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IN SEARCH OF A GROUND IMAGE OF THE SURFACE OSCILLATIONS AT THE MAGNETOPAUSE

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Abstract. Magnetopause surface eigenmodes were suggested as a potential source of dayside high-latitude broadband pulsations in the Pc5-6 band (~1-2 mHz) and as a mechanism of the "magic" frequency occurrence. However, the search for a ground signature of these modes has not provided encouraging results. The comparison of Svalbard SuperDARN radar data with the latitudinal structure of Pc5-6 pulsations recorded by magnetometers covering near-cusp latitudes showed that often the latitudinal maximum of the pulsation power maximizes ~2º-3º deeper in the magnetosphere than the dayside open-closed field line boundary (OCB). Here the OCB-ULF correspondence is further examined by comparison of the latitudinal profile of the near-noon pulsation power with the equatorward edge of the auroral red emission from the scanning photometer data. In most analyzed events the "epicenter" of the Pc5-6 power is at ~2º lower latitude than the optical OCB proxy. Therefore, the dayside Pc5-6 pulsations cannot be associated with the ground image of the magnetopause surface modes or last field line oscillations. A lack of ground response to these modes beneath the ionospheric projection of the OCB is puzzling. As a possible explanation, we suggest that a high variability of the outer magnetosphere near the magnetopause region may suppress the wave excitation efficiency. This additional mechanism of damping of field line oscillations is caused by stochastic fluctuations of the magnetospheric plasma and background magnetic field. To quantify this hypothesis, we consider a driven field line resonator terminated by conjugate ionospheres with stochastic fluctuations of the eigenfrequency. The solution of this problem predicts a substantial deterioration of resonant properties of the MHD resonator even under a relatively low level of background fluctuations. This effect may explain why a ground response to magnetopause surface modes or last field line oscillations is lacking at the OCB latitude, but can be seen at somewhat lower latitudes with more regular and stable magnetic and plasma structure. With an account of ~2º offset, the maximum of Pc5-6 power can be used as a simple indicator of the dayside OCB latitude.

1. Introduction. Long-period pulsations in the Pc5-6 band (*T*~3-15 min) are known to be a persistent feature of the ULF activity at dayside high latitudes. A potential source of these high-latitude long-period pulsations could be the magnetopause surface eigenmodes [*Plaschke et al.*, 2009; *Hartinger et al.*, 2015] or oscillations of the last field line [*Lanzerotti et al.*, 1999; *Urban et al.*, 2011]. The "magic" pulsation frequencies were reinterpreted in terms of standing Alfvenic surface mode discrete eigenfrequencies (Kruskal-Schwarzschild modes) at the magnetopause [*Archer et al.*, 2013].

A characteristic frequency Ω_A of Alfven field line oscillations in a dipole-like magnetic field can be estimated as

$$\Omega_A = \frac{V_A}{LR_E}$$

where V_A is the Alfven velocity near the top of a field line, and LR_E is the radial distance to a field line. The Alfven wave continuum is terminated by frequency of the last closed field line.

Properties of MHD surface mode are similar to that of Alfven waves: both are non-compressive disturbances, and are guided along background magnetic field B. Both Alfven field line oscillations and surface waves on a steep gradient are modes of the MHD resonator terminated by the conjugate ionospheres. The frequency of a surface mode Ω_S lies between the Alfven frequencies (Ω_A^1, Ω_A^2) at both sides of the interface between two media with magnetic field $B_{1,2}$ and plasma density $\rho_{1,2}$ (e.g., magnetosphere and magnetosheath)

$$\Omega_S = \frac{1}{LR_E}\sqrt{\frac{B_1^2 + B_2^2}{\mu(\rho_1 + \rho_2)}} \quad \Omega_A^1 < \Omega_S < \Omega_A^2$$

In a realistic inhomogeneous magnetosphere global MHD disturbances are coupled to local standing field line Alfven oscillations. The energy of discrete spectrum mode (e.g., surface mode) is irreversibly converted into the energy of Alfven continuum. This process is most effective at a resonant shell *L* where $\omega \rightarrow \Omega(L)$. Pumping of wave energy into the resonator results in the growth and narrowing of the spatial resonant peak, terminated by a dominant dissipation mechanism.

Here we present a typical example of the correspondence between dayside ULF power structure and OCB proxy, determined from the auroral optical data. To interpret the observational results we present a simplified model of the MHD resonator with fluctuating eigenfrequency driven by an external source.

2. Dayside OCB and ULF activity. To unambiguously resolve the association of dayside high-latitude ULF activity with the OCB, the advantage of the Svalbard complex can be used. It comprises the latitudinal IMAGE magnetometer chain along the geomagnetic longitude Λ~110°, SuperDARN radar, and the meridian scanning photometer at Longyearbyen (LYR).

A ground response to the magnetopause surface modes is expected to be beneath the ionospheric projection of the open-closed field line boundary (OCB). The dayside OCB proxy can be determined either as an enhanced spectral width of the SuperDARN radar return signal [*Baker et al.*, 1995], or as the equatorward boundaries of the cusp aurora determined by meridian scanning photometer [*Johnsen and Lorentzen*, 2012].

Irregular Pulsations at Cusp Latitudes (IPCL) and narrow-band Pc5 waves were found to be a ubiquitous element of ULF activity in the dayside high-latitude region [*Kleimenova et al.*, 1985]. The comparison of the latitudinal structure of broadband Pc5-6 pulsations recorded by magnetometers covering near-cusp latitudes with the OCB radar proxy showed that the maximum of the IPCL power maximized somewhat deeper in the magnetosphere [*Pilipenko et al.*, 2015]. The spatial structure of broadband dayside Pc5-6 pulsation spectral power was found to have a localized latitudinal peak, but not under the cusp proper as was previously thought, but several degrees southward from the equatorward cusp boundary. Therefore, these pulsations cannot be associated with the ground image of the magnetopause surface modes or last field line oscillations. The earlier claims of the dayside monochromatic Pc5 wave association with the OCB [*Lanzerotti et al.*, 1999] also seems doubtful.

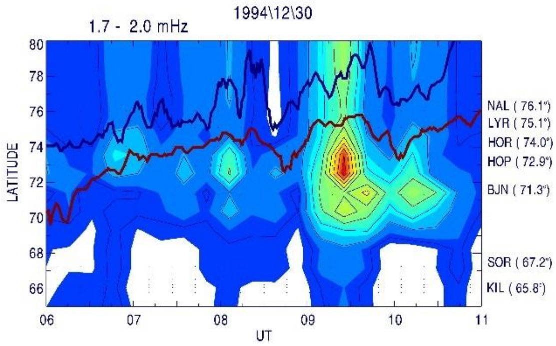

Figure 1. The 2002, Jan. 04 event: magnetic keogram, constructed from the X-component magnetometer data, and superposed the equatorward and poleward boundaries of the cusp aurora (red and blue lines).

To verify the results obtained with the SuperDARN radar, we use the meridian scanning photometer to identify the cusp aurora equatorward boundary (dayside OCB proxy). We present a typical example of the correspondence between the OCB from LYR photometer and the latitudinal structure of wave power in the Pc5-6 band from magnetometer data. We consider the 1994, Dec. 30 event, when the Svalbard complex is around noon and auroral activity is observed above LYR.

We will concentrate on the time interval near the geomagnetic noon, ~09-10 UT (MLT noon is ~09 UT). During this interval, quasi-periodic irregular pulsations are observed along the IMAGE magnetometer chain with two dominating spectral peaks: at ~1.4 mHz and ~2.2 mHz (not shown).

A magnetic keogram, constructed from the X-component magnetometer data (Fig. 1), enables us to monitor the time evolution of the latitudinal distribution of 1.7-2.0 mHz band-integrated spectral power along the geomagnetic meridian. The superposition of the magnetic keogram with the equatorward and poleward boundaries of the cusp aurora identified from photometer data indicates that the Pc5-6 pulsation power is located ~2° equatorward of the optical OCB proxy.

The presented example illustrates a commonly observed regularity: a ground response to driving of the outer magnetosphere is observed not beneath the last closed field line, but somewhat deeper in the magnetosphere. In attempt to comprehend these observational results, we take into account that the magnetospheric plasma and background magnetic field experience substantial stochastic fluctuations, especially in the outer magnetosphere near the magnetopause. Hence, the eigenfrequency of the MHD resonator also must experience stochastic fluctuations. Below we consider a simple model of homogeneous MHD resonator with stochastic fluctuations of its eigenfrequency. This model enables us to examine possible deterioration of field line resonant response to an external monochromatic driving.

3. A resonator with fluctuating eigenfrequency. We consider a simple model of homogeneous resonator terminated by conjugated ionospheres. Let us suppose that its eigenfrequency Ω (either Ω_A or Ω_S) experiences stochastic fluctuations

$$\Omega^2(t) = \Omega^2[1+\delta\xi(t)]$$

where ξ(*t*) is the stationary stochastic function with vanishing time-average <ξ> =0 and unit dispersion $<\xi^2>=1$. The relevant auto-correlation function *K*(τ) satisfies the condition $<\xi^2>=K(0)=1$. The parameter δ characterizes the amplitude of eigenfrequency fluctuations, such as $|\Delta\Omega^2/\Omega^2|\sim\delta$.

The equation for field line oscillations driven by large-scale compressional waves or for surface waves buffeted by the magnetosheath disturbances is formally reduced to the equation for a driven harmonic oscillator with eigenfrequency Ω [*Hollweg*, 1997]. This modeling equation describes oscillations characterized by a variable *x*(*t*)

$$x_{tt} + 2\gamma x_t + \Omega^2[1+\delta\xi(t)]x \;=\; A\Omega^2\cos\omega t \quad (1)$$

Here A is the amplitude of a driver, and γ is the damping factor of the resonator.

In the case of low level fluctuations, δ<<1, the approximate solution of (1) can be found by iteration method, developed in the theory of nonlinear stochastic mechanics [*Dimentberg*, 1980]. Beyond the small-δ approximation, this equation was numerically solved in [*Coult et al.*, 2013]. We seek a solution in the following form:

$$x(t) = x_0(t) + \delta x_1(t) + \delta^2 x_2(t) + ... \qquad (2)$$

Substitution of (2) into (1) and grouping of all the terms of the same δ order provides an infinite system of equations in respect to $x_i(t)$. In the 0-approximation one obtains the classical formula for a driven linear oscillator

$$x_0(t) = b_0 \sin(\omega t + \varphi_0),$$
$$b_0 = A\frac{\Omega^2}{\sqrt{(\Omega^2 - \omega^2)^2 + 4\gamma^2\omega^2}}, \qquad (3)$$
$$\varphi_0 = \arctan\frac{\Omega^2 - \omega^2}{2\gamma\omega}$$

Features of this solution are a resonant peak and phase reversal near the resonance ω→Ω. In the absence of background fluctuations (δ=0), the peak amplitude $b_0^{(\max)}$ and the semi-width of the spectral peak Δω are determined by the damping factor γ of the system, or otherwise by the Q-factor $Q = \Omega / 2\gamma$.

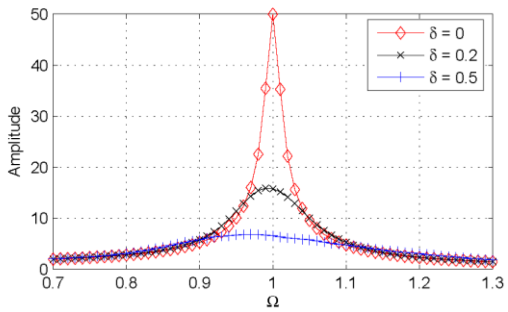

Figure 2. Amplitude of oscillations b(ω) using *A*=1, Ω=1, γ=0.01, and noise with spectrum 1/*f*. The height of the peak for each curve is the effective Q factor.

In subsequent approximations (i=1,2,...) the fluctuation-induced correction to the solution can be found from a recurrence formula. Keeping terms up to δ² order, it follows that near the resonance ω→Ω

$$\langle x(t)\rangle = b\sin(\omega t + \varphi_0 - \varphi_1),$$
$$\frac{b}{b_0^{(\max)}} \approx 1 - \delta^2 \frac{\Omega^3}{4\gamma\omega_1^2}\left[J^{(-)} - J^{(+)}\right] \qquad (4)$$

Here $J^{(\pm)} = \int_0^\infty K(\tau)e^{-\gamma\tau}\cos[(\omega \pm \omega_1)\tau]d\tau$, $\omega_1^2 = \Omega^2 - \gamma^2$.

The additional phase shift $\varphi_1 \cong o(\delta^2)$ in (4) is of no importance to us. The relationship (4) predicts that the amplitude of the resonant oscillations should change under the influence of stochastic fluctuations of Ω. When the spectral density Φ(ω) of ξ(*t*) fluctuations is a non-growing function, these fluctuations cause a decrease of average amplitude of resonant oscillations. This deterioration of resonator properties is not related to the occurrence of anomalous resistivity or viscosity in a turbulent plasma. This decrease of the resonant response to an external monochromatic driving is caused by stochastic deviations of eigenfrequency from exact resonance.

We consider how the system response varies with the amplitude of the background fluctuations characterized by δ (Fig. 2). We use the noise with power spectrum 1/*f*. Without fluctuations, the classic curve shows a sharp resonant peak near ω=Ω. The addition of noise (δ≠0) reduces the height of the resonant peak and increases its width, whereas the effect is more pronounced for a larger δ.

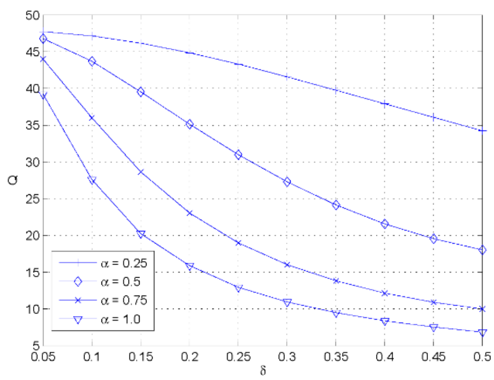

Figure 3. The dependence of the Q-factor of the resonator on δ for A=1, Ω=1, γ=0.01, and various α.

The suppression of resonant oscillation depends essentially on the spectrum of fluctuations. For a model problem, we choose noise functions with power spectrum $1/f^{\alpha}$, where 0≤α≤1. In Fig. 3, we measure the effective Q factor for several values of spectral index α as a function of δ. Smaller values of α result in less sensitivity of the Q factor to δ. For white noise (α=0), the effect is absent. The effect increases with an increase of α. The deterioration of resonant properties may be quite substantial: fluctuations with δ=0.2 and α=1.0 decrease the Q-factor more than 3 times, from ~50 to ~15.

Discussion. The dayside magnetopause with a step-like jump in magnetic field strength and plasma density may be imagined as a stressed membrane with reflecting boundaries in the northern and southern ionosphere, which can be resonantly excited by magnetosheath turbulence. The MHD modeling of the magnetospheric response to impulsive solar wind dynamic pressure increases, showed that waves with 1.8 mHz frequency are excited whose global properties cannot be explained by other known ULF wave modes [*Hartinger et al.*, 2015]. Thus, magnetopause surface eigenmodes could be a potential source of magnetospheric dayside ULF waves with f<2 mHz driven by quasi-periodic fluctuations of the magnetosheath dynamic pressure.

So far, magnetospheric field line oscillations have been modeled in a plasma with steady parameters. However, a realistic plasma medium is highly fluctuating because of small-scale plasma processes. Therefore, the eigenfrequency of the field line resonator Ω should experience inherited fluctuations because of stochastic variations of B, ρ, and field line length. Here we have considered the effect of such background fluctuations on driven field line standing oscillations. Our estimates indicate the necessity to consider seriously a possible effective damping of ULF waves due to background magnetospheric fluctuations. The effect considered here may explain a lack of narrowband ULF waves during magnetically disturbed periods, when the magnetospheric turbulence level is substantially elevated.

More specifically, this effect may be responsible for suppression of field line standing oscillations at the magnetopause or very close to it. Deeper in the magnetosphere, away from the magnetopause, the magnetospheric magnetic field and plasma become more regular, and the level of their fluctuations decreases. As a result, a resonant response to an external driving becomes evident. The proposed mechanism may interpret the puzzling lack of ground response to surface modes or last field line oscillations near the OCB projection, and it merits further validation and verification. The suppression of resonant field line oscillations is dependent not only on the level of fluctuations but on their spectral form as well. For more definitive conclusions a more detailed information about the power and spectra of background magnetospheric turbulence is necessary.

Conclusion. The latitudinal structure of dayside broadband Pc5-6 pulsations recorded by magnetometers covering near-cusp latitudes has the maximum of the pulsation power ~2° deeper in the magnetosphere than the OCB determined either with SuperDARN radar or scanning photometer. To interpret a puzzling lack of ground response to last field line oscillations or surface mode at magnetopause, we suggest that stochastic fluctuations of the magnetospheric plasma and magnetic field can suppress the excitation of standing MHD oscillations in a close vicinity of the magnetopause. To quantify this hypothesis, we have considered the model of a driven field line resonator with stochastic fluctuations of the eigenfrequency. The results of analytical calculations has shown the deterioration of resonant properties owing to background fluctuations.

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