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PROPERTIES OF THE BACKWARD WAVE OSCILLATOR MODEL OF VLF CHORUS GENERATION INFERRED FROM CLUSTER MEASUREMENTS

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Abstract. A generation mechanism for chorus was suggested by Trakhtengerts (1995) on the basis of the backward wave oscillator (BWO) regime of the magnetospheric cyclotron maser. According to this model, step-like deformation on the electron distribution function is the most important factor of chorus generation, but such a feature is very difficult to observe. By measuring the frequency sweep rates in chorus elements detected by the Cluster spacecraft we determine the mean values and distributions of a dimensionless parameter characterizing the step feature. These values are in agreement with the results of numerical simulations of chorus elements based on the BWO model.

1. Introduction

VLF chorus emissions are the most mysterious signals among natural ELF/VLF radiation. Chorus emissions are observed as a succession of repeating discrete elements, more often with increasing frequency. It is generally accepted that the chorus emissions are generated by the cyclotron instability of radiation belt electrons near the equatorial region. However, two principal problems relating to chorus emissions remain, i.e., the generation of the dynamical spectrum of separate chorus elements, and an origin of succession of chorus elements. To solve these problems Trakhtengerts [1,2] proposed a new regime of the cyclotron instability in the magnetosphere. It is the backward wave oscillator (BWO) regime of VLF chorus generation which is similar to the backward wave oscillator in laboratory electronic devices.

Cyclotron interactions of natural ELF/VLF noise-like emissions and energetic electrons produce a specific step-like deformation of the distribution function. This step-like deformation yields the large growth rate of the whistler-mode waves and the development of the absolute cyclotron instability in a narrow region near the equatorial plane. The instability produces a succession of discrete signals with an increasing frequency within each element. It is clear that a sharp gradient (or a step-like deformation) on the electron distribution function is the most important parameter of the BWO model. However, theoretical estimates show that the step is rather small [3]. The detection of this step-like feature requires an energetic electron detector with a very good resolution of the energy and the pitch angle, about several percent. At the present time the satellite instruments do not provide such a resolution. Therefore the step-like features of the distribution functions have not been observed directly so far.

However, the properties of the step in the BWO model determine the dimensionless parameter $\boldsymbol{q}$ which characterizes the excess of an energetic electron flux over a threshold of the BWO regime. This parameter, in turn, determines the frequency sweep rate of chorus elements. Thus, by measuring the frequency sweep rate in the source region we can obtain indirect information about the properties of a step on the distribution function. A decrease of the mean values of the frequency sweep rate with increasing mean cold plasma density was demonstrated in [4]. This result is in agreement with the BWO model if the $\boldsymbol{q}$ parameter is independent of the plasma density. Here we determine and analyze the values of the $\boldsymbol{q}$ parameter in the magnetospheric BWO model for individual chorus elements on the basis of instantly measured plasma densities. Then we compare $\boldsymbol{q}$ values, obtained in experiment, with results of numerical simulations of the BWO model and discuss the distributions of the $\boldsymbol{q}$ parameter. In the last section we summarize our results.

2. Theoretical Background

The expression for the frequency sweep rate of chorus elements $\mathbf{d}f/\mathbf{d}t$ can be written as [2, 5]

$$df/dt = W_{tr}^{2} \qquad (1)$$

where the trapping frequency W_{tr} is determined by the formula $W_{tr} = (\boldsymbol{ku}w_H\, \boldsymbol{b})^{1/2}$, and $\boldsymbol{b}=\boldsymbol{B}_{\sim}/\boldsymbol{B}_L$ is the ratio of the whistler wave magnetic field amplitude $\boldsymbol{B}_{\sim}$ to the geomagnetic field $\boldsymbol{B}_L$, w_H is the electron gyrofrequency, and $\boldsymbol{u}$ is the electron velocity component across the geomagnetic field.

In the case of the BWO regime, the growth rate g_{BWO} is related to the trapping frequency W_{tr} [1,2] as

$$g_{BWO}/W_{tr} \approx 3\pi/32 \qquad (2)$$

Substituting Eq. (2) into Eq. (1) yields

$$df/dt = 0.3\, g^2_{BWO} \qquad (3)$$

According to the BWO model, in the case of propagation along the magnetic field the growth rate is given by [5,6]

$$\gamma_{BWO} = \pi/2 * (q^{1/2} - q^{-1/3})/T_0 \qquad (4)$$

In Eq. 4 T_0 is the characteristic time scale of the BWO defined as

$$T_0 = l_{BWO}\,(1/Vg + 1/V^*) \qquad (5)$$

where $l_{BWO} \approx (R^2L^2/k)1/3$ - the length of the chorus source region, $V^* = 2\pi\,(f_H - f)/k$ is the parallel velocity of resonant electrons, $Vg = 2\,V^*f/f_H$ is the group velocity of the whistler-mode waves, L is the L-shell, f and f_H are the wave frequency and electron gyrofrequency, and q is the dimensionless parameter quantifying the excess of energetic electron density above the generation threshold. Note that parameter q is proportional to the height of the step [5] and the aim of this work is to determine and analyze this parameter for the magnetospheric BWO.

Substituting Eq. (4) in Eq. (3) gives the following equation for q:

$$(q^{1/2} - q^{-1/3})^2 = 3 * (2/\pi)^2 * df/dt * T_0^2 \qquad (6)$$

As it follows from equations (5) and (6), to obtain the parameter q one needs simultaneous measurements of the frequencies and sweep rates of chorus elements, magnetic fields and plasma density in the source region. CLUSTER satellites provide all these data.

3. Analysis of the *q* parameter for the magnetospheric BWO using CLUSTER observations

To analyze the sweep rate of the chorus elements on the CLUSTER satellites we used measurements of the WideBand Data (WBD) instrument [7], providing high-resolution measurements of one electric or one magnetic component. The WHISPER active sounder [8] onboard the CLUSTER spacecraft was used to measure the local electron densities n_e. For 7 CLUSTER orbits the plasma density was measured with a good resolution (from 4s to 50s) during the time interval when chorus emissions were observed. For these CLUSTER orbits we obtained the frequency sweep rates for about 7000 elements and calculated the q parameter values for each chorus element in the source region near the equator ($\pm 5^0$).

Figure 1 shows the values of the q parameter, depending on the cold plasma density for all chorus elements detected on the 7 Cluster orbits. Chorus elements with frequencies below and above one half of the electron gyrofrequency are plotted with black and grey colors, respectively. For calculation of the characteristic time scale of BWO T_0 we use the lower frequency of chorus elements. Figure 1 shows that the parameter q varies in a wide range, but it does not show a definite dependence on the plasma density, and the q values are higher for the upper band chorus.

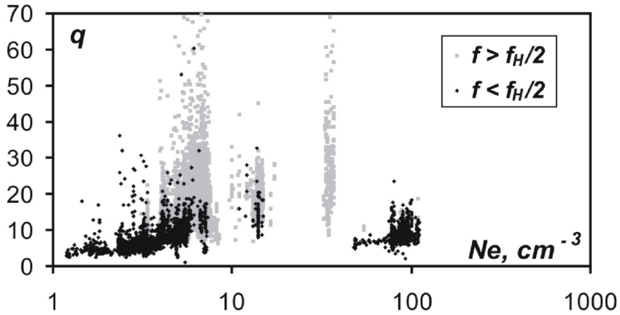

Fig. 1. Parameter q for chorus emissions below (black diamond) and above (gray square) one half of the gyrofrequency for different plasma densities

The mean values of the q parameter (q_m) for the intervals $f/f_H = 0.1$ as a function of chorus frequency are given in Fig. 2. The vertical lines mark the standard deviation of the q values. As is seen in Fig. 2 the mean values of q are higher for the upper band chorus: for the lower band, q_m ($f/f_H < 0.5$) ≈ 8 and for the upper band, q_m ($f/f_H > 0.5$) ≈ 19.

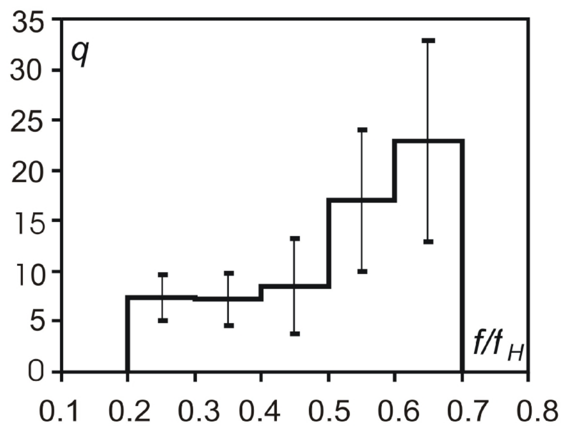

Fig. 2. The mean values of the parameter q in the interval 0,1 f / f_H, depending on the chorus frequency normalized to the gyrofrequency.

The values of the frequency sweep rate for the studied 7 orbits show no dependence on the frequency of chorus emissions. This means (see Eq. 6) that large q for the upper band of chorus is due to large T_0 which increases with increasing frequency (see Eq.5).

The average values of the q parameter, obtained from the CLUSTER experimental data, are in agreement with simulation results by Demekhov and Trakhtengerts [9]. Fig.3 shows results of a numerical simulation of the chorus dynamic spectrum based on the BWO model for different values of the parameter $q = S/S_{thr}$ quantifying excess of the energetic electron flux S over the generation threshold S_{thr}. It is seen that a significant excess of the flux over the threshold value ($q \sim 10$) is required for the generation of discrete elements. For smaller q values (e.g., $q \sim 3$), the dynamic spectrum shows only some broadening near the initial generation frequency and possibly some sidebands.

Significant scatter of the q values was observed during each Cluster passage through the generation region. Fig.4 illustrates this scatter by showing the distributions of the q parameter for the lower and upper bands of the chorus emissions. The distributions of q have an asymmetric shape with a long tail towards higher values.

This scatter of the q values is related to the scatter in the frequency sweep rate of the chorus elements, which is typical for CLUSTER observations [4].

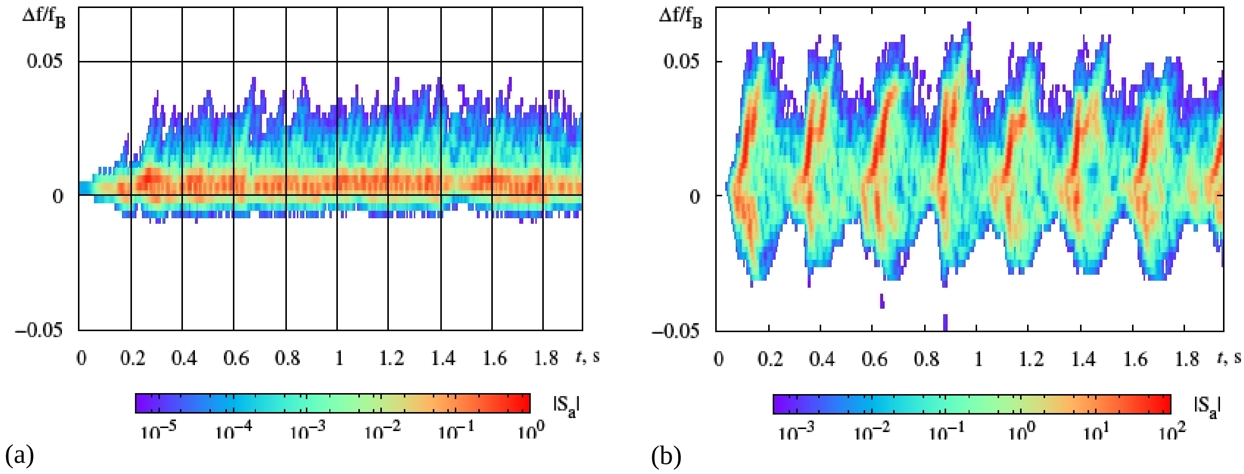

Fig. 3. Dynamic spectrums on exit of the BWO generation region for different values of parameter $q = S/S_{thr}$ (a) $q = 3$, i.e., smaller electron flux, (b) $q = 12$, i.e., larger electron flux.

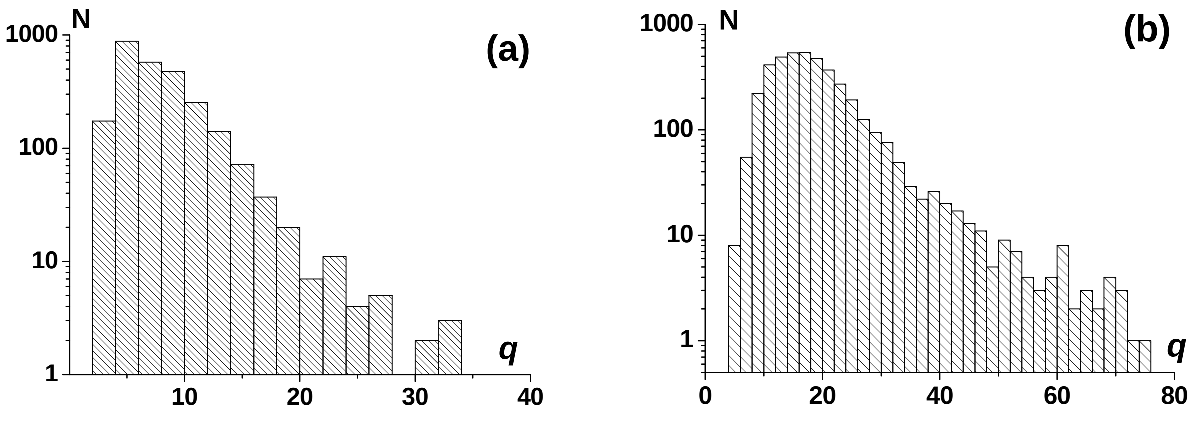

Fig. 4. The distribution of the q parameter for chorus elements with frequencies below (a) and above (b) one half of the gyrofrequency for 7 orbits of the CLUSTER spacecraft.

4. Conclusions

We determined a dimensionless parameter q for the magnetospheric BWO generating chorus VLF emissions. This parameter quantifies an excess of the electron flux over the absolute-instability threshold. The parameter q is related to the step feature on the electron distribution function. Using the measured spectral characteristics of VLF chorus elements detected onboard the CLUSTER spacecraft and the electron density we determined the values and variations of the ***q*** parameter in the generation region. The results of numerical simulations of chorus elements based on the BWO model are in accord with the values of the ***q*** parameter obtained from the CLUSTER data.

Significant scatter of the ***q*** parameter values was observed during each Cluster passage of the generation region. Parameter ***q***, characterizing the step-like deformation of the distribution function of energetic electrons, is proportional to the height of the step and the concentration of energetic electrons. Therefore, we assume that significant scatter of the ***q*** parameter characterizes the scatter in the step parameters. We believe that further analysis of the ***q*** parameter on the basis of CLUSTER data along with the data on the flux of energetic electrons will allow us to improve the understanding of the electron distribution function dynamics in the chorus generation region.

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