JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 112, A10223, doi:10.1029/2007JA012501, 2007

Subauroral proton spots visualize the Pc1 source

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Received 27 April 2007; revised 24 July 2007; accepted 7 August 2007; published 30 October 2007.

[1] Recent observations from the IMAGE spacecraft revealed a new type of proton aurora – subauroral proton spots, which map onto the vicinity of the plasmapause. It has been suggested that this proton aurora is produced by energetic proton precipitation after the interaction of ring current particles with electromagnetic ion cyclotron (EMIC) waves in the equatorial plane of the magnetosphere. We prove this suggestion by comparing observations from IMAGE with geomagnetic pulsations Pc1, which are a ground signature of EMIC waves. We found that when the proton spot is nearly conjugated with the ground station equipped with a pulsation magnetometer, the station always observes Pc1. Moreover, there is a good agreement between the appearance/disappearance of the spot and the beginning/end of the Pc1 train. We conclude that the subauroral proton spots are images on the ionospheric ‘‘screen’’ of magnetospheric regions where the ion cyclotron instability develops leading to an intense scattering of energetic protons into the loss cone.

Citation: Yahnin, A. G., T. A. Yahnina, and H. U. Frey (2007), Subauroral proton spots visualize the Pc1 source, *J. Geophys. Res.*, *112*, A10223, doi:10.1029/2007JA012501.

1. Introduction

[2] Observations from the IMAGE spacecraft revealed several types of the proton aurora (the luminosity produced by precipitation of magnetospheric protons after charge exchange with atmospheric constituents). Besides the main proton auroral oval, which is, most probably, due to pitch angle scattering of plasma sheet and outer radiation belt protons in the region of non-adiabatic movement [e.g., *Sergeev et al.*, 1983], some subauroral proton auroras can be also observed, which originate from quasi-dipole magnetic field lines [*Frey*, 2007]. These are detached subauroral proton arcs [*Burch et al.*, 2002; *Immel et al.*, 2002], proton aurora flashes [*Hubert et al.*, 2003; *Fuselier et al.*, 2004; *Zhang et al.*, 2003], and subauroral proton spots [*Frey et al.*, 2004]. As shown by comparison with data from low-orbiting satellites (FAST and DMSP, which measured precipitating particles with energy up to 30 keV), the above mentioned types of proton auroras are produced by precipitations of energetic protons. The mean energy of the protons has been estimated as large as >10 keV, >20 keV, and >30 keV for auroral flashes, detached arcs, and subauroral spots, respectively. All these types of proton auroras were suggested to be the result of particle scattering due to the interaction with electromagnetic ion cyclotron (EMIC) waves [*Spasojevic et al.*, 2004; *Fuselier et al.*, 2004; *Frey et al.*, 2004], although no comparison of the proton aurora and wave observations was done. Recently, some observations confirming this suggestion for detached proton arcs were performed by *Immel et al.* [2005], *Fraser et al.* [2005], and *Sakaguchi et al.* [2007]. A proof of the relationship between other types of subauroral proton auroras and EMIC waves is, nevertheless, an important task.

[3] The EMIC waves propagate from their magnetospheric source to the ionosphere along magnetic field lines. In the ionosphere a part of the wave energy can be transformed into the compressional mode and propagate in the ionospheric waveguide away from the foot point of the field line from the magnetospheric source [e.g., *Greifinger and Greifinger*, 1968]. The ground-based signatures of EMIC waves are geomagnetic pulsations in the range of Pc1 and Pc2 (0.2–5 Hz and 0.1–0.2 Hz), respectively. Thus observation of these pulsations on the ground can be used as an indicator of cyclotron interaction in the magnetosphere [e.g., *Kangas et al.*, 1998].

[4] There are several kinds of pulsations in the Pc1 range having different morphology [*Fukunishi et al.*, 1981]. One may note that the morphology of some pulsations in this range is similar to that of some proton auroras. For example, the morphology of a wide class of quasi-monochromatic ‘‘hydromagnetic (HM) whistlers’’ and ‘‘periodic HM emissions’’ [*Fukunishi et al.*, 1981] or so-called ‘‘pearl’’ pulsations seems to be similar to the morphology of subauroral proton spots studied by *Frey et al.* [2004]. Both the proton spots and the pulsations occur mainly in the day-morning MLTs during the recovery of magnetic storms. However, such similarity can be just occasional, so more detailed comparison is needed and will be presented in this paper.

[5] The present study combines IMAGE observations of subauroral proton spots with simultaneous observations of geomagnetic pulsations on the ground. To avoid a possible influence of the signal attenuation due to ionospheric propagation, the selection criterion is applied of nearly

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0148-0227/07/2007JA012501$09.00

Table 1. Proton Spot and Pc1 Characteristics

1 Date YYMMDD	2 UT (spot) HHMM	3 CGLat (spot) deg.	4 MLT (spot)	5 Pc1 on the ground	6 Pc1 mean frequency, Hz	7 UT (Pc1) HHMM	8 LPEP Overhead
010228	0446–0728	65 ÷ 67	7.5–9.5	Yes	0.33	0442–0738	Yes
030625(a)	1254–1319	−60.5 ÷ −62.5	15.2–15.4	Yes	0.47	1252–1323	no data
030625(b)	1308–1338	−59 ÷ −60	13.5–15.0	Yes	0.7	1308–1341	no data
030717	1135–1334	−57.5 ÷ −60.5	13.5–15.0	Yes	0.73	1150–1335	no data
041121	0112–0141	−56 ÷ −58	2.0–3.2	Yes	1.10	0106–0147	no data
050210	1517–1607	−61 ÷ −63	17.0–18.3	Yes	0.45	1512–1621	Yes
050917	2311–2334	−55 ÷ −57	∼03	Yes	1.30	2311–2340	no data

conjugated locations (ΔMLT < 2 h) of the spot with the ground station.

2. Data

[6] The ground observations used in this study were performed by the Polar Geophysical Institute at the geomagnetic observatory Lovozero (67.97°N, 35.02°E; Corrected Geomagnetic latitude (CGLat) is 64.3°; MLT = UT + 3). The geomagnetic pulsations were registered by the search coil magnetometer with a sampling rate of 40 Hz. The instrument has a low-frequency cut-off 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.

[7] The proton aurora observations were provided by the Spectrographic Imager (SI) detector of the FUV instrument onboard 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]. Among the proton spot events observed in 2000–2003 and considered by *Frey et al.* [2004], only one (the event on 28 February 2001) satisfied the criterion of conjugacy with the Lovozero ground station. Therefore an additional search has been performed in IMAGE data from 2003–2005. As the result, five new events were selected, which map close to the meridian of Lovozero. Because of the evolution of the IMAGE orbit all these events were observed in the southern hemisphere. As all proton spots were observed equatorward of the auroral oval on closed field lines the IGRF-10 model was used for inter-hemispheric mapping.

[8] Additionally, data from MEPED and TED instruments onboard the low-orbiting NOAA POES satellites, measuring particles with energies E > 30 keV and E < 20 keV, respectively [*Evans and Greer*, 2000], were used to identify the particles responsible for the auroral spots. The satellites of the NOAA POES series have polar circular orbits at altitudes around 800 km. The MEPED instrument measures energetic protons with two solid-state detector telescopes. The NOAA satellites are three-axis stabilized, and one detector views along the Earth-satellite radial vector. At high latitudes (L > 3) the detector viewing along this direction measures particles within the loss cone. The second detector views perpendicularly to the Earth-satellite vector. It observes particles that will magnetically mirror above the atmosphere. The TED instrument measures the total energy flux of particles within the loss cone at high latitudes.

3. Results

[9] The list of selected events is presented in Table 1. Entries of the table are date (row 1) and UT interval of the spot observation (2), latitude (3) and range of MLT (4) where the spot was observed. The entries also include information on ground-based observations: if the pulsations were observed (5), their frequencies (6), and the interval of observations (7).

[10] Examples of images showing the spots for each of the six selected events are presented in Figure 1. The spots often move approximately along the same latitude with the speed less than corotation, and their size and brightness can significantly vary (see *Frey et al.*, 2004 for detailed description of the spot properties). The location of Lovozero or the conjugate point of this ground station is marked by a star on each image.

[11] Figure 2 represents spectrograms of geomagnetic fluctuations in the range of 0.05–2(4) Hz observed in Lovozero for the selected events. The spectrograms demonstrate that every proton spot event is associated with pulsations Pc1 on the ground. Note, that colors on the spectrograms do not reflect the actual intensity of the Pc1 emissions. In fact, the intensity varies significantly between different events. The dynamic range on every plot was exaggerated to show the pulsations clearly. The pulsations are mainly "pearls" or diffuse bands with "pearl" elements. White horizontal bars on the spectrograms mark intervals of the proton aurora spot observations. One may note that the time of appearance/disappearance of the spot (row 2 in the Table 1) often coincides (within a few minutes) with the beginning/end of the Pc1 train (row 7 in the Table). All presented Pc1 event are very isolated in time (for several hours to days) from a preceding Pc1 activity. It is therefore unlikely that the coincidence of Pc1 and spots in time is occasional.

[12] In most events the Pc1 intervals are longer than the intervals of the optical spot observation. The only exception is an event on 17 July 2003 when the spot is seen since 1135 UT. In this case the Pc1 amplitude grew very slowly, so it was difficult to determine the exact moment when Pc1 started. The distinguishable Pc1 signal in Lovozero is seen since ∼1150 UT. The same signal is also seen at stations of the Finnish pulsation magnetometer network separated by one hour of MLT from the meridian of Lovozero and situated closer to the spot projection. It is interesting to note that low-latitudinal stations of the Finnish network

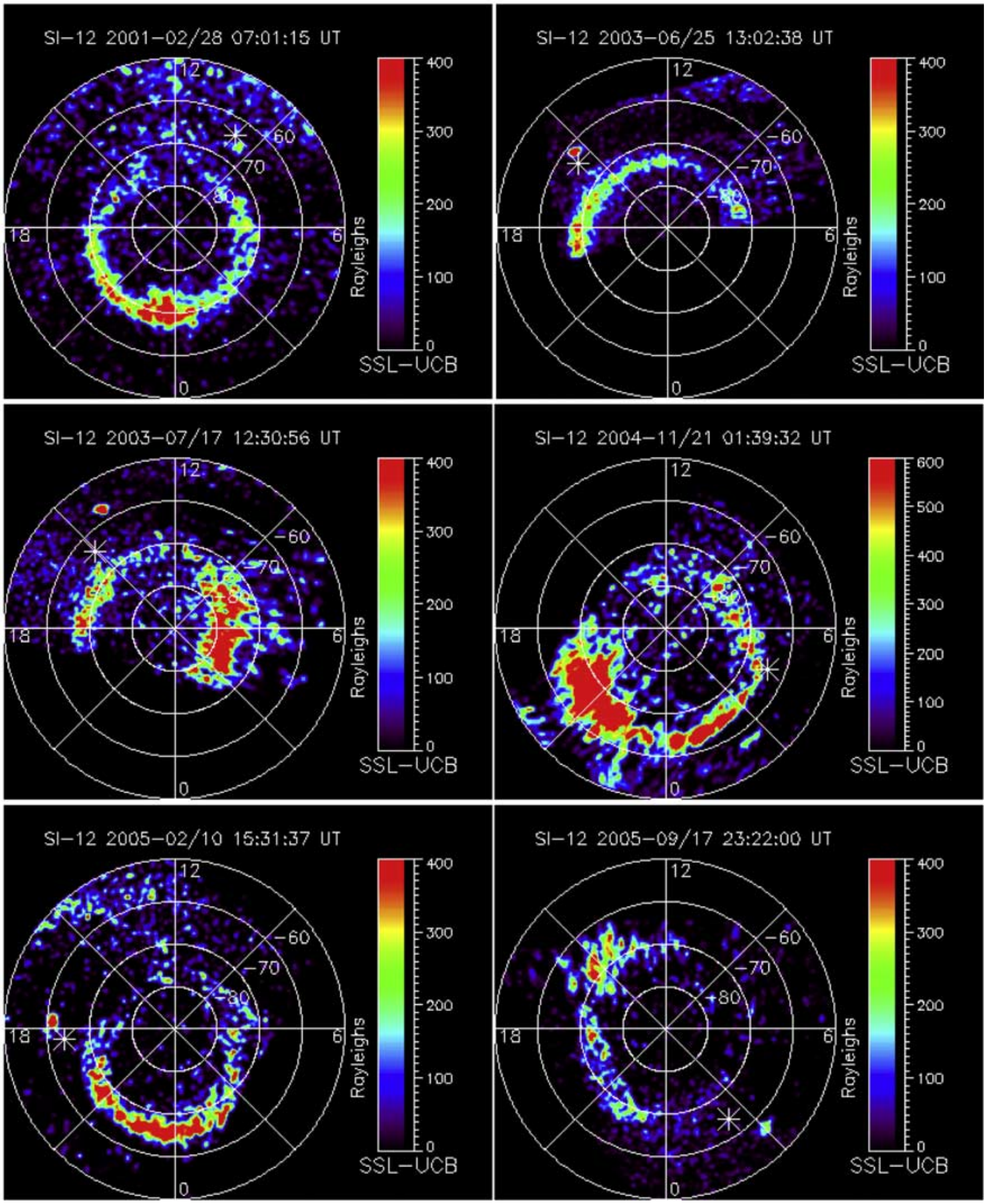

Figure 1. Examples of proton aurora images for all six selected events of subauroral spots nearly conjugated with the projection of the ground station Lovozero. The projection of the ground station is marked by a white star.

started to observe the Pc1 signal at ~1130 UT (data note shown), i.e., close to the moment of proton spot appearance. It should also be noted, that the spot in this event was at lower latitude than Lovozero station.

[13] On 25 June 2003 two-band Pc1 were observed. At 1252 UT the Pc1 train started at a frequency of 0.47 Hz. This band ended at 1323 UT. Another Pc1 band at frequency 0.7 Hz started at 1308 UT and ended at 1341 UT. The first band is associated with the proton spot that appeared at 1254 and disappeared at 1319 UT. At 1308 UT a new spot appeared equatorward of the first one (Figure 3). For the last time this spot is seen at 1338 UT.

[14] When the trace of the low-orbiting NOAA POES satellite crossed the region of the spot observation (events of 28 February 2001 and 10 February 2005), a sharp isolated, localized enhancement of the precipitating flux of protons having energy E > 30 keV without similar variations in the low energy component was observed (Figure 4; also, see the last row in Table 1 for a summary of these observations). On the upper panel of Figure 4 the data from MEPED are

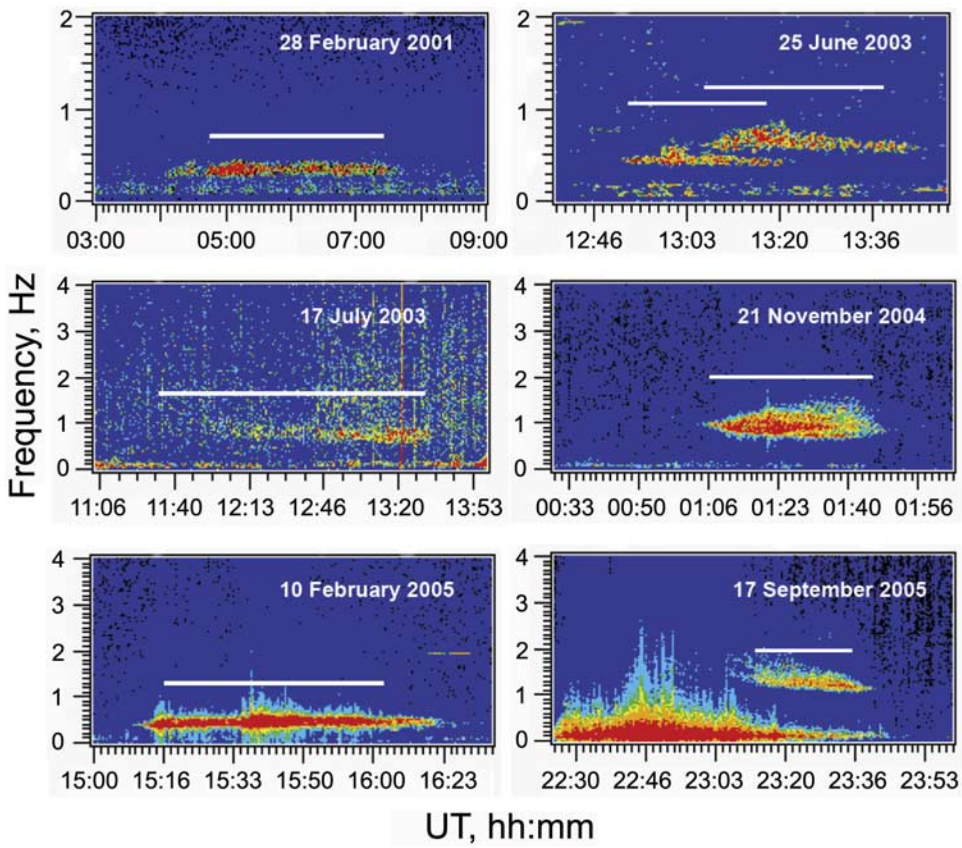

Figure 2. Spectrograms of geomagnetic variations in Lovozero for the six selected events. White horizontal bars mark the time interval of the optical spot observations from the IMAGE satellite.

presented. The precipitating (trapped) flux of >30 keV protons is shown by a thick (thin) line. The middle panel presents the data from TED. On 28 February the NOAA-15 satellite in the northern hemisphere registered the proton precipitation burst at ~0645 UT. The location of the burst was ~67 CGLat and ~9.5 MLT. The precipitation was observed right above the expected location of the spot. The precipitating proton flux was relatively weak, this agrees with the fact that at this moment the intensity of the spot as well as its size were reduced. On 10 February the NOAA-15 satellite registered the energetic proton precipitation burst in the northern hemisphere at ~1537 UT (at ~62 CGLat and ~17.5 MLT) while the spot observations were in the southern hemisphere. The images of the proton aurora combined with tracks of the NOAA-15 satellite are shown at the bottom of Figure 4. For the case when the NOAA and IMAGE satellites are in the same hemisphere (opposite hemispheres) the NOAA-15 track is shown by the solid (dashed) line. (Note that the proton aurora images are not coinciding in time with particle measurements. For the illustration purpose we selected the closest images where proton spots are most clearly seen. In fact, the location of the spots did not change significantly within a few minutes but their brightness did.) Like in Figure 1 the location of the ground station Lovozero is marked by the star. The NOAA-15 footprints for two instants (two minutes before and two minutes after the precipitation burst) are shown by

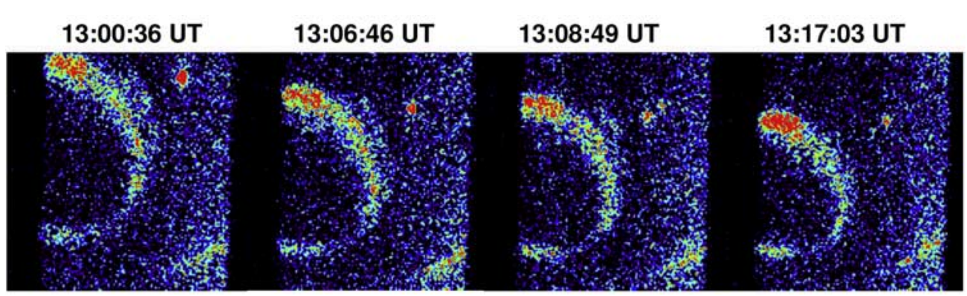

Figure 3. Sequence of raw images (not mapped) of the proton aurora for the event of 25 June 2003 demonstrating the occurrence of the second proton spot at 1308 UT. See text for details.

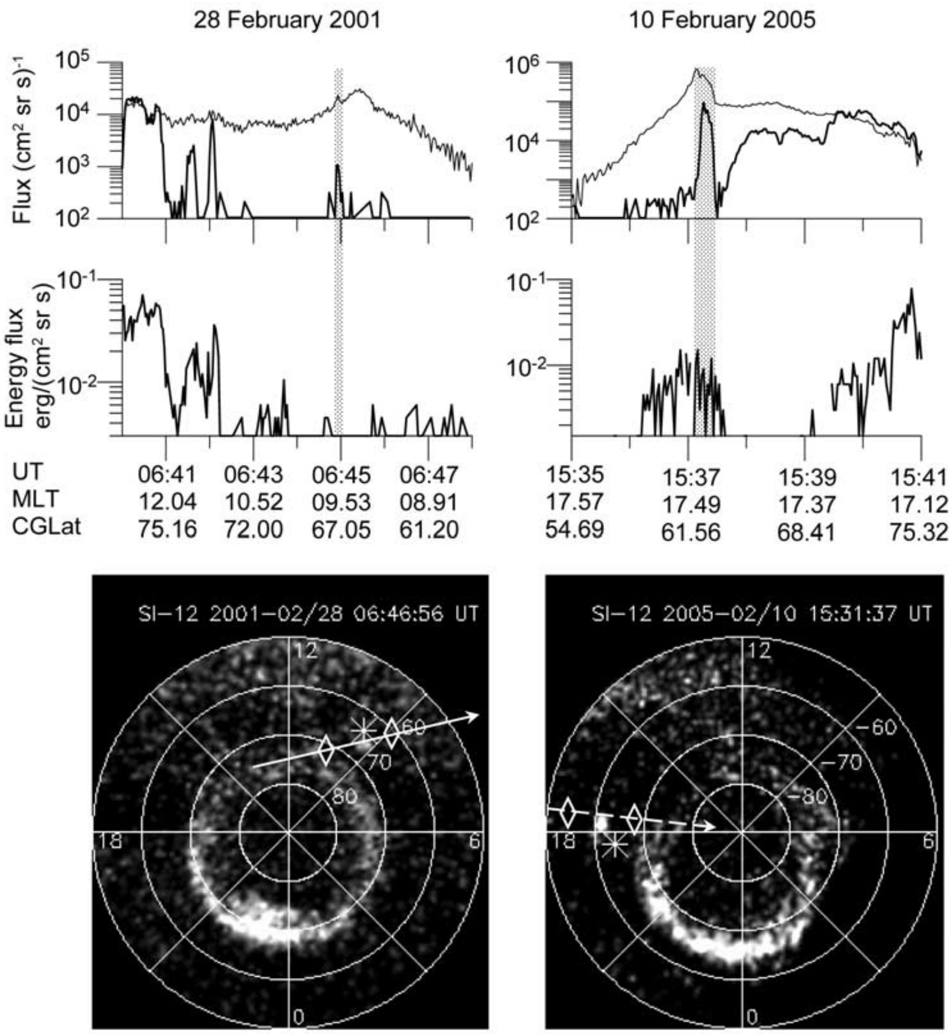

Figure 4. Proton data as measured by NOAA POES during the proton spot observations on 28 February 2001 (on the left) and 10 February 2005 (on the right). The upper panels present data from MEPED (trapped and precipitating flux of protons with energy E > 30 keV). The middle panels show data from TED (E < 20 keV, precipitating flux). The times of close encounter with the proton spots are shown by shaded strips. The lower panels present images of the proton aurora with tracks of the NOAA-15 satellite. Direction of the satellite movement is indicated by the arrow. See text for more details.

diamonds. It is clear that the location of the spot agrees with that of the proton precipitation burst.

4. Discussion

[15] The presented data and their summary in Table 1 clearly indicate a close relationship between proton spots and pulsations Pc1. First of all, this is evidenced by the near coincidence in the occurrence time of the spots and pulsations. The fact that the pulsations start (end) slightly earlier (later) than the associated proton spot can be explained with an insufficient imager sensitivity to observe weak proton auroras. *Frey et al.* [2004] noted that the proton spots have low intensity (in the events considered here the intensity was always less than 500 R) and they are visible only because of the very low instrument background of the proton imager. At the beginning/end of their appearance the proton spots can just be too dim to be observable by the proton imager.

[16] Another argument in favor of a relationship between the spots and Pc1s (as ground signatures of the EMIC waves) is the relation of the spot latitude and the frequency of the associated Pc1 (rows 3 and 6 in the Table). Figure 5 demonstrates this relation. The higher is the latitude of the spot the lower is the Pc1 frequency, which is always below of the equatorial He+ gyrofrequency at latitudes of the corresponding spots. The dependence is very similar to that between latitude and frequency of the Pc1/EMIC waves observed in space by *Erlandson et al.* [1990, Figure 10]. Note that every separate spot has relatively stable latitude [*Frey et al.*, 2004]. This agrees with the constancy of the Pc1 frequency.

[17] The proton spot/Pc1 relationship proves the same origin for these two phenomena. Obviously, it is the ion cyclotron instability that produces both the growth of the EMIC waves (Pc1) and the scattering of energetic protons into the loss cone (proton precipitation). Thus the proton aurora spots visualize magnetic field lines where the insta-

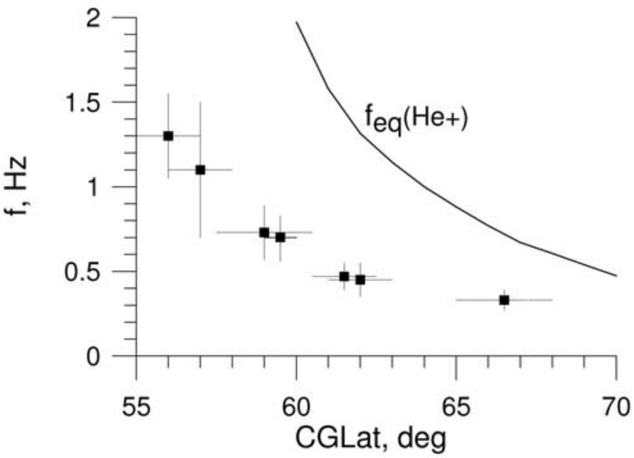

Figure 5. Dependence of the mean Pc1 frequency on the mean latitude of the associated proton spot (black squares). Vertical bars indicate the frequency width of the Pc1 band. Horizontal bars show the latitudinal range where the proton spot was observed. The equatorial gyrofrequency of the He+ is also shown.

bility develops. According to *Frey et al.* [2004], the spots map onto the magnetospheric equatorial plane in the vicinity of plasmapause undulations. This agrees with past studies showing the relation between the Pc1 generation and the location of the plasmapause [e.g., *Fraser and Nguyen*, 2001]. The plasmapause undulation allows the energetic protons drifting westward around the Earth to meet the gradient of the cold plasma density, so the enhanced interaction of protons with ion cyclotron waves is expected in the undulation region. This scenario explains why the proton precipitation is localized both in latitude and longitude.

[18] On the basis of DMSP satellite data and comparison of images from different instruments onboard IMAGE, *Frey et al.* [2004] concluded that proton spots are produced by precipitation of protons with mean energy E > 30 keV. The above mentioned comparison with NOAA POES observations (Figure 4) showed that indeed, the spots correlate with a specific pattern of the localized precipitation of energetic protons (LPEP) that has been identified by *Yahnina et al.* [2000, 2002, 2003] as closely related to the pulsations Pc1. The latitudinal width of this LPEP has been found to be about 0.5–1° [e.g., *Yahnina et al.*, 2000], that is, a few times less than the latitudinal size of the spot (about 3 degrees). This apparent inconsistency can be explained by the spreading of the proton beam in the atmosphere due to charge exchange [e.g., *Johnstone*, 1972; *Kozelov*, 1993] and by the point spread function of the proton imager [*Mende et al.*, 2000]. The latitudinal localization of the proton spot and LPEP agrees with that of the EMIC waves observed in space [e.g., *Erlandson et al.*, 1996; *Mursula et al.*, 1994]. The longitudinal extension of the proton precipitation related the EMIC waves can not be revealed from the LPEP observations. However, proton spots give a clear evidence of the longitudinal localization (typically, less than 1 h of MLT) of the region of the intense ion cyclotron interaction. This agrees with some previous estimates made on the basis of ground measurements of the Pc1 signal characteristics [see *Fraser and Nguyen*, 2001, and references therein].

5. Conclusions

[19] The close association of proton aurora spots with the pulsations Pc1 confirms the suggestion by *Frey et al.* [2004] on the EMIC instability as the source of this form of subauroral proton aurora. Thus optical observations of the proton aurora enabled the visualization of the region (or rather, its projection onto the ionosphere) of the intense ion cyclotron interaction resulting both in Pc1/EMIC waves and strong scattering of the protons into the loss cone.

[20] The optical data enable us to conclude that the Pc1 source is localized both in latitude and longitude. In agreement with numerous past studies, which related the Pc1 source to the plasmapause, this study [see also *Frey et al.*, 2004] suggests that the source is associated with an azimuthal gradient of the cold plasma that appears due to a ripple at the plasmapause.

[21] **Acknowledgments.** The authors thank Jyrki Manninen (Sodankylä Geophysical Observatory) for information on pulsation observations at the Finnish network. The data from NOAA POES are provided by NOAA. The study of A.G.Y. and T.A.Y. is performed in frames of the basic research program No 16/3 "Solar activity and processes in the Sun-Earth system" of the Russian Academy of Sciences (RAS) and program No 16 "Plasma processes in the solar system" of the Division of Physical Sciences of RAS. The work of these authors is supported by the Russian Foundation for Basic Research (grant No 05-05-64214). The work of H.U.F. is supported by NASA under the award NNG05GF24G.

[22] Zuyin Pu thanks Andrei Demekhov and Finn Soraas for their assistance in evaluating this paper.

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