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IMPORTANCE OF THE ELECTRON PLASMA PARAMETER FOR EXCITATION OF CHORUS AND FORMATION OF MAGNETIC FIELD IRREGULARITY IN THE REGION OF THEIR EXCITATION

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Abstract. A threshold condition has been established for excitation of VLF electromagnetic radiation with a chorus structure of the dynamic spectrum in the daytime magnetosphere using the BPA (Beam Pulse Amplifier) mechanism for amplifying short noise electromagnetic pulses. The kappa distribution was used as a model function of the electron velocity distribution in the magnetosphere. Calculations performed for this distribution have shown that the threshold for excitation of chorus largely depends on the electron plasma parameter equal to the ratio of gas-kinetic pressure of electrons to magnetic pressure. This pattern is not contradicted by the dependence of the probability of excitation of chorus on the degree of magnetic field irregularity, which we derived from observations made by the Van Allen Probe spacecraft. It is sharp fluctuations in the magnetic field strength near its local minima outside the plasmasphere where the radiation under study can be excited. If there is an irregularity, the probability of detecting chorus is >70 %; and if there is no or very low irregularity, the probability of the absence of any emissions is ~80 %. The results indicate a common reason for the excitation of chorus and the magnetic field irregularity — a small but finite value of the plasma parameter.

Keywords: VLF emissions, chorus, wave-particle interaction, data analysis, middle magnetosphere.

INTRODUCTION

Chorus electromagnetic radiation with frequencies of the order of several kilohertz and repetition periods of discrete elements amounting to tenths of a second is usually generated outside of the plasmapause in the dawn and prenoon sectors of the middle magnetosphere. According to experimental data from the CLUSTER, THEMIS, and Van Allen Probe spacecraft, chorus are excited in a region shaped like a cigar elongated along the magnetic field more than 2000 km in length and 300 km in average diameter [Bell et al., 2009; Agapitov et al., 2017] near a local minimum of the magnetic field. Typically, chorus in the excitation region is discrete emissions in two spectral bands centered slightly below half the minimum electron cyclotron frequency for a magnetic flux tube considered. According to morphological studies, chorus is generated by electrons from radiation belts with 10–20 keV energies [Kasahara et al., 2009].

There is experimental data and theoretical calculations indicating that chorus can accelerate some electrons to high energies (several megaelectronvolts) for approximately several hours [Meredith et al., 2003]. From a more general point of view, the question concerning the acceleration of a small part of electrons by electromagnetic waves to relativistic energies has also been addressed in earlier works (see, e.g., [Summers et al., 1998; Horne, Thorne, 1998]). Accelerated high-energy particles in radiation belts pose a danger to spacecraft and are one of the critical factors of space weather. Operation of spacecraft, stability of communication and navigation systems depend on space weather. Some energetic electrons enter the upper atmosphere, where they manifest themselves as pulsating auroras [Nishimura et al., 2010; Miyoshi et al., 2015]. Thus, the interaction of charged particles with chorus ensures energy exchange between electrons in different energy channels and has many other geophysical manifestations.

To explain the observed discrete spectral forms of chorus electromagnetic radiation, cyclotron generation of different types are often discussed under the assumption of high anisotropy of the energetic electron distribution function [Trakhtengerts, 1995; Omura et al., 2008; Fu et al., 2014]. Yet, accumulated observational data cannot always be explained by the cyclotron mechanism of electromagnetic radiation generation. Important results have been obtained in [Zhou et al., 2015], where it is shown that chorus in the dayside magnetosphere can be generated in regions with marginally stable plasma, and the efficiency of this generation depends on the length of the region of wave-particle interaction. The Beam Pulse Amplifier (BPA) mechanism proposed by Bespalov and Savina [2018, 2019] can answer to many questions that arise when interpreting key features of experimental data.

The results obtained in this work agree with those of the BPA mechanism of chorus amplification [Bespalov, Savina, 2021]. As shown below, the main reason for their excitation is not too small value of the plasma parameter

$$\beta_e = 8\pi P_e / B^2, \tag{1}$$

in the rarefied magnetosphere. Note that (1) is briefly called plasma β.

The first section provides information about two possible types of wave-particle interaction at the Cherenkov resonance. We briefly describe fundamentals of the BPA mechanism theory. A condition is obtained for effective amplification of short noise pulses with kappa distribution of energetic electrons by velocity modulus. The second section gives specific examples of the relationship of the degree of magnetic field irregularity with chorus generation. The method of quantifying the magnetic field irregularity is detailed. We present the results of statistical processing of observational data. We compare Van Allen Probe A and B data. A magnetic field irregularity model is proposed, and the threshold excitation condition for the kappa distribution of energetic electrons by energy is calculated. In conclusion, we summarize the results.

1. CONDITIONS FOR WAVE-PARTICLE INTERACTION IN CHORUS GENERATION IN THE DAYSIDE MAGNETOSPHERE

1.1. Two types of wave-particle interaction at the Cherenkov resonance

The observed anisotropy of the distribution function of energetic electrons, particle fluxes, and their energy is often insufficient to reach the instability threshold at cyclotron resonance as a possible frequently discussed chorus generation mechanism. There is no such problem for the wave-particle interaction at the Cherenkov resonance.

It is well known that there are two interaction types at the Cherenkov resonance (see, e.g., [Artsimovich, Sagdeev, 1979]). In the first type, when $(\Delta V_z)^2 >> (\gamma / k_z)^2$, in deriving the formula for the growth rate γ at strongly bloomed beams in the Landau approximation, the finite width of the wave—particle resonance is neglected and the thermal beam spread in the field-aligned particle velocity ΔV is assumed to be much greater than the resonance width. Then, for each unstable wave with a longitudinal component of wave vector k_z a small group of resonance particles is found in the beam distribution function, whose contribution to the growth rate is determined by the slope of the distribution function. In the second type, when $(\Delta V_z)^2 << (\gamma / k_z)^2$, the entire beam as a whole is in resonance with an unstable wave. It is in this case that the development of the effective beam amplification we are interested in is possible.

1.2. BPA mechanism of chorus excitation

For typical conditions in the chorus excitation region, the emission frequency ω

$$\omega_{LH} < \omega < \omega_B < \omega_p,$$

where ω_{LH} is the lower hybrid frequency; $\omega_B = eB/(mc)$, $\omega_p = (4\pi n_p e^2 / m)^{1/2}$ are the electron cyclotron and plasma frequencies; e is the electron charge; m is the electron mass; n_p is the plasma density; c is the velocity of light. Many properties of electromagnetic waves propagating in the specified whistler range in the quasilongitudinal approximation [Ginzburg, 1967] in a cold relatively dense plasma are described by the well-known [Helliwell, 1965] dispersion equation

$$\omega_w = \frac{\omega_B |k_z| (k_z^2 + k_x^2)^{1/2}}{k_z^2 + k_x^2 + \omega_p^2 / c^2}, \tag{2}$$

where k_z and k_x are wave vector components along and across the magnetic field $\vec{B}$. It can be seen from (2) that under the condition $k_x^2 + k_z^2 = (\omega_p / c)^2$ the equation reduces to $\omega = c\omega_B / (2\omega_p) |k_z|$. There is therefore a specific velocity indicated by the red dashed line in Figure 1 and corresponding to the equality between the longitudinal phase and group velocities along the magnetic field (along the Z-axis)

$$V_{ph\,z} = V_{gz} = u_G, \tag{3}$$

where $u_G = c\omega_B / (2\omega_p)$ is the Gendrin velocity [Helliwell, 1995] independent of the magnitude of the transverse component of wave vector k_x.

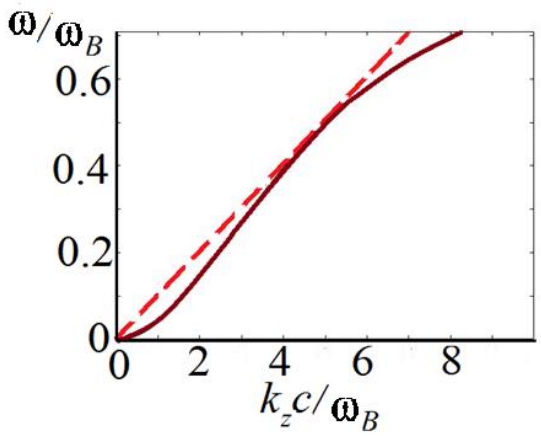

Figure 1. Dispersion relation determined by Equation (2). The red dashed line explains the possibility of equality between phase and group velocities (3)

There are interesting features of the evolution of the short electromagnetic pulse incident on a homogeneous layer of magnetized plasma if conditions (3) hold for spectral components. Such a pulse is a stationary wave in the z coordinate, and its wave field can be written as

$$\begin{aligned} \vec{E}_{\sim} &= \vec{E}_{\sim}\left(z - u_{\mathrm{G}} t\right), \\ \vec{B}_{\sim} &= \vec{B}_{\sim}\left(z - u_{\mathrm{G}} t\right). \end{aligned} \tag{4}$$

Short electromagnetic pulse with wave field (4), according to simple kinematic considerations [Bespalov, Savina, 2021] fundamental for the BPA mechanism, can interact for a long time only with a small part of energetic particles, which we call a cloud of active electrons. These electrons flew into the region of wave-particle interaction together with a pulse, and the small spread of their longitudinal velocities relative to the Gendrin velocity must satisfy the condition

$$\Delta V_z \simeq u_{\mathrm{G}}^2 t_{\mathrm{p}} / l \le \gamma / k_z < u_{\mathrm{G}}, \tag{5}$$

where t_{p} is the pulse duration; l is the length of the wave-particle interaction region. According to (5), the active electron cloud density with the distribution function f is determined by the expression

$$n_{\mathrm{b}} = \int\limits_{u_{\mathrm{G}} - (1/2)\Delta V_z}^{u_{\mathrm{G}} + (1/2)\Delta V_z} \left(\int\limits_0^{\infty} f \, 2\pi V_{\perp} dV_{\perp} \right) dV_z, \tag{6}$$

where the interval of integration along the field-aligned velocity V_z is defined by condition (5).

The spatiotemporal evolution of the active electron cloud in electromagnetic pulse field (4) is described by the quasi-hydrodynamics equations, which, after linearization, take the form

$$\begin{aligned} &\frac{\partial n_{\mathrm{b}\sim}}{\partial t} + u_{\mathrm{G}} \frac{\partial n_{\mathrm{b}}}{\partial z} + n_{\mathrm{b}} div\left(\vec{V}_{\sim}\right) = 0, \\ &\frac{\partial \vec{V}_{\sim}}{\partial t} + u_{\mathrm{G}} \frac{\partial \vec{V}_{\sim}}{\partial z} + \frac{e}{mc}\left(\vec{V}_{\sim} \times \vec{B}\right) = \\ &= -\frac{e}{m}\vec{E}_{\sim} - \frac{e u_{\mathrm{G}}}{mcB}\left(\vec{B} \times \vec{B}_{\sim}\right) \end{aligned} \tag{7}$$

where $n_{\mathrm{b}\sim}$, n_{b} are perturbed and unperturbed densities of active electrons, $\vec{V}_{\sim}$, $u_{\mathrm{G}}\left(\vec{B}/B\right) = \vec{V}_0$ are perturbed and unperturbed velocities of active electrons. In (7), the first equation is a linearized continuity equation; the second is a linearized equation of motion of active electron in Euler coordinates. Note that the last term on the right side of the second equation in (7) corresponds to the expression $-c/(mc)\left(\vec{V}_0 \times \vec{B}_{\sim}\right)$, derived when linearizing the Lorentz force. After turning to spectral components, expression for resonance current density in pulse (4) can be written as

$$j_{rz} = i \frac{n_{\mathrm{b}} e^2 \omega}{m\left(\omega - k_z u_{\mathrm{G}}\right)^2} E_{\sim}. \tag{8}$$

Taking into account the resonance current in Maxwell's equations, we can write the standard equation for spectral electromagnetic pulse components [Ginzburg, 1967]

$$\vec{k}\left(\vec{k}\vec{E}\right) - k^2\vec{E} + \frac{\omega^2}{c^2}\hat{\varepsilon}\vec{E} = 0, \tag{9}$$

in which nonzero components of the plasma dielectric permittivity tensor are determined by the expressions

$$\begin{aligned} &\varepsilon_{11} = \varepsilon_{22} = 1 - \frac{\omega_{\mathrm{p}}^2}{\omega^2 - \omega_{\mathrm{B}}^2}, \\ &\varepsilon_{12} = -\varepsilon_{21} = i\frac{\omega_{\mathrm{B}}\omega_{\mathrm{p}}^2}{\omega\left(\omega^2 - \omega_{\mathrm{B}}^2\right)}, \\ &\varepsilon_{33} = 1 - \frac{\omega_{\mathrm{p}}^2}{\omega^2} - \frac{n_{\mathrm{b}}\omega_{\mathrm{p}}^2}{n_{\mathrm{p}}\left(\omega - k_z u_{\mathrm{G}}\right)^2}. \end{aligned} \tag{10}$$

These formulas differ from the well-known expressions for cold plasma only by the last term in ε_{33} resulting from resonance current density (8). The dispersion equation of interest, which represents the determinant of (9) equal to zero, in the quasi-longitudinal approximation is reduced to the form [Bespalov, Savina, 2019]

$$\left(\omega - \omega_{\mathrm{w}}\left(k_z, \theta\right)\right)\left(\omega - \left|k_z\right| u_{\mathrm{G}}\right)^2 = \frac{n_{\mathrm{b}}\omega_{\mathrm{B}}^3}{32 n_{\mathrm{p}}} \sin^2\theta \left|\cos\theta\right|^3, \tag{11}$$

where the modulus sign accounts for the possibility of wave propagation in two directions, $\sin\theta = k_{\perp} / \left(k_z^2 + k_{\perp}^2\right)^{1/2}$ and $\cos\theta = k_z / \left(k_z^2 + k_{\perp}^2\right)^{1/2}$. Dispersion equation (11) that is a third-order equation with respect to the complex frequency has been analyzed in [Bespalov, Savina, 2019]. The relationship between the real part of the frequency and the growth rate for an unstable solution is illustrated in Figure 2. Note that under conditions for approximation validity $\omega_{\mathrm{w}} \simeq \left|k_z\right| u_{\mathrm{G}}$ the unstable solution of Equation (11) of interest has a frequency and a growth rate

$$\begin{aligned} &\omega = \frac{\left|\cos\theta\right|}{2}\omega_{\mathrm{B}}, \\ &\gamma = \frac{\sqrt{3}}{4}\left(\frac{n_{\mathrm{b}}}{4 n_{\mathrm{p}}}\sin^2\theta\left|\cos\theta\right|^3\right)^{1/3}\omega_{\mathrm{B}}. \end{aligned} \tag{12}$$

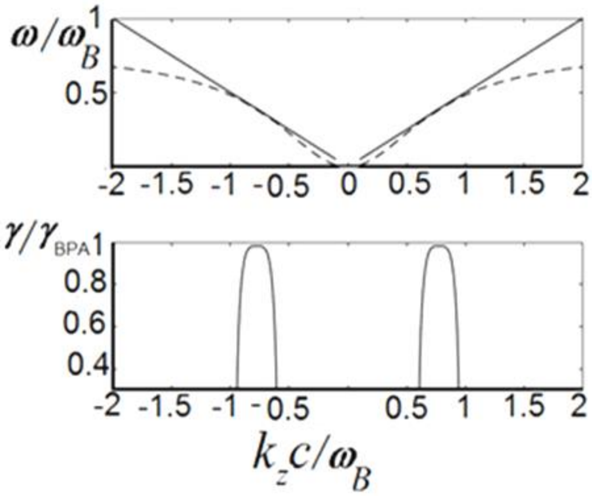

Figure 2. Dependence of the frequency (dashed line) and the growth rate of the unstable solution of Equation (11) on the longitudinal wave-vector component

Bespalov et al. [2022] have shown that when implementing the BPA mechanism of chorus excitation in magnetospheric ducts of enhanced and depleted cold-plasma density with refractive reflection $\theta \simeq 20^{\circ}$ and then, according to Equations (12), the emission frequency

$$\omega = \omega_{\mathrm{BPA}} \simeq 0.47\omega_{\mathrm{B}} \tag{13}$$

and their growth rate

$$\gamma = \gamma_{\mathrm{BPA}} \simeq 0.13\left(\frac{n_{\mathrm{b}}}{n_{\mathrm{p}}}\right)^{1/3}\omega_{\mathrm{B}}. \tag{14}$$

1.3. Condition for effective amplification of noise pulses for kappa distribution of energetic electrons by velocity modulus

Angular and energy distributions of energetic electrons in the middle magnetosphere depend on many factors, the most important of which are the power of particle sources and the mechanisms of their losses. Both processes are caused by the wave-particle interaction. The results of long-term observations have shown that in many cases for energetic electrons in the middle magnetosphere the loss cone is narrow, and the kappa distribution is realized in terms of velocity modulus [Benson et al., 2013] with the parameter k equal to two,

$$f(V) = \frac{n_{\mathrm{p}}}{2\pi\sqrt{2}\alpha^{3}\left(1+\dfrac{V^{2}}{2\alpha^{2}}\right)^{3}}, \tag{15}$$

where $n_{\mathrm{p}} = \int_{0}^{\infty} f(V)4\pi V^{2}dV$ is the electron density, α is the characteristic velocity of energetic (hot) electrons satisfying the condition $\alpha<u_{\mathrm{G}}$. For distribution function (15), it is easy to write down the condition for effective amplification of short noise pulses. We begin with the electron pressure expression

$$P_{\mathrm{e}} = \int_{0}^{\infty}\left(\frac{mV^{2}}{2}\right) f\,4\pi V^{2}dV = \frac{3\pi}{4}n_{\mathrm{p}}m\alpha^{2}. \tag{16}$$

Setting down the expression included in growth rate (14) for the active electron cloud density

$$n_{\mathrm{b}} = (\Delta V_{z})2\pi\int_{0}^{\infty} fV_{\perp}dV_{\perp} \simeq$$

$$\simeq \frac{\gamma}{k_{z}}\frac{n_{\mathrm{p}}}{4\sqrt{2}\alpha\left(1+\dfrac{u_{\mathrm{G}}^{2}}{2\alpha^{2}}\right)^{2}} \tag{17}$$

and considering the ratio $\left(\dfrac{c\omega_{\mathrm{B}}}{\alpha\omega_{\mathrm{p}}}\right) = \dfrac{B^{2}}{4\pi mn_{\mathrm{p}}\alpha^{2}} = \dfrac{3\pi}{2\beta_{\mathrm{e}}}$, we get an expression for the growth rate

$$\gamma \simeq 0.01\omega_{\mathrm{B}}\beta_{\mathrm{e}}^{3/4}. \tag{18}$$

Effective excitation of chorus emissions is possible with a sufficiently effective amplification of short noise pulses, which occurs when the condition is met

$$2\gamma l / u_{\mathrm{G}} > 5. \tag{19}$$

where the length of the wave-particle interaction region is equal to the scale of the longitudinal variation in the magnetic field in the parabolic approximation [Bespalov, Trachtenhertz, 1986] $l \simeq a$, $a = \left(3\sqrt{2}/2\right)r_{\mathrm{E}}L$, where r_{E} is the Earth radius; L is the magnetic shell parameter. Comparing expressions (18) and (19) shows that chorus excitation takes place at not too small plasma parameter

$$\beta_{\mathrm{e}} = \frac{8\pi P_{\mathrm{e}}}{B^{2}} > 0.05. \tag{20}$$

2. MAGNETIC FIELD IRREGULARITY IN THE CHORUS EXCITATION REGION

2.1. Specific examples of the relationship between the degree of magnetic field irregularity and chorus excitation

Modern observational data amassed during the implementation of the Van Allen Probe mission makes it possible to advance in the justification of derived estimate of plasma parameter (1). When working with observational data [http://emfisis.physics.uiowa.edu/Flight/], we have found that the presence of chorus depends on the irregularity (fine structure with sharp jumps of several gamma) of the geomagnetic field near its local minima. Figure 3 gives two typical examples explaining this dependence. At 03:00-05:00 UT (*a*), the magnetic field was irregular and there were clear chorus spectral elements (*c*, *e*). In the dynamic spectrum (*d*), no chorus was detected when the magnetic field varied smoothly (*b*).

2.2. Quantitative estimation of magnetic field irregularity

To quantify the index of magnetic field irregularity ΔB>0, we have constructed a fitted curve for each event and have calculated the standard deviation of the observational data from the corresponding approximation. The irregularity index ΔB can be divided into two intervals: $0 < \Delta B \leq 2$ nT, where the lowest probability of detecting chorus emissions is observed, and $\Delta B \geq 2$ nT, where chorus emissions are most likely to be detected.

According to the proposed algorithm, the irregularity index ΔB is 5.72 and 0.24 nT (Figure 4, *a*, *b*). The findings allow us to assume that for the event (*a*) the probability of detecting chorus is high, whereas for the event (*b*) it is low. For example, according to calculations, for the events shown in Figure 3, ΔB=3.35 (*a*) and 0.48 nT (*b*).

2.3. Results of statistical data processing

We have analyzed 152 events occurring in January, February, and November 2015, for which high-resolution EMFISIS (Electric and Magnetic Field Instrument Suite and Integrated Science) wave data is available [Kletzing et al., 2013]. Each event represents data from 2–4 hour observations near the local magnetic field minimum. From visual selection and sampling

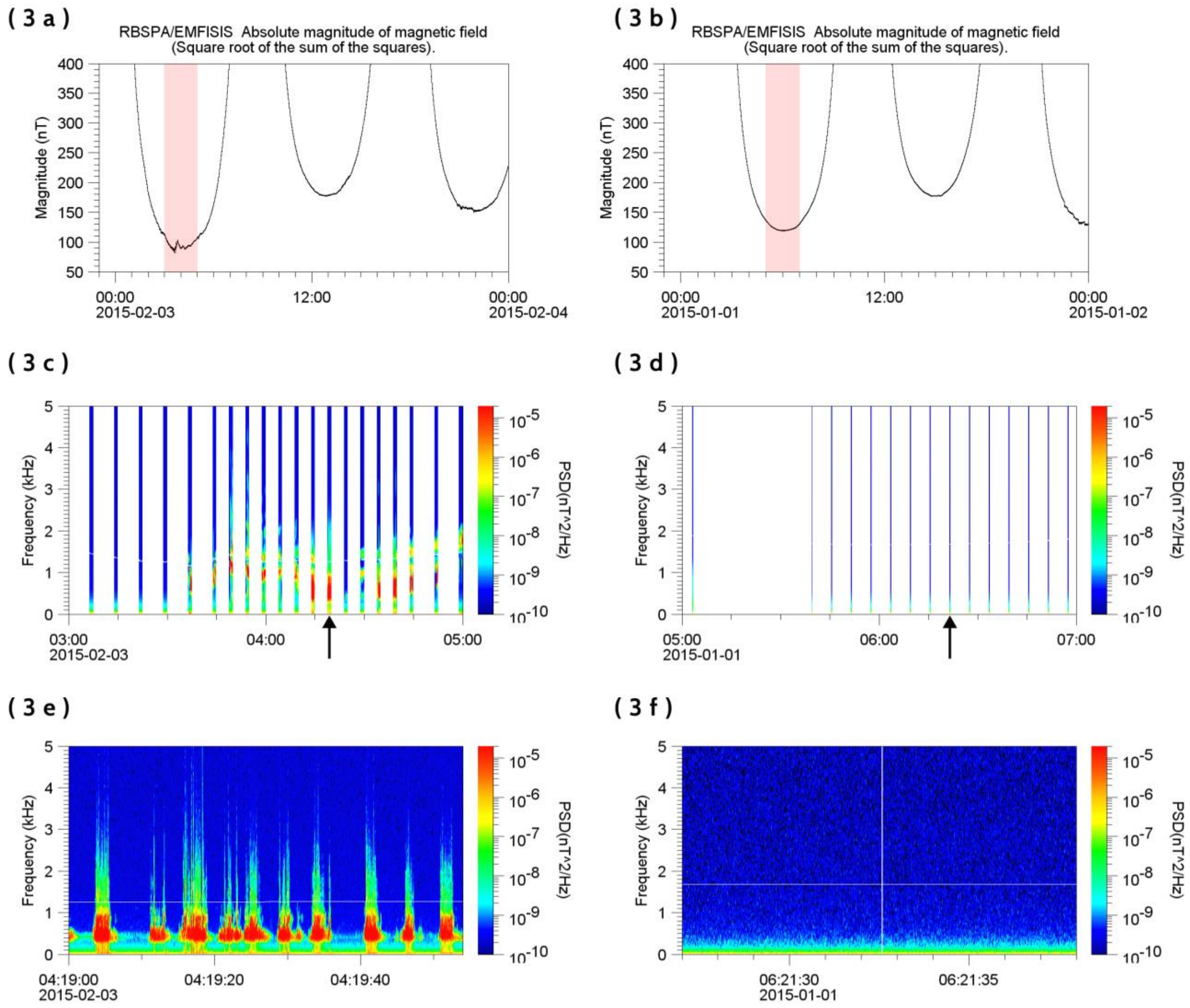

Figure 3. Examples of simultaneous observation of the magnetic field and the dynamic spectrum in the frequency range of chorus emissions. In panels *c* and *d*, vertical lines indicate time intervals with available high-resolution observational data suitable for spectral processing

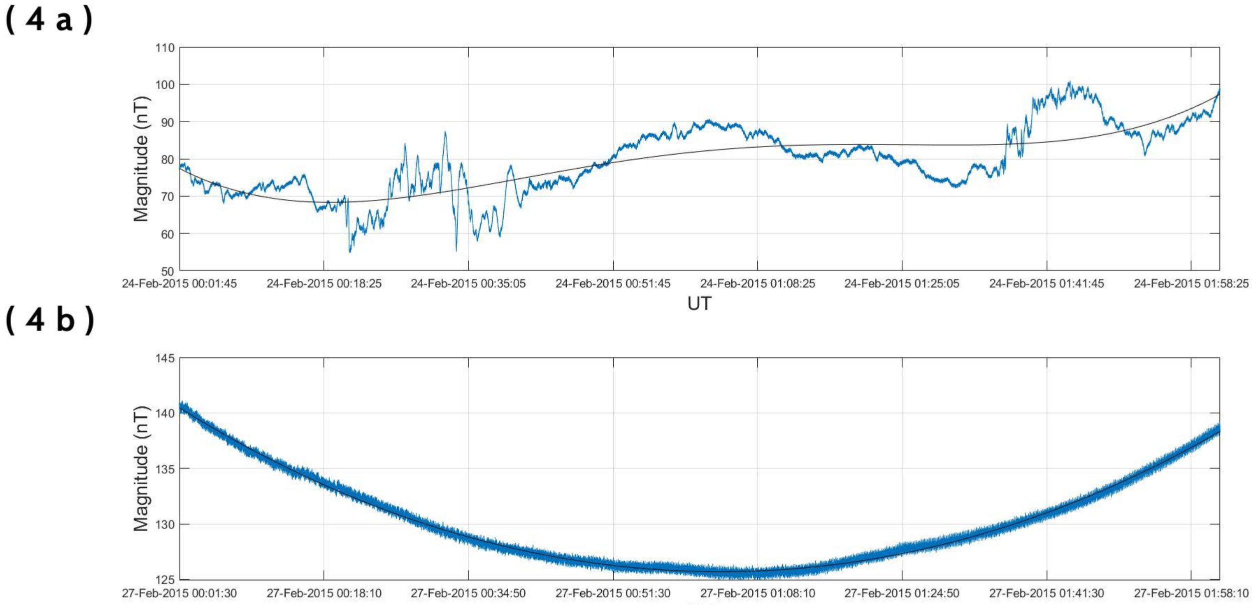

Figure 4. Examples of time dependence of the magnetic field, which illustrate the algorithm for calculating the irregularity index

numerical verification of the magnetic field irregularity by the criterion from Subsection 2.2, it has been found that 58 events do not have magnetic field irregularity, 81 % of which have a spectrum (see Figure 3, *f*) without chorus emissions; 94 events have magnetic field irregularities, 66 % of which feature chorus emissions.

Figure 5 gives an example that explains the obtained pattern well. At ~05:00–06:00 UT (*a*), the magnetic field had no irregularities (ΔB=0.23 nT); at 06:00–07:00 UT, there were irregularities, an increase in the density of >200 eV electrons according to HOPE (Helium-Oxygen-Proton-Electron mass-spectrometer) data (*b*); clear chorus spectral elements were recorded at the same time (*c*, *d*).

2.4. Comparison of data from Van Allen Probe A and B

Comparing Van Allen Probe A and B data proved useful for two reasons. Firstly, it allowed us to conclude that magnetic field irregularities are not wave-like, but are caused by quasistationary currents in plasma. Secondly, it expands the database for statistical processing of the relationship between the irregularity of ΔB and the probability of chorus excitation.

Figure 6 exemplifies a burst of chorus recorded by Van Allen Probe A and B on January 2, 2015 between 06:40 and 06:45 UT. The burst was observed in the lower band with frequencies below half the minimum electron cyclotron frequency. The use of observational data from two spacecraft with the same equipment and similar trajectories is known to provide information about the space-time pattern of phenomena. The plots of the magnetic field recorded by the two spacecraft have similar details, which indicates the spatial (non-wave) nature of the magnetic field irregularity and shows a large spatial region of synchronous chorus excitation.

2.5. The proposed model of magnetic field irregularity and some arguments in its support

In our opinion, both the magnetic field irregularity and the chorus arising after magnetic disturbances have a common source in the form of ~10 keV electrons drifting from the dawn side of the magnetosphere to dusk side in the inhomogeneous curved geomagnetic field. The electron flux can be assumed to have small-scale irregularities in the direction transverse to the magnetic field. With such a non-wave magnetic field irregularity, pressure balance in the transverse direction takes place under relatively quiet conditions

$$P = P_e + P_i + \frac{B^2}{8\pi} = const. \qquad (21)$$

Therefore, assuming that the ion pressure remains constant $\delta P_e + 2B/(8\pi)\delta B = 0$ and hence

$\delta\beta_e = 8\pi / B^2 \delta P - 2\left(8\pi P_e / B^3\right)\delta B = -2\left(1+\beta_e\right) B\delta B.$

For the macroscopic stability of the middle magnetosphere, there should be $B_e \ll 1$ and that is why we obtain an estimate of the plasma parameter variation due to the presence of the quasistationary current system in the magnetosphere,

$$\delta\beta_e = -2\,\delta B/B. \qquad (22)$$

From this we can draw a conclusion concerning the plasma parameter inhomogeneous across the magnetic flux tube with $\beta_e \simeq 0.05$. In this case, we can explain both the magnitude of magnetic field jumps and chorus generation by the BPA mechanism for amplifying short noise electromagnetic pulses. Note that for quite large values of the plasma parameter the magnetospheric configuration loses stability and the chorus excitation conditions cease to hold.

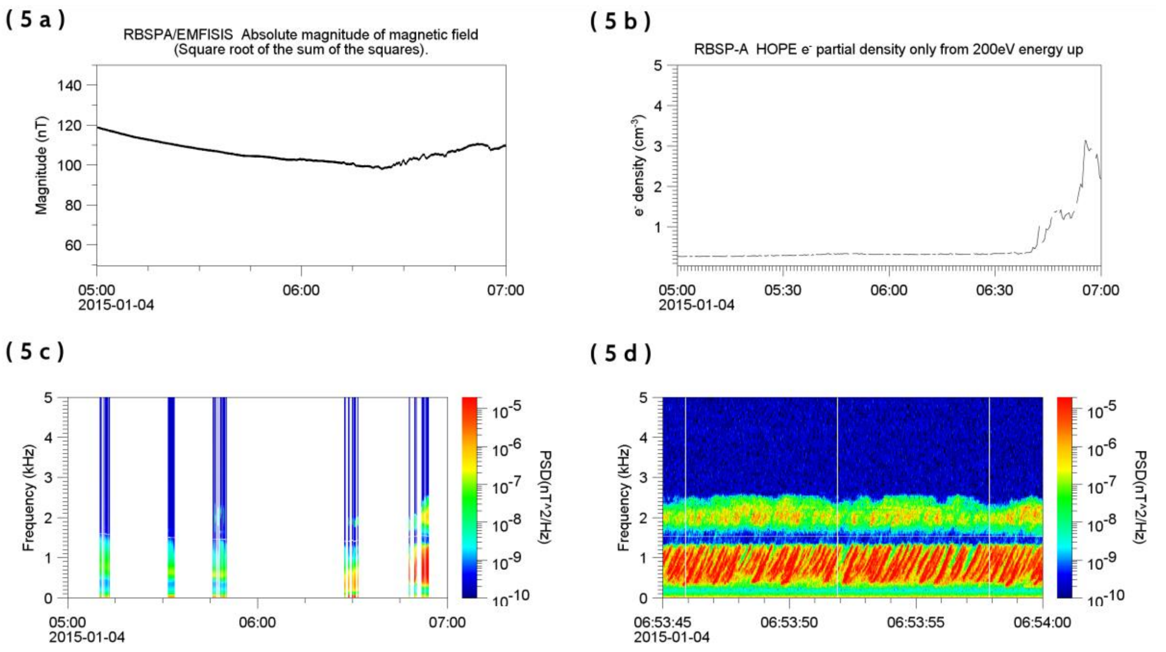

Figure 5. Typical example illustrating the dependence of the occurrence of chorus on the magnetic field irregularity. Vertical lines in panel *c* denote time intervals with available high-resolution observational data suitable for spectral processing

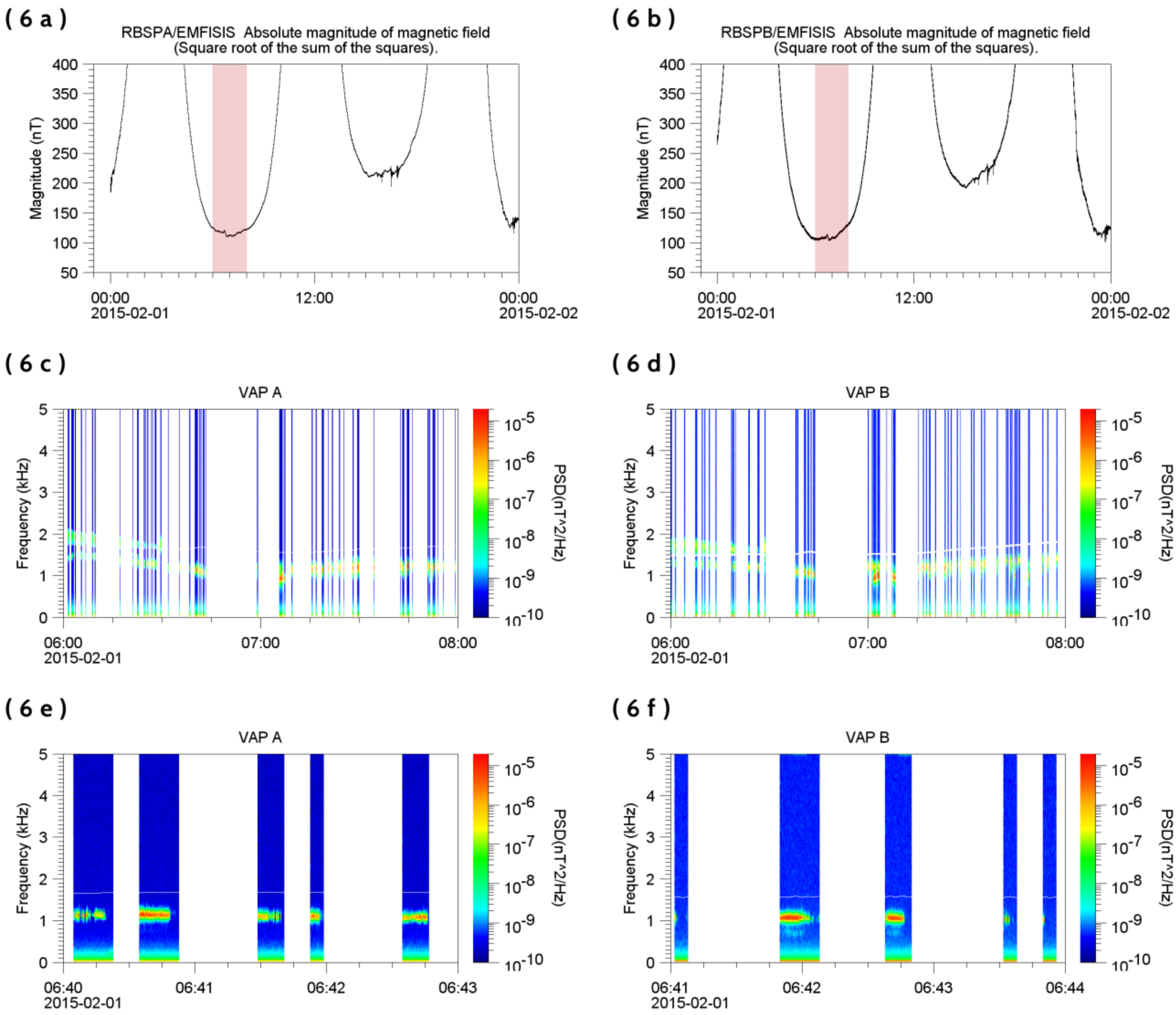

Figure 6. An example of an event with chorus emissions recorded by Van Allen Probe A and B on January 2, 2015 between 06:40 and 06:45 UT. In panels *c* and *d*, vertical lines indicate time intervals with available high-resolution observational data suitable for spectral processing

CONCLUSION

We have analyzed excitation of chorus in the magnetospheric regions without strong anisotropy of the distribution function of energetic electrons by amplification of short noise pulses. The kappa distribution is chosen as the function of their distribution by velocity modulus. We have established that at not too small values of the plasma parameter the natural electromagnetic pulse amplifier is very effective.

When working with the observational data from the Van Allen Probe mission, we found that VLF electromagnetic radiation with the chorus structure of the dynamic spectrum depends on the magnetic field irregularity near its local minima. In the presence of irregularity, the probability of detecting chorus is more than 70 %, and in the absence or a very low level of irregularity, the probability of absence of any radiation is ~80 %. Analysis of data from two spacecraft has shown that magnetic field irregularities are not wave-like and are probably associated with quasistationary currents. We have proposed a model of close relationship between magnetic field irregularities and chorus excitation.

Thus, the results of calculations and observational data complement each other and are consistent with the conditions for the implementation of the BPA mechanism of chorus excitation in the magnetosphere. We have estimated the plasma parameter at $\beta_e \simeq 0.05$, responsible for both chorus excitation and magnetic field irregularity.

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