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Evidence for subauroral proton flashes on the dayside as the result of the ion cyclotron interaction

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[1] A series of proton aurora flashes produced by the precipitation of energetic protons equatorward of the main auroral oval was observed between 0700 and 1300 UT on 31 May 2005 on the dayside with the Imager for Magnetopause-to-Auroral Global Exploration (IMAGE) Far Ultraviolet (FUV) imager. At the same time multiple bursts of geomagnetic pulsations within the Pc1 range known as "hydromagnetic emission bursts" were observed on several ground stations located in the conjugate MLT sector. The pulsation bursts are well correlated with the appearance of the proton aurora conjugated with the ground stations. The frequency width of the pulsation burst correlates and the upper frequency anticorrelates, respectively, with the latitudinal width and lowest latitude of the proton aurora at the meridian of the ground station. Observations at the meridional network of pulsation magnetometers show that the maximum pulsation spectral density is detected at stations conjugated with proton flashes. The close relationship between pulsations and proton precipitation (aurora) indicates their common source. We conclude that the source is the cyclotron instability of the ring current ions that is stimulated by impulsive magnetospheric compressions. The magnetosphere compressions are, indeed, confirmed by plasma data from the Geotail spacecraft in the duskside magnetosheath. They show a series of plasma pressure pulses during the time interval of interest. Also standard midlatitude magnetograms indicate large-scale magnetospheric compressions.

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1. Introduction

[2] Observations from the Imager for Magnetopause-to-Auroral Global Exploration (IMAGE) spacecraft revealed many new features of the auroral display [*Frey*, 2007]. Among others, several types of proton aurora were detected equatorward of the nominal proton aurora oval: proton aurora spots [*Frey et al.*, 2004], proton arcs [*Immel et al.*, 2002], and proton aurora flashes [*Hubert et al.*, 2003]. These subauroral structures are produced by the precipitation of energetic protons. As the mechanism for the proton precipitation, the scattering of ring current/plasma sheet ions into the loss cone due to interaction with ion cyclotron waves is often suggested. For some types of the proton auroras this mechanism was recently confirmed by observations of signatures of the electromagnetic ion cyclotron (EMIC) waves as subauroral proton spots exhibit a nice correlation with quasi-monochromatic Pc1 pulsations observed on the ground [*Yahnin et al.*, 2007]. Some further evidence was presented for a relationship between subauroral proton arcs and EMIC waves in space [*Fraser et al.*, 2005] and Pc1 pulsations on the ground [*Sakaguchi et al.*, 2007].

[3] Subauroral proton flashes last for ~10 min; they are observed on the dayside and are closely related to enhancements of the solar wind dynamic pressure, that is, magnetospheric compressions [*Hubert et al.*, 2003; *Zhang et al.*, 2002; *Fuselier et al.*, 2004]. Using data from geosynchronous spacecraft, *Fuselier et al.* [2004] analyzed magnetospheric plasma properties within the region where the proton aurora flashes map to. They concluded that during magnetospheric compressions the plasma parameters change in the direction of increasing the cyclotron instability increment. However, direct signatures of the EMIC waves were not reported yet in relation to proton aurora flashes, except in a very recent paper by *Zhang et al.* [2008] who observed EMIC waves onboard the Polar spacecraft in the region conjugated with the auroral flash.

[4] *Fukunishi et al.* [1981] introduced the term "hydromagnetic (HM) emission bursts" to describe a specific type of geomagnetic pulsations in the Pc1 range. The total duration of this type of pulsations during a 25-months' period was ~200 h [*Fukunishi et al.*, 1981], that is, the probability to observe these emissions was around 1%. This type of pulsations (pulses of ULF waves in the frequency range from tenths to 1–2 Hz with duration of several minutes and irregular repetition intervals of some 10–20 min) closely relates to magnetospheric compressions [e.g., *Anderson et al.*, 1996; *Kangas et al.*, 2001; *Safargaleev et al.*, 2002]. The

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Table 1. List of Ground Stations

Station	Station Abbreviation	Geographic Coordinates		Corrected Geomagnetic Coordinates		L Value
		Latitude	Longitude	Latitude	Longitude	
Kilpisjarvi	KIL	69.0	20.9	65.9	104.2	6.1
Ivalo	IVA	68.6	27.3	65.1	108.9	5.7
Sodankylä	SOD	67.4	26.4	64.0	107.4	5.3
Rovaniemi	ROV	66.8	25.9	63.4	106.6	5.1
Oulu	OUL	65.1	25.9	61.7	105.6	4.5
Nurmijarvi	NUR	60.5	24.6	57.0	102.4	3.4
Lovozero	LOZ	68.0	35.1	64.2	114.5	5.4

HM emission bursts on the ground are observed on the dayside [*Fukunishi et al.*, 1981] as well as their magnetospheric counterpart [*Anderson and Hamilton*, 1993; *Anderson et al.*, 1996]. Thus, the morphology of these pulsations resembles that of the proton flashes, and one may suggest the relationship of these two phenomena.

[5] In this paper we will present direct evidence of a close relationship between proton flashes and HM bursts. This will be done on the basis of observations during an interval of 0700–1300 UT on 31 May 2005.

2. Data

[6] The proton aurora data were provided by the Spectrographic Imager (SI) of the Far Ultraviolet (FUV) instrument on board the IMAGE spacecraft, which was designed to select the Doppler shifted Lyman H-alpha line at 121.82 nm in the ultraviolet part of the optical spectrum and to reject the non-Doppler shifted Lyman H-alpha from the geocorona at 121.567 nm (see *Mende et al.* [2000] for details).

[7] The ground observations of geomagnetic pulsations were performed by the search coil magnetometer of the Polar Geophysical Institute at the geomagnetic observatory Lovozero (CGLat = 64.2°, MLT = UT + 3) and by the Finnish network of search coil magnetometers located at CGLat = 57.0°–65.9°, MLT = UT + 2. The list of ground stations registering the magnetic pulsations is presented in Table 1.

[8] The instrument in Lovozero has a low-frequency cutoff at 0.05 Hz and a plateau-like amplitude response from 0.1 Hz up to tens of Hz. The transformation factor of the instrument is 240 mV/nT at frequencies above 0.1 Hz and the sensitivity threshold is <0.1 pT/Hz$^{1/2}$ at 0.1 Hz. The magnetometers of the Finnish chain have over the same frequency range a linear frequency response of 1.4 V/(nT*Hz) with an instrumental noise figure of ~1 pT/Hz$^{1/2}$ at 1 Hz. The magnetometers of the Finnish network are identical and intercalibrated, so they can be used for comparison of intensity of the pulsations at stations along the meridian.

[9] During the interval of interest the Geotail spacecraft left the magnetosphere and probed the magnetosheath plasma. Definitive moments from CPI Solar Wind Analyzer on board the Geotail spacecraft [*Frank et al.*, 1994] were used in this study. The data with 1 min resolution were taken from CDAWeb (http://cdaweb.gsfc.nasa.gov/). The INTERMAGNET data were used to monitor the magnetic variations at middle latitudes. Finally, NOAA POES data of the particle flux at altitude ~800 km were used to determine the particle parameters responsible for the proton aurora flashes.

3. Observations

[10] A series of proton flashes were observed within the interval under study. Figure 1 presents some examples of these flashes observed by IMAGE in the southern hemisphere. The flashes are similar to those described by *Hubert et al.* [2003], *Zhang et al.* [2002], and *Fuselier et al.* [2004]. They are located on the dayside, equatorward of the main auroral oval. The flashes have a lifetime of 5–15 min. Their maximal size reaches up to 10° in latitude and up to 5 h of MLT. The data from several passes of NOAA POES satellites are available in the dayside. In agreement with earlier studies [*Zhang et al.*, 2002] the precipitation of energetic (E > 10 keV) protons is observed by these NOAA satellites above the proton flashes (not shown).

[11] Projections of the northern ground stations observing geomagnetic pulsations onto the southern ionosphere are shown in Figure 1 by white asterisks. The interhemispheric mapping was done using the IGRF-10 model. During the interval under study a sequence of HM emission bursts, with temporal behavior resembling that of the proton auroral flashes was detected with the ground search coil magnetometers (Figure 2a).

[12] Let us compare the development of the flashes and pulsation bursts. Note that IMAGE provides auroral displays with ~2 min cadence. For the timing of geomagnetic pulsations we used spectrograms with much higher resolution than in Figure 2 (not shown).

[13] The flash presented in Figure 1 (top) started to develop at 0811–0813 UT. This happened some 1 h of MLT eastward of the ground station Lovozero. Only very weak pulsations can be distinguished at this time on the high time resolution spectrogram. The sharp increase of the pulsation intensity was detected around 0818 UT when the western edge of the region of the proton aurora appeared at a distance of about 0.5 h of MLT from the ground station. During the next flash event, which started at 0824–0826 UT, again out of the Lovozero meridian, the strong pulsations were detected around 0830 UT when proton auroras appeared close to the ground station. Timing of the flash event that started at 1012–1014 UT at the meridian of Lovozero showed that strong pulsations started at ~1013 UT, that is, simultaneously with the flash onset within the time resolution of auroral images. Every pulsation burst stopped when the proton aurora flash disappeared.

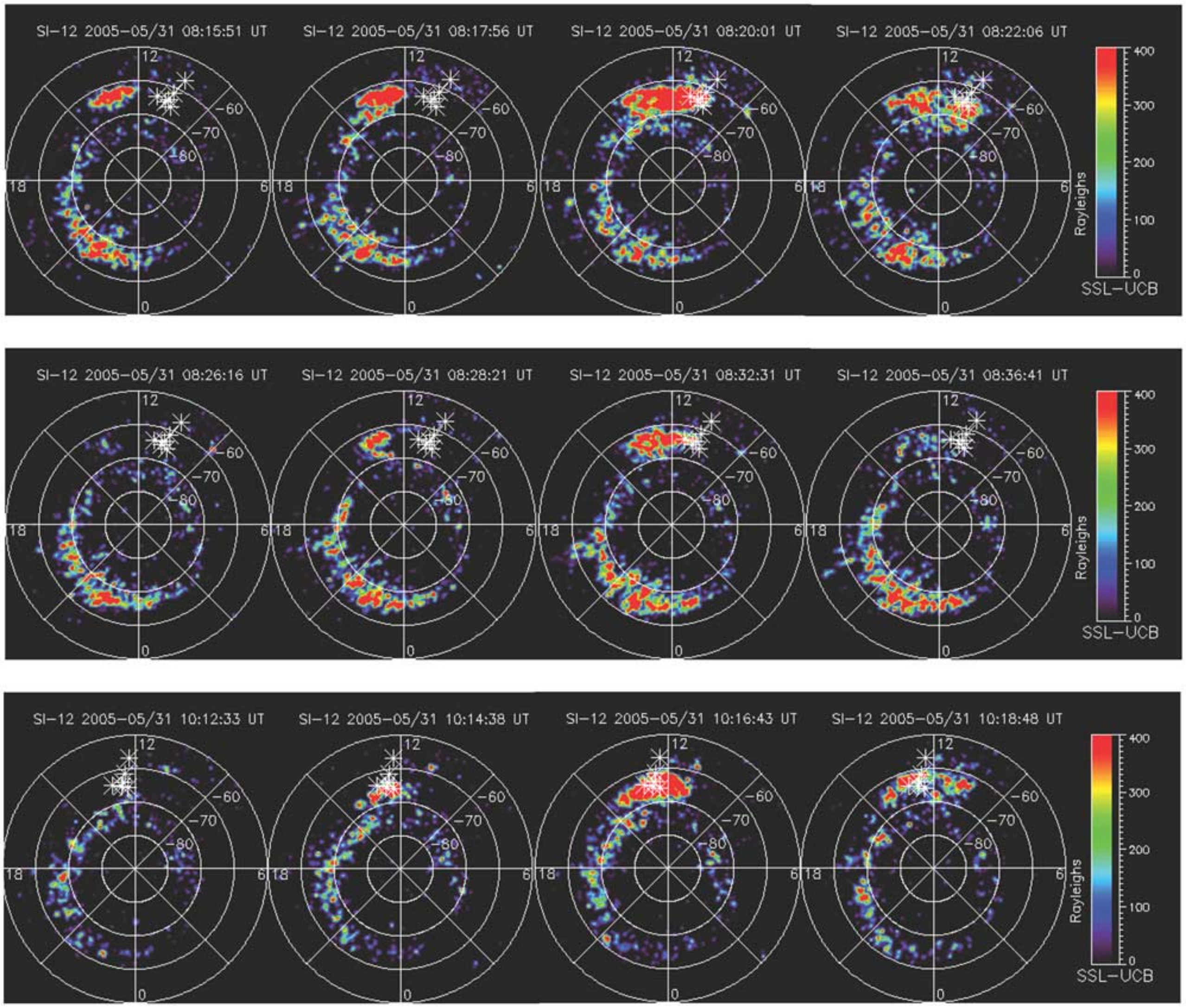

Figure 1. Examples of the proton flashes observed on 31 May 2005 by the FUV instrument onboard the Imager for Magnetopause-to-Auroral Global Exploration (IMAGE) spacecraft. White asterisks mark conjugate locations of the ground search coil magnetometers.

[14] Figures 2b and 2c show the variation of the proton aurora intensity above the conjugate location to Lovozero. Every enhancement of the aurora intensity is associated with a pulsation burst. The frequency range of geomagnetic pulsations significantly varies (especially, the upper cutoff). The upper frequency of the Pc1 bursts is anticorrelated with the lower latitude of the proton aurora at the meridian of Lovozero (Figure 2d). The lower is the latitude of the equatorward boundary of the proton aurora the higher is the upper frequency of the corresponding Pc1 burst.

[15] Similar pulsations were also observed at stations of the Finnish meridional magnetometer network. This allows us to compare the spectra and intensity of the pulsation at different locations along their meridian. Some spectra at stations of the network for selected time intervals are presented in Figure 3. The power spectra were obtained by averaging over 10 nonredundant 512-point FFT realizations resulting in a power spectral density time average of 2 min. The times given are in the center of the time average interval.

[16] As noted before, during the proton aurora flash that started at 0811–0813 UT the aurora first developed eastward of the ground stations (Figure 1). It appeared conjugated with the Finish network meridian at 0818–0820 UT at the time of onset of the pulsation bursts. The maximal intensity of pulsations was observed at stations IVA, SOD, and ROV. The low and high frequencies corresponding to the half-width of the pulsation spectrum were 0.9 and 1.4 Hz. Further in time, at the meridian of the network the proton aurora propagated poleward, and this propagation was accompanied by the expansion of the pulsation spectra to lower frequencies. By ~0821 UT the low frequency of the half-width decreased from 0.9 to 0.6 Hz. The maximal intensity was detected at the low frequency part of the spectrum at the stations situated in the poleward part of the network (KIL, IVA), right under the bright proton auroras.

[17] At ~1015 UT, when the proton aurora flash occupied latitudes of 65°–68°C GLat, the pulsations have maximum intensity at stations located in the poleward part of the

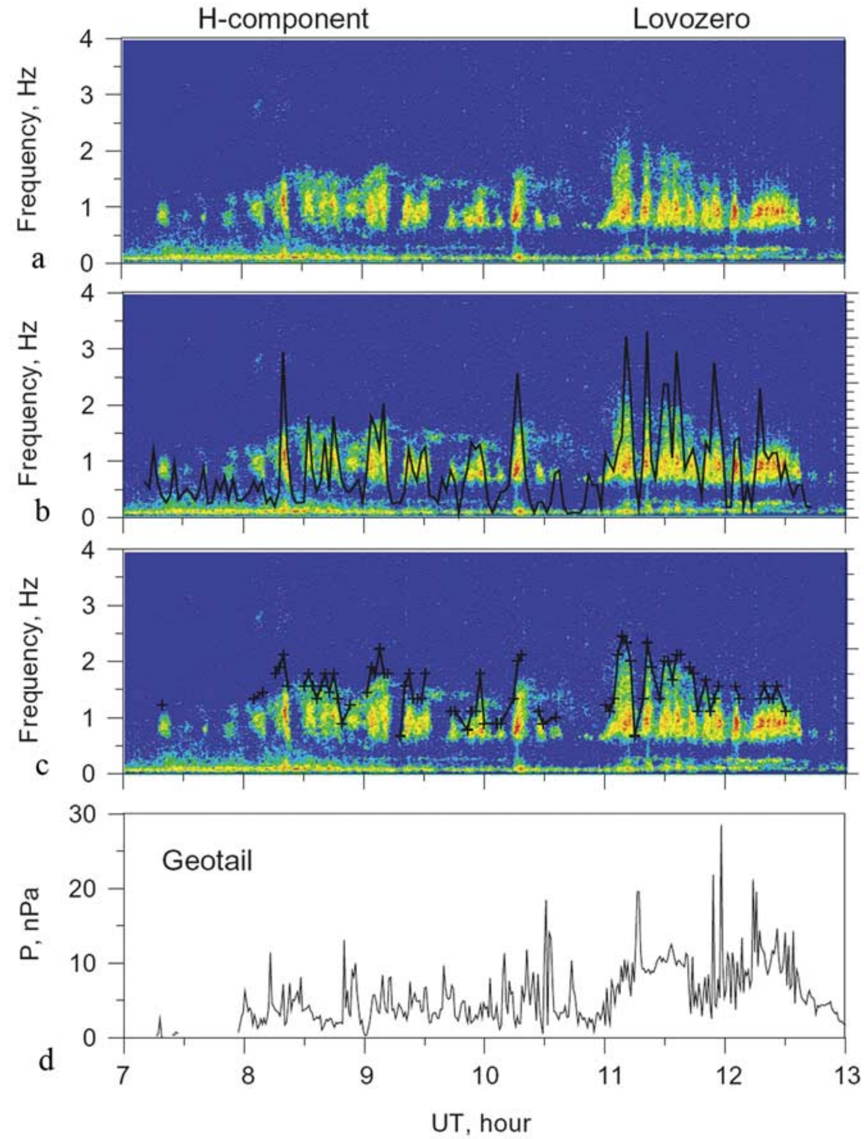

Figure 2. (a) Spectrogram of geomagnetic pulsations in the range 0.1–4 Hz obtained on 31 May 2005 at Lovozero showing a sequence of HM emission bursts; (b) the same spectrogram combined with the graph showing the variation of the proton aurora intensity (black line) above the Lovozero conjugate location; (c) the same spectrogram combined with the graph showing the variation of the low-latitude boundary of the proton aurora (black line with crosses) at the meridian of Lovozero; (d) plasma pressure variations in the dusk side magnetosheath as measured by the Geotail spacecraft.

network (KIL, IVA, SOD). The low and high frequencies at the half-width were 0.7 and 1.3 Hz, respectively. During the development of this flash the proton aurora shifted to low latitudes (Figure 1). Simultaneously, the upper frequency increased and at 1017 UT it was equal to 1.6 Hz. The relative change of the pulsation intensity at higher frequencies was different at different stations. At 1017 UT the maximal intensity at higher frequencies was observed at stations SOD, ROV, OUL, that is, in the middle part of the network, and a less pronounced increase of intensity was observed at high latitudinal stations KIL and IVA (these stations are located close to the poleward edge of the proton aurora display) as well as at the most equatorial station NUR (it was out of the proton aurora region).

[18] Until 0715 UT the Geotail spacecraft was in the magnetosphere close to the afternoon magnetopause. A brief entry into the magnetosheath at ~0715 UT indicates the inward and outward motion of the magnetopause, which confirms the possibility of the magnetospheric compression at this time. A weak proton flash was observed at 0717 UT (not shown). At ~0800 UT Geotail entered the duskside magnetosheath and measured multiple enhancements of the dynamics pressure (Figure 2d). Some of the pressure pulses correlate with ground and ionospheric signatures (auroral flashes and HM emission bursts), but some do not (perhaps due to the spacecraft location away from the noon sector). Anyway, the data from the magnetosheath show that the magnetosphere experienced multiple compressions during the interval under study.

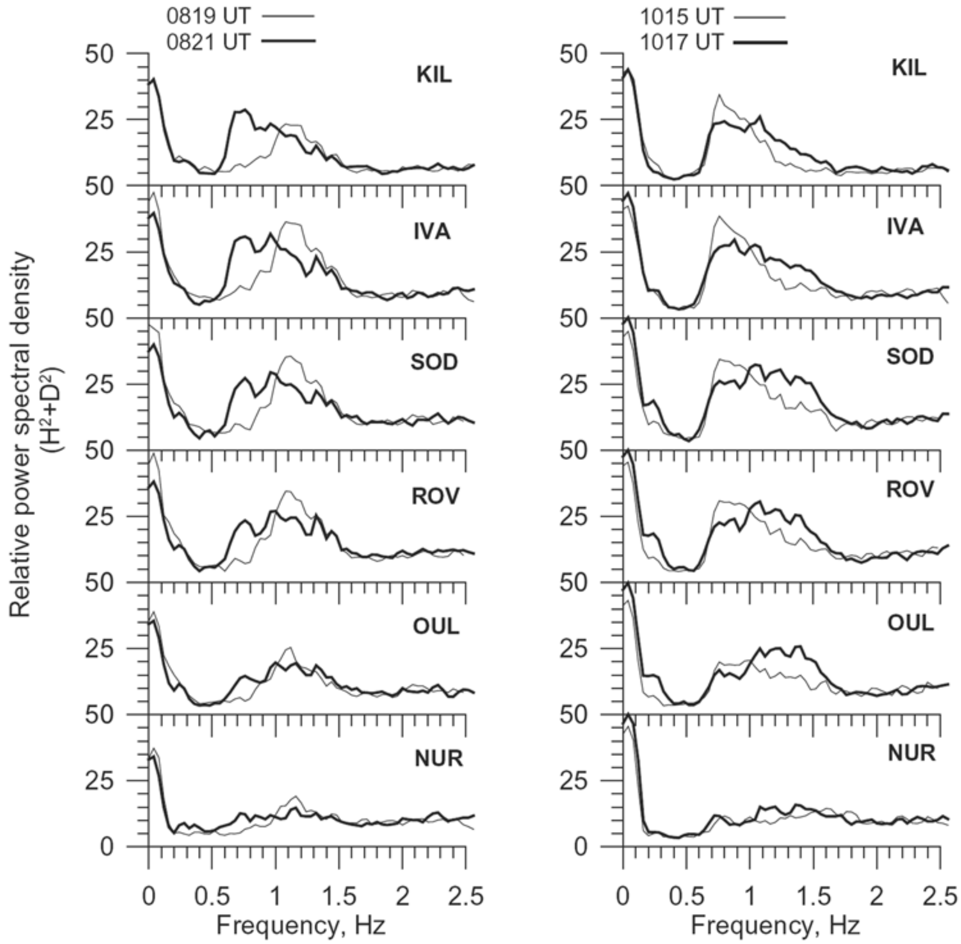

Figure 3. Power spectra of two individual HM bursts (cf. Figure 2) as observed at the Finnish meridional chain of stations. For each burst two consecutive time intervals were selected to demonstrate the intensity changes as a function of latitude (cf. Table 1) during the temporal evolution of the bursts. For details see text.

[19] The multiple compressions are also confirmed by data of INTERMAGNET midlatitude stations. This becomes evident in Figure 4 where magnetograms from the stations Lviv, Alma Ata, Irkutsk, and Memambetsu are shown, spanning almost 8 h of MLT. During the interval under study these stations scanned the day-late-evening MLT sector. The sharp increases in the X component of the magnetic field are nearly coherent at all four stations (signature of the magnetosphere compressions) and coincide in time with HM emission bursts shown in Figure 2.

[20] A survey of conjugated IMAGE FUV and ground-based pulsation observations revealed several intervals similar to the one described above. Our interval was selected because it represents the longest series of proton flashes. The other intervals demonstrated equally convincing a close relationship between subauroral proton aurora flashes and HM emission bursts.

4. Summary

[21] We found a nice correlation between the proton aurora flashes and ground HM emission bursts. The pulsation burst appears right at the time of the appearance of the proton aurora above (near to) the location conjugated with the ground station observing the pulsations. The cessation of the pulsations is associated with the disappearance of the auroras.

[22] The frequency spectrum of the HM emission burst and distribution of its intensity along the meridian is related to the latitudinal location of the proton aurora. Poleward (equatorward) expansion of the auroras associates with the spreading or shift of the spectrum toward low (high) frequencies, which is more pronounced at stations located at higher (lower) latitudes. The intensity of the pulsations along the meridian is higher in the region occupied by the proton auroras.

[23] Multiple pulses of the plasma pressure are observed in the magnetosheath suggesting multiple compressions of the magnetosphere during the flash/pulsation burst observations. The global nature of the compressions is confirmed by ground-based midlatitude magnetic observations.

5. Discussion and Conclusion

[24] *Anderson and Hamilton* [1993] analyzed the hot proton pitch angle distribution measurements from AMPTE/CCE

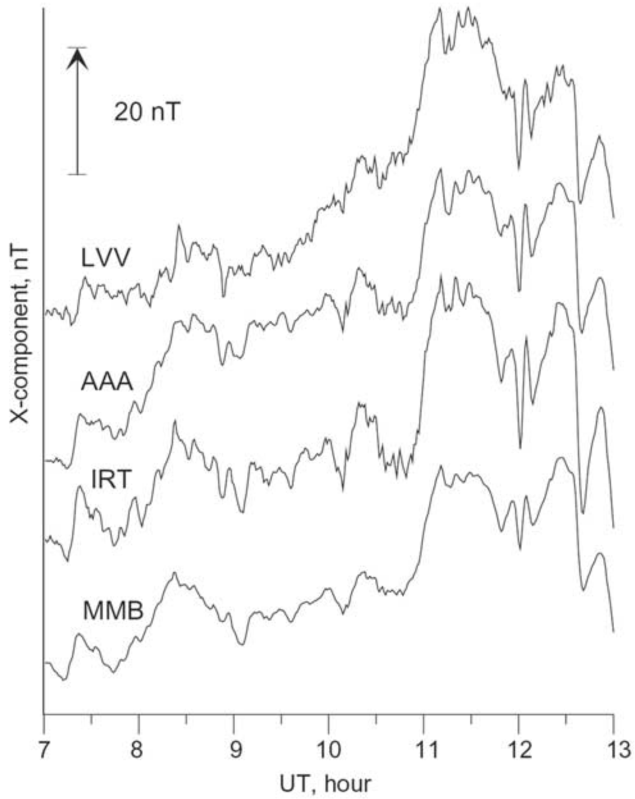

Figure 4. Magnetograms (X component) from four widely spaced midlatitude stations for the interval 0700–1300 UT of 31 May 2005.

during compressions and concluded that the compressions increase the EMIC wave growth rate in the equatorial magnetosphere. *Anderson et al.* [1996] found almost a one-to-one correspondence of the sequence of the compression induced EMIC waves in the dayside outer magnetosphere with that of HM emission bursts on the ground.

[25] Scattering of energetic protons is a necessary element of the ion cyclotron interaction, so the observations of the dayside subauroral proton flashes during the compressions do support the conclusion of compression-induced ion cyclotron instability. Analyzing plasma parameters on the basis of data from geosynchronous satellites in the region where the proton flashes map to, *Fuselier et al.* [2004] also came to the conclusion that the magnetospheric compression leads to an increase of the increment of the EMIC wave generation. However, until now there were no direct observations (except the only event described by *Zhang et al.* [2008]) confirming the development of the cyclotron instability in the subauroral proton flash region.

[26] Such observations are presented in our Figure 2. The observations provide two kinds of evidence for the ion cyclotron mechanism. First, there is an unambiguous temporal and spatial correlation between flashes and pulsations bursts. Second, the dependence of the upper frequency cutoff on the latitude of the equatorward boundary of the proton luminosity, directly relates to the dependence of the EMIC wave frequency on the magnetic field strength in the source region.

[27] It is worth noting that a nice temporal-spatial correlation between the two phenomena observed in different hemispheres means their interhemispheric conjugacy, which is a clear consequence of the common mechanism operating in the equatorial magnetosphere.

[28] Since the particles precipitate along magnetic field lines, the proton aurora marks the field lines linked to the magnetospheric region where the instability develops. As to geomagnetic pulsations, they are also suggested to be able to propagate from the ionospheric footprint of the magnetospheric source to the observing point in the ionospheric waveguide. Our observations show that, at least for pulsations in the considered Pc1 range, the wave attenuates significantly. The detectable intensity of pulsations is observed only when the source (proton auroras) appears in close vicinity of the observing point. Although this conclusion is qualitative, it agrees with measurements of the ULF wave attenuation in the high-latitude ionospheric waveguide performed by *Neudegg et al.* [2000]. Thus, the ground observations of the HM emissions mean the closeness of the source footprint.

[29] On the basis of comparison of the HM emission bursts onboard AMPTE/CCE and on the ground, *Anderson et al.* [1996] concluded that the source of the emissions may extend 1–2 h of MLT in azimuth. For the event considered by *Anderson et al.* [1996] this extent was, evidently, a lower limit. The observations of the subauroral proton flashes show that, indeed, the source region can be large. Numerous examples presented by *Hubert et al.* [2003], *Zhang et al.* [2002, 2008], *Fuselier et al.* [2004] and here are as large as 4–6 h in azimuth and 10 degree in latitude (few R_E in the equatorial plane).

[30] Our simultaneous observations of the HM emissions bursts and subauroral proton flashes provide the clear evidence for the ion cyclotron interaction as the mechanism of the proton precipitation responsible for this type of proton auroras. This, in particular, means that observations of the subauroral proton flashes can be used for visualization of the region in the magnetosphere where the magnetosphere compressions produce the conditions for the cyclotron instability development.

[31] **Acknowledgments.** Data from the Finnish pulsation magnetometer chain were kindly provided by the Sodankylä Geophysical Observatory. Data from Geotail CPI-SWA (PI is L. Frank) were obtained through the CDAWeb system (http://cdaweb.gsfc.nasa.gov/). NOAA POES data were provided by NOAA. Magnetometer data were obtained via INTERMAGNET (http://www.intermagnet.org/). The stations which data are used in this paper were operated by the Japan Meteorological Agency, Institute of Solar-Terrestrial Physics of Siberian Branch of the Russian Academy of Sciences, Institute of the Ionosphere of Republic Kazakhstan, and Institute of Geophysics of the National Academy of Sciences of Ukraine. The study of T.A.Y. and A.G.Y. is performed in frames of the basic research program 16/3 "Solar activity and processes in the Sun-Earth system" of the Presidium of the Russian Academy of Sciences (RAS) and program 16 "Plasma processes in the solar system" of the Division of Physical Sciences of RAS. A.G.Y. appreciated an exchange visit to the University of Oulu in June 2007, financed by the Academy of Finland, which is herewith greatly acknowledged. The work of HUF was supported by NASA under the award NNG05GF24G.

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