scales of up to several tens of seconds. Time scales of this radiation originate from scattering by both the irregularities of the interplanetary plasma (scales of duration from 1 to 5 s) and the Earth's ionosphere (scales of duration from 30 to 60 s) [*Carr et al.*, 1983]. 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. Such bursts on the dynamic spectra represent discrete intense radiation generated near the local gyrofrequency of electrons in Jupiter's lower magnetosphere and ionosphere and show a negative frequency drift in the frequency-time plane [*Carr et al.*, 1983].

[3] 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 Δf occupied by the burst, $\Delta f/f \sim 10^{-2} \div 10^{-1}$, 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, e.g., *Flagg et al.*, 1976; *Krausche et al.*, 1976; *Riihimaa*, 1977; *Carr and Reyes*, 1999, and references therein]. An example of the dynamic spectrum with a train of *S* bursts observed on 6 July 1999 (Kharkov, Ukraine) using radio telescopes UTR-2 (Ukrainian T-shaped Radio telescope) is shown in Figure 1. In the work of *Litvinenko et al.* [2004a, 2004b] an intriguing internal time structure of the simple linear *S* burst was studied. They showed that the internal structure of the

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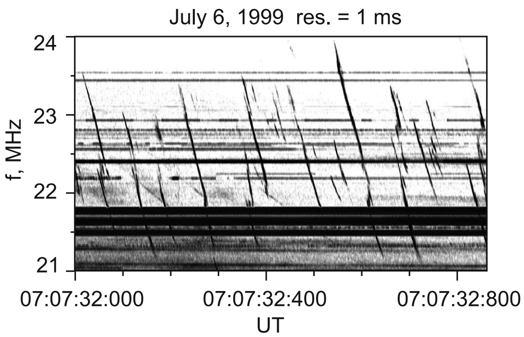

Figure 1. Dynamic spectrum with a train of *S* bursts.

simple *S* burst signal consists of very short pulses (duration 6–15 μs), which can be also organized in some kind of quasiperiodic structure.

[4] In the dynamic spectra of the Jovian decametric emission, *Riihimaa* [1968, 1977, 1992] discovered one more type of radiation, which he named narrowband *L* emission. Similar emission type was observed by *Flagg et al.* [1976]. Authors named the latter emission type a narrowband (NB) emission. This emission is quasi-continuous and has a narrow frequency spectrum. A characteristic feature of the mentioned narrowband emissions is that its dynamic spectrum is time varied. Namely, fluctuations with the frequency of the emission band appear with the time (Figure 2) and sometimes the narrowband emission transforms to a train of *S* bursts, and vice versa, as the noise storm develops (Figure 3). 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.

[5] An interesting example of the dynamic spectrum of narrowband emission obtained with high frequency and temporal resolution is presented in Figure 4 [*Litvinenko et al.*, 2009, Figure 10]. In this spectrum, the emission shows a quasi-harmonic oscillation of the frequency band with a characteristic frequency of about 2 Hz, which gradually drifts toward the lower frequencies. Besides, one more characteristic time scale of about 2 s of repetition of trains of these quasi-harmonic oscillations can be singled out. All the decameter radiation types mentioned above have a general characteristic, videlicet, in the dynamic spectra they appear in the small frequency range $\Delta F \ll f$. In our work we

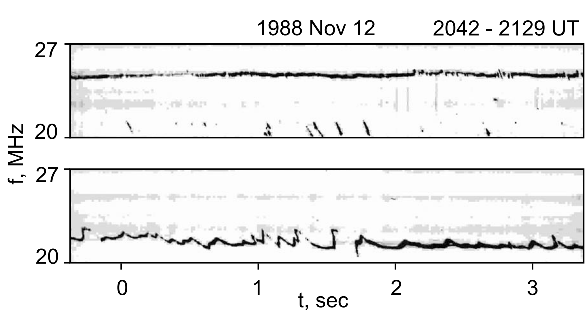

Figure 2. Example of dynamic spectrum of the narrowband emission recorded on 12 November 1988 (adapted from *Riihimaa* [1992]).

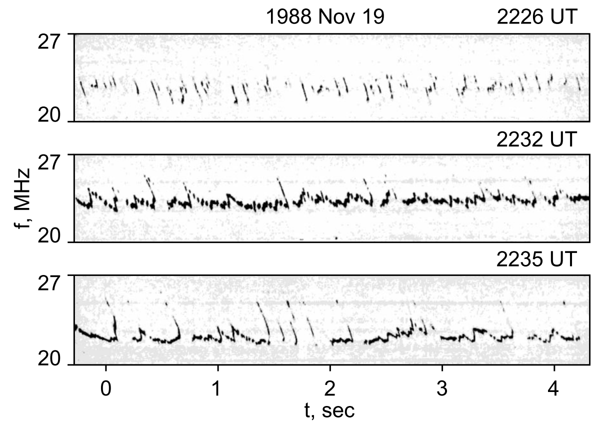

Figure 3. Example of dynamic spectrum of the narrowband emission recorded on 19 November 1988 (adapted from *Riihimaa* [1992]).

associate such types of the decameter radiation and the narrowband *S* bursts, with the narrowband emission' concept. In our opinion this association is reasonable as it is showed in the given work. The different forms of the fine structure, of initially continuous narrowband emissions, are dependent on propagation condition.

[6] The generation of *S* emission has been studied in many papers [*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* [1965], is usually related to the adiabatic motion of the radiating electrons along the planetary magnetic field lines. *Rather* [1976], *Melrose* [1986], and *Willes* [2002] proposed a nonlinear feedback mechanism for the generation of Jovian *S* emissions. This mechanism also enable the interpretation of the interaction of *S* bursts with constant frequency narrowband *L* bursts [*Willes*, 2002]. However, in this paper the problem related to the identification of the wave amplification

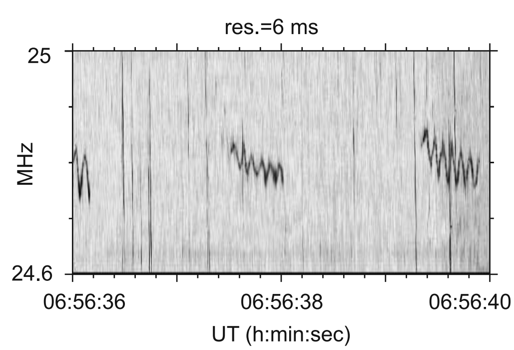

Figure 4. Example of dynamic spectrum of the narrowband emission with an oscillating frequency spectrum (adapted from *Litvinenko et al.* [2009]).

mechanism and the mechanism responsible for the occurrence of quasiperiodic trains of *S* bursts remains open.

[7] The origin of the fine structure, in particular, the occurrence of *S* bursts and their trains have very seldom been considered. *Ryabov* [1994] proposed the curvature radiation occurring as the relativistic electrons move along the planetary magnetic field disturbed by the electrical current of the Alfvén wave as the source of *S* bursts. The radiation pulses are formed due to raptures of the current circuit. However, this model assumes that an electrical current greater than 10^8 A exists in the Jupiter-Io circuit, but this was not confirmed by the experimental data. Another approach to solve the problem of the *S* burst occurrence was proposed by *Ergun et al.* [2006]. In this paper, it was hypothesized that the *S* pulses are due to the existence of resonant Alfvén oscillations in the Jovian upper ionosphere. These oscillations are excited in the ionospheric Alfvén resonator, which as *Su et al.* [2006] assumed can be realized in the Jovian ionosphere. Characteristic times of the magnetohydrodynamic eigenmodes of the resonator were found in that paper, and it was shown there that these times are in fairly good agreement with the periods of trains of *S* emission pulses. However, the mechanism relating the eigenmodes of the ionospheric Alfvén resonator and the *S* emission was not considered by *Ergun et al.* [2006]. As the reason for the occurrence of impulsive *S* emission, *Hess et al.* [2007] consider the acceleration of electrons by the electric field of an Alfvén wave propagating in Io's magnetic flux tube. The repetition period of *S* bursts is determined by the period of the propagating Alfvén wave. This model explains fairly well the occurrence of trains of broadband (occupying a band of the order of more than 10 MHz) [see *Hess et al.*, 2007, Figure 2] *S* bursts. The occurrence of narrowband *S* bursts and their relation to NB emission was not considered by *Hess et al.* [2007]. The plasma model of NB and *S* emission generation assumes that the impulsive character of the radiation is due to the fact that a pulsed mode of conversion of plasma waves into electromagnetic radiation is realized in the source [*Zaitsev et al.*, 1986]. Depending on the plasma parameters in the source, the conversion can be either continuous (when continuous electromagnetic radiation, i.e., NB emission, is generated by the source) or pulsed (the source emits a train of *S* bursts) with a period of the order of the inverse frequency of electron-ion collisions in the plasma. For the plasma parameters characteristic of the Jovian ionosphere, the pulsation periods turn out to be of a few milliseconds. Periodic trains of *S* bursts with such characteristic times were observed, e.g., in the observations described by *Krausche et al.* [1976] and *Flagg et al.* [1976]. The plasma model accounts for the origin of short-period (about a few milliseconds) trains of *S* emission pulses, whereas the trains with longer periods (tens of milliseconds or more) cannot be realized within the framework of this model.

[8] 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 nonstationary 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). The main features of the proposed parametric mechanism are given in section 2. The results of numerical simulation of propagation of the extraordinary electromagnetic wave with frequency close to the cutoff frequency in a magnetized plasma in the presence of a nonstationary disturbance of the magnetic field are presented in section 3. The application of this mechanism for the explanation of the Jovian *S* bursts and NB emission appearance and their interaction are discussed in section 4.

2. Nonresonant Parametric Transformation of the Radiation Frequency in a Magnetized Plasma

[9] It is well known that the propagation of waves in a medium with nonstationary variation in parameters can be accompanied by the amplitude-frequency modulation of a signal and the broadening of its frequency spectrum. These phenomena are due to a parametric interaction of radiation and medium. There are resonant and nonresonant parametric interactions between waves and the propagation medium. For the resonant interaction the spatial and temporal scales of the medium parameters variations are in the certain relations with the frequency and wave number of the waves which are propagating in the medium. For the Jovian decametric narrowband emission, the mechanism of nonresonant parametric interaction seems more promising. In this case, no special constraints are imposed on the law of variation in the medium parameters. In particular, such a mechanism can be aperiodic, e.g., as is the case with the magnetic field at the footprints of Io's magnetic flux tube.

[10] For a study of variations in the frequency-time structure of the waves generated in the *S* emission source in the case of nonstationary disturbances of the medium parameters, one can use the geometric-optical approximation generalized to the case of nonstationary media [*Ostrovskii and Stepanov*, 1971; *Kravtsov et al.*, 1974]. This can be done when the parameters $p(\vec{r}, t)$ of the medium are fairly slow functions of time t and spatial coordinates $\vec{r}$,

$$\chi \sim \frac{1}{\omega p_i}\left|\frac{\partial p_i}{\partial t}\right| \sim \frac{1}{k p_i}\left|\frac{\partial p_i}{\partial \vec{r}}\right| \ll 1. \tag{1}$$

[11] In this case, the radiation propagates in a sufficiently small region and for a short time in about the same way as in a homogeneous stationary medium with parameters close to the parameters $p(\vec{r}, t)$ of this region. The solution for components f_i of the vectors of electric $\vec{E}$ and magnetic $\vec{B}$ fields of the propagating radiation is sought in the form [*Ostrovskii and Stepanov*, 1971]

$$f_i(\vec{r},t) = \left(f_i^{(0)}(\vec{r},t) + \chi f_i(\vec{r},t)^{(1)} + \chi^2 f_i(\vec{r},t)^{(2)} + \cdots\right) \exp^{\imath\varphi(\vec{r},t)}, \tag{2}$$

where φ is a phase of the wave. Substituting (2) into the corresponding wave equations, we obtain a successive system of equations for $f_i^{(0)}$ $(\vec{r}, t)$, f_i $(\vec{r}, t)^{(1)}$, f_i $(\vec{r}, t)^{(2)}$, etc. From the requirement of existence of a nontrivial solution for $f_i^{(0)}$ $(\vec{r}, t)$ we obtain the equation

$$\frac{c^2}{\omega^2(\vec{r},t)} k^2(\vec{r},t) = n^2\left(\omega(\vec{r},t), \vec{k}(\vec{r},t), p_i(\vec{r},t)\right), \tag{3}$$

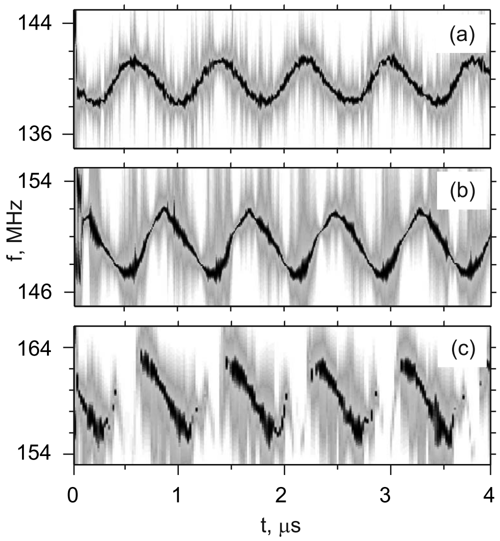

Figure 5. Dynamic spectra of the initially continuous quasi-monochromatic wave of the whistler range after the passage across the region with periodic disturbance of the magnetic field for (a) $f = 140$ MHz, (b) $f = 150$ MHz, and (c) $f = 160$ MHz (adapted from *Gushchin et al.* [2008]).

where $\omega(\vec{r}, t)$ and $\vec{k}(\vec{r}, t)$ are determined by the relationships

$$\omega(\vec{r}, t) = \frac{\partial \varphi(\vec{r}, t)}{\partial t}, \vec{k}(\vec{r}, t) = -\nabla \varphi(\vec{r}, t). \tag{4}$$

[12] For a study of the spectrum transformation of the propagating wave, it is convenient to use the equations directly determining the variations $\omega(\vec{r}, t)$ and $\vec{k}(\vec{r}, t)$. These equations can easily be obtained by differentiating (3) with respect to $\omega(\vec{r}, t)$ and $\vec{k}(\vec{r}, t)$ and taking into account that $\frac{\partial \vec{k}(\vec{r}, t)}{\partial t} = -\omega\,(\vec{r}, t)$ [*Stepanov*, 1969]:

$$\frac{\partial \omega}{\partial t} + (\vec{V}_g \nabla)\omega = -\omega \left(\frac{\partial (n\omega)}{\partial \omega} \right)^{-1} \frac{\partial n}{\partial t}\bigg|_{\omega, \vec{k}} \tag{5}$$

$$\frac{\partial \vec{k}}{\partial t} + (\vec{V}_g \nabla)\vec{k} = -\omega \left(\frac{\partial (n\omega)}{\partial \omega} \right)^{-1} \frac{\partial n}{\partial \vec{r}}\bigg|_{\omega, \vec{k}}. \tag{6}$$

[13] In (2)–(6), n is the refractive index of the medium, $\vec{V}_g$ is the vector of the group velocity of the wave, ω and $\vec{k}$ are the frequency and the wave vector of the wave, and the derivative on the right-hand side of (5) and (6) is taken for constant ω and $\vec{k}$. From (5) and (6) it is seen that in a homogeneous stationary medium, in which $n(\vec{r}, t) = const$, the disturbances of the wave vector $\vec{k}$ and frequency ω propagate in space unvaried, with group velocity $\vec{V}_g$. Variation 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, and the wave vector $\vec{k}$ is varied in the presence of spatial inhomogeneity of the medium, i.e., at $\frac{\partial n}{\partial \vec{r}}\big|_{\omega, \vec{k}} \neq 0$.

[14] Dynamic spectra of radiation, obtained by a laboratory experiment analyzing the propagation of a quasi-monochromatic wave in a magnetized plasma with strong frequency dispersion and periodic disturbance of the magnetic field are presented in Figure 5. The experimental setup represented a vacuum chamber of 10 m in length and 3 m in width, in which a plasma column of 4 m in length and 1.5 m in diameter was created. Detailed description of the experimental setup can be found by, e.g., *Gushchin et al.* [2008]. In a dense magnetized plasma with $f_{Be}^2 \ll f_{pe}^2$ ($f_{pe} = 2.8$ GHz and $f_{Be} = 225$ MHz are the plasma frequency of electrons and the electron gyrofrequency, respectively), whose magnetic field is modulated with the frequency $\Omega = 1$ MHz and amplitude $\delta B \simeq 2 \times 10^{-2} B$, a quasi-monochromatic wave of the whistler range $f_0 < f_{Be}$, where f_0 is the wave frequency in the source region, was generated. The receiving antenna was located at a distance $\Delta z = 25$ cm from the source.

[15] It is seen in Figure 5 that the initially continuous quasi-monochromatic signal propagating in the nonstationary region is modulated both in frequency (Figures 5a–5c) and in amplitude (Figures 5c). The magnitude of the frequency deviation increase as the frequency approaches the electron cyclotron frequency, i.e., as the frequency dispersion increases. The amplitude δf of frequency modulation of a signal in relative units can amount to about the relative disturbance δB of the magnetic field, and $\delta f/f \sim \delta B/B$.

[16] The amplitude-frequency modulation of the initially quasi-monochromatic signal is stipulated by two effects: the nonresonant parametric modulation of the signal frequency due to a time variation in the refractive index, whose instability is stipulated by a harmonic variation in the magnetic field, and strong frequency dispersion of the medium, i.e., the dependence of the refractive index and group velocity of the propagating electromagnetic radiation on frequency [*Gushchin et al.*, 2008]. Depending on the phase of the variable magnetic field, the signal frequency is shifted toward larger or smaller frequencies. Frequency dispersion of the medium results in that different frequency parts of the frequency-modulated signal move with different group velocities. This results in compression and extension of separate parts of the wave, and a frequency drift appears in the dynamic spectrum. Strong frequency dispersion can lead, even on short wave propagation paths, to the fractionation of a frequency-modulated signal into separate wave packets following each other with characteristic time determined by the characteristic time of variation in the medium parameters.

3. Propagation of the Extraordinary Electromagnetic Wave in a Magnetized Dispersive Plasma With Nonstationary Disturbance of the Magnetic Field

[17] 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 nonstationary disturbance of the planetary magnetic field.

[18] For finding a solution to the system of equations (5) and (6) within the framework of the geometric-optical approximation, one can use the method of characteristics. In the particular case of a homogeneous nonstationary magnetized plasma, the system of equations for the characteristics has the form [*Ostrovskii and Stepanov*, 1971]

$$\frac{d\vec{r}}{dt} = c\left(\frac{\partial n\omega}{\partial\omega}\right)^{-1}\frac{\vec{k}}{k}, \tag{7}$$

$$\frac{d\omega}{dt} = -\omega\left(\frac{\partial n\omega}{\partial\omega}\right)^{-1}\left.\frac{\partial n}{\partial t}\right|_{\omega,\vec{k}}, \tag{8}$$

where c is the speed of light.

[19] 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, the system of equations (7) and (8) takes the form

$$\frac{dz}{dt} = c\frac{\left[\left(f^2 - f_{\rm L}^2(z,t)\right)\left(f^2 - f_{\rm R}^2(z,t)\right)\right]^{1/2}\left(f^2 - f_{\rm UH}^2(z,t)\right)^{3/2}}{f\left[f^4 - 2f^2 f_{\rm UH}^2(z,t) + f_{\rm UH}^2(z,t)\left(f_{\rm L}^2(z,t) + f_{\rm R}^2(z,t)\right) - f_{\rm L}^2(z,t)f_{\rm R}^2(z,t)\right]}, \tag{9}$$

$$\frac{df}{dt} = -\frac{\left(f^2 - f_{\rm L}^2(z,t)\right)\left(f^2 - f_{\rm R}^2(z,t)\right)f_{\rm Be}(z,t)}{f\left[f^4 - 2f^2 f_{\rm UH}^2(z,t) + f_{\rm UH}^2(z,t)\left(f_{\rm L}^2(z,t) + f_{\rm R}^2(z,t)\right) - f_{\rm L}^2(z,t)f_{\rm R}^2(z,t)\right]}\frac{df_{\rm Be}(z,t)}{dt}. \tag{10}$$

[20] In (9) and (10), $f_{\rm UH} = \sqrt{f_{\rm Be}^2 + f_{\rm pe}^2}$ is the upper-hybrid resonance frequency, $f_{\rm R} = 0.5\left(\sqrt{f_{\rm Be}^2 + 4f_{\rm pe}^2} + f_{\rm Be}\right)$ is the cutoff frequency of the fast extraordinary wave, $f_{\rm L} = 0.5\left(\sqrt{f_{\rm Be}^2 + 4f_{\rm pe}^2} - f_{\rm Be}\right)$ is the cutoff frequency of the slow extraordinary wave, and $f_{\rm pe}$ and $f_{\rm Be}$ are the plasma frequency of electrons and the electron gyrofrequency, respectively; the ray coordinate z is reckoned across the undisturbed magnetic field $\vec{B}_0$.

[21] 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 and only weakly depends on frequency. In the 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.

[22] According to the radio occultation experiments with various spacecrafts, in particular with Galileo orbiter, the electron density profile in the Jovian ionosphere depends on many conditions (solar activity, spacecraft latitudes, day hours, and so on). *Hinson et al.* [1997] reported on the peak electron density $N_0 \approx 10^5$ cm^{-3} located at the altitude $h_{\rm m} \approx$ 900 km with thickness $H \approx 200$ km in the evening sector, and correspondingly in the morning sector these parameters are $N_0 \approx 2 \times 10^4$ cm^{-3}, $h_{\rm m} \approx 2000$ km, and $H \approx 1000$ km. The directivity pattern of the Jovian decametric radiation source is a hollow cone, which is magnetic field aligned and has an angular aperture $2\theta_{\rm c} \approx 120° - 150°$ [*Dulk*, 1965; *Shaposhnikov et al.*, 2000]. For definiteness assuming $\theta_{\rm c} \simeq 60°$, we find that the ionospheric path length $l_{\rm i}$ ($l_{\rm i} = H/\cos\theta_{\rm c}$) of the decametric electromagnetic radiation for the above mentioned parameters of the ionosphere is 400 and 2000 km, respectively.

[23] Consider at first a simple 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:

$$B(z,t) = B_0\left(1 + \delta B\sin(\Omega t)\exp\left(-\frac{(z - z_0)^2}{a^2}\right)\right). \tag{11}$$

[24] Here, a is the characteristic spatial scale, δB is the maximum disturbance amplitude $\delta B \ll B_0$, and z_0 is the coordinate of the maximum of the magnetic field disturbance. The source is located at the point $z = z_{\rm s}$ ($z_{\rm s} \le z_0$) and generates a quasi-monochromatic, linearly polarized wave at the frequency $f > f_{\rm R}$, 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 lie in a range of 2 to 400 Hz [*Carr and Reyes*, 1999; *Litvinenko et al.*, 2004b]. The magnetic field B_0 = 7 G.

[25] The results obtained by numerical solution of the system of equations (9) and (10) for different values of the ratios $f/f_{\rm R}$ and $\delta B/B_0$ and the value of the disturbance region a are presented in Figures 6–10.

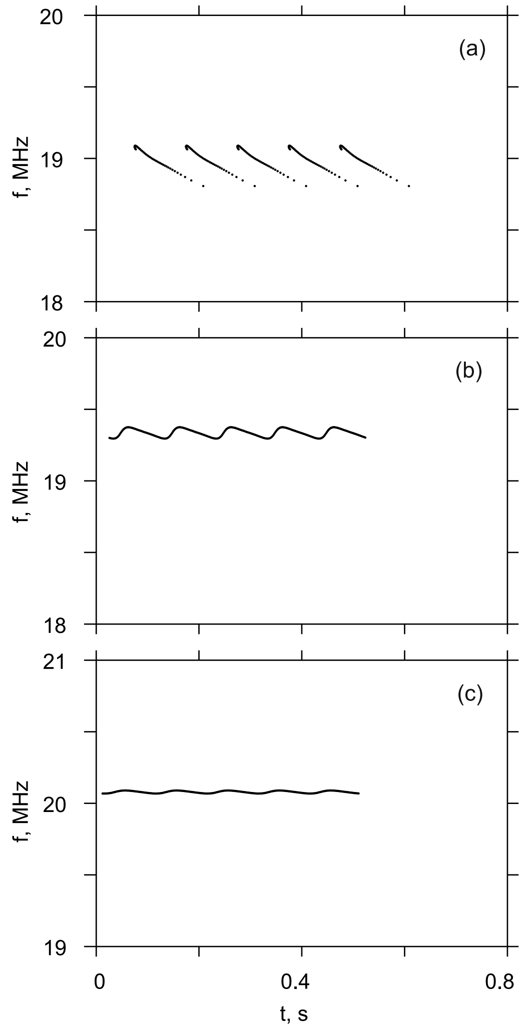

Figure 6. Examples of calculated dynamic spectra of decametric emission at the output of the Jovian ionosphere with $N_0 = 10^4$ cm^{-3} and $H = 1000$ km. Disturbances of the magnetic field along the wave propagation path is described by function (11) with $\Omega/2\pi = 10$ Hz, $\delta B/B_0 = 0.02$, and $a = 100$ km. The dynamic spectra are constructed for the radiation generated at the frequencies (a) $f = 1.02 f_R$, (b) $f = 1.04 f_R$, and (c) $f = 1.08 f_R$.

[26] The numerical calculations performed in accordance with the plasma parameters characteristic of the Jovian ionosphere confirm the results obtained in the course of the laboratory experiments and described in section 2. Propagation of a quasi-monochromatic signal through a nonstationary 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 narrowband *S* bursts (Figures 6a and 7a–7c), NB emission drifting over the frequency spectrum (Figures 6b, 6c, and 8a–8c), inverted V events (Figures 9a–9c). Also, bursts with positive drift (Figure 10), which were observed in a number of experiments, can appear [*Ellis*, 1975; *Riihimaa*, 1977; *Boudjada et al.*, 1996]. The occurrence of bursts with positive frequency drift is due to the fact that the time $\tau = a/V_g$ of passage of a signal through the region with disturbed magnetic field is long compared with the disturbance period $T \geq 2\pi/\Omega$.

[27] The form of the structure depends on many reasons, such as the magnitude of the magnetic field disturbance and sizes of the disturbed region, dispersion determined by the ratio f/f_R, parameters of the ionosphere, and length of the ionospheric path. Calculations also show that the fine structure of the dynamic spectrum depends on the form of the disturbing magnetic field. Figure 11 shows the dynamic spectra of the decametric radio emission transmitted through the region with nonstationary disturbance of a magnetic field whose profile is more complex than in the previous case:

$$B(z,t) = B_0\left(1 + \exp\left(-\frac{(z - z_0)^2}{a^2}\right)\right) \cdot (\delta B_1 \sin(\Omega_1 t) + \delta B_2 \sin(\Omega_2 t)). \qquad (12)$$

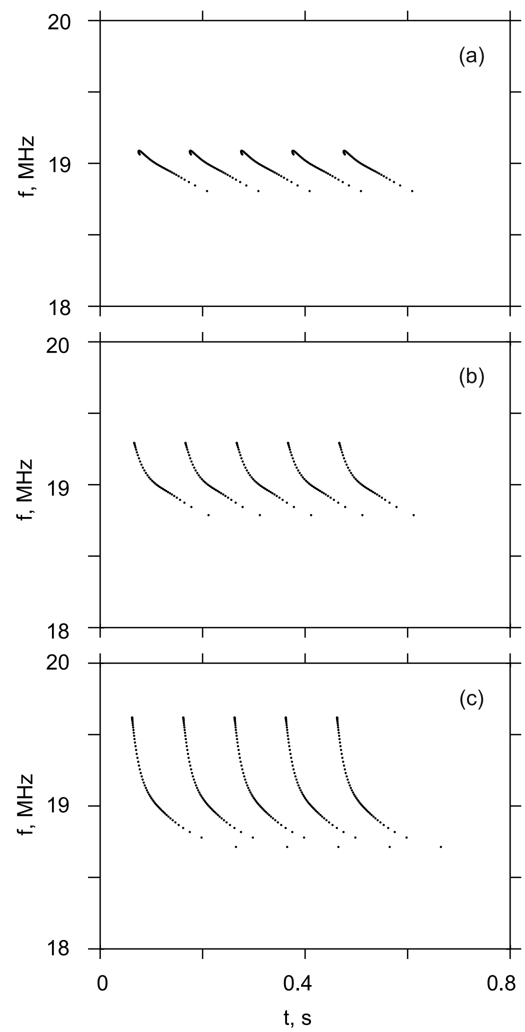

Figure 7. Examples of calculated dynamic spectra of decametric emission at the output of the Jovian ionosphere with $N_0 = 10^4$ cm^{-3} and $H = 1000$ km for the radiation generated at frequency $f = 1.02 f_R$. Disturbances of the magnetic field along the wave propagation path is described by equation (11) with $\Omega/2\pi = 10$ Hz, $a = 100$ km and different values of disturbance amplitude $\delta B/B_0$: (a) 0.02, (b) 0.04, and (c) 0.08.

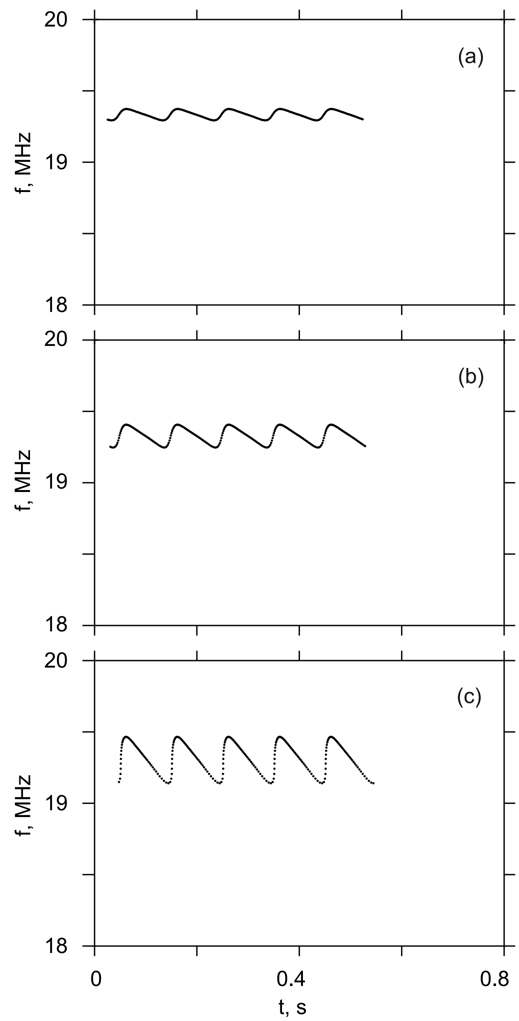

Figure 8. Examples of calculated dynamic spectra of decametric emission at the output of the Jovian ionosphere with N_0 = 10^4 cm^{-3} and H = 1000 km for the radiation generated at frequency f = 1.04f_R. Disturbances of the magnetic field along the wave propagation path is described by equation (11) with $\Omega/2\pi$ = 10 Hz, $\delta B/B_0$ = 0.02 and different lengths a of the disturbance region: (a) 100 km, (b) 200 km, and (c) 400 km.

[28] More complex structures arise in this case. For example, Figure 11a shows a dynamic spectrum in which trains of quasi-harmonic oscillations of the frequency spectrum with frequency $\Omega_1/2\pi$ are repeated with the period $T_2 = 2\pi/\Omega_2$. These quasi-harmonic oscillations drift gradually toward lower frequencies. A similar structure was observed in the experiment (see Figure 4). Figures 11b and 11c show other examples of calculated dynamic spectra, which are similar to those observed in the experiments [see, e.g., *Riihimaa*, 1992].

[29] Note that in this paper we have given examples of the dynamic spectra calculated for the radiation propagating in a plasma with the parameters $N_0 = 2 \times 10^4$ cm^{-3} and H = 1000 km. Similar spectra were obtained for a plasma with another set of parameters, namely N_0 = 10^5 cm^{-3} and H = 200 km.

4. Discussion

[30] In section 3 we showed, using a simple example, 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 nonstationary magnetic field can vary dramatically. Depending on propagation conditions, different forms of the fine structure, ranging from continuous 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.

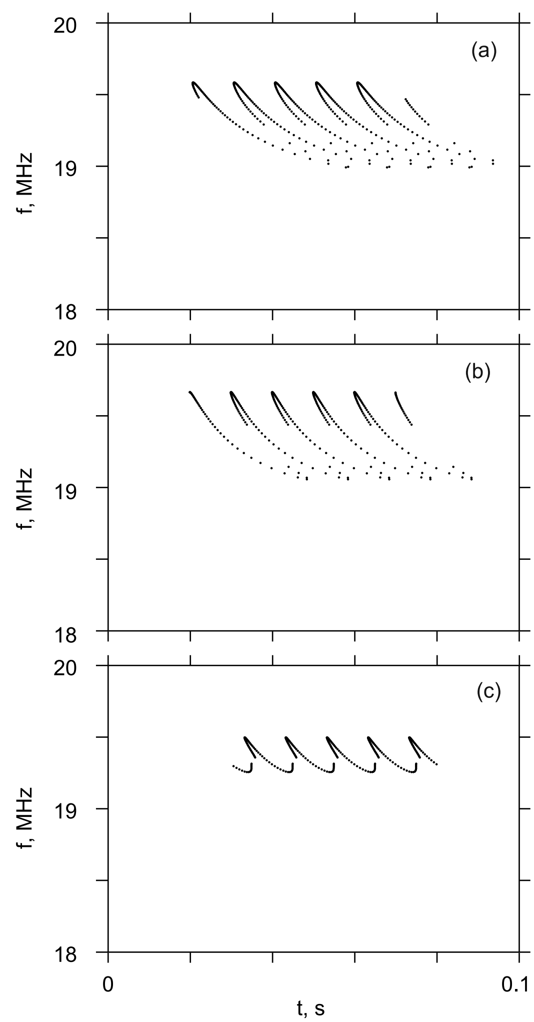

Figure 9. Examples of calculated dynamic spectra of decametric emission at the output of the Jovian ionosphere with N_0 = 10^4 cm^{-3} and H = 1000 km for the radiation generated at frequency f = 1.04f_R. Disturbances of the magnetic field along the wave propagation path is described by equation (11) with $\delta B/B_0$ = 0.02, different lengths a of the disturbance region: (a) 100 km, (b) 200 km, and (c) 400 km, with modulation frequency $\Omega/2\pi$ = 100 Hz.

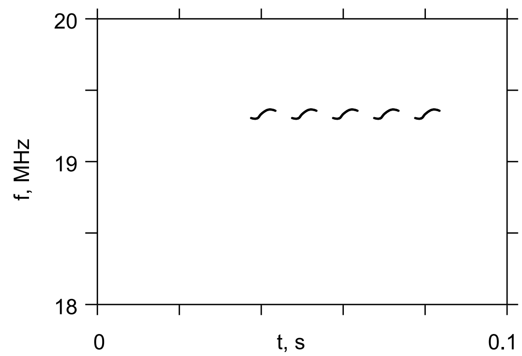

Figure 10. Example of the dynamic spectrum with positive frequency drift. The spectrum is obtained for the radiation with frequency $f = 1.04 f_R$, at the output of the Jovian ionosphere with $N_0 = 10^4$ cm^{-3} and $H = 1000$ km. Disturbance of the magnetic field along the wave propagation path is described by equation (11) with $\Omega/2\pi$ = 100 Hz, $\delta B/B_0$ = 0.02, and a = 600 km.

For example, the drift of generated frequencies toward the cutoff frequency of the extraordinary mode (an increase in the frequency dispersion) can lead to the result that a structure of the continuous NB emission type in the dynamic spectrum is replaced by a quasiperiodic train of *S* bursts, and vice versa, the shift of emitted frequencies away from the cutoff frequency (a decrease in the frequency dispersion) in the dynamic spectrum of a train of *S* bursts is replaced by continuous NB emission.

[31] A necessary condition for the occurrence of quasiperiodic trains of *S* bursts in the model we propose is that nonstationary 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 of Jupiter can ensure the required disturbance. According to *Su et al.* [2006], conditions for the formation of such a resonator are realized in the Jovian ionosphere between the conductive layer and the peak of Alfvén velocity at the topside of the ionosphere (Figure 12). Eigenfrequencies of the Jovian ionospheric resonator depend on both the ionospheric plasma density and the ionospheric scale height and lie in a range between ~4 Hz and ~400 Hz. Their typical frequency is about 20 Hz. That is the values of eigenfrequencies are in good agreement with the observed periodicity of *S* bursts. Note here, that 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 electron acceleration mechanism or the localization of the acceleration region itself. In particular, the acceleration can occur in Io's ionosphere, as is supposed by *Zaitsev et al.* [2003], and this stipulates the correlation between the mentioned radiation and the position of Io in the orbit.

[32] 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 Figure 6c). According to modern concepts, the Jovian decametric emission corresponds to the fast extraordinary waves. The group velocity of these waves significantly depends on the frequency near the cutoff frequency. *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. However, *Hewitt and Melrose* [1983] do not discuss the possibility of realization of the proposed mechanism for the generation of the Jovian decametric radio emission. Another mechanism of generation of

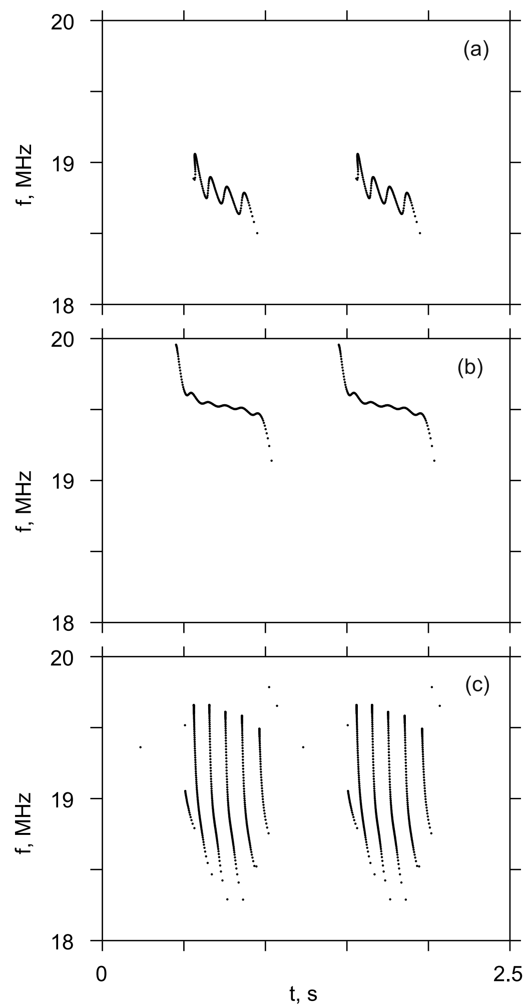

Figure 11. Examples of calculated dynamic spectra at the output of the Jovian ionosphere with $N_0 = 10^4$ cm^{-3} and H = 1000 km in the case where the disturbance of the magnetic field along the wave propagation path is described by equation (12) with $\Omega_1/2\pi$ = 10 Hz, $\Omega_2/2\pi$ = 1 Hz, and a = 400 km. The spectra are presented for the cases (a) f = $1.01 f_R$, $\delta B_1/B_0 = 0.01$, and $\delta B_2/B_0 = 0.03$, (b) $f = 1.01 f_R$, $\delta B_1/B_0$ = 0.1, and $\delta B_2/B_0$ = 0.03, and (c) f = $1.05 f_R$, $\delta B_1/B_0$ = 0.01, and $\delta B_2/B_0$ = 0.08.

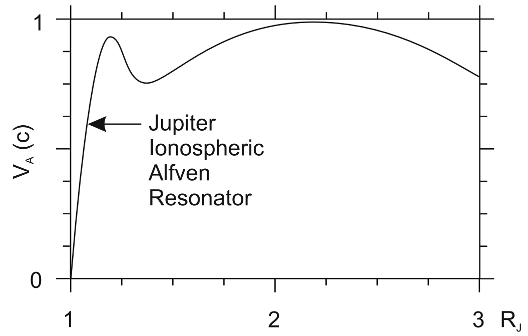

Figure 12. The Alfvén velocity V_A along the Io-Jupiter magnetic flux tube where c is the speed of light and R_J is Jupiter's radius (adapted from *Ergun et al.* [2006]).

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 with frequencies close to the cutoff frequency. We would like to note here that our parametric mechanism of the formation of trains of *S* bursts and other mechanisms of train formation (the pulsing regime of plasma wave conversion into electromagnetic radiation [*Zaitsev et al.*, 1986], for example) can be realized independently of each other. As a result, a complex fine structure with different time scales will appear in the dynamic spectrum of the Jovian decametric radio emission.

[33] We specially would like to remark that in our parametric model proposed in this paper we discuss an origin of fine structure only for narrowband decameter radiation, i.e., radiation which locates in a frequency range Δf which is much smaller than radiating frequency, $\Delta F \ll f$. This is reasonable due the following considerations. First, variation of radiation frequency δf, which is caused by nonstationary variation of a magnetic field, is proportional to amplitude of disturbance δB, $\delta f/f \sim \delta B/B$. In real conditions of a planetary magnetic field these disturbances are insignificant, $\delta B/B \ll 1$, that leads only to small changes of radiation frequency, $\delta f/f \ll 1$. For narrowband radiation these variations of frequency are essential, because $\delta F\ \Delta f$, and, in opposite, they are insignificant for broadband radiation, which frequency band is comparable with radiating frequency, $\delta F \leq f$ and, accordingly, $\delta F \ll f$. Besides, it is necessary to satisfy the requirement of a strong frequency dispersion of medium in which radiation propagates. As we already marked above (section 3), only the ionosphere of the planet satisfies to this condition. Outside of the Jovian ionosphere the refraction coefficient is close to unit, so the changes in the dynamic spectrum which are caused by frequency dispersion will be negligible. Thus, the proposed parametric mechanism for the formation of the fine structure is inefficient for sources outside the ionosphere of the planet. Jovian decameter radiation is generated at frequencies which are close to the local gyrofrequency of electrons. This leads to the fact that in an inhomogeneous magnetic field the source height above the surface of the planet is related to the frequency of radiation. The ionosphere of Jupiter occupies a range of heights Δh, which is much smaller than the characteristic scale of variation of the planetary magnetic field, $\Delta h \ll R_J$, where R_J is a radius of Jupiter; the radiation sources of the different frequencies f are located at heights corresponding to gyroresonant levels $f_{Be} \simeq f$, so a small range of heights, occupied by the sources, causes the generation of radiation in a narrow range of frequencies $\Delta f \ll f$. Thus, the implementation of the parametric mechanism imposes restrictions on the location and size of the generation area in height, i.e., in the direction which is approximately orthogonal to the direction of propagation.

[34] 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 nonstationary variation in the magnetic field gives rise to an amplitude-frequency modulation of the decametric emission, which leads to a significant broadening and modification of its frequency spectrum. Depending on propagation conditions in the 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 when continuous radiation is generated in the source. The form of the fine structure of the dynamic spectrum and its variation with time are determined by conditions in the source and in its close vicinity as well as by their time variations. This allows the dynamic spectra containing *S* bursts to be used for radioastronomical diagnostics of the Jovian ionosphere.

[35] **Acknowledgments.** The work was supported by the Russian Foundation for Basic Research (project 08-02-00119-a and 09-02-90406-Ukr-f-a), the Ukrainian State Fund for Fundamental Researches (Project F28.2/005), the General Physics Division of the Russian Academy of Sciences (the Basic Research Program "Plasma Processes in the Solar System"), and the Academic exchange program of the Austrian Academy of Sciences.

[36] Philippa Browning thanks the reviewers for their assistance in evaluating this paper.

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