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Identification of Sources of Pc1 Geomagnetic Pulsations on the Basis of Proton Aurora Observations

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Abstract—The relationship between proton aurora and geomagnetic pulsations Pc1, which are an indicator of development of ion-cyclotron instability in the equatorial magnetosphere, are studied on the basis of the observations of proton aurora from the *IMAGE* satellite, observations of particle fluxes onboard the low-orbiting *NOAA* satellites, and geomagnetic pulsation observations at the Lovozero observatory. A conclusion is drawn that the subauroral spots in the proton emission projected into the magnetosphere near the plasmapause are two-dimensional images at the ionospheric "screen" of the region of intense scattering of energetic protons into the loss cone at the development of an ion-cyclotron instability.

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INTRODUCTION

Observations of proton auroras by the FUV (Far Ultraviolet Imager) instrument onboard the high-apogee satellite *IMAGE* [1] made it possible to detect and study some new types of auroras, in particular, subauroral proton spots (SPS) [2]. SPS are projected onto the equatorial plane of the magnetosphere in the vicinity of the plasmapause, where they have dimensions of the order of 0.5–1.0 R_E. The spots move eastward along the constant latitude with a velocity close to the corotation velocity, this fact also indicating to their relation to the plasmasphere. It has been assumed [2] that the spots are related to precipitation of protons caused by the development in the equatorial plane of electromagnetic ion-cyclotron (EMIC) instability.

The result of development of an EMIC instability is scattering of protons of the ring current into the loss cone and generation of EMIC waves at frequencies below the gyr frequency of protons (see, for example, [3]). The transverse left-polarized waves at frequencies from some tenths of a hertz to a few hertzs could, under certain conditions, propagate along magnetic field lines to words the ionosphere [4].Oscillations at these frequencies can propagate from the base of the field line of a source across the magnetic field in the ionospheric waveguide (see, for example, [5]). On the surface of the Earth, these waves are detected as quasi-monochromatic geomagnetic pulsations Pc1.

In a series of papers [6–8] a close relationship was found between the geomagnetic pulsations Pc1 and the localized in latitude (~1°) precipitation of protons with energy $E > 30$ keV recorded at the low-orbiting satellites *NOAA POES*. This relationship is confirmed both by similarity of the morphology of Pc1/EMIC waves and the localized precipitation of energetic protons (LPEP) [7, 8] and by direct comparisons of Pc1 observations on the Earth's surface and protons at the low-orbiting satellite with simultaneous observations of EMIC waves and pitch-angle scattering of energetic protons into the loss cone near the equatorial plane [9]. Therefore, observations of LPEP can be used as an indicator of the field tube where ion-cyclotron interaction occurs.

Measurements onboard the satellites with a polar orbit (such as *NOAA*) make it possible to be sure only in the latitude localization of the proton precipitation related to Pc1. The question on the longitudinal localization of this precipitation and, accordingly, on the longitudinal localization of the region of intense scattering of protons by cyclotron waves in the magnetosphere still remains open.

Subauroral proton spots are observed to the equator from the proton oval at the recovery phase of geomagnetic storms mainly in the morning and daytime sectors [2]. The similarity of morphological features of SPS, LPEP, and Pc1 allows one to assume interrelation of all these events. In order to check this assumption, in this paper we compare simultaneous observations of the spots of proton aurora, localized proton precipitation, and ground-based observations of Pc1 pulsations. To do that, the data of the *IMAGE* and *NOAA* satellites will be used, as well as observations of geomagnetic pulsations at the Lovozero observatory of the Polar Geophysical Institute.

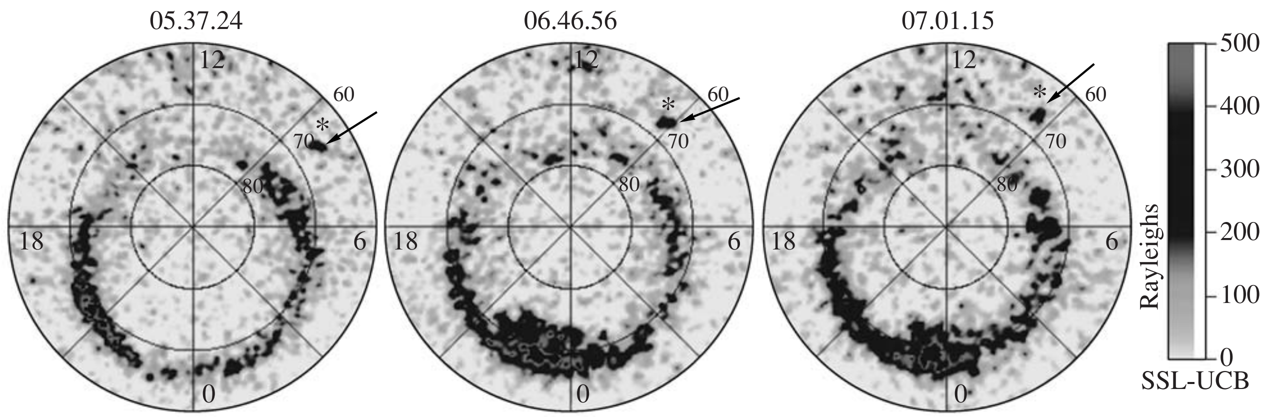

Fig. 1. Images of proton auroras according to the data of the *IMAGE* satellite for three moments of time on February 28, 2001. The subauroral proton spot is marked by an arrow near 09 MLT at latitudes of 65°–67°. The position of the Lovozero observatory is shown by an asterisk.

DATA

The observations of the proton auroras at the high-apogee (~9 R_E) satellite *IMAGE* were made with the SI12 detector of the FUV instrument [1], which took global images in the hydrogen Layman-α emission (121.6 nm) every two minutes. The geomagnetic pulsations within the range 0.05–5 Hz at the Lovozero observatory (67.97°N, 35.02°E, MLT = UT + 3) were recorded by an induction magnetometer. The frequency of the data collection was 40 Hz. The measurements of precipitating and quasi-trapped (with pitch-angles of 0° and 90°, respectively) protons with energy $E > 30$ keV at the low-orbiting (800 km) satellites *NOAA POES* [10] were also used.

RESULTS OF OBSERVATIONS

In [2], 7 events of subauroral spots of proton emission observed in the Northern Hemisphere in 2000–2002 were described. When comparing them with the data of magnetic measurements at the Lovozero observatory, it was found that in three events (August 27, 2000, July 28, 2001, and August 3, 2002) the observations of SPS were not accompanied by pulsations. In these cases the ground-based station was located, respectively, at longitudinal distances of 7, 11, and 11 MLT hours from the region of the spot observation. In three other cases (September 20, 2000, November 26, 2001, and September 6, 2002), when the ground-based station was located, respectively, at distances of 3.8, 6, and 6 MLT hours from the spot, it recorded the Pc1 pulsations, however, these pulsations had small amplitudes, and the times of beginning and end of pulsation detections did not coincide (by more than an hour) with the time of the proton spot observation. In one event (February 28, 2001) the proton spot and the ground-based station were located at a distance of less than 1 MLT hour (Fig. 1). In this event the appearance (disappearance) of the proton spot correlates well with the beginning (end) of the Pc1 recording. The first signs of SPS appeared at 04:11–04:13 UT at MLT = 7.2. The spot was observed in the dawn sector at latitudes of 65–67°, and its intensity was only slightly higher than the sensitivity limit of the FUV instrument (100 R). Then the spot disappeared and appeared again at 04:46 UT. It drifted eastward with the average velocity slightly lower than the corotation velocity (V/Vc = 0.7). After 07:28 UT at MLT = 9.5, the spot has disappeared.

Figure 2 shows the spectrogram of geomagnetic pulsations observed at the Lovozero observatory on February 28, 2001. Pulsations Pc1 are distinctly seen, their frequency being of about 0.3–0.4 Hz. Pulsations of a small intensity were observed from 04:10 UT. They increased sharply at 04:42 UT and stopped at about 07:38 UT. In this event the moments of sharp intensification and end of Pc1 pulsation registration at the ground-based station coincided with the moments of appearance and disappearance of the spot to an accuracy of a few minutes.

In those cases when satellites of the *NOAA POES* series flied over an SPS, the observations were compared with the particle flux measurements. An example of such a comparison for one of the events considered (September 26, 2001) was described in detail in [9]. Crossing the region conjugated to a bright proton spot in the 06 MLT sector at a geomagnetic latitude of about 55°, the *NOAA-15* satellite detected a powerful ($4.2 \cdot 10^6$ cm^{-2} sr^{-1} s^{-1}) isolated precipitation burst of energetic ($E > 30$ keV) protons (with a latitudinal dimension of ~1°). The localized burst of energetic protons was one of the most intense events among the LPEP events related to the Pc1 pulsations [8].

In the February 28, 2001 event at 06:44 UT, the *NOAA-15* satellite also crossed the SPS region and registered a LPEP whose latitudinal dimension was about 0.5°. In this case, the intensity of the burst of precipitating protons was rather low ($1.1 \cdot 10^3$ cm^{-2} sr^{-1} s^{-1}), this fact being caused by the decrease in the brightness and

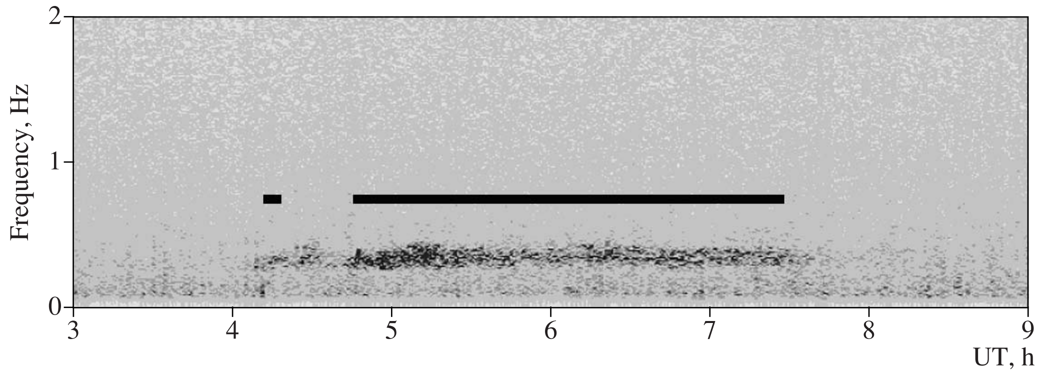

Fig. 2. Spectrogram of fluctuations of the geomagnetic field at the Lovozero observatory in the waveband 0.05–2 Hz within the interval 03:00–09:00 UT on February 28, 2001. Horizontal line shows the interval of observations of the subauroral proton spot.

dimensions of SPS just at the moment of the satellite passage.

Additional viewing of the images of proton auroras from the *IMAGE* satellite for 2003–2005 made it possible to select 5 events in which the projection of SPS onto the Northern Hemisphere was at a distance of no more than 2 MLT hours from the Lovozero observatory (these events were considered in detail in [11]). The spots were observed in the Southern Hemisphere (this fact is related to the evolution of the satellite orbit and to a shift of the satellite apogee into the Southern Hemisphere). In all five cases, the Pc1 pulsations were observed at the Lovozero observatory, and, in the same way as in the February 28, 2001 event, the interval of observations of SPS in each case coincided (within an accuracy of a few minutes) with the interval of pulsation observations.

DISCUSSION

The good agreement between the lifetime of a proton event and the time of Pc1 observations in the cases when the ground-based station is conjugated to the spot projection clearly indicates to their common source. The cyclotron instability of protons of the ring current in the magnetosphere at their contact with cold plasma irregularities could be such a source. Apparently, in the events considered, the azimuth irregularity of the outer plasmasphere manifesting itself in the wave-like structure of the plasmapause [2] can be such an irregularity, or a "cloud" of cold plasma separated from the plasmasphere.

The discrepancy between the time of SPS observation and the time of Pc1 rerecording (and even complete absence of these pulsations) for the events when the ground-based station is located at a distance of more than 3 MLT hours from SPS is consistent with the ideas on a rapid damping of Pc1 at their propagation in the ionospheric waveguide in the longitudinal direction. In particular, the authors of [12] came to a similar conclusion comparing the observations of EMIC waves onboard the *Polar* satellite with the ground-based observations of Pc1. In that paper the maximum longitudinal distance at which the EMIC waves, close in frequency, were observed simultaneously both on the Earth's surface and at the satellite was estimated as 1–1.5 MLT hours.

The latitudinal localization of the Pc1 source estimated on the basis of the LPEP measurements onboard low-orbiting satellites [7] and location of the source in the region of the plasmapause (the comparison of SPS with observations of the plasmasphere by the EUV instrument onboard the *IMAGE* satellite [2] indicates to this fact) agree well with the results of observations of EMIC waves by satellites (see, for example, [13]) and on the Earth's surface (see, for example, [14]). The longitude localization of the subauroral proton spot (the region of intense diffusion in the equatorial plane), which (as it follows from Fig. 1 and the data presented in [2]) is less than 1 MLT hour agrees with the estimates of the localization of the Pc1 source obtained earlier in the experiments in which the position of the source was estimated on the basis of measurements of polarization characteristics and arrival time of Pc1 signal at low-latitude stations [14]. At the same time, this contradicts to the conclusion of [13] made on the basis of observations of EMIC waves at the low-orbiting satellite *Freya*: that the Pc1 source has a longitudinal length of more than 3 MLT hours. In this connection, it is worth noting that in the event on November 26, 2001, the satellites *NOAA-15* and *NOAA-16*, in addition to the burst of precipitation of energetic protons within the 06 MLT sector, recorded localized intensifications of the flux of quasi-trapped energetic protons approximately at the same latitude but in the other sectors of MLT. These intensifications of the 90-degree proton flux were not accompanied by fluxes of precipitating protons. (Similar, almost simultaneous observations of bursts of c energetic protons at the same latitude in various MLT sectors were also described in papers [7, 15]). According to the data (presented in [2]) of the EUV instrument on the cold plasma distribution in the equatorial plane during this event, these localized intensifications of the flux of trapped protons were projected onto the plasmapause latitude, while the proton spot was projected into the region of local azimuth irregularity of cold plasma in the vicinity of the plasmapause. Apparently, in the plasmapause, within a wide sector of MLT, weak diffusion of energetic protons over pitch angles proceeds (and also some activity of the EMIC emissions could be registered there), while LPEP and proton spot are associated with the local region of intense scattering into the loss cone in the region of irregularity (azimuthal gradient) of the cold plasma. In this region the intensity of EMIC waves is substantially higher and can be registered on the Earth's surface in the form of Pc1 pulsations.

5. CONCLUSIONS

A close interrelation between the subauroral spots of proton emission caused by precipitation of protons with energy $E > 30$ keV and geomagnetic pulsations Pc1 is demonstrated in this paper. It is shown that the Pc1 source in the magnetosphere is localized both in latitude and longitude. The data presented indicate to a possibility of diagnostics of the region of ion-cyclotron interaction in the equatorial plane of the magnetosphere using observations of proton auroras.

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