FEATURES OF GENERATION OF QUASI-PERIODIC VLF EMISSIONS WITH SIGNIFICANT FREQUENCY DYNAMICS INSIDE THE PLASMASPHERE

P. A. Bespalov[a,b,] *, O. N. Savina[a,b,] **

[a]*Federal Research Center A.V. Gaponov-Grekhov Institute of Applied Physics of the Russian Academy of Sciences, Nizhny Novgorod, Russia*

[b]*HSE University, Nizhny Novgorod, Russia*

**e-mail: pbespalov@mail.ru*

***e-mail: onsavina@mail.ru*

Receives March 06, 2025

Revised April 19, 2025

Accepted May 22, 2025

Abstract. Several basic models of frequency dynamics in quasi-periodic VLF emissions with spectral form repetition periods from 10 to 300 s are considered. In all cases, we are talking about manifestations of cyclotron instability of electron radiation belts, which are well described within the framework of the plasma magnetospheric maser theory based on the averaged self-consistent system of quasi-linear equations for waves and particles. Not so clear spectral fragments are characteristic of QP 1 bursts, which are hisses with resonant modulation predominantly near the upper spectral band by geomagnetic pulsations of the *Pc* 3-4 range. Analysis of the general problem of equilibrium in radiation belts shows the possibility of its instability, which is caused by the difference in the pitch-angle dependences of the particle source power and the stationary distribution function. In the nonlinear regime of this instability, QP 2 emissions are formed, usually with a clear increase in frequencies in individual spectral fragments. The main focus of this work was to study QP 2 emissions with significant frequency dynamics. In this case, new possibilities for diagnosing of space plasma are being revealed and the conditions for generating frequently observed mysterious quasi-periodic radiation with large and very fast dynamics of the frequency spectrum, which can be represented as a product of functions that depend on time and frequency, are being established. The study of important details of the excitation of quasi-periodic VLF emissions with significant frequency dynamics inside the plasmasphere has interesting prospects for further research, and the already achieved level of understanding of magnetospheric processes has a real diagnostic potential.

Keywords: *quasi-periodicVLF emissions, cyclotron instability, plasma magnetospheric maser, frequency spectrum dynamics, plasmasphere*

DOI: 10.31857/S00167940250506e2

1. INTRODUCTION

In many cases, conditions characteristic of plasma magnetospheric maser (PMM) operation are observed in electron radiation belts inside the plasmasphere for electromagnetic VLF emissions. The relatively dense magnetized plasma and the ends of the magnetic trap form a resonator for VLF electromagnetic waves. Energetic electrons with energies of about 40 keV serve as the active substance. The particle source acts as a pump, and the population inversion associated with the natural transverse anisotropy of the distribution function of energetic electrons in the presence of a loss cone provides cyclotron instability (CI) of electromagnetic waves [Bespalov and Trakhtengerz, 1986]. Often in the morning and afternoon subauroral magnetosphere, the PMM is a high-quietness oscillating system with an intrinsic frequency Ω_J. The presence of the PMM natural frequency corresponding to periodic processes of accumulation of energetic particles in radiation belts and their ejection into the ionosphere during bursts of electromagnetic radiation is the primary cause of quasiperiodic electromagnetic VLF emissions with periods of repetition of spectral forms of 10-300 s [Bespalov and Trakhtengerets, 1976].

These so-called quasi-periodic (QP) emissions are usually observed in the morning and afternoon sectors of the inner magnetosphere at frequencies of several kilohertz and have a recurrence period of spectral shapes from ten seconds to several minutes (see, e.g., [Sato and Kokubun, 1980; Smith et al., 1998; Engebretson et al., 2004; Nemec et al., 2016a,b]). They are recorded both by the DEMETER, CLUSTER, VanAllenprobes, and THEMIS spacecraft (see, e.g., [Hayosh et al., 2014; Titova et al., 2015]), by ground-based observations (see, e.g., [Smith et al., 1991; Manninen et al., 2012; Manninen et al., 2013]), and by simultaneous space and ground-based data (see, e.g., [Bezdeková et al., 2020]).

In many cases, observations show the simultaneous appearance of modulated noise emissions, geomagnetic pulsations, and particle precipitations in conjugate regions of the ionosphere (see, e.g., [Raspopov and Kleimenova, 1977]). Such properties are characteristic of QP1-radiations, probably, caused by changes in the CN increment by geomagnetic compression pulsations.

Along with those described above, QP2-radiations with clearly repeating spectral forms, mostly not accompanied by geomagnetic pulsations, have been observed [Sato et al., 1977; Sato and Kokubun, 1980; Sato and Fikunishi, 1981]. The nature of such radiations is related to the instability of the stationary state of radiation belts [Bespalov, 1981] and the development of the auto-oscillatory process in them [Bespalov, 1982]. Many important questions of the theory of formation of quasiperiodic radiations have been investigated for conditions guaranteeing small frequency dynamics of radiations.

The purpose of this work is to study the conditions of excitation of quasi-periodic VLF emissions with significant frequency dynamics inside the plasmasphere. In doing so, new possibilities of space plasma diagnostics are elucidated, and the conditions of generation of frequently observed quasi-periodic emissions with large and very fast dynamics of the frequency spectrum are established.

Section 2 summarizes the initial equations of the PMM theory. Section 3 briefly summarizes the results on the spectrum dynamics of quasi-periodic VLF emissions. Section 4 discusses the reason for the dynamics of the wave spectrum in a single burst of QP emissions. Section 5 discusses the excitation conditions of quasi-periodic VLF emissions, whose spectral shapes can be represented as a product of time-dependent and frequency-dependent functions. Section 6 summarizes the results of the paper.

2. INITIAL EQUATIONS OF THE THEORY UNDER WEAK PITCH-ANGLE DIFFUSION

The plasmonic magnetospheric maser (PMM) is a quasi-closed subsystem of the magnetosphere in which the resonant interaction of radiation belt electrons with whistler-band electromagnetic waves is realized. Inside the plasmasphere, the conditions are met under which the effective interaction of radiation belt electrons with electromagnetic waves of the whistling range at cyclotron resonance is possible

$$\omega - k_{\parallel} V_{\parallel} = \omega_B , \qquad (1)$$

where ω and $k_{\parallel}$ are the frequency and longitudinal (along the magnetic field) component of the wave vector of the electromagnetic wave, $V_{\parallel}$ and ω_B are the longitudinal velocity and gyrofrequency of the electron.

The CN dynamics of electron radiation belts is well described in the framework of PMM theory. To describe relatively slow processes with a characteristic time scale $\Delta t >> T_g > T_b$ one can use a system of quasilinear equations averaged over the period of bounce oscillations of energetic electrons between magnetic plugs T_b and over the period of group propagation T_g between magnetically conjugate regions of the ionosphere, and having the following form [Bespalov and Trakhtengerz, 1986]:

$$\frac{\partial F}{\partial t} = \left(\int_0^{\infty} \hat{D} \varepsilon_{\omega} F d\omega \right) - \frac{F}{\tau} + J , \qquad (2a)$$

$$\frac{\partial \varepsilon_{\omega}}{\partial t} = \frac{2}{T_g} \left(\Gamma - |\ln R| \right) \varepsilon_{\omega} = \left(\int_0^{\infty} \int_{x_c}^{1} \hat{K} F dx dV \right) \varepsilon_{\omega} - \nu \varepsilon_{\omega} . \qquad (2b)$$

Here $F(t,x,V)$ is the averaged distribution function of energetic electrons in the magnetic field tube, $J(x,V)$ is the power of the energetic particle source, $\tau(V)$ is the particle loss time due to collisions and transport, $x = V_{\perp L}/V$ is the sine of the equatorial pitch angle of the particle, $\varepsilon_{\omega}(t)$ is the spectral energy density of whistler waves, Γ is the averaged gain of whistler waves during a single passage of the radiation belt, $\nu(\omega) = 2|\ln R|/T_g$ - decrement of attenuation due to all factors, $R(\omega)$ - effective coefficient of reflection from the ionosphere from above, $\hat{D}(x,V,\omega)$ and $\hat{K}(x,V,\omega)$ - known differential diffusion operator in the space of adiabatic invariants and the operator of whistler wave amplification at a single passage of the radiation belt, x_c - boundary of the loss cone, which at weak pitch-angle diffusion is practically empty. The efficiency of the CN depends weakly on the angle of the wave normal with respect to the magnetic field up to angles of the order of $\theta \simeq 30°$. Equation (2a) describes the pitch-angle and velocity modulus diffusion of energetic electrons due to wave interactions, and Equation (2b) is the averaged transport equation with averaged CN increment for electromagnetic waves. The differential operators, $\hat{D}$ $\hat{K}$ have a rather complicated form (see, e.g., [Bespalov and Trakhtengerts, 1986; Trakhtengerts and Rycroft, 2008]). Therefore, the question of the dynamics of the wave spectrum is not a simple one. Even in the stationary state of radiation belts, there are almost no results about the wave spectra and energy distributions of particles at the CH threshold.

3. SOME RESULTS OF THE ANALYSIS OF THE DYNAMICS OF THE SPECTRUM OF QUASIPERIODIC ONCH RADIATIONS

Many theoretical results about the dynamics of CNs were obtained without taking into account the frequency dynamics. It can be reasonably done, for example, if the parameter $\beta_* = \frac{\omega_{pL}^2 V^2}{\omega_{BL}^2 c^2} > 1$ [Bespalov, 1981]. Then, if the condition $1 < \beta_*(1 - T_{\|}/T_{\perp})$, in which $T_{\|}/T_{\perp}$ - characterizes the anisotropy of the distribution function of energetic electrons in the generation region, is fulfilled, the wave spectrum is localized near frequency

$$\omega \simeq \frac{\omega_{BL}}{\beta_*} \qquad (3)$$

and does not experience significant dynamics.

For a suitable power of energetic electron sources in a magnetic field tube with a large spread in the longitudinal velocity at the magnetic equator, the model with a step on the distribution function, which was proposed in [Bespalov and Trakhtengerz, 1980], shows good results in explaining the properties of VLF bursts evolving relatively slowly toward high frequencies.

A comparison of the geomagnetic pulsation spectra and envelope spectra at the realization of QP 1 VLF emissions in the PMM, carried out in the review [Bespalov and Kleimenova, 1989], confirmed the conclusions about the presence, at the realization of the developed CN in the morning and daytime magnetosphere, of highhquency oscillations with frequency

$$\Omega_J = \left(\frac{\nu}{T_l}\right)^{1/2}, \qquad (4)$$

where the characteristic lifetime of energetic electrons in the magnetic trap is

$$T_l \simeq \frac{N}{2S}, \qquad (5)$$

where N is the average content of energetic electrons in the magnetic field tube, S is the average flux of particles ejected from the tube into one of the two conjugate regions of the ionosphere.

Useful results are obtained from numerical calculations of spectra within the perturbation method and from processing observational data on quasi-periodic VLF emissions [Pasmanik et al., 2019].

In the next section, we move from summarizing the necessary basics to discussing new advances in the study of quasi-periodic emissions with significant frequency dynamics.

4. THE CAUSE OF THE WAVE SPECTRUM DYNAMICS IN A SINGLE BURST OF QP-RADIATION

There is an intrinsic reason for the dynamics of the wave spectrum in the system of equations (1). Let us consider qualitatively the dynamics of the frequency spectrum under the conditions of the quasiperiodic QP2 mode not associated with geomagnetic pulsations. The analysis of the properties of the averaged cyclotron amplification coefficient of whistler waves at a single passage of the radiation belt $\Gamma(\omega, F)$, which is included in equation (2b) and its structure is explained in the Appendix, is quite useful. Two frequency dependences $\Gamma(\omega, J)$ and $\Gamma(\omega, F_\circ)$ turn out to be the most important. The mutual position of the maxima of these dependences determines the direction of frequency change within an electromagnetic pulse. To clarify the physical meaning of this statement, let us consider the initial stage of accumulation of energetic electrons in a magnetic trap under initial conditions when the spectral energy density is at the noise level $\varepsilon_\omega(t=0) = \varepsilon_*$, and there are practically no particles in the magnetic trap $F(t = 0) = 0$. In such a case, according to the initial equations (2), the distribution function will grow according to a linear law

$$F = J \cdot t . \qquad (6)$$

Accordingly, at this stage the gain has the following form $\Gamma(\omega, F = J \cdot t) = t\Gamma(\omega, J)$ and according to equation (2b)

$$\varepsilon_\omega = \varepsilon_* \, exp\left(\frac{1}{T_g(\omega)} \left(t^2 \Gamma(\omega, J) - 2t \left| \ln R(\omega) \right| \right) \right) \qquad (7)$$

the maximum of the spectral energy density as the particles accumulate will be determined by frequency maximum of the function $\Gamma(\omega, J) / T_g(\omega)$.

At further accumulation of particles the diffusion in the space of adiabatic invariants is switched on, and the maximum of the spectrum of waves shifts closer to the maximum of the spectrum in the stationary state. The stationary state of the system of waves and particles is determined by the averaged quasi-linear equations (2), which at $\frac{\partial}{\partial t} = 0$ have a solution for the distribution function $F = F_0(x, V)$ and the spectral energy density of waves $\varepsilon_\omega = \varepsilon_{0\omega}$, corresponding to the gain $\Gamma(\omega, F_0)$. At realization of the quasi-periodic regime the system does not reach the stationary state, particles fall out of the magnetic trap and the process of particle accumulation starts again. The frequencies corresponding to the maximum of the spectral wave energy density are largely determined by the anisotropy of the pitch-angle distribution function. The higher the anisotropy, the higher the frequency. Therefore, at the initial stage, the wave spectrum is determined by the angular dependence of the source, and closer to the maximum of the electromagnetic radiation burst, is determined by the distribution function F_0 in the steady state. As a result, the frequency of electromagnetic radiation increases within an individual burst if the power of the particle source has a less pronounced pitch-angle dependence than the steady-state distribution.

Usually, when realizing QP2-type radiations, there is often a change in the average frequency of radiation, from which one can infer the angular dependence of the particle source power. If within the electromagnetic burst the frequency of radiation increases, it indicates that the power of the particle source is more isotropic than it could be in the steady state, if the frequency drops, the particle source has high anisotropy.

5. DYNAMICAL SPECTRA OF QP2-RADIATIONS WHOSE SPECTRAL SHAPES CAN BE REPRESENTED AS A PRODUCT OF TIME-DEPENDENT AND FREQUENCY-DEPENDENT FUNCTIONS

In addition to those already mentioned, there are often QP2-radiations for which the spectral shapes (logarithm of the spectral energy density of the waves) can be represented as a function with separating variables

$$\ln(\varepsilon_\omega(t)) = \ln(\varepsilon(t)) \Delta(\omega), \qquad (8)$$

where the function $\Delta(\omega)$, characterizing the frequency dependence, can be normalized without restriction of generality by the condition $\int_0^{\infty} \Delta(\omega) d\omega = 1$. Fig. *1a* and Fig. *2a* show two typical examples of dynamic spectra of quasi-periodic emissions, which show elements with large and almost synchronous variation at different frequencies with a period of about one minute. Synchrony is understood here in the sense that the logarithm of the spectral energy density at different frequencies has the same time dependence. In both cases, the electromagnetic emissions were observed during daytime hours local time. The panels of Fig. *1b*, *c* and Fig. *2b*, *c* show on-board magnetometer data and plasma concentration data indicating observations inside the plasmasphere. We note that waveguide propagation is not required for the realization of QP2 emissions. This conclusion of the theory is supported by known data from simultaneous observations on several spacecraft (see, e.g., [Li et al., 2021]).

Fig. 1.

Fig. 2.

5.1 Three conditions for the realization of quasiperiodic QP2 emissions, whose spectral shapes can be represented as a product of functions depending on time and on frequency

First, periodic oscillations in the PMM with a frequency close to (4) can be realized at certain values of the source powers of energetic particles. For example, in the evening sector of the magnetosphere, the power of the sources can be insufficient to reach the CH threshold. In the night sector of the magnetosphere, on the contrary, the power is excessively large. In such a case, the amplification of electromagnetic waves is large and the wave energy density adjusts very quickly to the stationary level, and the excitation of quasi-periodic radiations does not occur. The optimum value of the power of particle sources usually occurs in the daytime and morning sectors of the magnetosphere, where the condition is met [Bespalov, 1982].

$$\Omega_J^2 = \left(\int_0^{\infty} \int_{x_c}^{1} \hat{K} J dx dV \right) > 0 , \qquad (9)$$

which shows that the oscillatory modes of the CN take place only at a suitable dependence of the particle source power on the pitch angle and velocity.

Second, for self-excitation of QP2 emissions, the particle source power must have a suitable dependence on the pitch angle and energy corresponding to the instability of the stationary state. It was once shown [Bespalov P.A., 1981] that this is possible because of the functional difference between the particle source power $J(x,V)$ and the steady-state distribution function $F_0(x,V)$. Calculations based on the analysis of the system of equations (2) showed that the characteristic equation of small oscillations near the stationary state has the form

$$\lambda^3 + \Omega_J^2 \lambda + 2\Omega_J^2 \gamma_J = 0. \qquad (10)$$

and specific examples of pitch-angle dependence of particle sources were given, at which the solution of the characteristic equation (10) has the form $\lambda = \pm i\Omega_J + \gamma_J$, where $\gamma_J > 0$, and the possibility of realization of auto-oscillatory processes for specific PMM parameters was substantiated. Note that the formula for calculating the value γ_J is given in [Bespalov, 1982].

Third, there should be a certain frequency dependence of the reflection coefficient from the ionosphere above. Let us assume that a developed periodic mode is realized. Then, at a suitable time origin, the distribution function in the interval between electromagnetic pulses grows proportionally to time, repeating the angular dependence of the particle source power $F = J(\kappa, V)t$. The spectral density of electromagnetic waves satisfies the averaged transport equation (*2b*), which can be written as

$$\frac{\partial}{\partial t}\left(\frac{T_g}{2}\ln\left(\varepsilon_\omega(t)\right)\right) = \Gamma - \left|\ln R\right| \qquad (11)$$

and integrate in (11) over the period $T(\omega)$, which may depend on frequency

$$T(\omega) = \frac{2\left|\ln R(\omega)\right|}{\Gamma(\omega, J)}. \qquad (12)$$

For QP2 radiations, the spectral forms of which can be represented as a product of functions depending on time and on frequency, the period (12) does not depend on frequency and it is possible at the same frequency dependence of the reflection coefficient of whistler waves from the ionosphere from above and the averaged coefficient of cyclotron amplification of whistler waves at a single passage of the radiation belt, in which the power of sources of energetic electrons in the magnetic field tube is substituted instead of the distribution function.

6. CONCLUSION

Thus, the significant frequency dynamics in quasi-periodic VLF emissions is determined by several factors:

- The frequency dependence of the attenuation decrement of whistler waves in the magnetospheric resonator, determined by the ionospheric overhead reflection coefficient;
- frequency dependence of the wave spectrum in the PMM stationary state;
- the frequency dependence of the averaged gain, in which the power of energetic electron sources in the magnetic field tube is substituted instead of the distribution function;
- the presence of waveguides for whistling waves and other factors affecting the reflection coefficient of electromagnetic waves from the ionosphere from above.

The study of the details of excitation of quasi-periodic VLF emissions with significant frequency dynamics within the plasmasphere has interesting prospects for further research, and the level of understanding of magnetospheric processes already achieved has important diagnostic potential.

APPENDIX

STRUCTURE OF THE AVERAGED AMPLIFICATION FACTOR OF WHISTLER WAVES

The averaged cyclotron amplification factor of whistler waves at a single passage of the radiation belt in equation (2b) $\Gamma(\omega, F)$ has the following form:

$$\Gamma = \frac{1}{2} T_g \left(\int_0^\infty \int_{x_c}^1 \hat{K} F dx dV \right). \qquad \text{(P1)}$$

In this expression, the differential operator is under the integrals

$$\hat{K} = G(\omega, x, V) \left[(Vx) \frac{\partial}{\partial V} + \left(\frac{\omega_{BL}}{\omega} - x^2 \right) \frac{\partial}{\partial x} \right]. \qquad \text{(P2)}$$

The differential operator (P2) acts on the averaged distribution function of energetic electrons $F(t, x, V)$ in the magnetic field tube, which is normalized by the condition

$$2\pi\sigma \int_0^\infty \int_{x_c}^1 F T_b V^3 x dx dV = N, \qquad \text{(P3)}$$

where N is the content of energetic electrons in the magnetic field tube with unit cross section at the ionospheric level, $x_c = \sigma^{-1/2}$, $\sigma = B_{max} / B_L$ is the slug ratio. The differential operator includes the still known non-negative function $G(\omega, x, V)$, a specific expression for which is given, for example, in [Bespalov and Trakhtengerz, 1986].

ACKNOWLEDGEMENTS

The authors are grateful to P.D. Shkareva for her help in presenting the observational data. The authors thank the makers of the Van Allen Probes spacecraft and their instruments for allowing free use of the data available on the website (http://emfisis.physics.uiowa.edu/Flight/).

FUNDING

The study was supported by a grant from the Russian Science Foundation (project No. 25-22-00237).

CONFLICT OF INTERESTS

The authors declare that they have no conflict of interest.

REFERENCES

1. *Bespalov P.A., Trakhtenherts V.Yu.* On nonlinear oscillatory processes in the Earth's magnetosphere // Izv. vuzov. Radiophysics. V. 19. No. 5-6. P. 801-811. 1976.

2. *Bespalov P.A., Trakhtenherts V.Yu.* Cyclotron instability of the Earth's radiation belts. In: Questions of plasma theory. V. 10. Moscow: Atomizdat. P. 88-163. 1980

3. *Bespalov P.A.* Self-regulation of plasma cyclotron "maser" radiation // Letters to the JETF. V. 33. No. 4. P. 192-195. 1981.

4. *Bespalov P.A., Trakhtenherts V.Yu*. Alfvenov masers. Gorky: IPF RAS. 190 p. 1986.

5. *Bespalov P.A., Kleimenova N.G.* Influence of geomagnetic pulsations on whistling radiation near the plasma pause // Geomagnetism and aeronomy. V. 29. No. 2. P. 177-191. 1989.

6. *Manninen Yu., Kleimenova N.G., O.V. Kozyreva, Bespalov P.A., Raita T.* Quasi-periodic VLF radiation, VLF choruses and geomagnetic pulsations Rs4 (April 3, 2011 event) // Geomagnetism and Aeronomy. V. 52 No. 1. P. 82-92. 2012.

7. *Raspopov O.M., Kleimenova N.G.* Disturbances of the electromagnetic field of the Earth. Part 3. VLF radiation. L.: LSU. 144 p. 1977.

8. *Bespalov P.A.* Self-exitation of periodic cyclotron instability regimes in a plasma magnetic trap // Phys.Scripta. V. 1982. N T2B. P. 576–579.1982. https://doi.org/10.1088/0031-8949/1982/T2B/044

9. *Bezdeková B., Nemec F., Manninen J., Hospodarsky G.B., Santolik O., Kurth W.S., Hartley D.P.* Conjugate observations of quasiperiodic emissions by the Van Allen probes spacecraft and ground-based station Kannuslehto // J. Geophys. Res.-Space Physics. V. 125. № 6. ID e27793. 2020. https://doi.org/10.1029/2020JA027793

10. *Engebretson M.J., Posch J.L., Halford A.J., Shelburne G.A., Smith A.J., Spasojevic M., Inan U.S., Arnoldy R.L.* Latitudinal and seasonal variations of quasiperiodic and periodic VLF emission in the outer magnetosphere // J. Geophys. Res. V. 105. № A5. ID A05216. 2004. https://doi.org/10.1029/2003JA010335

11. *Hayosh M.F., Nemec F., Santolik O. and Parrot M.* Statistical investigation of VLF quasiperiodic emissions measured by the DEMETER spacecraft // J. Geophys. Res. -Space Physics. V. 119. P. 8063–8072. 2014. https://doi.org/10.1002/2013JA019731

12. *Li J., Bortnik J., Ma Q., Li W., Shen X., Nishimura Y., et al.* Multipoint observations of quasiperiodic emission intensification and effects on energetic electron precipitation // J. Geophys. Res: - Space Physics. V. 126. ID e28484. 2021. https://doi.org/10.1029/2020JA028484

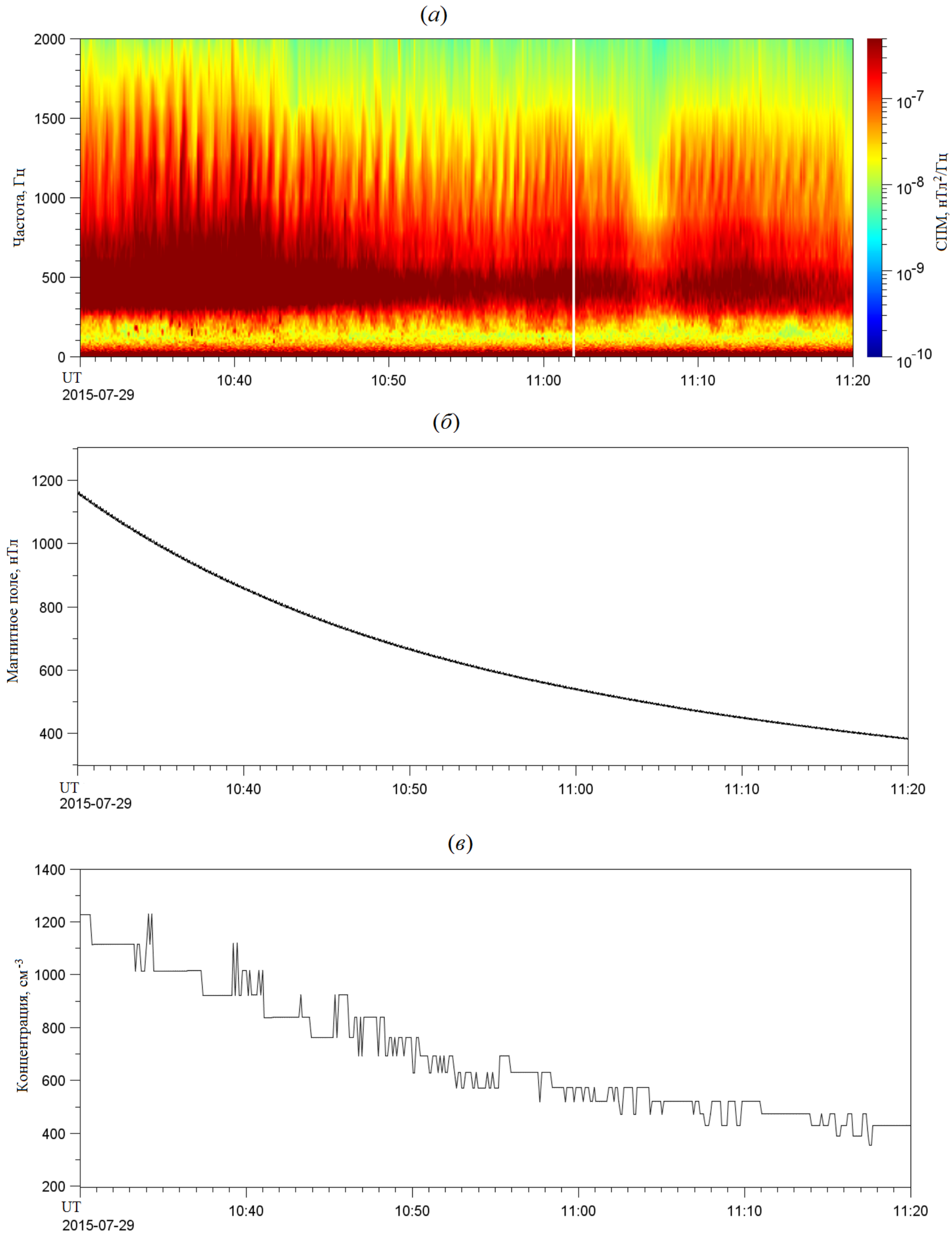
13. *Manninen J., Kleimenova N.G., Kozyreva O.V., Bespalov P.A., Kozlovsky A.E.* Non-typical ground-based quasi-periodic VLF emissions observed at L ~ 5.3 under quiet geomagnetic condition at night/ J. Atmos. Solar-Terr. Phys. V.99. P. 123–128. 2013. https://doi.org/10.1016/j.jastp.2012.05.007

14. *Nemec F., Hospodarsky G., Pickett J.S., Santolik O., Kurth W.S., Kletzing C.* Conjugate observations of quasiperiodic emissions by the Cluster, Van Allen Probes, and THEMIS spacecraft // J. Geophys. Res. -Space Physics. V. 121. № 8. P. 7647–7663. 2016a. https://doi.org/10.1002/2016JA022774
15. *Nemec F., Bezdekova B., Manninen J., Parrot M., Santolik O., Hayosh M., Turunen T.* Conjugate observations of a remarkable quasiperiodic event by the low-altitude DEMETER spacecraft and ground-based instruments // J. Geophys. Res. -Space Physics. V.121. № 9. P. 8790–8803. 2016b. https://doi.org/10.1002/2016JA022968
16. *Pasmanik D.L, Demekhov A.G., Hayoš M., Nemec F., Santolik O., Parrot M.* Quasiperiodic ELF/VLF emissions detected onboard the DEMETER Spacecraft: theoreticalanalysis and Comparison whith observations // J. Geophys. Res. -Space Physics. V.124. № 7. P. 275–284. 2019. https://doi.org/10.1029/2018JA026444
17. *Sato N., Hayasfi K., Kokubun S., Oguti T., Fukunishi H.* Relationships between quasi-periodic VLF-emission and geomagnetic pulsationn // J. Atm. Terr. Phys. V. 36. № 9. P. 1515–1526. 1974. https://doi.org/10.1016/0021-9169(74)90229-3
18. *Sato N., Kokubun S.* Interaction between ELF-VLF emissions and geomagnetic pulsations: quasi-periodic ELF-VLF emissions associated with Pc 3-4 magnetic pulsations and their geomagnetic conjugacy. J. Geophys. Res. V.85. № A1. P. 101–113. 1980. https://doi.org/10.1029/JA085iA01p00101
19. *Sato N., Fukunishi H.* Interaction between ELF-VLF-emissions: Classification of quasi-periodic ELF-VLF-emissions based on frequency-time spectra // J. Geophys. Res. V. 86. № A1. P. 19–29. 1981. https://doi.org/10.1029/JA086iA01p00019
20. *Smith A.J., Carpenter Y., Corcuff Y., Rash J.P.S., Bering E.A.* The longitudinal dependence of whistler and chorus characteristics observed on the ground near L=4. // J. Geophys. Res. - Space Physics. V.96. № A1. P. 275–284.1991. https://doi.org/10.1029/90JA01077
21. *Smith A.J., Engebretson M.J., Klatt E.M., Inan U.S., Arnoldy R.L., FukunishiH.* Periodic and quasiperiodic ELF/VLF emissions observed by an array of Antarctic stations // J. Geophys. Res. V. 103. № A10. P. 23611–23622. 1998. https://doi.org/10.1029/98JA01955
22. *Titova E.E., Kozelov B.V., Demekhov A.G., Manninen J., Santolik O., Kletzing/C. A., Reevesal G.* Identification of the source of quasiperiodic VLF emissions using ground-based and Van Allen Probes observations // Geophys. Res. Lett. V.42. P. 6137–6145. 2015. https://doi.org/10.1002/2015GL064911
23. *Trakhtengerts V.Y., Rycroft M.J.* Whistler and Alfven mode cyclotron masers in space. Cambridge University Press, Cambridge, UK, 2008. https://doi.org/10.1017/CBO9780511536519

FIGURE CAPTIONS

Fig. 1. (*a*)-Dynamic power density spectrum (PDS) of quasi-periodic VLF emissions from the Van Allen Probe A spacecraft data for the 29.07.2015 event at magnetic shells L =2.9-4.2 in the local time range LT = 12:45-14:25. (*b*)-Data from the onboard magnetometer. (*c*)-Data on plasma concentration.

Fig. 2. (*a*)-Dynamic power density spectrum (PDS) of quasi-periodic VLF emissions from Van Allen Probe A spacecraft data for the event on 30.06.2017 at magnetic shells $L=2$.8-4.7 in the local time range LT = 10:30-12:30. (*b*)-Data from the onboard magnetometer. (*c*)-Plasma concentration data.



(а)
Частота, Гц
2000
1500
1000
500
0
СПМ, нТл²/Гц
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
UT
2015-07-29
10:40
10:50
11:00
11:10
11:20
(б)
Магнитное поле, нТл
1200
1000
800
600
400
UT
2015-07-29
10:40
10:50
11:00
11:10
11:20
(в)
Концентрация, см⁻³
1400
1200
1000
800
600
400
200
UT
2015-07-29
10:40
10:50
11:00
11:10
11:20

Fig. 1.

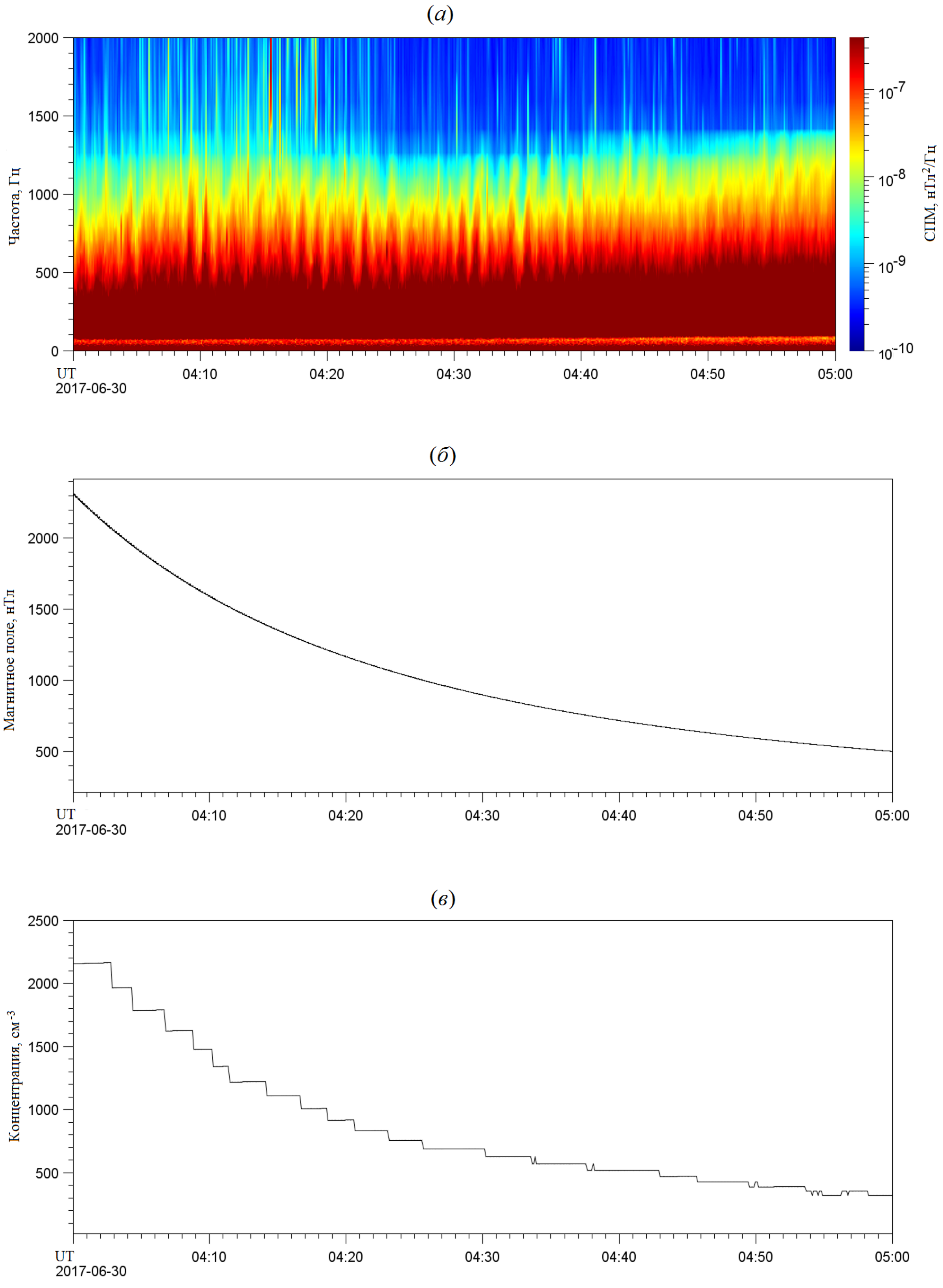

(а)
Частота, Гц
2000
1500
1000
500
0
СПМ, нТл^2/Гц
10^{-7}
10^{-8}
10^{-9}
10^{-10}
UT
2017-06-30
04:10
04:20
04:30
04:40
04:50
05:00
(б)
Магнитное поле, нТл
2000
1500
1000
500
UT
2017-06-30
04:10
04:20
04:30
04:40
04:50
05:00
(в)
Концентрация, см$^{-3}$
2500
2000
1500
1000
500
UT
2017-06-30
04:10
04:20
04:30
04:40
04:50
05:00

Fig. 2.