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GEOMAGNETIC PULSATIONS IN 1–4 mHz FREQUENCY RANGE (Pc5/Pi3) IN THE MAGNETOTAIL AT DIFFERENT LEVELS OF DISTURBANCES IN THE INTERPLANETARY MEDIUM

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Abstract. In this paper, we study parameters of geomagnetic pulsations in the 1–4 mHz frequency range (Pc5/Pi3) in the magnetotail, utilizing data obtained by Cluster satellites at different levels of fluctuations in the interplanetary magnetic field (IMF) and the solar wind dynamic pressure in 2016. Particular attention is given to the conditions of "zero" disturbance when amplitudes of fluctuations in the interplanetary medium are smaller compared to their typical values. Both under quiet and disturbed conditions, waves of different spatial scales are recorded, with the occurrence rate of large-scale waves increasing under undisturbed conditions. Amplitudes of the large-scale waves occurring in the magnetotail under low intensity of fluctuations outside the magnetosphere are from few tenths to a few nanoteslas (nT), and their power is approximately equal in longitudinal and transverse components. Presumably, these waves are magnetotail eigen-modes.

Keywords: magnetosphere, geomagnetic pulsations, magnetotail.

INTRODUCTION

The question of the relationship between the induced response of the magnetosphere to external action and the active generation of wave and pulse disturbances inside the magnetosphere is one of the most important in magnetospheric physics.

The region of tail lobes and their ionospheric projections — polar caps — features low (as compared to the more active polar cusp and auroral oval regions) amplitudes of electromagnetic oscillations in the range of few millihertz. At the same time, due to the huge size of the magnetotail, the total energy of these oscillations is not low. Dimensions of the magnetotail are tens of Earth radii (R_E = 6370 km) in the transverse direction and hundreds in the longitudinal one. The Alfvén velocity in the magnetosphere varies from several hundred kilometers per second in the plasma sheet and boundary layers, such as low-latitude (LLBL) and high-latitude (HLBL) boundary layers, to several thousand kilometers per second in the tail lobes. Such values of the tail size and Alfvén velocities in it allow for waveguide modes and resonance oscillations in the range of few millihertz (Pc5/Pi3), the existence of which was predicted in [Patel, 1968; Siscoe, 1969]. The magnetotail can contain all main branches of MHD waves: Alfvén, fast (FMS) and slow (SMS) magnetosonic. A special type is the so-called flapping mode caused by oscillations of the tail as a whole [Tsutomu, Teruki, 1976]. Simplified models [Walker et al., 1993] give wave propagation frequencies and velocities close to observable ones, but leave open the question of possible source of large-scale oscillations and mode transformation mechanisms. More realistic models, both numerical [Allan, Wright, 2000] and analytical [Leonovich, Mazur, 2008; Mazur et al., 2010], made it possible to describe the main types of oscillations, to study their generation, propagation, and transformation. A detailed overview of the main types of MHD oscillations can be found in [Leonovich et al., 2015].

Direct experimental estimation of wave spatial scales and simultaneous measurements of electromagnetic field and plasma parameters became possible with the launch of the multisatellite missions THEMIS and Cluster [Angelopoulos, 2008; Escoubet et al., 2001]. Ground-based observations at high latitudes have revealed the presence of intrinsic wave activity of the ultralow-frequency (ULF) range in the polar caps [Ballatore et al., 1998; Yagova et al., 2004; Francia et al., 2005]. At the same time, even the integral parameters of the oscillations cannot be fully predicted from the solar wind (SW) and interplanetary magnetic field (IMF) parameters in front of the bow shock [Yagova, 2015; Yagova et al., 2010;].

ULF waves in the magnetotail and their relationship with the magnetic field and plasma fluctuations in front of the bow shock and in the magnetosheath at low geomagnetic activity have been studied for individual events in [Sarafopoulos, Sarris, 1994]. The authors concluded that the fluctuations detected are global in nature. Similar waveforms and spectra were recorded simultaneously by several satellites spaced a few tens of R_E apart. Global pulsations were observed in the plasma sheet boundary layer (PSBL), tail lobes, and magnetosheath. Quiet conditions were estimated using geomagnetic indices. Sarafopoulos [1995] has shown that from event to event polarization in a plane perpendicular to the tail changes from almost linear to circular. A statistical study of the amplitude of long-period ULF waves near the equatorial plane of the magnetosphere has been carried out in [Wang et al., 2015], using data from THEMIS satellites. The average amplitude of pulsations in the plasma sheet was shown to increase in the Pc5 range with the level of SW dynamic pressure fluctuations. A statistical study of Pc5 waves in the magnetotail [Zhang et al., 2018] was based on the analysis of wave disturbances whose central frequency remained unchanged for at least three periods. The study showed a decrease in the frequency of pulsations with distance from Earth, the predominance of standing waves in the near tail and traveling waves in the far tail. The pulsations considered feature the dawn-dusk asymmetry in the occurrence rate and polarization and an increase in the occurrence rate at high SW speeds and amplitudes of SW dynamic pressure fluctuations. Wave disturbances were generally observed at low and moderate auroral activity. The choice of undisturbed conditions by geomagnetic indices reduces the contribution of intense disturbances inside the magnetosphere, but does not allow us to discrimibate the tail's egenmodes from the forced oscillations associated with fluctuations in the SW dynamic pressure and IMF parameters. Such forced oscillations are analyzed, for example, in [Kim et al., 2004]. Using magnetometric measurements made at a ground-based low-latitude station and in the magnetotail, the authors examine fluctuations directly related to pulse and quasi-periodic SW dynamic pressure fluctuations. Apparent periods of these fluctuations range from 2 to 6 min; in the time domain, they practically coincide with fluctuations in SW, and the maximum coincidence between pulsations on Earth and in the tail is observed with a shift of 120 s.

Yagova et al. [2017] and Nosikova et al. [2022] have shown that specific high-quality oscillations in the tail lobes occur with almost complete switch-off of fluctuations of the same frequency range in the interplanetary medium. A detailed analysis of pulsations in the range of a few millihertz in both polar caps and the magnetotail before a non-triggered isolated substorm allowed an assumption to be made that these pulsations can act as a precursor of a weak non-triggered substorm.

In this paper, to identify the tail's eigen oscillations we examine 1–4 mHz (Pc5/Pi3) pulsations at different levels of IMF and SW dynamic pressure fluctuations in front of the bowshock, using Cluster measurements. Section 1 describes data and processing methods; Section 2 provides examples of pulsations in the magnetotail and formulates hypotheses for statistical analysis whose results are presented in Section 3.

1. DATA AND PROCESSING

The method is based on the identification of intervals for the analysis from the intensity of IMF and SW dynamic pressure fluctuations in front of the bowshock and on the comparison between parameters of the fluctuations in the magnetotail for high and low levels of fluctuations outside the magnetosphere.

Fluctuations in the interplanetary medium are analyzed from measurements made at the libration point and recalculated to the subsolar point of the magnetopause. The data is available with a minute resolution on NASA's website [https://cdaweb.gsfc.nasa.gov]. For the analysis, we have used variations in three IMF components and SW dynamic pressure P_{SW}. We took intervals with full coverage and absence of instrumental outliers, and for them we estimated the Power Spectral Density (PSD) by the Blackman—Tukey method [Jenkins, Watts, 1972] in a sliding 96-min window with a 10-min step.

Simultaneously, we analyzed magnetic field variations in the tail lobes from Cluster-1 and -4 data. The initial data was presented in the geocentric solar ecliptic (GSE) system, in which the origin is in the Earth center, the X-axis is directed from Earth to the Sun, the Z-axis is normal to the ecliptic plane positively directed to the north, and the Y-axis lies in the ecliptic plane positively directed to the evening, so that the **XYZ** vectors form the right-hand triple. For the intervals selected, the satellites were at distances from $7R_E$ to $14R_E$ from the Earth center, which corresponds to the near-tail region. For further processing, the magnetic field was transformed from the GSE system into the Cartesian coordinate system connected with the main magnetic field, in which the component B_τ is oriented along the main magnetic field, B_ρ is perpendicular to it and lies in a plane the tangent to the field line and passing through the center of Earth, and B_ϕ forms a right-hand triple of vectors with them. In the tail lobe, these components are approximately parallel to B_x, B_z, and B_y of the GSE system. Spectral estimation was made for the magnetic field components and the interplanetary medium parameters. We calculated PSD and cross-spectra for the pairs composed of magnetic field components measured by one or two satellites. To study the spatial scale of pulsations in the tail, we employed data from two Cluster satellites; and to analyze the relationship of pulsations in the tail with parameters outside the magnetosphere, we estimated cross-spectra for the pairs B_{tail}/B_{IM} and B_{tail}/P_{SW}, where the indices "tail" and "IM" refer respectively to the magnetotail and to the interplanetary medium. To assess the degree of similarity in signals, we used the spectral coherence γ^2 defined as the ratio of squared cross-spectrum PSD to the product of autospectra PSD [Jenkins, Watts, 1972]. To determine the spatial scale of coherent (γ^2>0.5) signals in the tail, we estimated the phase difference $\Delta\phi$ and the spectral ratio R, equal to the PSD ratio of similar components on Cluster-1 and -4.

2. EXAMPLES OF PULSATIONS IN THE MAGNETOTAIL AT DIFFERENT LEVELS OF FLUCTUATIONS IN THE INTERPLANETARY MEDIUM

2.1. Event 1: September 19, 2016

An example of oscillations observed in the magnetotail on September 19, 2016 (day 263) at high intensity of fluctuations in the interplanetary medium is given in Figure 1. Figure 1, *a* shows fluctuations of the vertical IMF component; variations of the other two components are similar: the fluctuations are not regular, have an amplitude 5–8 nT, and their apparent quasi-periods vary from 5 to 15 min, which is manifested in the almost flat PSD spectrum (Figure 1, *b*). Pulsations in the tail lobe are more regular, their apparent period is ~15 min, and the amplitude is ~1 nT (in Figure 1, *a*, they are enlarged). In the PSD spectrum, the main power is concentrated at frequencies below 2 mHz. Spectral coherence between the oscillations in the interplanetary medium and in the tail is low (Figure 1, *c*). That time, the satellites were located in the northern lobe of the magnetotail at a distance of 7.9R_E (Cluster-4) and 8.8R_E (Cluster-1) from the Earth center. Waveforms of the pulsations (Figure 1, *d*) and their spectra (Figure 1, *e*) are similar, but not identical. In the low-frequency part of the spectrum (f<2 mHz), spectral coherence of the pulsations on the two satellites is approximately 0.8 (Figure 1, *f*) and the phase difference $\Delta\phi\approx36°$ (Figure 1, *g*), which corresponds to antisunward propagation with a phase velocity of 330 km/s. The group velocity determined from the disturbance that began after t=30 min is 320 km/s. Thus, the group and phase velocities are close to each other and have the same order of magnitude as the SW velocity. Note that the SW velocity measured at the libration point and recalculated to the subsolar point of the magnetopause is about 400 km/s for the interval shown in Figure 1.

2.2. Event 2: July 18, 2016

Pulsations in the magnetotail with amplitudes of the order of 1 nT may also occur at a much lower intensity of IMF fluctuations in front of the bowshock than in event 1. An example of pulsations in the tail observed at a low amplitude of IMF fluctuations on July 18, 2016 (day 200) is given in Figure 2.

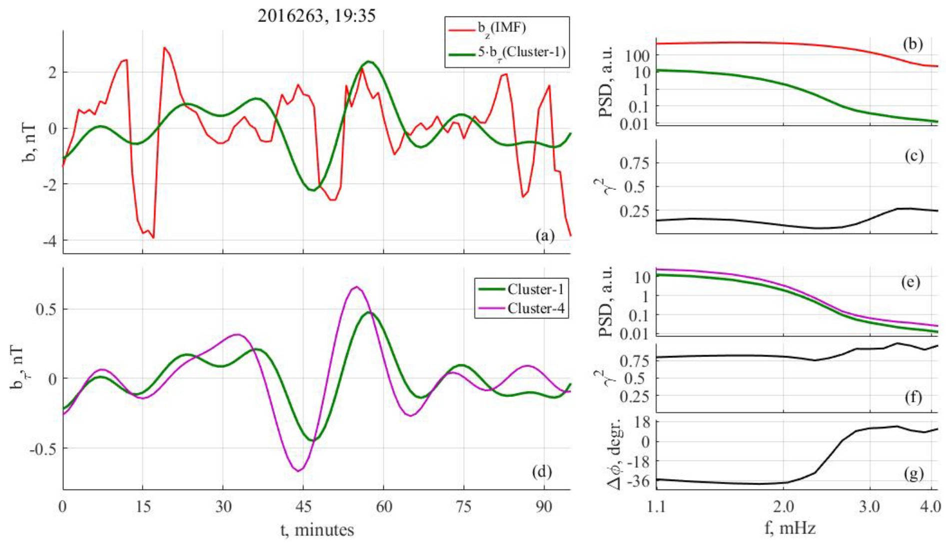

Figure 1. Pulsations in the magnetotail (longitudinal component) and simultaneously measured IMF vertical component fluctuations observed on September 19, 2016 (day 263), t=0 is 19:35 UT: signal in the time domain (*a*); PSD (*b*); spectral coherence (*c*). Signals (*d*), PSD (*e*), spectral coherence (*f*), and phase difference (*g*) in the tail lobe as measured by Cluster-1 and -4 satellites

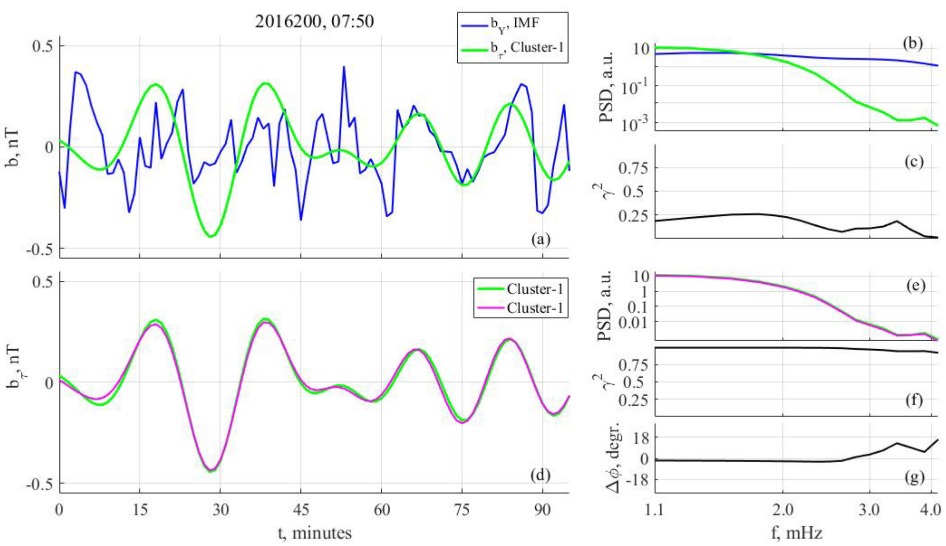

Figure 2. The same as in Figure 1 for the IMF B_y component. Event on July 18, 2016 (day 200), t=0 is 07:50 UT

Figure 2, *a* depicts similar waveforms of disturbances of the IMF B_y component and the longitudinal component of the field in the tail, but they are observed for a short period of time (after t=60 min) and do not affect the spectral coherence for the entire interval, which remains low (Figure 2, *c*). As for event 1, the pulsation PSD in the tail (Figure 2, *b*) decreases rapidly with frequency after 2 mHz, and the spectrum of IMF fluctuations is almost flat. In contrast to event 1, the waveforms of the pulsations recorded on the two satellites in the magnetotail are almost identical (Figure 2, *d*). This is reflected in the same spectra (Figure 2, *e*), in the spectral coherence close to unity (Figure 2, *f*), and in the phase difference close to zero (Figure 2, *g*).

This finding is similar to that described in [Nosikova et al., 2022] for the August 8, 2007 event when large-scale pulsations in the magnetotail also occurred against the background of almost complete switch-off of external disturbances. To understand whether such a coincidence is accidental or not, we analyze the distributions of Pc5/Pi3 pulsation parameters in the magnetotail at different fluctuation amplitudes in front of the bowshock.

3. STATISTICS

We denote the pulsations as sunchronous at $1R_E$, if their spectral coherence is as high as γ^2>0.9 and the phase difference is small, so that $\mu=\cos(\Delta\phi)>0.9$. These parameters are found from cross-spectra calculated for pairs of corresponding components at two Cluster satellites. Let us figure out how the occurrence of such pulsations depends on the intensity of IMF and SW dynamic pressure P_{SW} in front of the bowshock. As a parameter characterizing the pulsation amplitude we utilize the frequency integral power P_f for P_{SW} and IMF; the P_f value total for all the three components is taken for IMF.

P_f histograms for P_{SW} and IMF are presented in Figure 3. We have used all the intervals when Cluster-1 and -4 were in the tail lobe at a distance from $0.6R_E$ to $1.5R_E$ from each other, and the data quality allowed us to estimate the spectrum for P_{SW} and magnetic field components in the interplanetary medium and magnetotail. Red dashed lines mark the P_f values that cut off 15 % of the intervals with minimum and maximum intensity of fluctuations in the interplanetary medium, hereinafter referred to as quiet. Comparing the probability of occurrence of synchronous pulsations in the magnetotail allows us to estimate the effect of IMF and SW dynamic pressure fluctuations on oscillations in the magnetotail. Synchronous pulsations occur both under quiet and disturbed conditions outside the magnetosphere, but their proportions differ significantly. If for disturbed conditions the proportion (in time) of synchronous pulsations is 15 %, then for quiet conditions, 54 %. Thus, synchronous pulsations at distances $\sim 1R_E$ are observed in the magnetotail mainly at low amplitude of extra-magnetospheric fluctuations.

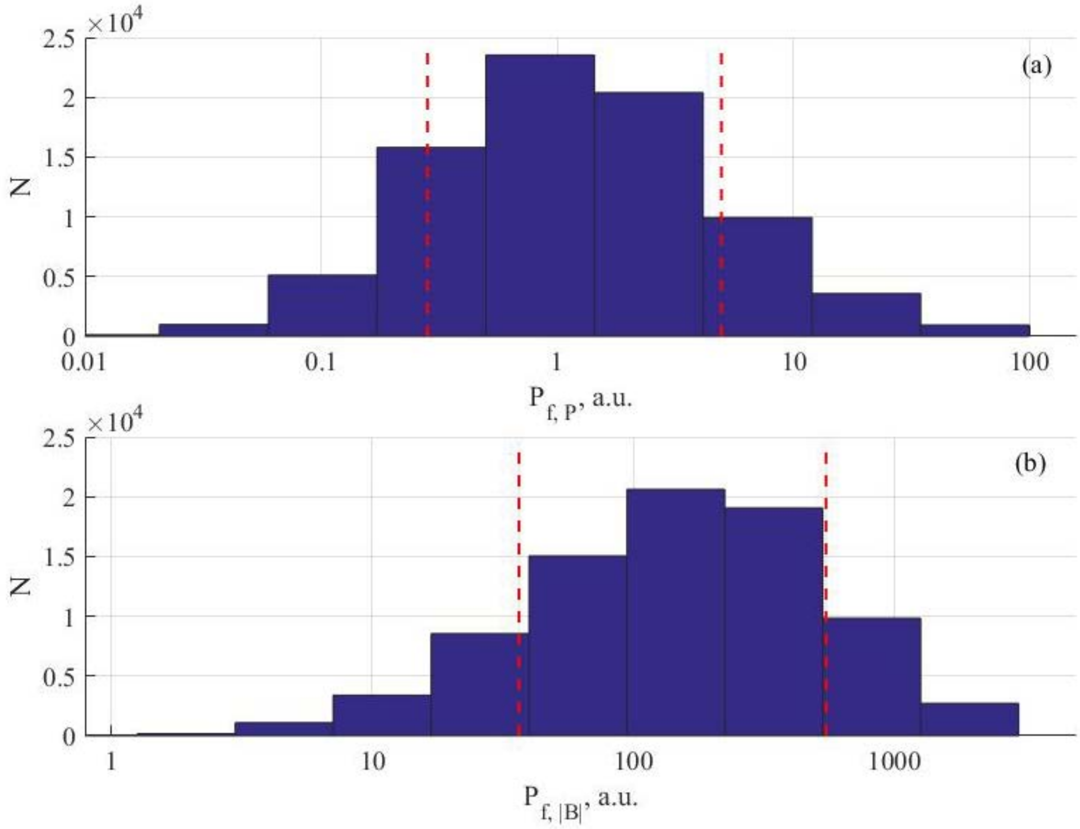

Figure 3. Distribution of the number of events N by power P_f of fluctuations of the SW dynamic pressure (*a*) and IMF (*b*). Red dashed lines mark 15 % levels of maximum and minimum intensities

Because of the small number of intervals when the synchronous pulsations were detected under disturbed external conditions, we consider three groups of pulsations: disturbed (D), quiet non-synchronous (Q_n), and quiet synchronous (Q_s). The phase difference for the corresponding components on the two satellites is used to determine the parameter k_{eff}=Δϕ/ΔR, which has inverse length dimension. For a disturbance propagating along the magnetic field, k_{eff} is equal to the wavenumber. Distributions of the empirical probability density function (PDF) by k_{eff}, plotted from the longitudinal component B_τ, are shown in Figure 4. Since the group Q_s by the selection creteria included pulsations with a small phase difference, more than 90 % of the pulsations fall into the interval $k_{eff}<0.1R_E^{-1}$, i.e. their spatial scale is greater than $10R_E$. The group Q_n features two maxima at $k_{eff}<0.2R_E^{-1}$ and $k_{eff}\approx 0.5R_E^{-1}$, and the distribution mean value $k_{eff}\approx 0.3R_E^{-1}$. For group D, two distribution maxima are observed at $0.1<k_{eff}<0.2R_E^{-1}$ and $k_{eff}\approx 0.65R_E^{-1}$, and the average is $k_{eff}\approx 0.5R_E^{-1}$. Thus, the pulsations of groups D and Q_n have a spatial scale of ~$1R_E$. Further, the terms large- and small-scale refer to pulsations of groups Q_s and Q_n/D respectively.

Check whether there are differences between spectral and polarization parameters of the pulsation groups identified by their spatial scale in the magnetotail and by the level of disturbance outside the magnetosphere. Figure 5 plots PDF distributions by the total power Σ(P_f) (*a*) and by the spectrum slope α (*b*). Comparing Σ(P_f) for the two

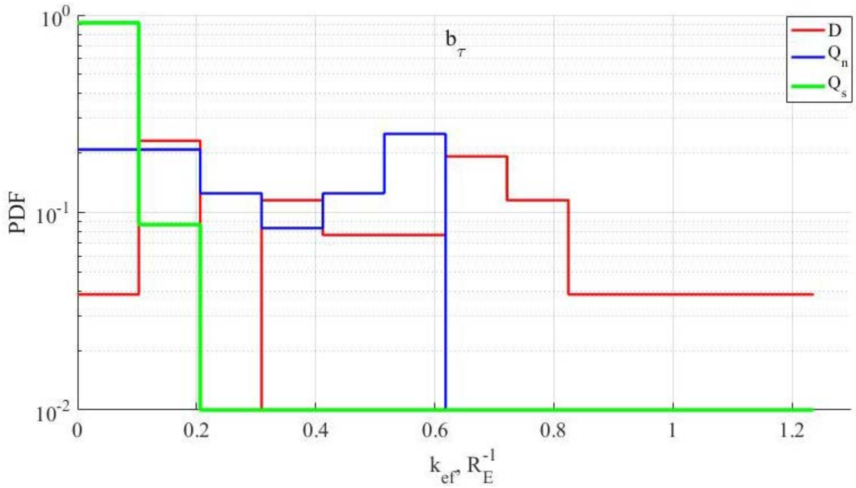

Figure 4. PDF distribution by the parameter k_{eff}, determined from the B_τ component, for three groups of pulsations

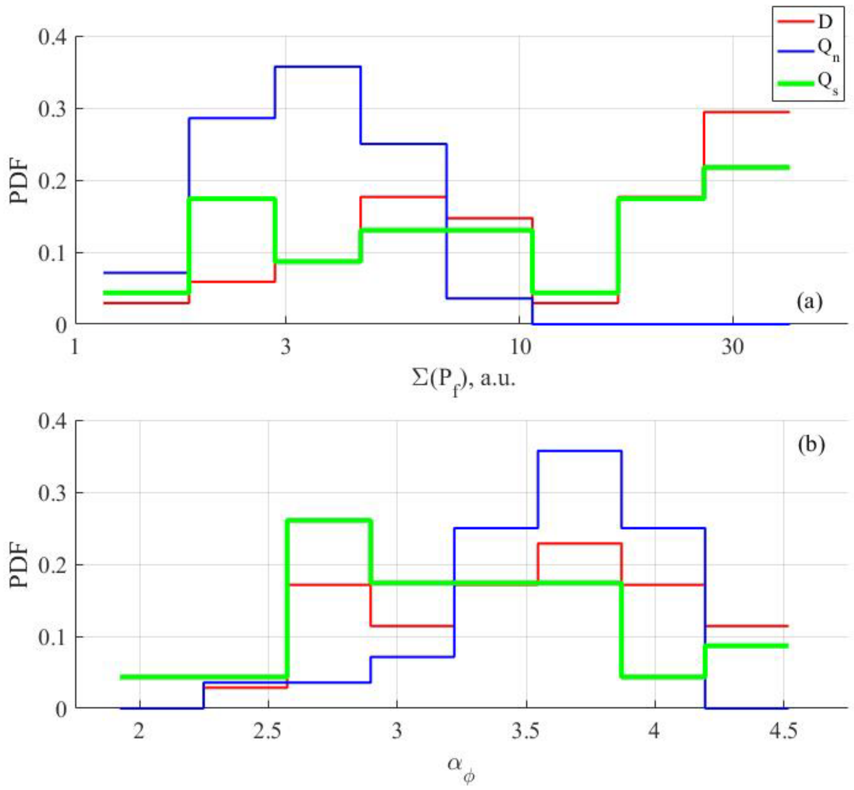

Figure 5. PDF distributions by the total spectral power Σ(P_f) (*a*) and by the spectrum slope α of the B_ϕ component (*b*) for three groups of pulsations, as derived from Cluster-1 data

groups of small-scale pulsations shows that the distribution for group Q_n (quiet background) is shifted toward lower values as compared to group D (disturbed background). The average value of the spectral power for group Q_n is almost by an order of magnitude smaller than that for group D. At the same time, the power of large-scale pulsations recorded against the quiet background (group Q_s) is significantly higher than that of small-scale ones (group Q_n), and is comparable to the power of pulsations under disturbed conditions (group D). The relative contribution of low and high frequencies is quantified by the spectrum slope parameter α.

For group Q_s, α shifts toward low values, i.e. pulsation spectra of this type are enriched with high frequencies compared to the pulsation spectra of other groups.

The polarization parameters are given in Figure 6 by the ratio R_N of the transverse component power to the total power (*a*) and by the parameter $\mu_{\rho-\phi}$ (*b*) characterizing polarization of pulsations in the plane normal to the main magnetic field: $\mu_{\rho-\phi}=\cos(\Delta\phi_{\rho-\phi})$, where $\Delta\phi_{\rho-\phi}$ is the phase difference between pulsations of the field components B_ρ and B_ϕ. Linear polarization corresponds to $\mu_{\rho-\phi}=\pm1$. Pulsations of group D feature a minimum value of R_N, which is equivalent to the predominant contribution to the total power of the longitudinal component, whereas small-scale pulsations under quiet conditions (group Q_n) are mainly transverse. For large-scale pulsations, the most probable value of R_N is approximately 2/3, which corresponds to the equidistribution of power between the three components. The group D pulsations (disturbed background) are dominated by polarization close to linear in the plane perpendicular to the main field — maximum distribution is observed at $\mu_{\rho-\phi}\approx\pm1$. For the group Q_n pulsations, elliptical polarization prevails with maximum distribution at $\mu_{\rho-\phi}\approx0.6$. For large-scale pulsations (group Q_s), polarization is close to linear: maximum distribution at $\mu_{\rho-\phi}\approx1$.

Thus, the pulsation groups distinguished by the spatial scale in the magnetotail and the level of fluctuations outside the magnetosphere also differ in spectral and polarization parameters. The spectral power of pulsations with a spatial scale of $1R_E$ significantly depends on the level of disturbances outside the magnetosphere and decreases sharply at low amplitude of IMF and SW dynamic pressure fluctuations; the power of large-scale pulsations developing under quiet conditions is close to the power of small-scale pulsations arising at high level of disturbance outside the magnetosphere.

4. DISCUSSION

The analysis has revealed that the 1–4 mHz pulsations recorded in the magnetotail fall into two subtypes:

1) Pulsations with a spatial scale of the order of $1R_E$ whose amplitude depends on the amplitude of IMF and SW dynamic pressure (P_{SW}) fluctuations in the same frequency range;

2) Large-scale pulsations observed as synchronous and identical at distances of ~$1R_E$, which are detected against a quiet background and are characterized by amplitudes comparable to those of small-scale pulsations at a high amplitude of IMF and P_{SW} fluctuations.

The mean slope of the spectrum of large-scale pulsations is lower than that of small-scale ones, and the power is approximately equally distributed between the components.

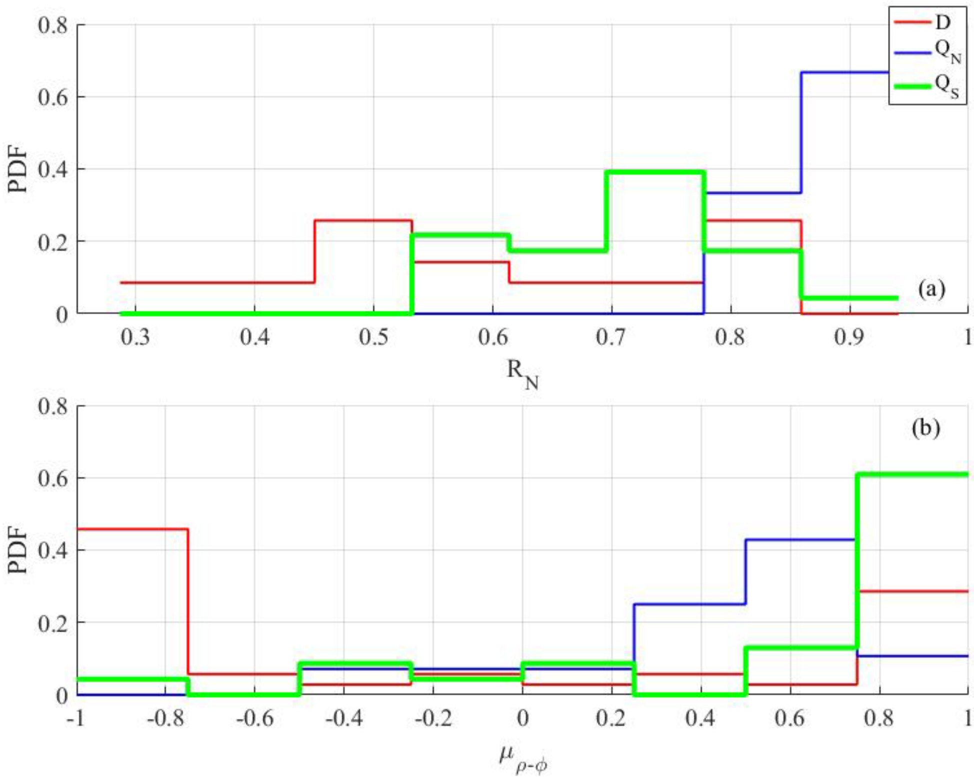

Figure 6. PDF distributions by the ratio R_N (*a*) and $\mu_{\rho-\phi}$ (*b*) for three groups of pulsations according to Cluster-1 data

The observable periods of these fluctuations range from several hundred to a thousand seconds. Such periods are equivalent to the balloon mode developing when the plasma sheet is undisturbed [Reddy, Lakhina, 1996], or to flapping of the tail as a whole [Zhang et al., 2002; Sergeev et al., 2006]. In addition, multi-satellite measurements [Cai et al., 2009] have revealed longitudinal density irregularities in the magnetotail. Their related irregularities of the Alfvén velocity allow for resonant excitation in plasma flow [Hasegawa et al., 2006].

In this work, we utilize the SW parameters in front of the bowshock, which leads to a small additional delay and possible distortion of the SW parameters relative to the region of the interplanetary medium closest to the site of observation of pulsations. Since in this paper we use the results of magnetic field measurements at distances not exceeding $14R_E$, this delay, found from the SW velocity, is short compared to the length of the interval (96 min) for which the spectra were calculated. At the same time, localizing the source of the oscillations under study requires a direct comparison of pulsations in the tail lobe with magnetic field fluctuations at the nearest points of the magnetosheath and interplanetary medium.

Heacock, Chao [1980] and Yagova et al. [2017] have identified a connection between the ULF oscillations of the millihertz range in the polar caps and the subsequent auroral substorm. Changes in the pulsation parameters are observed 2–4 hrs before the substorm without an obvious external trigger. Nosikova et al. [2022] for one case have shown a high coherence of pulsations in both polar caps and large-scale pulsations in the magnetotail observable at the "zero" level of external disturbance. The question about the statistical relationship of non-triggered substorms and other transient processes in the magnetosphere with the parameters of geomagnetic pulsations in the range of a few millihertz in the magnetotail calls for a separate study.

CONCLUSIONS

The study of geomagnetic pulsations in the 1–4 mHz range (Pc5/Pi3) in the tail lobe from magnetic field measurements on Cluster satellites in 2016 has shown that it is possible to identify groups of pulsations of different spatial scales: large-scale (of the order of or greater than $10R_E$) and smaller-scale with a characteristic scale of the order of R_E. The amplitude of the smaller-scale pulsations depends on the amplitude of IMF and SW dynamic pressure fluctuations, whereas large-scale pulsations occur mainly at a low level of fluctuations outside the magnetosphere with amplitudes close to the amplitude of small-scale pulsations at a high level of fluctuations outside the magnetosphere. The large-scale pulsations are characterized by a smaller spectrum slope than the small-scale ones and an approximately equal distribution of spectral power between the components.

For the analysis, we used magnetic field measurement data from the Cluster satellites and the IMF and SW dynamic pressure parameters available at [https://cdaweb.gsfc.nasa.gov/cgi-bin/eval2.cgi]. The work was financially supported by the Russian Foundation for Basic Research, project No. 20-05-00787.

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