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Small-Scale Structure of Ionospheric Absorption of Cosmic Noise During Pre-Onset and Sharp Onset Phases of an Auroral Absorption Substorm

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Abstract

Impulsive pulsations of ionospheric absorption were found in imaging riometer measurements at Kilpisjärvi during the pre-onset and onset phases of auroral absorption substorms. The periods of the pulsations varied between 2 and 18 minutes during the pre-onset phase and from 2 to 90 seconds during the onset phase. The onset was characterized by fast northward or southward propagation. A comparison of absorption and magnetic field spectra show close to the same features. The results support models suggesting that processes associated with the substorm can be found on closed field lines.

Key words: Substorm, cosmic noise absorption

1. Introduction

Studies of energetic electron precipitation E>30 keV made with riometer chains in the northern hemisphere have given us a picture of substorm-related energetic electron precipitation on a global scale (*Hargreaves et al.,* 1975; *Pytte et al.*, 1976a, b; *Ranta,* 1978, *Ranta et al.*, 1981; *Ranta et al.,* 1983; *Ranta and Ranta*, 1983; *Ranta and Ranta*, 1984). A pre-onset absorption bay, also called the growth phase, often precedes the onset, beginning to develop 1-1.5 h before the onset. The bay occurs between L-values 3 and 19 and may cover as much as 150^0 of geomagnetic longitude, generally in the longitudinal sector where the substorm breaks up and to the west of it. Even though the substorm breaks up at or near the midnight meridian, the preceding bay may, in some geophysical conditions, appear in the afternoon sector. The preceding bay moves slowly southward, intensifying during the movement. This equatorward movement is consistent with an ExB drift in a cross-magnetotail electric field of between 0.5 and 1 mV/m. The precipitation occurs in a narrow band of latitude, perhaps less than 50 km wide. The particles causing the preceding bay are probably precipitated from the inner boundary of the plasma sheet, possibly from the outer radiation zone, due to strong pitch angle diffusion and/or scatter.

The onset usually occurs at the eastern edge of the preceding absorption bay. The onset is first seen near magnetic midnight and then spreads to higher and lower latitudes as well as eastward and westward. Eastward propagation occurs at about constant L-shells and westward propagation towards higher L-values. The onset moves to the west in two separate latitude ranges. To the west of the break up the preceding bay continues its southward movement. In multiple onset substorms, the absorption onsets may propagate to the west in narrow latitudinal ranges, the first onset in the north and the others more to the south, showing that in the region where the substorm expansive phase originates there may still be equatorward movement after a breakup occurs. The westward propagating onsets coincide in the north with PiB and in the south with IPDP magnetic pulsation events (*Ranta et al.*, 1983). The injection area affected during the first minute of the onset typically extends over 1-2 L-values, but as much as 30^0 of geomagnetic longitude. The onset later spread to cover 1-10 L-values, and up to 130^0 of longitude.

The large-scale energetic electron precipitation patterns have been recorded by broad-beam riometers which integrate a large area with relatively poor time resolution. In general, substorm features recorded by riometers are nevertheless similar to those observed by optical means if one takes into account that absorption bays tend to lie somewhat south of optical aurora. Today's imaging riometers give us a new tool with which to study, in detail, energetic electron precipitation patterns produced in response to magnetospheric changes.

Ranta and Yamagishi (1997) studied the small-scale structure of the electron density in the D region during the onset phase of an auroral absorption substorm, using imaging riometer measurements from Tjørnes. They found that the precipitation during the onset phase may be localized. After the substorm onset, the ionospheric absorption was observed to pulsate with a period of 1-12 minutes, possibly due to the magnetohydrodynamic, field line resonance in the nightside magnetosphere.

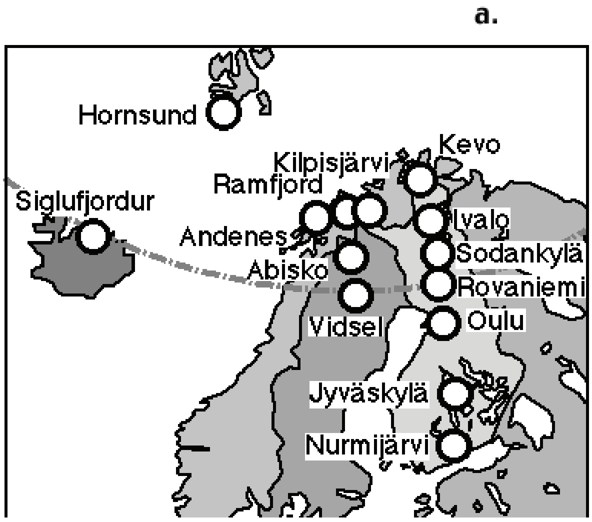
The short-duration spike events, which are a common feature of substorm-associated auroral absorption in the midnight sector, were studied by *Hargreaves et al.* (1997) using imaging riometer measurements from Kilpisjärvi (L=5.9) and the South Pole (L=13). They found the spike events to be closely similar at the two latitudes. The events were elliptical in shape with the major axis along rather than across the L shells; median dimensions were 167 km by 74 km at the South Pole, and 190 km by 80 km at Kilpisjärvi. In each case, the perturbed region of the ionosphere mapped to an almost circular region at the magnetospheric equatorial plane, and the total magnetic flux included within the event was similar at the two latitudes. The velocities of the events varied from several 100 m/s to 2 or 3 km/s; the motion tended to be poleward at the beginning of a precipitation event, and often was equatorward towards the end. The east-west component did not show any consistency of direction at Kilpisjärvi, though in magnitude it may be as large as the north-south component. It was shown that the true duration of the spike events is only 1-2 min. The slowly moving absorption bay, which may precede the intense precipitation of substorm onset, appeared at Kilpisjärvi in the form of an arc-like feature extending east-west across the entire field of view, but containing structure. Its typical north-south extent was 60-100 km, and its equatorward speed a little over 100 m/s.

In this paper we study the small-scale structure of electron density in the D region and corresponding magnetic signatures during two auroral absorption substorms with a sharp (spike) onset and during the preceding pre-onset phase. Imaging riometer and magnetic measurements obtained at Kilpisjärvi, and broad beam riometer measurements made in the Nordic Countries were used as data.

2. Measurements

The development of substorm events with a sharp onset was studied with imaging riometer measurements made at Kilpisjärvi (69.05^{o}N, 20.79^{o}E, L=5.9). The riometer system operates at 38.2 MHz and relies on an array of 64 crossed half-wave dipoles over a ground plane, with a set of Butler matrices to form 49 independent beams. The signals are received on a time sharing basis into seven riometers with a time resolution of one second. The zenithal beam is 13 degrees wide between half power points and the best spatial resolution at 90 km is 20 km. The oblique beams are considerably wider. A view of the coverage at 90 km is shown in Figure 1b. The beam numbers shown in the Figure 1b are used in referring data obtained by that beam. The eighth riometer is connected to a broad-beam antenna at the site and covers a circle with radius of 50 km at the 90 km level *(Hargreaves et al.*, 1997, *Detrick and Rosenberg*, 1990). The absorption data is compared with magnetometer X-component at Kilpisjärvi, time resolution 10 s. For the comparison 10 s averages of absorption data are used. In comparing absorption with magnetic data, one should note that the magnetometer responds to fields created by current structures from large distances whereas absorption is created by local ionizing precipitation.

The substorm events were also observed by a network of broad-beam riometer stations located between L-values 4 and 14 and between longitudes 30^{o} E and 20^{o} W. A list of the riometer stations with their geographic coordinates and operating frequencies is given in Table 1. The locations of the stations are shown in Figure 1a. To study the pre-onset and sharp onset phases of an auroral absorption substorm the following two events are discussed.



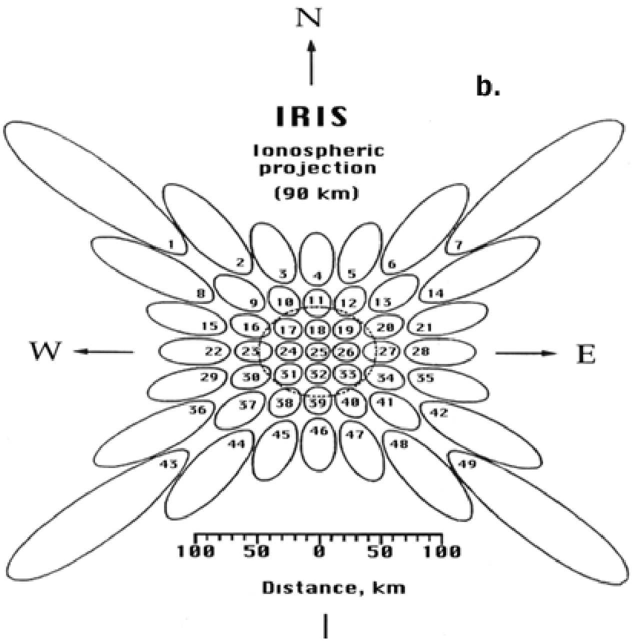


Fig. 1. a) Riometer stations. b). The patterns of antenna beams of the imaging riometer at Kilpisjärvi, at the height of 90 km.

Table 1. Riometer stations.

Station			Geographic coordinates	
Hornsund	30.0 Mhz	HOR	77°00'N	15°36'E
Kilpisjärvi	38.2	KIL	69 03	20 47
Ivalo	30.0	IVA	68 36	27 25
Sodankylä	30.0	SOD	67 25	26 24
Rovaniemi	32.4	ROV	66 34	26 01
Jyväskylä	32.4	JYV	62 24	25 22
Abisko	30.0	ABI	68 24	18 54
Siglufjördur	30.0	SIG	66 12	18 54

3. The substorm events

3.1. 6 October 1994

On 6 October 1994 the planetary K_p index between 12 and 24 UT had values 4, 4, 3 and 4. A smooth absorption bay preceded the onset between 1820 and 1840 UT. The first sharp onset was observed at Kilpisjärvi at 2047 UT and the preceding bay between 1950 and 2046 UT. The second sharp onset occurred at 2128 UT. The first sharp onset was also seen at Ivalo, at 2047 UT, but not at Sodankylä or Rovaniemi. The second sharp onset occurred first at Kilpisjärvi and later south of it.

Figure 2a presents the images for the whole antenna area, during the pre-onset phase with 1 minute time resolution for 2000-2100 UT and during the sharp onset with 1 second time resolution for 2046:37-2047:36 UT, Figure 2b. During the pre-onset phase the images show arc-like features, small-scale structure inside the arc and southward movement of the precipitation region. The velocity of the southward movement was about 4 km/min. The pre-onset absorption almost disappears before the onset. During the onset a movement to the north and west can be seen, and there are very localised structures of the precipitation region.

The Figure 3a presents absorption images for column 1 comprising the beams 1, 8, 15, 22, 29, 36 and 43 and covering at the height of 90 km an area of 200 km in north-south direction and 30 km in east-west direction. The time interval is 2000-2100 UT, the maximum absorption is 1.2 dB and the time resolution 1 minute. The southward movement is clearly seen during the preceding phase. The absorption area in north-south direction during the pre-onset phase is about 90 km, and small-scale structure can be seen inside the absorption area. Intensifications of absorption are apparent.

The Figure 3b shows the absorption images during the first onset for column 3 comprising the beams 3, 10, 17, 24, 31, 38 and 45 for 2046:00-2051:00 UT, with 1 second time resolution with the maximum absorption of 6 dB. A rapid northward movement can be observed with a velocity of 1.5 km/s. The precipitation is pulse like, with periods of 2 to 80 seconds and covering an area of 30 km in north-south direction. A detailled study of data shown in Figure 2b reveals that intensifications in absorption can be seen in almost every beam with periods varying from 2 to 9 seconds and from 30 to 70 seconds. Intensifications are not seen in beams 1, 7, 43, 44, 45 and 49. The periods of 2 to 9 seconds are seen, for example, in beams 10, 11 and 23.

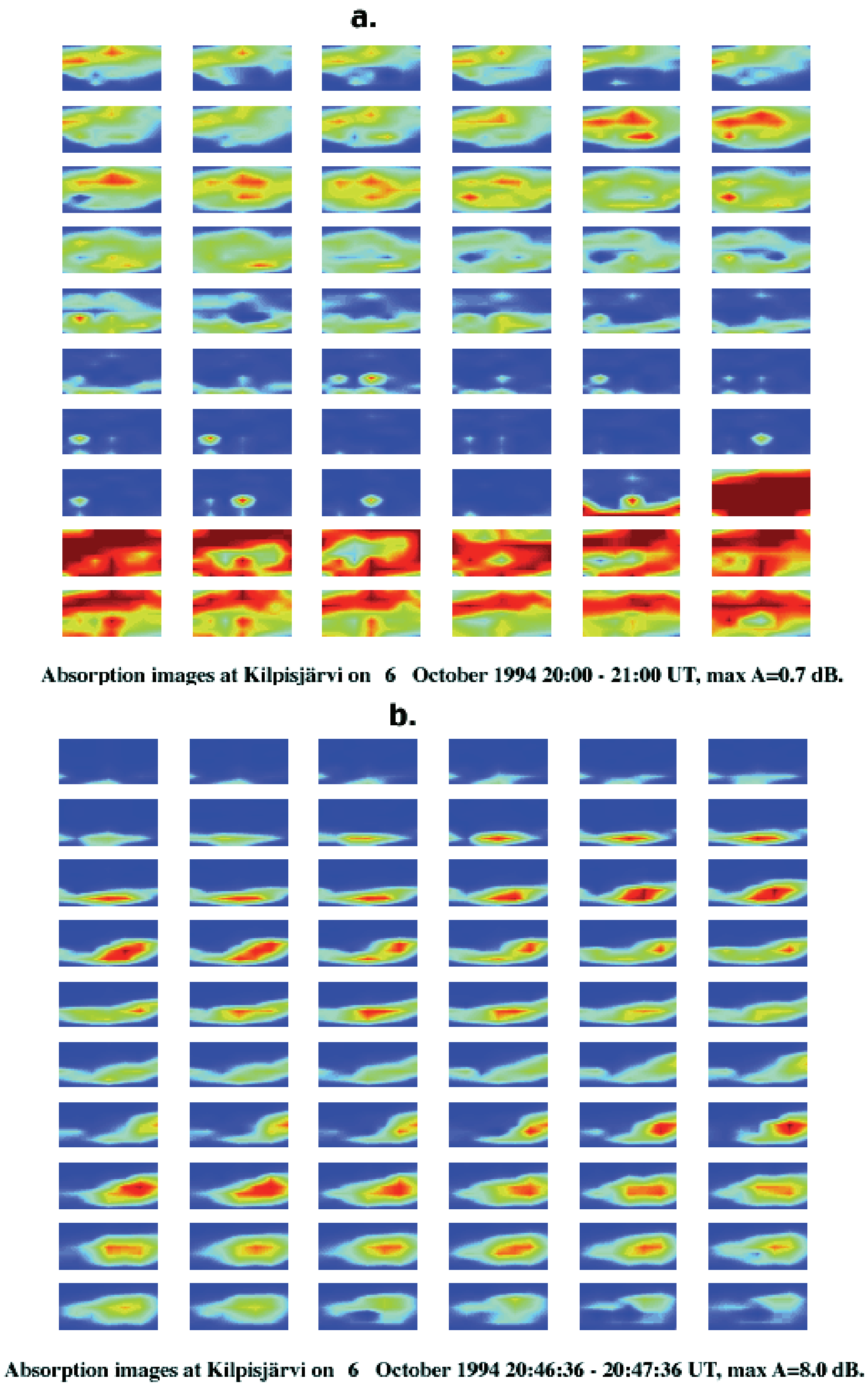


Fig. 2. a) Absorption images at Kilpisjärvi for the whole antenna area on 6 October 1994 in the interval 2000-2100 UT. The images were recorded every 60 seconds and the upper limit of the absorption scale is 0.7 dB. b). Absorption images at Kilpisjärvi for the whole antenna area on 6 October 1994 between 2046:37 and 2047:36 UT. The upper limit of the absorption scale is 8.0 dB.

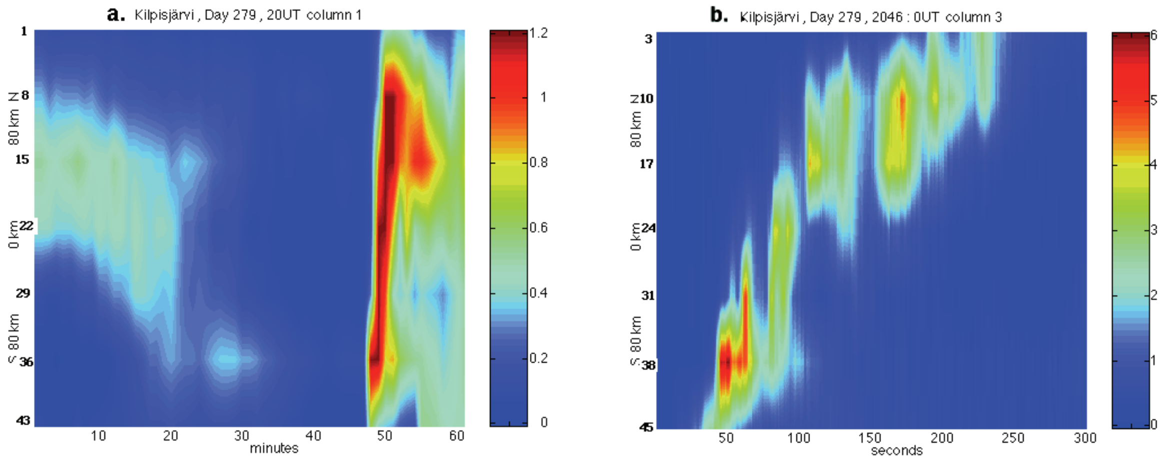


Fig. 3. a) Absorption images at Kilpisjärvi for column 1 (beams 1, 8, 15, 22, 29, 36 and 43) in north-south direction on 6 October 1994 in the interval 2000-2100 UT. The upper limit of the absorption scale is 1.2 dB. b). Absorption images at Kilpisjärvi for column 3 (beams 3, 10, 17, 24, 31, 38 and 45) in the north-south direction on 6 October 1994 in the interval 2046:00-2051:00 UT. The upper limit of the absorption scale is 6.0 dB.

Because the precipitation pattern has small scale size and its position changes in time in the antenna matrix, 10 s averages of maximum absorption observed by the antenna matrix were determined to compare absorption with local magnetic variations, Figure 4a. The absorption data was detrended by fitting it with 3rd degree polynomial to remove offsets and slow changes. Figure 5a shows power spectral density during the pre-onset phase, Figure 5b during the sharp onset, and Figure 5c during the decay of the event. As seen e.g. from Figure 2 the intensifications are rather irregular in nature, but during pre-onset phase a spectral maximum occurs at 0.6 mHz. During the onset maximum power occurs at higher frequencies, at 6 mHz, 16 mHz and 30 mHz with close to equal amplitudes. During the recovery of the event the spectrum maximizes at 15 mHz.

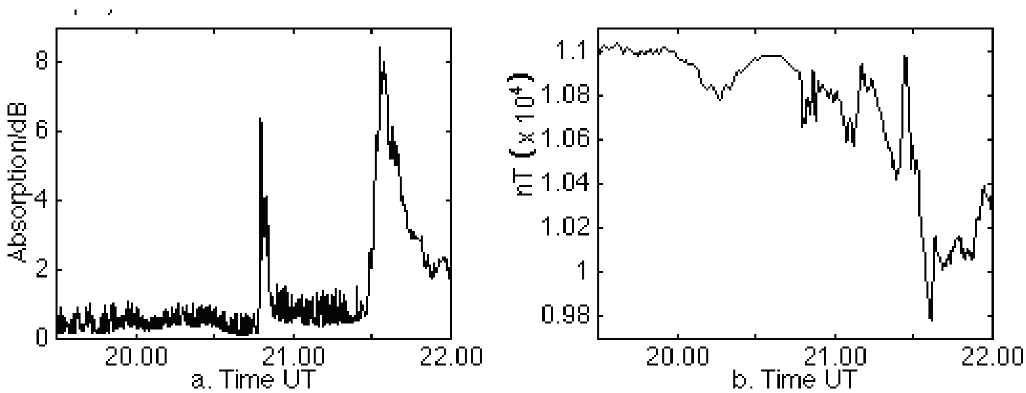


Fig. 4. a). Maximum absorption observed by imaging riometer at Kilpisjärvi on 6.10.1994, 1930-2200 UT. b) Magnetic X component at Kilpisjärvi on 6.10.1994, 1930-2200 UT.

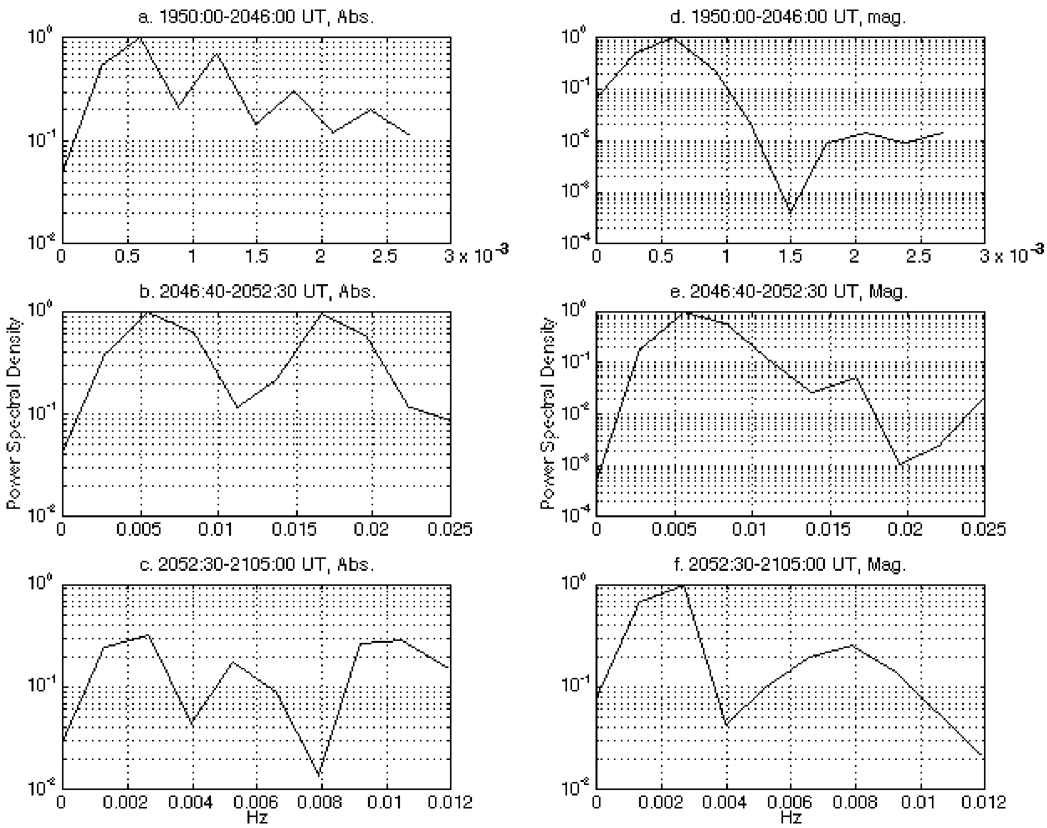


Fig. 5. Absorption and magnetic power spectral densities for the event on 9.10.1994. a) Absorption power spectral density of pre-onset phase b) Absorption power spectral density of onset phase c) Absorption power spectral density of recovery phase d) Magnetic power spectral density of pre-onset phase e) Magnetic power spectral density of onset phase f) Magnetic power spectral density of recovery phase.

Figure 4b shows magnetometer data for the event. The magnetometer data was detrended by dividing it into three parts and fitting them with 2nd degree polynomial to remove offsets and slow changes. The reconstructed data was finally fitted with 3rd degree polynomial. Figure 5d shows spectrum during the preonset phase, Figure 5e during the onset phase and Figure 5f after the onset. During pre-onset phase a maximum in spectrum occurs at 0.6 mHz. During the onset phase the maximum is at 6 mHz, and minor maxima at 16 mHz and at around 30 mHz. During the recovery the power spectrum shows maximum at 2.5 mHz and a second one at 7.5 mHz. For the second onset at 2128 UT the absorption and magnetic spectra have maxima at 2 mHz (Figure 6a, b).

3.2 11 April 1995

On 11 April 1995 between 12 and 24 UT the planetary K_p index obtained values 2, 2, 3 and 3. According to the imaging riometer data the pre-onset phase began to develop after 17 UT and moved to the south, intensifying during the movement. During the southward movement pulsating forms developed in the pre-onset bay. The first onset was seen at Ivalo at 1838 UT, at Sodankylä at 1838 UT and at Rovaniemi at 1838

UT. The second onset occurred at Ivalo at 1849 UT, at Sodankylä at 1851 UT and at Rovaniemi at 1849 UT. Small-scale structure during the onset phase was seen at Ivalo, Kilpisjärvi, Sodankylä and Rovaniemi, where the data were available with an accuracy of 1 or 10 second time resolution.

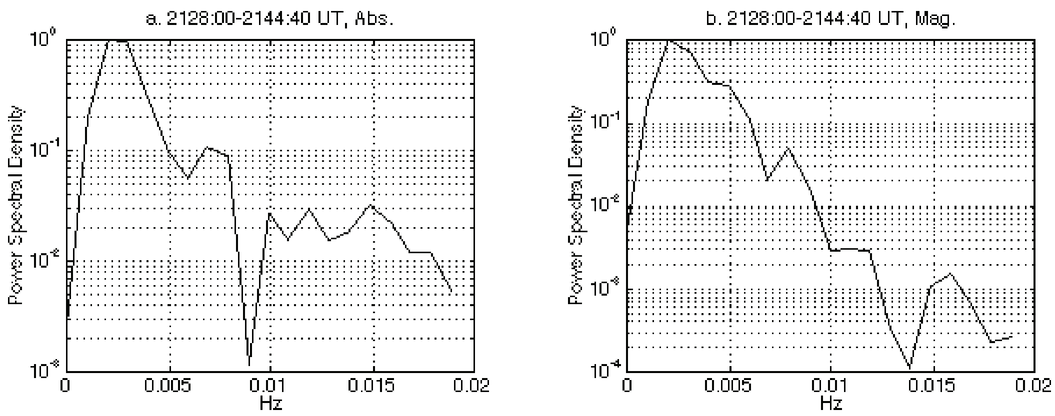


Fig. 6. a) Absorption power spectral density for the event on 6.10.1994, 2128:00-2144:40 UT.
b) Magnetic power spectral density for the event on 6.10.1994, 2128:00-2144:40 UT.

The first sharp onset starts at 1847:43 UT. The absorption, which lasts for 40 seconds, enlarges to the west covering an area of about 100 km in the north-south direction. The second sharp onset starts at 1848:47 UT and lasts for 35 seconds. After 15 seconds a new intensification starts, lasting for 30 seconds. The maximum absorption during the first intensification is 6 dB and during the second one 11 dB. Figure 7a shows 10 s averages of maximum absorption observed by the imaging riometer and Figure 7b the magnetometer X-component.

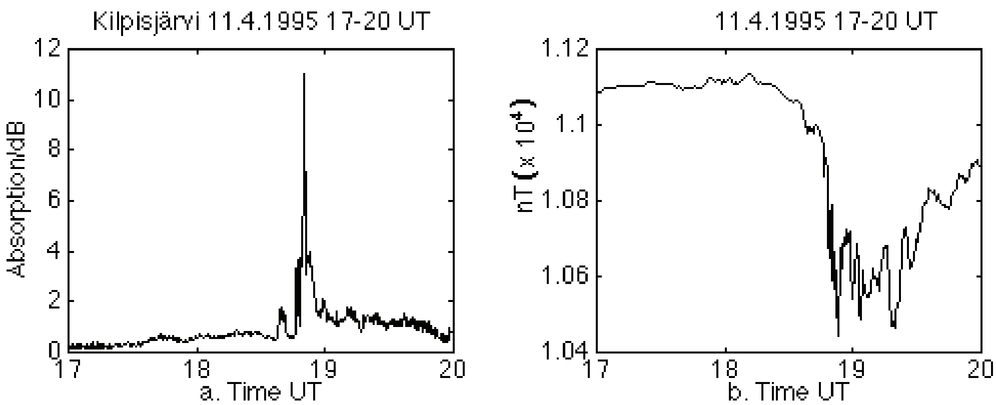


Fig. 7. a). Maximum absorption observed by imaging riometer at Kilpisjärvi on 11.4.1995, 17-20 UT. b) Magnetic X component at Kilpisjärvi on 11.4.1995, 17-20 UT.

The absorption power spectral density for detrended 10 s data during the pre-onset phase is shown in Figure 8a, during the onset Figure 8b and after onset in Figure 8c. During the pre-onset phase maximum spectral peak occurs at frequency range 0.2-1 mHz. During onset the maximum power occurs at 5 mHz and a second maximum occurs at 11 mHz. After the onset the maximum in spectrum is at 0.8 mHz and a second one at about 4 mHz.

Figure 7b shows magnetometer X component for the event. During the pre-onset phase maxima in spectrum are at frequencies 0.4 mHz and 1.8 mHz, Figure 8d. During the onset the main wide maximum occurs at 8 mHz, Figure 8e. During the recovery main maximum occurs at 1 mHz, Figure 8f.

4. Results and discussion

1. A pre-onset phase, lasting from half an hour to one hour, was observed before the sharp, spike-like onset. During the pre-onset phase the absorption moved to the south at 1.7-12 km/min intensifying during the movement. The absorption bay was arc-like and structured. Pulsating forms with periods of 2-18 minutes developed during the movement. The pre-onset absorption disappeared in the northern latitudes of the Kilpisjärvi imaging riometer for several tens of minutes before the substorm onset. At the latitude, where the substorm broke up, it disappeared for about 1 minute whereas in the most southern beams it did not disappear at all.
2. The sharp, spike-like onset lasted from 1 to 3 minutes. Absorption during the spike sometimes was as strong as 12 dB. Pulsations in the absorption with periods of 2 to 90 seconds were seen only at a very localized span of latitudes. The onset moved to the south or to the north with velocities between 0.33 and 2.7 km/s. The precipitation area was highly localized, only about 20-30 km in north-south direction.
3. In the studied absorption events, during the pre-onset phase most of the spectral power is below 50 mHz which is the upper frequency limit obtained with 0.1 Hz sampling rate, whereas during the onset phase much of it occurs above that frequency. In the studied events, correlation between magnetic and absorption data is poor which is probably due to the nature of observation. Absorption is a measure of local particle precipitation whereas the magnetometer responds to changes in large-scale current systems. However, both the absorption and magnetic spectra show close to similar features indicating that both phenomena are controlled by common factors although the ionospheric responses may be in different phases.

Samson et al. (1992) have indicated from magnetometer and HF radar data the presence of magnetohydrodynamic field line resonance in the nightside magnetosphere during the whole interval of the substorm intensification including times before the onset of the first intensification. They found that these resonances have frequencies of about 1.3, 1.9, 2.6 and 3.4 mHz and are due to cavity modes or wavequide modes which form between the magnetopause and turning points on dipolelike magnetic shells outside the plasmasphere. Energy from these cavity modes tunnels to the field line resonance which are seen in the F-region by the HF radar and on the ground by the magnetometers. The 3.4 mHz cavity mode has a turning point just outside the plasmasphere, at approximately 5 Re and is the highest-order harmonic that should normally be observed. The pulsations in the magnetic and radar data were accompanied by oscillations in the 630 nm emissions. These oscillations were first seen during the growth phase. *Morse and Romick* (1982) have also reported fluctuations in the 557.7 nm emission from auroral arcs prior to auroral substorm onsets. The oscillations exhibited a variety of periods, but periods of about 10 minutes were common. The fluctuations typically started 20 minutes or so before the substorm. A number of intervals were identified in which substorm intensifications occurred when field line resonances existed in the region of the magnetosphere where the intensification occurred. In the events in question the ionospheric signatures of the substorm intensification began equatorward (earthward) of the existing field line resonances. These observations were interpreted as indicating that at least one component of the substorm mechanism must be active close to the Earth, probably on dipole-like field lines in regions with trapped and quasi-trapped energetic particles.

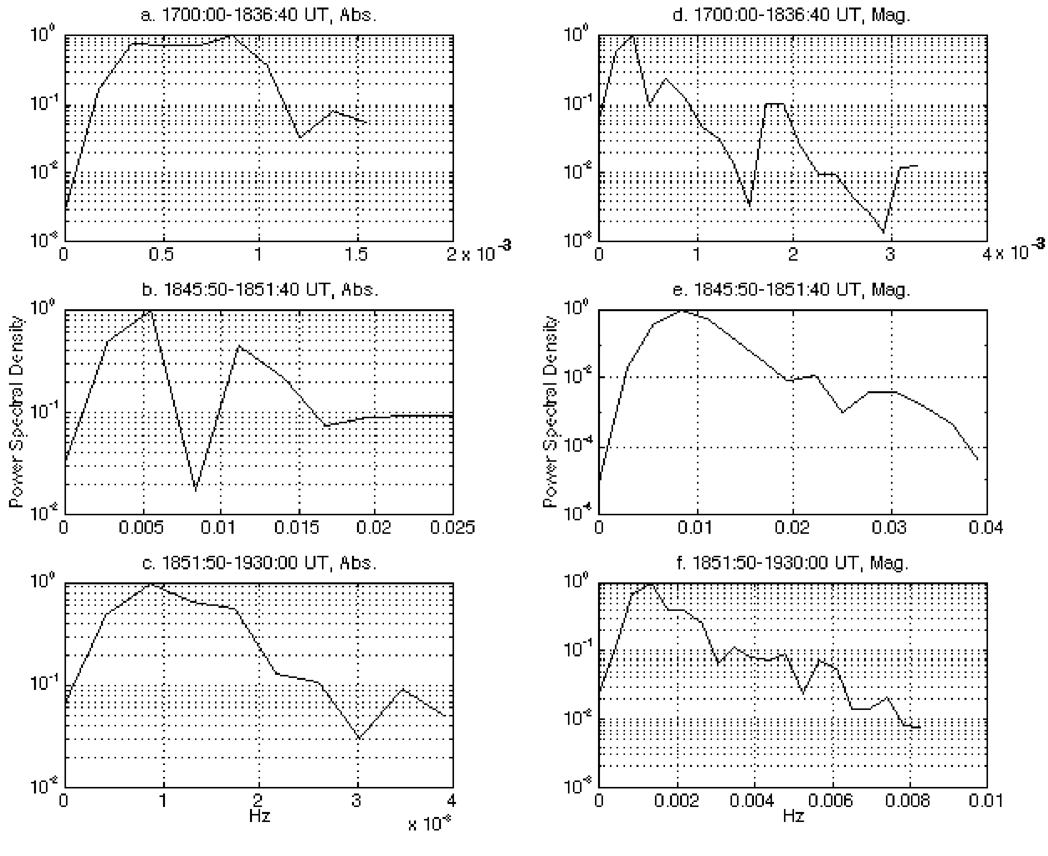


Fig. 8. Absorption and magnetic power spectral densities for the event on 11.4.1995. a) Absorption power spectral density of pre-onset phase b) Absorption power spectral density of onset phase c) Absorption power spectral density of recovery phase d) Magnetic power spectral density of pre-onset phase e) Magnetic power spectral density of onset phase f) Magnetic power spectral density of recovery phase.

Holter et al. (1995) investigated the electric and magnetic signatures of a substorm characterized by a dispersionless injection of energetic electrons and ions using GEOS 2 satellite data. They found both long-period and short-period oscillations. They interpreted long-period oscillations with period of 300 seconds as oscillations of entire field lines. Short-period transient oscillations with periods of 45-65 seconds they interpreted as wave modes trapped in a current layer which develops prior to the substorm breakup and is disrupted at breakup.

The results obtained in this study support the models suggesting that processes associated with onset can be found in some cases on the closed field lines. The precipitation during the pre-onset phase probably starts first in the area of the central plasma sheet and then with increased compression moves to lower latitudes. With increasing compression, pulsations in precipitation begin to develop with periods of 2-18 minutes, which are attributed to a signature of magnetohydrodynamic field line resonances. During the intensification of the substorm fast northward or southward movements were observed with localized pulsations having periods of 2 to 90 seconds. The localized features and short periods in pulsations suggest that in some cases local mechanisms may play an important role in substorm intensification. In cases where the onset was not spike-like, the periods of the pulsations were observed to be between 1 and 12 minutes (*Ranta and Yamagishi*, 1997) which correspond the periods observed in other studies.

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