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SC-ASSOCIATED VLF-EMISSIONS AT TWO CLOSELY SPACED AURORAL STATIONS: CASE STUDY DECEMBER 23, 2014

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Abstract. The SC effects in VLF emissions were studied basing on the simultaneous VLF observations at Finnish station Kannuslehto (KAN) and Russian station Lovozero (LOZ) located at the same geomagnetic latitude but separated by ~400 km in the longitude. The considered SC has happened on December 23, 2014 at 11.14 UT under northward IMF. Thus, geomagnetic and VLF effects in the magnetosphere were caused most of the enhancement of the solar wind dynamic pressure. There was the daytime SC associated VLF burst (VLFsc) and a succeeding strong VLF hiss, which started several minutes after SC. A sharp particle flux enhancement (typical for SC) was observed at first by THEMIS B (ThB) satellite, located in front of the magnetosphere at X=~50 Re and Y=~20 Re, about 10 min before the SC impulse observed on the ground. Increasing electron and ion fluxes were observed by ThA, ThD, and ThE in the evening sector (at X=~-7 Re, Y=~10 Re). These satellites recorded strong pressure depletion between the VLFsc burst and the subsequent VLF hiss onset. The VLFsc burst represented the composition of a high-frequency (~2-5 kHz) left-hand polarized part and a low-frequency (~0.5-1.5 kHz) right-hand polarized part. According to the KAN data, the VLF signals arrived from the meridian (North-South) direction. However, the LOZ 3-component receiver allows to estimate the signal arriving azimuth. It was found that the VLF high-frequency part arrived from the South, but the VLF low-frequency part arrived mainly from overhead. The plasmapause location estimated by RBSP (A and B) satellites showed that KAN and LOZ were mapped outside of the plasmapause. We suppose that the 2-5 kHz hiss burst was originated inside of the plasmasphere and the 0.5-1.5 kHz hiss –outside of it. In spite of the similarity of general spectrogram and polarization at KAN and LOZ, the small differences have been found, and the VLF signals arrived to these stations from different direction due to KAN location closer to the wave exit point than LOZ.

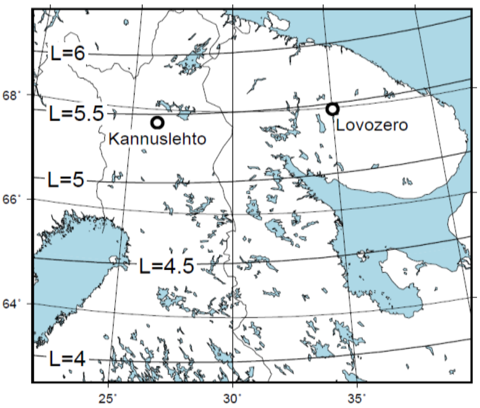

Figure 1. The map of the station location

1. Introduction

It is well known that a sudden commencement (SC) is caused by interplanetary shock and has been interpreted in terms of a compression of the magnetosphere [e.g., *Nishida*, 1978; *Shinbori et al.*, 2003; *Yu et al.*, 2015] resulting electron cyclotron VLF wave generation. Here the SC effects in VLF waves were studied basing on simultaneous VLF observations at Kannuslehto (KAN) in Finland and Lovozero (LOZ) in Russia. They are located at the same geomagnetic latitude but separated by ~400 km in the longitude (Fig. 1).

The studied SC event has occurred on 23 Dec 2014 at 11.14 UT under northward IMF (Fig. 2), i.e. there was no new particle input from the solar wind into the magnetosphere**.** But the previous day was disturbed and Kp was 5.

The plasmapause location estimated by the RBSP (A and B) satellite data showed that during the event, KAN and LOZ (the asterisk in Fig. 3) were mapped outside the plasmapause (Fig. 3) due to strong magnetic activity during previous day.

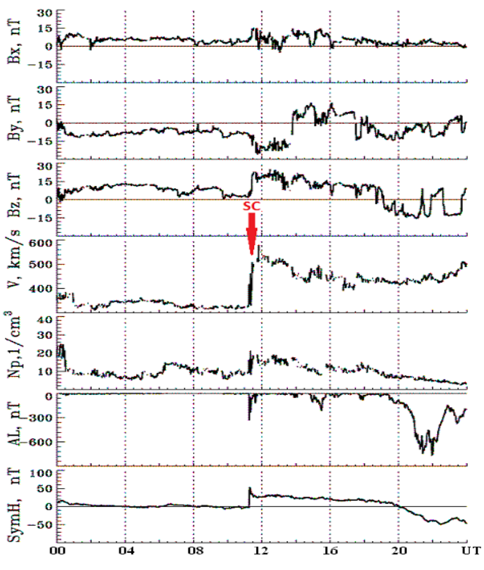

Figure 2. IMF and solar wind data

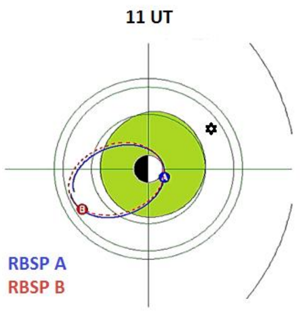

Figure 3. Plasmapause location by RBSP satellites.

2. Observation results and discussion

It was found that the short VLF burst at ~2-5 kHz, caused by the SC impulse at 11.14 UT, started 1 min later at both stations and lasted about 5 min. In a few minutes, this burst was replaced by the long lasting VLF hiss, which intensified after ~11.32 UT reaching the maximum intensity at the frequencies lower ~4 kHz (Fig. 4).

The main structure of the VLF emissions at KAN and LOZ was similar despite of the different instrumentation with the different sensitivity. In Fig. 4 a good similarity of the VLF spectral structure at LOZ and KAN is seen, both in 1 hour (a) and 10 min (b) time scales. Note, the computer programs of spectral analysis of VLF signals at these stations although based on the same physical principle, but had a small difference, which sometimes leads to a small difference in color presentation.

The results of detailed analysis of the VLF emission at KAN and LOZ during 10 minutes around SC are shown in Fig. 5. It is seen that the frequency of the first VLF burst increased very quickly from about 0.5 kHz to ~3.0 kHz, and then two frequency bands have appeared: the lower band at f < 2 kHz which was right-hand polarized at both stations, and the higher one at f ~2-4 kHz with the different sign of the polarization rotation at KAN and LOZ.

In Fig.5, one can see that at LOZ, the 2-4 kHz waves were strongly left-hand polarized. However, at KAN, during the first minute, these waves demonstrated the both (left- and right-hand) polarization, and later, after 11.16 UT, the wave became strongly right-hand polarized demonstrating their spatial proximity to the wave exit point from the ionosphere. So, we can conclude that at 11.15-11.19 UT, KAN was located closer to the 2-4 kHz wave exit point than LOZ.

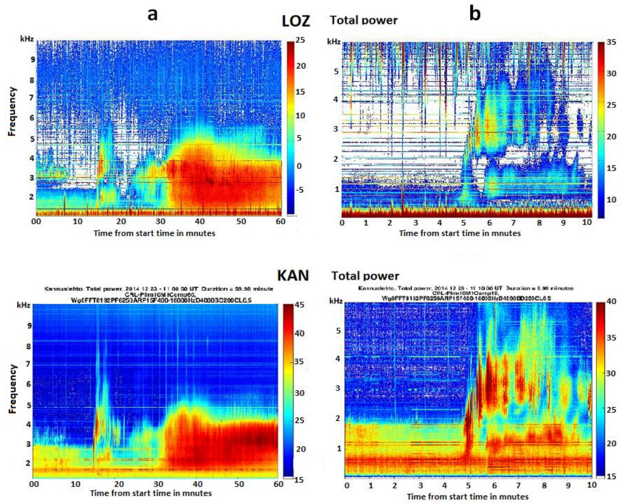

Figure 4. The VLF spectrograms (total power) at LOZ and KAN, (***a***) – at 11-12 UT (60 min full scale), (***b***) – at 11.10 -11.20 UT (10 min full scale).

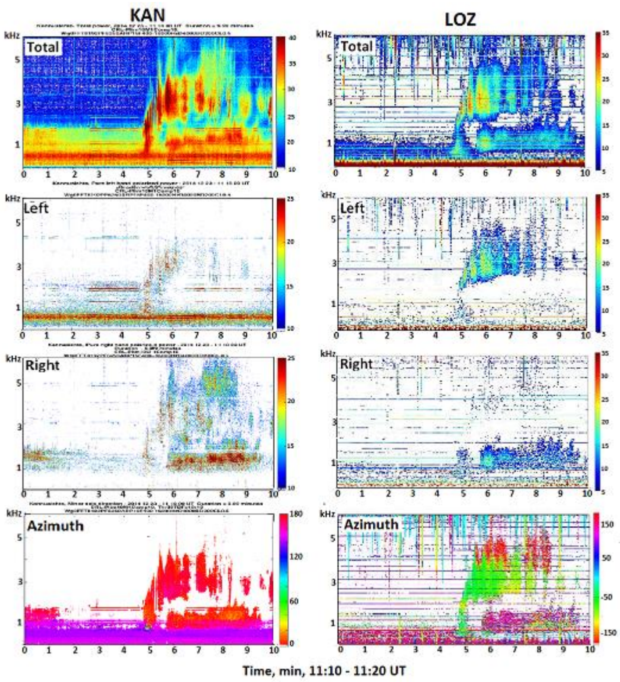

Figure 5. The VLF spectrograms (total power, left-hand and right-hand polarized wave power) and the azimuth of VLF wave arriving at KAN and LOZ in the 10-min interval (11.10-11.20 UT).

The azimuth of VLF wave arrival was calculated for both stations. However, it should be noted, at KAN, the wave arrival direction can be calculated with the uncertainty of 180 degrees because only two horizontal components of the magnetic field are recorded. But at LOZ also the vertical electric component was measured, which allow to calculate the azimuth of the wave arrival.

The calculation of the azimuth of VLF wave arrival showed (Fig. 5) that at KAN, the 2-4 kHz waves travelled along the North-South direction (red color). But at LOZ, the waves arrived from the West (green color), i.e., from the KAN location. That confirms our assumption that KAN was located close to the wave ionospheric exit point. It is important to mention, that at LOZ, the waves at higher frequency (f >~4 kHz) came from the South (red color) where the plasmapause was located (see Fig. 3)**.**

The strong hiss emissions at frequency up to 6 kHz were evolved several minutes after SC (Fig. 4a). The detailed analysis of this interval according LOZ data is presented in Fig. 6.

It is clearly seen that in the beginning of the event, polarization of VLF emissions was left-handed, which can be interpreted as the ionospheric exit point of the wave was located far away from this station, and the waves arrived long distance propagating in the Earth-ionosphere wave-guide [e.g., *Yearby and Smith*, 1994].

After ~11.20 UT, the wave polarization suddenly turned to a strong right-hand direction, which can indicate that the ionospheric exit point of wave was nearly overhead or between these stations.

We compared the ground-based VLF data with the measurements by THEMIS D (ThD) and THEMIS E (ThE) mission [*Angelopoulos*, 2008], located in this time in the evening flank of the magnetosphere (Fig. 7). They showed typical behavior of energetic electron and ion fluxes as well as magnetic field variations for SC.

The THEMIS B (ThB) satellite (do not shown here) was located in front of the magnetosphere at X=~50 Re and Y=~20 Re. These data demonstrated a sharp particle flux enhancement (typical for SC).

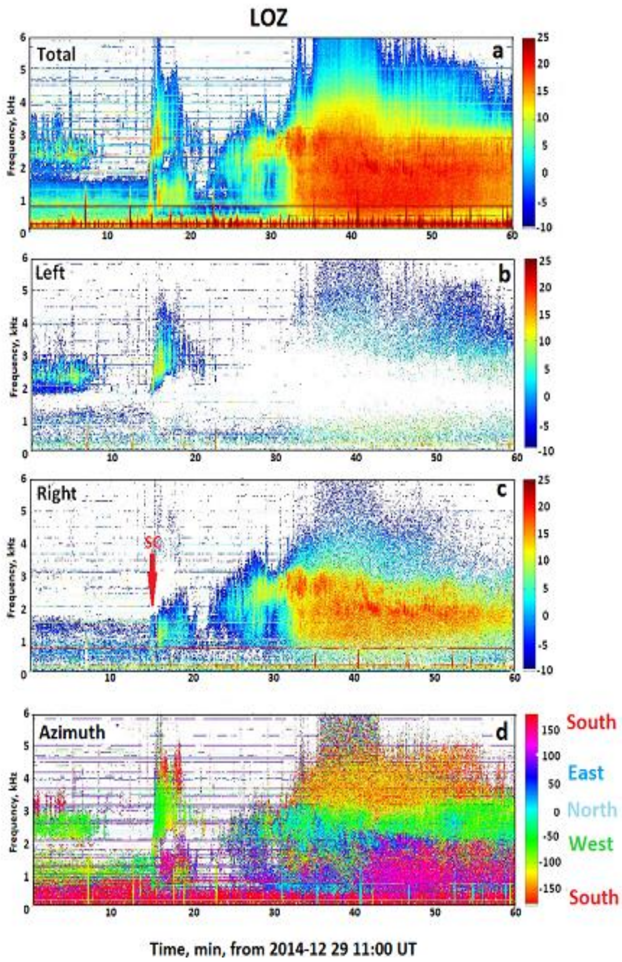

Figure 6. The results of the analysis of the LOZ VLF data (interval 11.00-12.00 UT).

It is seen (Fig. 7) that the VLF emission onset, associated with SC, coincided with a sharp electron and proton flux increase measured by ThD and ThE spacecraft. Apparently, that is a result of the electron cyclotron instability [*Trakhtengerts and Rycroft*, 2008] arising by the compression-induced changes in the electron phase space density and pitch angle distribution caused by SC [*Kennel and Petschek*, 1966].

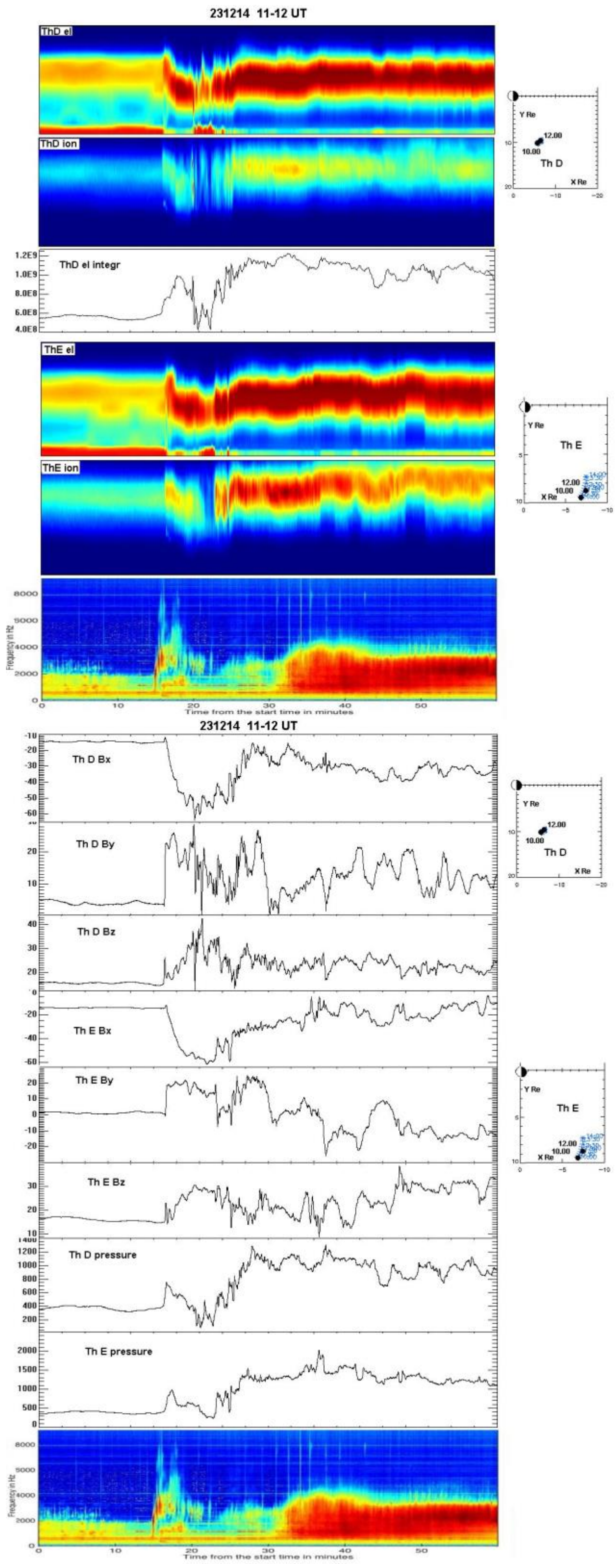

Figure 7. The energetic electrons and ions fluxes, magnetic field and pressure measured by THEMIS D and THEMIS E located in the evening flank of the magnesphere (at X=~-7 Re, Y=~10 Re) and VLF data at KAN (bottom panels).

We suppose that there were stored a lot of resonant trapped electrons due to previous geomagnetic activity with Kp=5 in the Earth radiation belt. It is the necessary condition for the development of the electron cyclotron instability caused by the SC impulse. That was shown by *Kleimenova and Osepian* [1982] who studied the SC effects in VLF emissions at subauroral latitudes. It was found that the SC associated VLF bursts occurred only if previous geomagnetic disturbances Kp >2.

The VLF gap (~11.20-11.30 UT) between the VLFsc burst and the following VLF hiss onset corresponds to the strong pressure depletion observed by ThD satellite (Fig. 7) and energetic particle decreasing (both, electrons and ions) measured by ThE and ThD satellites.

The ground-based VLF data showed [e.g., *Klemenova et al*., 1968, *Smirnova et al*., 1976] that the strongest daytime hiss was observed near the location of the plasmapause. Thus, the plasmapause can be a main wave channel guiding the plasmaspheric hiss from the magnetosphere into the ionosphere [*Inan and Bell*, 1977]. Then the VLF waves propagate through the ionosphere and due to travelling in the Earth-ionosphere wave-guide, the waves could arrive at ground receiver, located far away from the wave exit point. The sense of the polarization vector rotation provides the information how far is the VLF wave receiver location from ionosphere exit point.

We suppose that in the beginning of our event (the first minutes after SC), the VLF receiver at LOZ was located far away (strongly left-hand polarized waves at frequency of ~2-4 kHz, Fig. 5) from the wave ionospheric exit point, which roughly coincides with the plasmapause projection to the ionosphere. So, the source of the VLFsc burst was very localized in longitude. However, the polarization of the succeeding long-lasting VLF hiss was right-handed both at LOZ and KAN supporting a broad ionospheric wave exit area.

4. Conclusion

1. The SC led to the excitation of a short VLF burst with the strong left-hand polarization at LOZ and both (left- and right- hand) polarization at KAN. The 2-4 kHz waves arrived to KAN along the N-S meridian, but at LOZ they arrived from West. This may be due to the location of KAN, which was closer to the ionospheric wave exit point than LOZ and support the small longitudinal dimension of the wave exit area.

2. We suppose that the 2-4 kHz VLF burst was induced by the solar wind dynamic pressure impulse, which generated the electron cyclotron instability in the Earth radiation belt near the plasmapause. Required number of trapped resonant energetic electrons was provided by previous geomagnetic activity (Kp=5)

3. The gap between the first VLF burst and following hiss coincided with the strong pressure depletion and energetic particle decreasing, recorded at this time by the THEMIS D and E.

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