

# STORM-TIME VLF EMISSIONS CAUSED BY THE SOLAR WIND DISTURBANCES: A CASE STUDY ON 8 DECEMBER 2013

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**Abstract** This study is made of temporal variations of the daytime VLF emissions (1-6 kHz) occurred during the moderate magnetic storm ( $K_p = 6$ ) on 8 December 2013. The storm was associated with the Coronal Mass Ejection (CME). VLF emissions were recorded in the frequency band of 0.2-39 kHz during the dark winter at Kannuslehto (KAN,  $L \sim 5.5$ ) in Northern Finland. The results were compared with simultaneous variations in the solar wind and Interplanetary Magnetic Field (IMF). It was found that intense VLF chorus started after the pressure jump in solar wind (from 7 to 12 nPa) under the positive IMF  $B_z$ . The VLF emissions occurred in two separate frequency bands. The lower frequency (below  $\sim 2$  kHz) band represents the intense long lasting hiss with right-hand polarization, and in the upper frequency band (above  $\sim 2$  kHz) the left-hand polarized hiss bursts occurred during about 1 hour. The plasmasphere was strongly compressed, and due to that KAN was mapped outside of the plasmapause. We suppose that VLF chorus existed in the magnetosphere by the cyclotron instability of the radiation belt electrons. The low frequency chorus was generated outside of the plasmapause and arrived to KAN along the direction of N-S meridian. The high-frequency band was generated inside of the plasmasphere arrived to KAN almost along the meridian.

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**Keywords:** solar wind-magnetosphere interactions, magnetospheric physics, magnetic storm, wave-particle interaction, whistler-mode VLF emissions

## Introduction

The Sun–Earth system is a highly dynamic system in which a continuous exchange of mass, momentum and energy occurs between the solar wind and the Earth's magnetosphere. However, a full understanding of the magnetospheric response to the solar wind and to the variations of the Interplanetary Magnetic Field (IMF) is still an open problem, as they involve different mechanisms of energy release and multi-scale coupling phenomena. One of those could be the generation of natural electromagnetic plasma waves at the audio frequencies from 30 Hz to 30 kHz, known as whistler-mode very low frequency (VLF) emissions. They are common wave phenomena in the Earth's environment (Helliwell, 1965). These VLF waves are a very fundamental subject in the magnetospheric plasma physics due to their ability to efficiently interact with energetic electrons in the magnetosphere via a resonant interaction between the waves and energetic particles in the inner magnetosphere (e.g., Trakhtengerts, 1963; Kennel and Petshek, 1966; Hobara et al., 2000; Trakhtengerts and Rycroft, 2008) as it is shown in Fig. 1. These waves play a controlling role in the dynamics of Earth radiation belts and the precipitation of energetic electrons into the ionosphere.

The natural VLF emissions known as chorus and hiss have been observed both on the ground and in the space by satellites. In spite of a great significance of the satellite measurements, the ground-based VLF observations have an advantage because they allow

studying a temporal behaviour of these emissions. They also provide valuable information for understanding magnetospheric and ionospheric plasma processes associated with an influence of the solar wind and IMF disturbances. Due to limited number of the VLF ground stations and satellite data, which could cover the source region of the emissions observed on the ground, there are not enough experimental facts to develop an adequate theory of generation mechanism of different types of VLF waves.

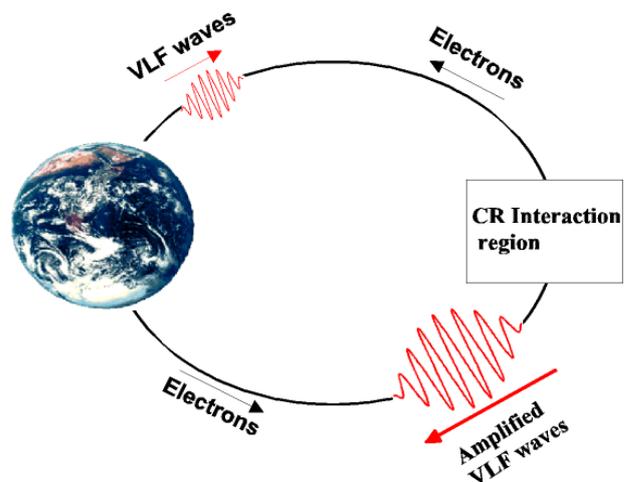


Fig. 1. The schema of the resonant interaction between waves and energetic particles. From the interaction area, the waves and particles propagate to the opposite direction.

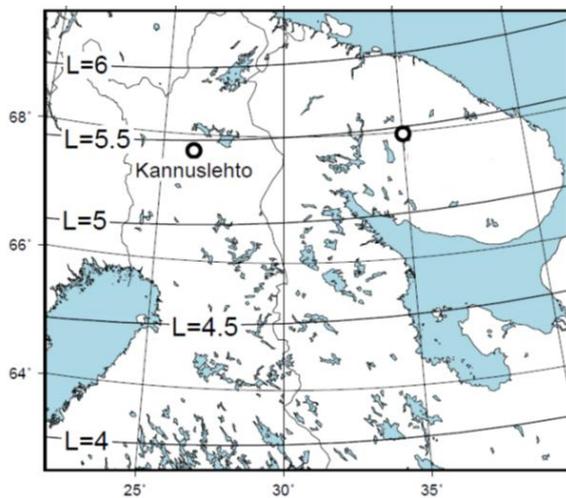


Fig. 2. A geographic map showing the location of KAN.

Thus, the ground-based VLF observations in the frequency range of 0.2–39 kHz carried out by Sodankylä Geophysical Observatory in Northern Finland are very important for such investigations. These waves were recorded at Kannuslehto station (KAN, geographic coordinates 67.74°N, 26.27°E, corrected geomagnetic coordinates  $\Phi = 64.2^\circ$ ;  $\Lambda = 107.9^\circ$ ,  $L \sim 5.5$ , where  $L$  is the distance in the Earth radii, the local magnetic noon near 09 UT). This station is located about 40 km to the northwest of the Sodankylä, the geographic map is presented in Fig.2. A very high-sensitivity VLF receiver and two orthogonal magnetic loop antennas oriented to the north–south and east–west directions were applied.

It is well known that magnetic storms as an important factor of the cosmic weather could be a source of different VLF emission generation. As an example, the moderate magnetic storm on 8 December 2013 ( $K_p = 6$ ,  $Dst \sim -70$  nT), associated with the Coronal Mass Ejection (CME) was analysed. This storm was accompanied by the non-typical high-frequency (~4–10 kHz) early morning hiss lasting about 2-hours (Kleimenova et al., 2015) and by the afternoon 1–3 kHz VLF emissions representing a sequence of the separated noise bursts with a strange “mushroom-like” shape (Manninen et al., 2015).

The aim of this work is to continue the study of magnetic storm on 8 December 2013, and to analyse the ground-based daytime VLF emissions caused by storm-time variations in the solar wind and IMF during the main phase of the storm.

### Observation results

The variations of the solar wind and IMF parameters and the geomagnetic conditions ( $SymH$  and  $AL$  indices) during the magnetic storm on 8 December 2013 are shown in Fig. 3. According to the  $SymH$  index variations, the main phase started around 03 UT after the sharp change of the IMF  $B_z$  from positive to negative (up to -26 nT) under very strong solar wind dynamic pressure ( $P_{sw}$ ) and stable solar wind velocity (~500 km/s). Substorm activity was developed in this time as it is demonstrated by the  $AL$  index variations.

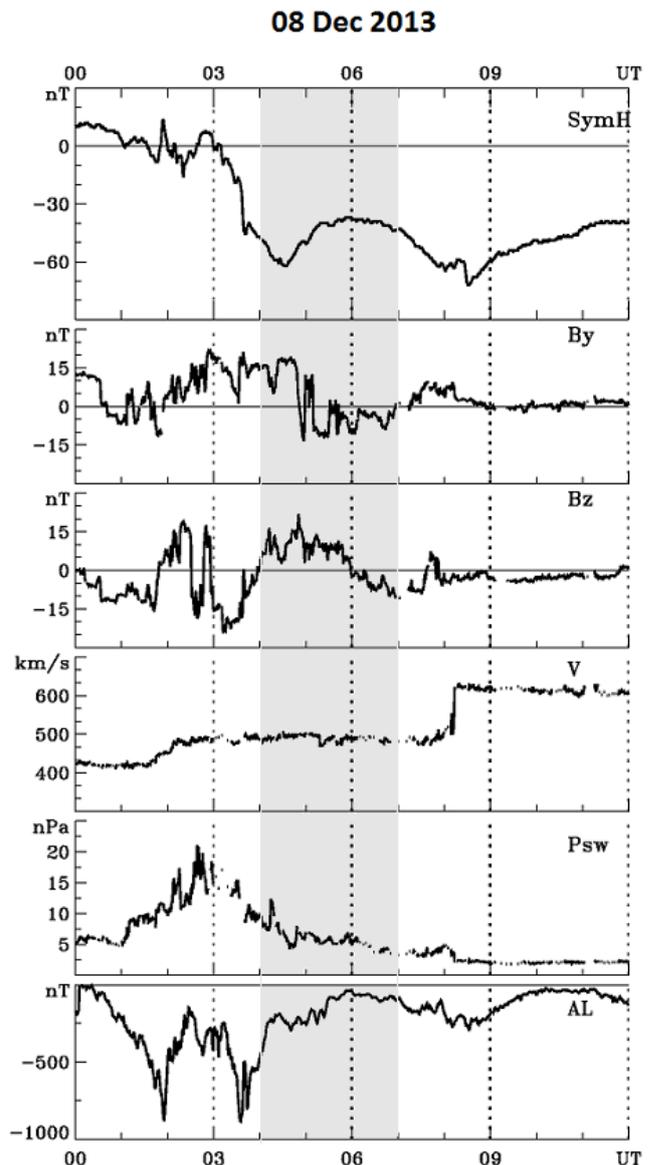


Fig. 3. Variations of some parameters of the solar wind (velocity -  $V$  and dynamic pressure -  $P_{sw}$ ), IMF ( $B_y$ ,  $B_z$ ), and the geomagnetic conditions ( $SymH$  and  $AL$  indices) during the magnetic storm on 8 December 2013.

Later on, around 04 UT, the IMF  $B_z$  turned strongly to positive values, and the  $P_{sw}$  significantly decreased. With turning IMF  $B_z$  northward and  $P_{sw}$  decreasing, the global substorm activity ( $AL$  index variations) suppressed.

The strong solar wind pressure compressed the magnetosphere and plasmasphere. The plasmapause location can be exhibited by the Van Allen Probes (RBSP) satellites (<http://enarc.space.swri.edu/PTP>). The data, based on RBSP-A and RBSP-B measurements, are presented in Fig. 4 for two time intervals during the main phase of this magnetic storm. It is clearly seen that in both times, KAN was mapped outside of the plasmasphere.

The total spectral power in the frequency range of 1–11 kHz, observed at KAN is shown in Fig. 5. The non-typical high-frequency hiss generated early morning

(01±03 UT) in the initial phase of the storm (see the left corner of the VLF spectrogram) was discussed by Kleimenova et al. (2015). Typical auroral hiss near 18 UT (see two red vertical bars in the right-hand part of the spectrogram) was observed in the evening. Here we focus on the daytime VLF emissions observed during the storm main phase after 04 UT.

The more detailed spectrograms (1-8 kHz, the total, left-hand and right-hand polarized wave power) for 03-09 UT are presented in Fig. 6. The bottom panel (Az) shows the angle direction (not the vector!) of the wave arrival. The red colour indicates the wave arrival roughly along the longitude (i.e., N-S direction), and green – along the latitude (i.e., E-W direction). One can see that the VLF emissions at the frequencies above ~2.5 kHz are left-hand polarized supporting their long travelling in the Earth-ionosphere wave guide, and KAN was located far from the wave exit point area (Yearby and Smith, 1994; Fedorenko et al., 2014). These emissions arrived mostly along E-W direction.

Contrary to that, the VLF emissions at the frequencies below ~2.5 kHz were right-hand polarized indicating that the ionospheric exit point of the wave was located near KAN. These emissions arrived almost along the N-S direction.

The temporal behaviour of these VLF emissions was compared with the variations in the interplanetary medium and the magnetosphere. Figure 7 displays the variations of some IMF and the solar wind parameters as well as the measurements of the 75 keV electron flux on the GOES-15 at 03-07 UT. This geostationary satellite (geographical latitude of 135° W) located in the night sector of the Earth while KAN is on dayside. One can see that the sharp onset of the long-lasting VLF emissions started after impulsive jump of the solar wind dynamic pressure (from 7 to 12 nPa) accompanied by small decrease of the IMF B. Such a small pressure increase could be a trigger of the generation of strong VLF emissions, probably, due to previous interval (02-04 UT) of very high Psw (up to 20 nPa) under the strong negative IMF Bz (up to -25 nT) provided a big amount of trapped energetic electrons loaded in the magnetosphere radiation belt.

Another strong high-frequency (~2.5±5.0 kHz) VLF burst was observed between 05.30 UT and 06.30 UT. As it is seen in Fig. 7, this VLF burst started after the increase of the energetic electron flux measured on GOES-15 in the night sector of the magnetosphere. This impulse was accompanied by the relatively pint-sized (~1 nPa) increase of the solar wind dynamic pressure (Fig. 7). A small (~100 nT) substorm-like magnetic disturbances were recorded at this time at high-latitude CBB (Cambridge Bay) station, which was located in the vicinity of the GOES-15 footprint. The substorm occurrence indicates an electron injection from magnetotail. However, in this time there were no significant magnetic disturbances at the lower latitudes, and the values of the AL index of substorm activity were very low (Fig. 3).

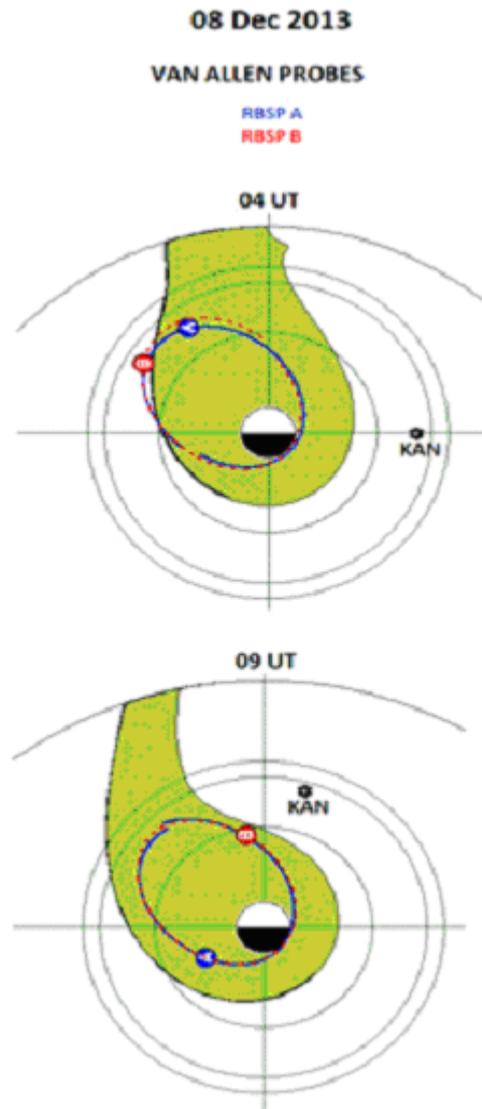


Fig. 4. The plasmopause location according to two Van Allen Probes measurements (RBSP A and RBSP A) in L coordinates, the circles correspond to L = 4, 6, 8.

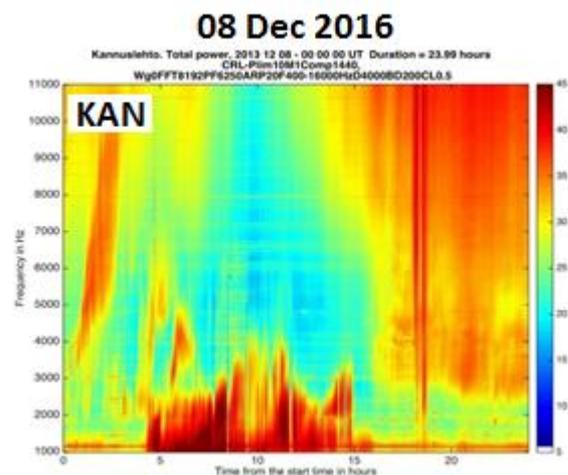


Fig. 5. The VLF spectrogram (total power) at KAN, frequency range of 1 - 11 kHz, and time 0 - 24 UT. Colour code is given in dB.

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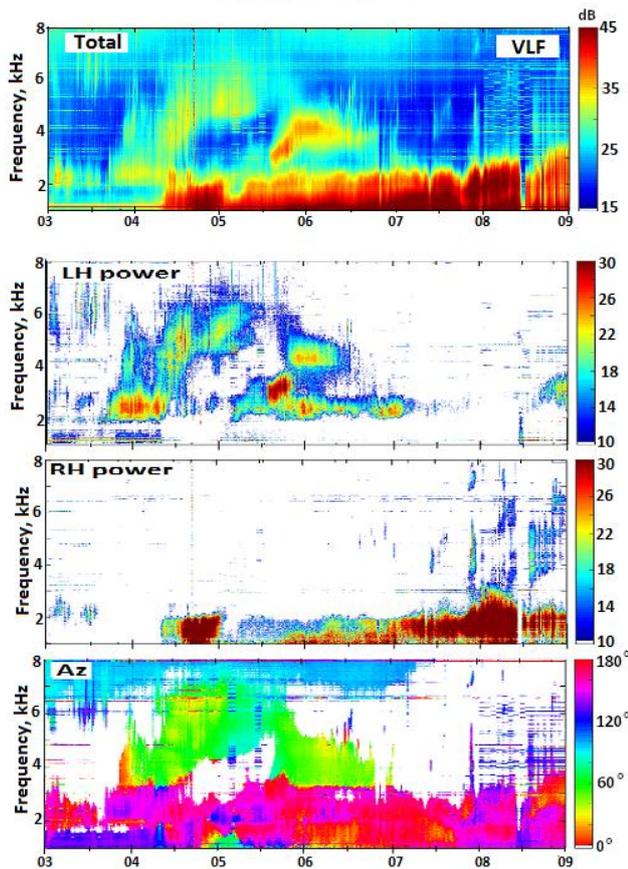


Fig. 6. The VLF spectrograms (total power, pure left-hand and pure right-hand circularly polarized wave power), at the bottom - the azimuthal angles of the wave arrival (Az).

We suppose that the electron injection from the magnetotail into the magnetosphere (recorded on GOES-15) and a small increase of the solar wind pressure provided the satisfactory conditions for the electron cyclotron instability and the generation of VLF emissions. The frequency band of emissions increased within about 30 minutes from  $\sim 2.6 \div 3.3$  kHz near 05.30 UT to  $\sim 3.3 \div 4.7$  kHz near 06 UT. That could indicate a latitude shift of the emission source to the lower latitudes. These VLF emissions could be generated inside of the plasmasphere in the morning sector, propagate to the dayside and reach KAN as left-hand polarized waves arriving from West-East direction.

### Discussion

It is known that the solar wind is coupled to the magnetosphere via the solar wind dynamic pressure ( $P_{sw}$ ) and the electric field. The pressure causes the change of the size and shape of the system, while the electric field ( $E \approx V \times B$ ) transfers energy, mass and moment into the magnetosphere. There are various modes of response of the magnetosphere to the solar wind variations. One of them can be VLF whistler-mode wave generation by the cyclotron instability of radiation energetic particles in the inner magnetosphere.

As a result of the cyclotron instability, the energetic electrons change the pitch-angle and become precipitated as it is seen in the schema in Fig. 1. We used the PGI (Polar Geophysical Institute) model (<http://webapps.pgia.ru/apm>) to show the global spatial distribution of the area of energetic electron precipitation known as a diffuse auroral zone – DAZ (Vorobjev and Yagodkina, 2005). This model is based on the statistical processing of the DMSP F6 and F7 spacecraft measurements. The equatorward boundary of the DAZ region is the  $b_{le}$  boundary on the night-side (Newell et al., 1996) and the equatorward boundary of the CPS (Central Plasma Sheath) type precipitation on the dayside (Newell et al., 1991). The map of the DAZ zone position at 05-06 UT, calculated with the PGI model, is shown in Fig. 8 by blue colour (the lowest latitude zone). It is seen that KAN was mapped inside this zone. Thus, it supports the hypothesis that studied VLF emissions were excited in the magnetosphere by the cyclotron instability of the radiation belt electrons, and caused by this instability precipitating energetic electrons are seen as the DAZ zone.

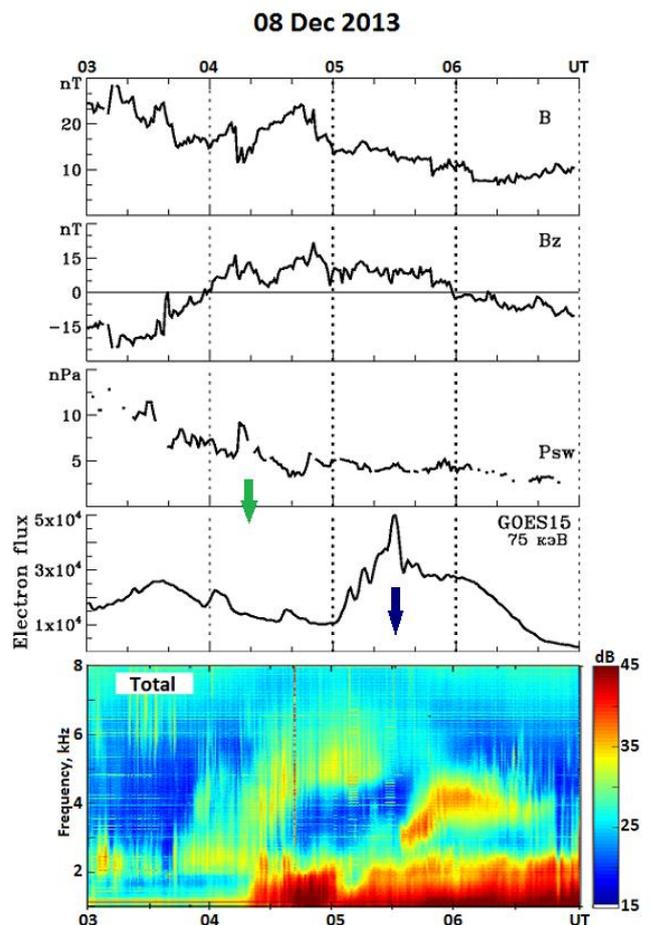


Fig. 7. The variations of IMF parameters (B and Bz), the solar wind dynamic pressure ( $P_{sw}$ ), the 75 keV electron flux on the geostationary GOES-15 satellite (geographical latitude of  $135^\circ$  W), and VLF total power at 03-07 UT in 1-8 kHz.

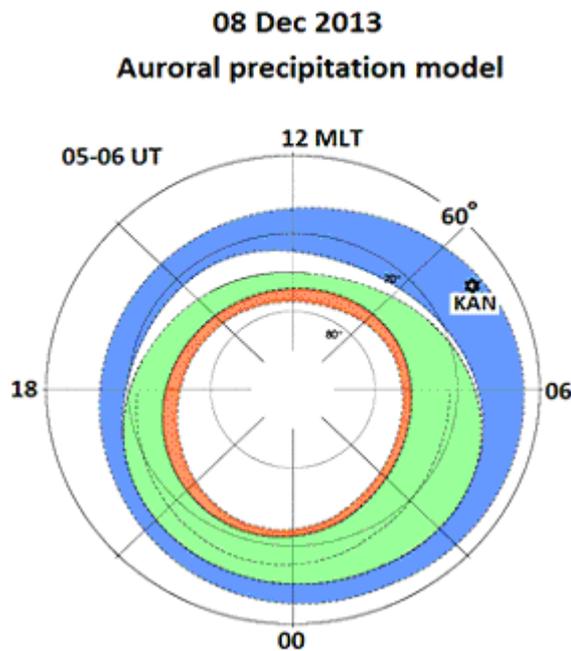


Fig. 8. Planetary distribution (corrected geomagnetic latitude - local geomagnetic time) of different type auroral precipitation according to the PGI model: blue - zone of diffuse precipitation (DAZ), green - auroral oval precipitation (AOP), red - soft diffuse precipitation (SDP).

The frequency of excited VLF waves is controlled by the equatorial electron gyrofrequency  $f_{ce}$ , which is proportional to the local magnetic field strength. Whistler-mode waves generating near the magnetic equator, are trapped in field-aligned columns of enhanced density and guided to the ionosphere by the magnetic field with an upper cut-off frequency at  $f_{ce}/2$ . (e.g. Smith et al., 1960). The  $f_{ce}$  value at magnetic field line of  $L \sim 5.5$  (KAN) is  $\sim 5$  kHz. Thus, the wave propagated roughly along the KAN magnetic field line, can be detected on the ground only at  $f \leq 2.5$  kHz with right-hand polarization. Such waves are seen in the bottom part of spectrograms in Fig. 6 as strong chorus emissions.

We suppose that VLF hiss emissions excited in the magnetosphere by the cyclotron instability of the radiation belt electrons. In the studied time, the plasmasphere was strongly compressed, and KAN was mapped outside of the plasmopause. The low frequency chorus was generated outside of the plasmopause, guided along the magnetic field line and arrived to KAN along the N-S meridian direction. The upper frequency band was generated inside of the plasmasphere, probably, in the vicinity of the plasmopause, and arrived to KAN almost along the meridian.

The obtained results demonstrate how even insignificant irregularity in the solar wind occurring after strong disturbances in Psw and IMF could produce some strong geophysical effects in the VLF wave generation in the dayside magnetosphere.

## Summary

1. We found that the intense VLF emissions appeared after an impulse in the solar wind dynamic pressure, which compressed the magnetosphere and plasmasphere. We suppose that the VLF chorus (below  $\sim 2$  kHz) was generated outside of the plasmopause via electron-cyclotron instability.

2. The upper frequency band (above  $\sim 2$  kHz) was, probably, generated inside the plasmasphere and arrived to KAN from lower L-shells along the Earth-ionosphere wave-guide becoming left-hand polarized.

3. The ground-based VLF observations could be a sensitive tool to study even insignificant disturbances in the solar wind and IMF.

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