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ULTRA LOW FREQUENCY EMISSIONS RANGING FROM 0.1 TO 3 Hz IN CIRCUMPOLAR AREAS

A.S. Potapov
Institute of Solar-Terrestrial Physics SB RAS, Irkutsk, Russia, potapov@iszf.irk.ru

A.V. Guglielmi
Schmidt Institute of Physics of the Earth RAS, Irkutsk, Russia, guglielmi@mail.ru

B.V. Dovbnya
Borok Geophysical Observatory of IPE RAS, Borok, Russia, dovbnya@inbox.ru

Abstract. We examine the characteristics of oscillations of two types in the high-frequency edge of the ULF range (0.1–3 Hz), serpentine emission (SE), and discrete frequency dispersed signals (DS). Oscillations of both the types are observed in the polar caps exclusively with induction magnetometers. Since these instruments are currently practically absent at high latitudes, the analysis has been carried out from records obtained at the stations Vostok and Thule close to the geomagnetic poles in 1968–1971. The DS occurrence rate is shown to have a sharp peak at local magnetic noon. This fact indicates that DS emergence is rigidly tied to the geomagnetic field line passing through the observation station. At the same time, the seasonal variation in the DS occurrence rate has the main peak in local summer and an additional peak in local winter. We have revealed before that at least a part of DS is excited in the foreshock region. Taking this into account, we can assume that the wave packets incident to the magnetopause fall on the external field lines mainly in the noon region and propagate along these lines in both directions, eventually reaching Earth's surface in the polar regions. Unlike DS, the SE occurrence rate has neither a daily nor a seasonal variation. We have tested and confirmed indirectly the hypothesis put forward earlier about the excitation of SE by cyclotron instability of protons in the solar wind, simulating frequency variations in ion-cyclotron waves at different levels of interplanetary plasma perturbation and comparing the results with the SE frequency variations observed under similar conditions. We conclude that it is necessary to resume continuous observations of ULF emissions, using induction magnetometers installed in polar caps near the projections of cusps and near geomagnetic poles.

Keywords: ultra low frequency electromagnetic waves, polar caps, cusp, magnetosphere, solar wind.

INTRODUCTION

The spectrum of ultra low frequency (ULF) oscillations in polar caps has its characteristic features due to polar areas with special structural elements of the magnetosphere. These are, firstly, geomagnetic tail lobes projecting to the polar caps; secondly, polar cusps and clefts on the noon side of the polar cap (from ±65° to 70° of geomagnetic latitude), where the field lines going into the tail border the lines connecting with the magnetosheath (cusps) or with the low-latitude boundary layer (clefts) [Farrell, van Allen, 1990]. These structures are associated with the processes affecting the magnetosphere dynamics: dayside magnetic reconnection, direct penetration of wave turbulence and plasma from the solar wind (SW) and magnetosheath [Sauvaud et al., 1998; Berthomier et al., 2004; Moiseev et al., 2015], magnetic pulses (MIE), and irregular pulsations (IPCL) [Lanzerotti et al., 1991; Yahnin et al., 1995; Sibeck, Korotova, 1996; Manweiler et al., 2018; Kurazhkovskaya, Klain, 2017; Guglielmi et al., 2017].

MIE and IPCL oscillations are in the extremely low frequency part of the ULF range. Here we want to draw attention to higher-frequency emissions with a carrier frequency from 0.1 to 2–3 Hz. These are frequency dispersed signals in the Pi1 range and narrowband continuous emissions with a modulated frequency varying within the above limits. They can be detected only by induction magnetometers. Such instruments connected to analog tape recorders in order to record ULF oscillations were installed during the International Geophysical Year in 1957–1958 and worked, in particular in high-latitude regions of Earth, in 1960–1970. Unfortunately, there are now virtually no such instruments in the polar caps; and there are no digital induction magnetometers there. We therefore use the data obtained at the stations Vostok (Antarctica) and Thule (Greenland) in 1968–1972. Table lists geographic and corrected geomagnetic coordinates of these stations, as well as the North and South geomagnetic poles for the epoch of 1968. Note that both Vostok and Thule were very close to the South and North geomagnetic poles, at distances of about 6° and 4° from them respectively.

This paper is aimed at attracting researchers' attention to the ULF emissions of the said type in the 0.1–3 Hz range, observed in the polar caps. They do not occur at lower latitudes, and therefore cannot be observed due to the absence of induction magnetometers operating in the polar caps. At the same time, as shown below, these emissions provide useful information on wave processes of the SW—geomagnetic field interaction and can be invoked to gain new knowledge of the outer magnetosphere.

DISCRETE FREQUENCY-DISPERSED SIGNALS

Pi1 pulsed signals with a sloped dynamic spectrum were periodically observed (Figure 1) in the polar caps. The slope can be both positive and negative. It most likely results from different frequency dispersion of waves during their propagation, but we do not address this issue and distinguish between subtypes of signals with dispersion of different types.

We have already examined DS that occur in the polar areas in [Guglielmi et al., 2019]. In that paper, we have found that the signal occurrence rate depends on the orientation of the interplanetary magnetic field (IMF) in the XOZ plane. Tilt of the MMP vector in the vertical plane determines the location of a foreshock (a region of increased wave activity before the near-Earth shock front) relative to the magnetosphere. It has been shown that in the south polar cap, the probability of observing DS is about two times higher for the southern location of the foreshock than for the northern one. This indicates the extramagnetospheric origin of, at least, some of the signals.

The analysis of DS records in the polar caps has been continued. The amount of the material we have from the station Thule is very limited, making it impossible to obtain reliable statistical results. In this paper, we therefore use records only from the station Vostok. We have established another interesting pattern that is also associated with the orientation of the magnetosphere relative to the interplanetary medium. The matter is that the diurnal variation in the probability of DS occurrence is fairly pronounced (Figure 2). But the most important thing is that the maximum occurrence rate at the station Vostok falls on the local magnetic noon (MLT), which differs from the geographical local time by approximately 8 hrs (see Table and Figure 3). This suggests that the DS occurrence rate depends not on local conditions of a station (illumination, state of the ionosphere, etc.), but on the location of the magnetic field line passing through the station with respect to the noon meridian.

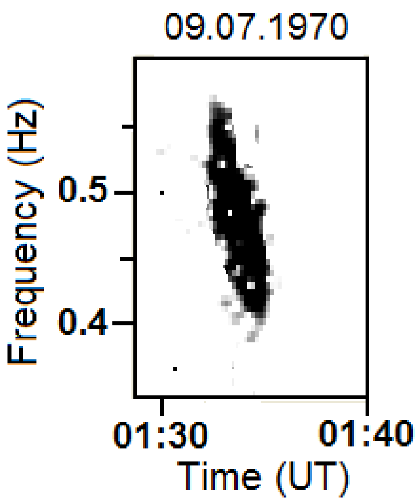

Figure 1. Dynamic spectrum of a discrete signal with a negative slope to the time axis, recorded at the station Vostok [Guglielmi et al., 2019]

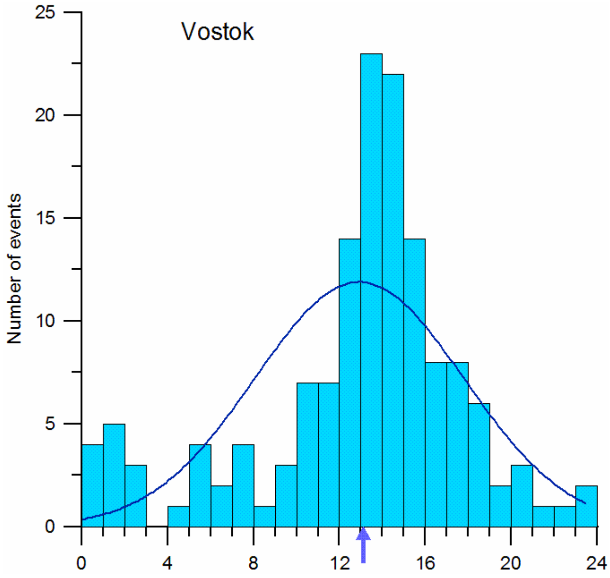

Figure 2. Diurnal variation in the occurrence rate of discrete signals at the station Vostok. The arrow indicates the local geomagnetic noon (MLT)

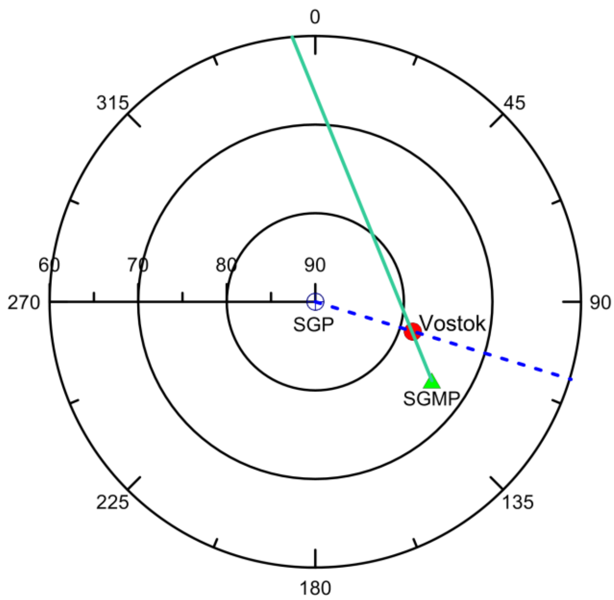

Figure 3. Diagram illustrating a relative position of the station Vostok, South geographic pole (SGP), and South geomagnetic (SGMP) pole. The blue dashed line shows the geographic meridian; the solid green line, the geomagnetic meridian of the station Vostok

In this case, the best conditions for observing DS exist when this field line is sunward. This may be due to the fact that the ULF pulses, excited in the foreshock or on the boundary of the magnetosphere, falling on external geomagnetic field lines slide along them into cusps, which are attractors for the waves incident from SW on the magnetopause [Guglielmi et al., 2017]. At magnetic noon, the magnetic dipole axis and the southern cusp funnel most strongly incline toward SW, especially in November–January. The hours around the magnetic noon are therefore best suited for DS penetration to Earth's surface.

Coordinates of the stations Thule and Vostok and geomagnetic poles for the epoch of 1968

Station	Geographic coordinates		Corrected geomagnetic coordinates		LT–UT	MLT–UT
Thule	76.5	291.3	85.8	34.1	–4.6	–2.8
Vostok	–78.5	106.8	–83.5	52.6	7.1	–1.1
North geomagnetic pole	80.2	279.8	90	–	–5.4	–
South geomagnetic pole	–74.3	125.9	–90	–	8.4	–

Let us see how the probability of observing DS depends on season. Figure 4 shows the seasonal variation in the occurrence rate of digital signals at the station Vostok in 1966–1969. Along the horizontal axis is the parameter sinφ, where φ is the Sun's longitude in ecliptic coordinates: sinφ=0 at points of the vernal and fall equinoxes, sinφ=±1 at points of the summer (+) and winter (–) solstices. As expected, DS most likely occur at the station Vostok in summer for the Southern Hemisphere. Almost half (46 %) of the DS events took place from October 24 to February 17 (sinφ < – 0.5). But there is a second peak in the plot, which corresponds to directly opposite conditions — winter in the Southern Hemisphere. It is much lower than the main one, but still 24 % of the DS events occurred from April 23 to August 20, when sinφ>0.5. We think that this could be due to the DS penetrating into the northern cusp — for them these conditions were the most favorable. Some of them could also simultaneously penetrate into the southern cusp and be observed at the station Vostok, for example, being reflected from the ionosphere and passing along the last closed field line connecting the two cusps. The length of the path from the subsolar point to Earth was, however, greater for such signals, therefore they were attenuated more strongly, and only the most powerful signals reached the station.

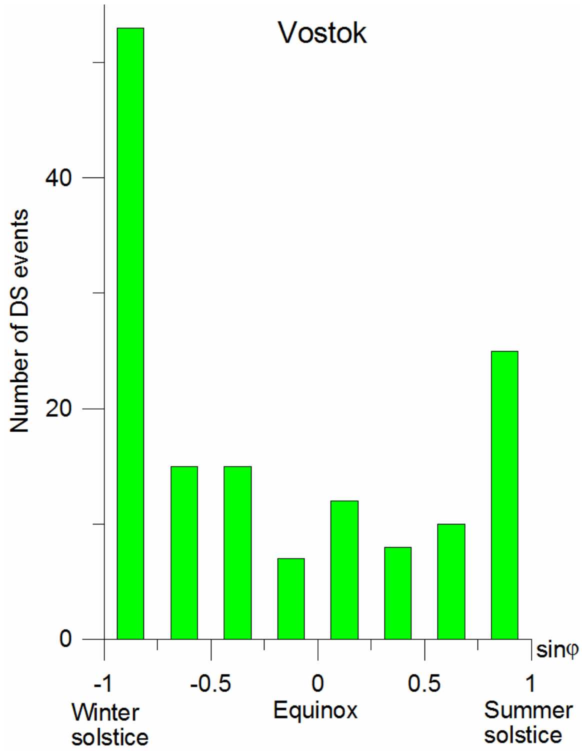

Figure 4. Seasonal variation in the occurrence rate of discrete signals at the station Vostok. Along the horizontal axis are sinφ values — the solar longitude measured from the vernal equinox

SERPENTINE EMISSION

Another type of oscillations observed with induction magnetometers only in the polar caps is serpentine emission. It was found in tape recordings of magnetic field oscillations at the station Vostok in the early 1970s [Guglielmi, Dovbnya, 1973, 1974a, b]. It was a narrow-band emission with a frequency ranging from 0.1 to 3 Hz, which sometimes lasted for several hours or even days. No seasonal and daily dependence of the occurrence rate or other SE characteristics were revealed. Emission frequency modulation is continuous with periods from several minutes to an hour. The most common period of frequency variation is 5 min. Besides the station Vostok, SE was observed at another Antarctic station Davis [Morris, Cole, 1987] and in the Arctic [Asheim, 1983].

Immediately after detecting SE, the authors interpreted its origin [Guglielmi, Dovbnya, 1973]. According to the proposed hypothesis, the emission is generated in the interplanetary medium as ion-cyclotron waves (ICW) due to the instability of solar wind protons. New impetus to the study of the emission was gained several years ago when it was assumed that the main source of SE frequency modulation is waves from the Sun [Guglielmi et al., 2015; Dovbnya et al., 2017]. In addition to the 5-min period characteristic both of the SE frequency modulation and of solar oscillations, other periods were also found which were observed both in the spectrum of SE frequency modulation and in the spectrum of observed solar oscillations [Dovbnya, Potapov, 2018].

While to date there are already direct satellite measurements of ICW in SW [Jian et al., 2009, 2010; Zhao et al., 2017], there is still no direct evidence for the interplanetary origin of SE because high resolution measurements of the magnetic field and plasma in space began after termination of the operation of induction magnetometers in the polar caps. It is therefore impossible to compare the characteristics (frequency, period, and nature of modulation frequency) of the SE parameters observed at Vostok and Thule with SW and IMF parameters or with the waves observed in the interplanetary medium. There is, however, another possibility — to simulate the expected behavior of the emission frequency relevant to the present time, using existing ideas about the mechanism of SE excitation and high-resolution direct measurements of IMF and SW plasma parameters.

The most detailed analysis of the emission excitation has been carried out in [Guglielmi, Potapov, 2017]. Physically, the SE generating mechanism is as follows. Distribution of protons with thermal anisotropy becomes unstable with respect to the excitation of ICW propagating along IMF lines. The velocity of ICW propagation is much lower than that of SW, therefore waves are carried away by the stream. For a stationary observer in a spacecraft or on Earth, the ICW angular frequency ω due to the Doppler effect is

$$\omega = \omega_{SW} + \mathbf{kU}_{SW}, \qquad (1)$$

where ω_{SW} is the wave frequency in convected coordinates; **k** is the wave vector; $\mathbf{U}_{SW}$ is the SW velocity vector. The analysis carried out in [Guglielmi, Potapov, 2017] has shown that the increment of the ion-cyclotron instability has a fairly sharp peak in the case of longitudinal wave propagation when the wave vector is directed along the magnetic field **B** and is approximately

$$k_{max} = k_p \approx \omega_{0p} / c,$$

where $\omega_{0p} = \sqrt{4\pi e^2 N_p / m_p}$ is the plasma frequency of protons; c is the velocity of light; e is the elementary charge; m_p and N_p is the proton mass and density in SW plasma. Furthermore, numerical estimates indicate that under typical conditions

$$\omega_{SW} \approx \Omega_p,$$

where $\Omega_p = eB/(m_p c)$ is the cyclotron frequency of protons. Substituting numerical values, we obtain for the SE carrier frequency the following expression:

$$f_{SE} = \omega/(2\pi) \approx 7 \cdot 10^{-4} U_{SW} N_p^{1/2} |\cos\psi| + 0.015B, \qquad (2)$$

where ψ is the angle between the SW velocity and the IMF vector, the velocity is measured in km/s; the density, in cm^{-3}; the magnetic field, in nT. We can see that the emission frequency is determined by a rather complex combination of SW velocity U, proton density N_p, IMF strength B, and by the mutual arrangement of the vectors **U** and **B**. Now, using (2), we can simulate the behavior of the frequency of assumed SE under different conditions of the interplanetary medium in Earth's orbit.

We have chosen two SE events, which lasted for several hours, from the observations made at the station Vostok in 1971. As derived from currently available OMNI hourly average values of plasma and IMF parameters ahead of near-Earth shock front, during these events SW disturbance levels were very different. In front of Earth's magnetosphere on May 8, 1971 disturbed conditions prevailed: the SW velocity at 13–24 UT decreased from about 620 to 580 km/s at a low proton density of ~2.5 cm^{-3} and an average IMF strength of ~3.6 nT. On the contrary, in the late afternoon of July 13, 1971 the SW velocity was ~430 km/s, while the IMF strength (6.2 nT) and the proton density (8.5 cm^{-3}) were slightly increased. Figure 5, *a*, *c* shows SE dynamic spectra for these time intervals. As we can see, the behavior of the emission frequency is quite significantly different: for July 13, 1971 it is characterized by quiet long-period variations, during May 8, 1971 chaotic jumps occur, and, although there are long-period variations too, fast irregular oscillations in amplitude are comparable with long-period oscillations.

Figure 5, *b*, *d* shows simulated variations of f_{SE}, constructed using Equation (2), from data on 2003 with minute resolution, taken from the high-resolution database OMNI [https://omniweb.gsfc.nasa.gov/form/omni_min.html]. We have selected intervals in which average conditions before the near-Earth shock front were close to those taking place during the selected intervals in 1971. The main IMF and plasma parameters are given in the caption. We can see a clear correspondence between the behavior of the frequency variations observed in 1971 and those simulated from data on 2003 for different conditions in SW.

In addition to records obtained with the induction magnetometer at the station Vostok, we have a very limited amount of data acquired with similar equipment at the station Thule. Among them were several fragments containing records on the serpentine emission made simultaneously with recording of SE at the station Vostok. One of these fragments is shown in Figure 6, *a*, *b*. There is a general correspondence between SE frequency variations at both the stations, but details of these variations are different. The differences may be attributed to the spacing between regions of wave penetration into the magnetosphere and further to Earth's surface.

DISCUSSION AND CONCLUSION

The ULF emissions of the two types considered — discrete signals and serpentine emission — are observed in the polar caps, but have different morphology and obviously different sources. The DS occurrence rate has a sharp peak in local summer in the local magnetic noon when the magnetic field line passing through a monitoring station is directed toward the solar wind, and the geomagnetic dipole axis is tilted as much as possible toward the Sun. The secondary seasonal peak occurs in local winter when the most favorable conditions exist in the opposite polar cap.

Besides, as has been shown previously [Guglielmi et al., 2019], the DS occurrence rate also depends on the vertical inclination of the IMF vector (but not on the sign of B_z) determining the foreshock orientation. Thus, there is reason to assume that the signals are generated in a foreshock or even ahead of it in SW, and with a favorable relative position of the IMF vector, the magnetic field line passing through the observation station, and the magnetic dipole tilt they penetrate into Earth's surface. Hence, for DS, evidence of the relationship between these signals and the interplanetary medium is the dependence of their occurrence rate on the IMF and geomagnetic field orientation.

Quite a different situation is observed for the serpentine emission. Its relationship with the interplanetary medium manifests itself in the SE frequency modulation, mainly contributed by variations of the IMF direction. As for the conditions of its penetration into Earth's

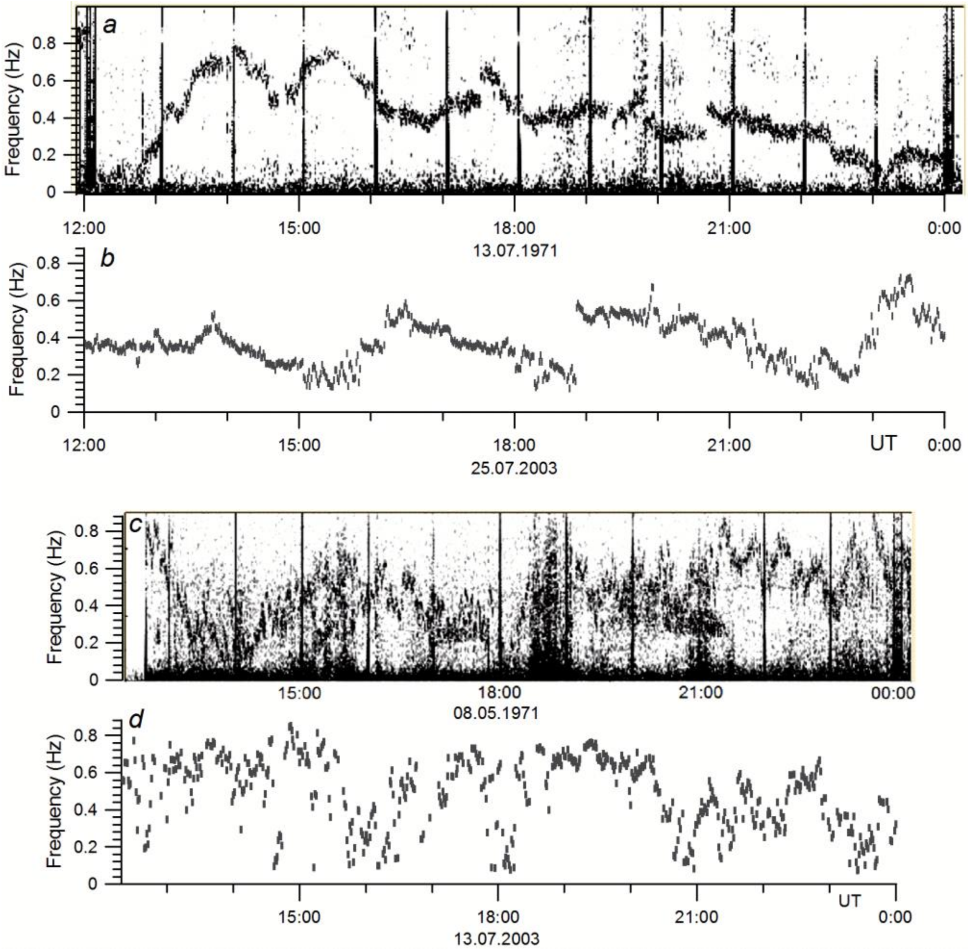

Figure 5. Two pairs of SE dynamic spectra, where the upper pair corresponds to quiet conditions in SW; the lower, to disturbed conditions: as derived from measurements at the station Vostok (*a, c*); the result of simulation of frequency variations of ICW, excited in SW, according to (2) (*b*, *d*). Mean parameters: U_{SW}=438 km/s, B=6.2 nT, N_p=8.4 cm^{-3} (*a*); U_{SW}=317 km/s, B=9.0 nT, N_p=13.5 cm^{-3} (*b*); U_{SW}=603 km/s, B=3.6 nT, N_p=2.4 cm^{-3} (*c*); U_{SW}=548 km/s, B=4.7 nT, N_p=3.2 cm^{-3} (*d*)

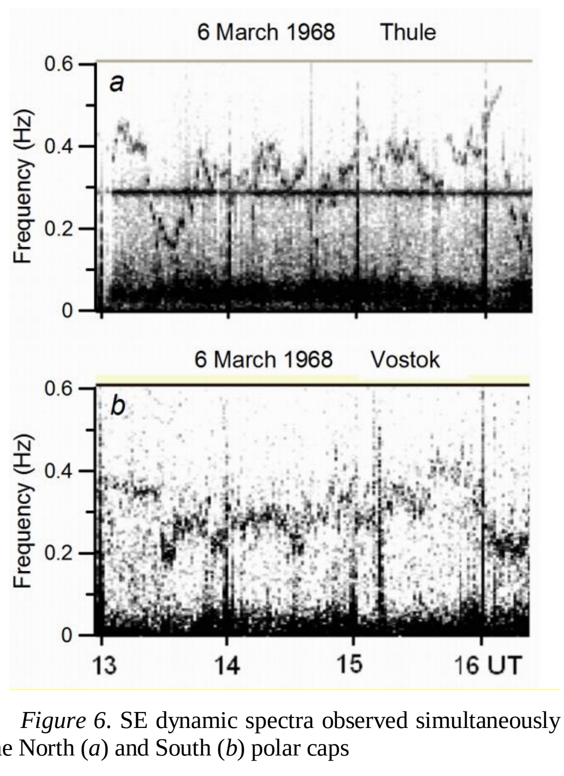

Figure 6. SE dynamic spectra observed simultaneously in the North (*a*) and South (*b*) polar caps

surface, this question remains open. The serpentine emission is a quasi-continuous emission, so the correct determination of the diurnal and/or seasonal variation requires research on associated amplitude variations, rather than on the SE occurrence rate. This, however, is not yet possible with the currently available material — separate spectrograms in which the emission amplitude is represented only as blackening. From an intuitive point of view, we could have hypothesized about SE penetration from SW into tail lobes and then into the polar caps. But we must remember that this emission was observed mainly near the geomagnetic poles (the observatories Thule and Vostok were located almost exactly in their locations in 1960–1970). The observatory Mirny located in the South polar cap has never recorded SE.

In general, the analysis results show the informativeness of ULF emissions with a frequency above 0.1 Hz observed in the polar caps near the geomagnetic poles and projections of magnetospheric cusps. We believe that the lack of modern instruments for observing such emissions is a significant gap in high-latitude geophysical research. Resumption of observations in the polar areas with modernly equipped induction magnetometers will provide important additional information on the interaction of the dayside outer magnetosphere with IMF and SW plasma streams.

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