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MAPPING THE PROTON AURORA SPOTS INTO THE MAGNETOSPHERE

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Abstract. Sub-oval proton auroras discovered by the IMAGE spacecraft correlate with electromagnetic ion-cyclotron (EMIC) waves (geomagnetic pulsations of the Pc1 range). This means that a common source of the waves and proton precipitation is the ion-cyclotron (IC) instability developing in the vicinity of the equatorial plane. Different forms of the proton auroras reflect different regimes of the IC instability and different conditions in the near-Earth equatorial magnetosphere. To understand what are the conditions for the generation of the sub-oval proton aurora one may map the aurora onto the equatorial plane and compare the projection with some important magnetospheric boundaries. In this report we compare the projection of so-called "proton aurora spots" with the location of the plasmapause. The latter is determined by the plasmapause formation model based on the quasi-interchange instability mechanism. The comparison shows that often the proton aurora spot source is located in the vicinity of the plasmapause or in the cold plasma gradient inside the plasmapause. In some events, the proton aurora spots map well outside the plasmapause. We assume that in the latter case the IC instability develops when westward drifting energetic protons interact with the cold plasma that was earlier detached from the plasmasphere.

1. Introduction

One of the main results of the IMAGE spacecraft mission is the global imaging of the "proton aurora" (the Doppler-shifted emission of neutral hydrogen atoms originating from precipitating protons after the charge exchange). Different types of the proton aurora equatorward of the main auroral oval were discovered. In particular, during the recovery phase of the magnetic storm, "proton aurora spots" with typical dimension of 100-300 km may appear (Frey et al., 2004). These spots have rather long (up to few hours) duration. They stay on approximately the same latitude and drift eastward with a co-rotation speed.

Unlike the proton aurora oval associates with the proton precipitation from the plasma sheet region, where the pitch-angle distribution of the protons is isotropic due to scattering in the weak equatorial magnetic field, the sub-oval proton auroras are related to the localized precipitation of the energetic protons (LPEP; see, Yahnin and Yahnina, 2007) within the anisotropic zone where the loss-cone is typically empty and the transverse temperature of protons is higher than the field-aligned temperature. Such transverse anisotropy is favorable for the development of the ion-cyclotron (IC) instability (e.g., Cornwall, 1965). Since this instability leads to scattering of protons into the loss-cone, it has been considered as a candidate for mechanism of precipitation responsible for the sub-oval proton auroras (e.g., Frey et al., 2004; Burch et al., 2003; Fuselier et al., 2004). The instability also leads to growth of EMIC waves; thus, correlation of proton auroras and EMIC waves (or geomagnetic pulsations in the Pc1 range, which are the signature of EMIC waves on the ground) is an important test to prove the mechanism of the proton aurora generation. Yahnin et al. (2007) and Yahnina and Yahnin (2012) showed close temporal and spatial relationship between the proton aurora spots and geomagnetic pulsations Pc1. This relationship strongly supports the IC instability as a mechanism of the proton precipitation responsible for the sub-oval proton aurora spots.

Although a primary source of the IC instability is the transverse anisotropy of proton temperature, other parameters (e.g., cold plasma density and hot plasma beta) are also important factors controlling the development of the instability. Cold plasma gradients are often considered as a location where the instability growth rate is maximal (e.g., Kozyra et al., 1984). To understand magnetospheric conditions in the source region, one may map the proton auroras into the magnetosphere and compare the projections with some important magnetospheric structures, for example, with the cold plasma distribution. Frey et al. (2004) compared proton aurora spot projections with plasmasphere images obtained with the IMAGE EUV instrument. They considered only two events and concluded that the proton aurora spots map into the vicinity of the cold plasma gradient (plasmapause or inner cold plasma gradient). Unfortunately, such direct comparisons of the proton auroras with EUV observations of the plasmasphere are scanty. Another way for such comparison is to use plasmasphere models. The aim of this paper is to compare projections of the proton aurora spots with the location of the plasmapause obtained from the numerical model based on the quasi-interchange instability mechanism for the plasmapause formation (see, e.g., Lemaire and Gringauz, 1998). The model calculates the position of the plasmapause for the required time interval, assuming the corotation and using the convection electric field model E5D (McIlwain, 1986) and the associated magnetic field model M2 (McIlwain, 1972). The electric field E5D depends on Kp-index, and for calculations the changes of Kp observed during the date given as input and 24 hours before are taken into account. It has been demonstrated that this plasmapause model reproduces the plasmapause observed from the IMAGE spacecraft rather well (e.g., Pierrard and Cabrera, 2005; Pierrard and Stegen, 2008).

2. Results of the sub-oval proton aurora spot mapping

The set of sub-oval proton aurora spot events for this study has been selected after a search through the IMAGE data for 2000-2005. In all, 17 events were selected. Most of them have been described by Frey et al. (2004) and Yahnin et al. (2007, 2008). The list of the events is given in Table 1. The entries in the Table are, respectively, the date when the proton aurora spot was observed, the time (in UT) selected for mapping, MLT of the proton aurora spot at this time, the latitudinal extension of the spot ($\Delta MLat_{sp}$), the radial extension of the spot projection (ΔL_{sp}), the location of plasmapause (L_{pp}) and, finally, the distance between the center of the spot projection and the modeled plasmapause (L_{sp} -L_{pp}). No special criteria for the selection of the moment when the mapping was performed were applied except the spot was well discerned. Since the spot stays approximately at the same latitude and drifts eastward with the co-rotation speed (Frey et al., 2004), mapping at other moments does not significantly change mutual locations of the spot projection and the plasmapause.

Table 1. Mutual location of the proton aurora spots and plasmapause.

	Date yyyymmdd	UT hhmmss	MLT hour	$\Delta MLat_{sp}$ °	ΔL_{sp} R_E	L_{pp} R_E	L_{sp}-L_{pp} R_E
1	20000827	040013	10.3	67.5-68.0	6.8-7.2	4.8	2.20
2	20000920	115257	10.8	56.5-58.5	3.3-3.7	3.8	-0.30
3	20010228	070115	09.3	65.0-68.0	5.6-7.2	4.8	1.60
4	20010728	190037	11.4	67.0-69.0	6.6-7.8	4.9	2.30
5	20011126	080653	04.3	55.0-56.5	3.0-3.3	4.3	-1.15
6	20020803	192733	10.0	60.0-62.0	4.0-4.5	4.2	0.05
7	20020906	015715	10.8	62.0-64.0	4.5-5.2	4.4	0.45
8	20030625	130035	15.3	60.5-62.5	4.1-4.7	4.0	0.40
9	20030714	132622	13.0	59.0-62.0	3.8-4.5	4.5	-0.35
10	20030717	122852	14.0	57.0-60.0	3.4-4.0	3.3	0.40
11	20040730	234429	03.6	58.0-60.0	3.6-4.0	3.9	-0.10
12	20040902	070201	10.8	59.0-62.0	3.8-4.5	4.3	-0.15
13	20041121	012909	02.0	56.0-58.0	3.2-3.6	4.2	-0.80
14	20050210	153137	17.8	60.0-62.0	4.0-4.5	4.0	0.25
15	20050509	135524	13.2	56.5-58.5	3.3-3.7	4.0	-0.50
16	20050531	102913	11.2	58.0-60.0	3.6-4.0	4.1	-0.30
17	20050917	232610	03.2	56.0-58.0	3.2-3.6	4.0	-0.60

To perform the mapping one needs a magnetic field model. It seems to be reasonable to use the same magnetic field model as for the calculation of the plasmapause location. The model M2 gives the magnetic field intensity in the equatorial plane. This model includes the noon-midnight asymmetry of the magnetic field, but at distances from the Earth up to 5 it only insignificantly differs from the azimuthally symmetric dipole field. Most of the proton aurora spot events listed in Table 1 were observed at magnetic latitude MLat < 63.5, which corresponds to L < 5. Thus, for mapping of these spots the dipole approximation comes true. For three of the events at higher latitudes, the mapping with the dipole magnetic field will somehow overestimate the distance of the spot projection from the Earth. In Figure 1 four examples of the mapping are presented. Before the event of 2 September 2004 the geomagnetic activity was low for a long time, in contrast to the event of 17 July 2003 when the activity was variable. This leads to different forms of the modeled plasmapause (black dots). Nevertheless, in both this cases the proton aurora spot (filled circle) maps onto the vicinity of the plasmapause. Conditions for the event of 28 February 2001 are characterized by modest geomagnetic disturbances during the preceding day and geomagnetic calmness just before the event. This associates with the expansion of the plasmapause. The spot maps even further from the Earth, and the distance between spot projection and plasmapause is ~1.5 R_E. On 26 November 2001 and preceding days the geomagnetic activity was variable. In this event, the center of the spot maps at distance ~1 R_E inside the modeled plasmapause. Mapping of this proton aurora spot relatively to the plasmasphere observed with IMAGE EUV has been done by Frey et al. (2004). The outer boundary of the cold plasma revealed from the EUV image is in a reasonable agreement with the modeled plasmapause (see, Fig. 5 by Frey et al.). At the same time, a gradient of cold plasma inside the plasmasphere at distance of ~3-3.5 R_E from the Earth is also clearly recognized. The projection of the proton aurora spot coincides with this gradient. Such gradients, however, cannot be reproduced with the plasmapause location model used in our study. Eleven of seventeen proton aurora spots listed in Table 1 map within 0.5 R_E into the vicinity of the modeled plasmapause like those shown in Fig. 1 a,b. Three spots map inside the plasmapause at distances larger than 0.5 R_E (as in Fig. 1 c), and other three spots map well outside the plasmapause (as in Fig. 1 d).

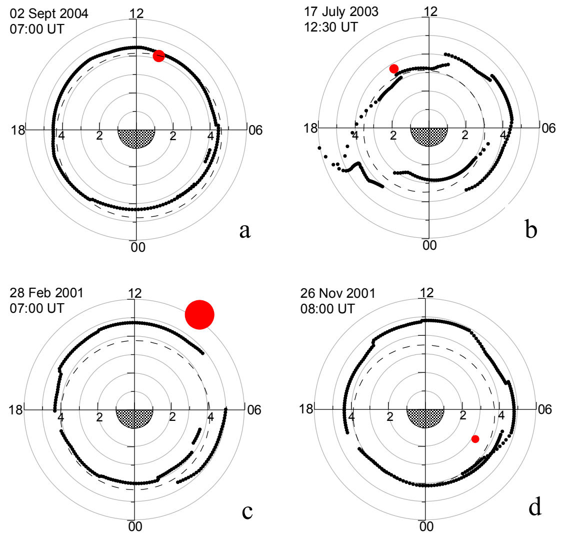

Fig. 1.

3. Discussion

According to Table 1, some 65% of the considered events (11 of 17) map into the vicinity (within 0.5 R_E) of the modeled plasmapause. This is consistent with the results of simultaneous space observations of the EMIC waves and plasmapause. For example, Erlandson et al. (1992; 1996) used Viking satellite measurements and observed the EMIC waves in the pre-noon sector just inside the plasmapause. Usanova et al. (2008, 2010) using, respectively, THEMIS and Cluster spacecraft data have found the EMIC waves in He^+ band just inside the plasmapause near noon. With the Polar spacecraft, Mursula et al. (2001) observed the EMIC waves in the pre-noon sector in the He^+ band at the inner plasmapause, while the waves in H^+ band were observed both at the plasmapause and just outside it. Fraser et al. (1996) observed the EMIC waves on CRRES near the plasmapause in the afternoon and night sectors.

Anderson et al. (1992) and Fraser and Nguyen (2001) argued that the EMIC waves are most probably observed outside the plasmapause. In the statistical study based on the EMIC wave and cold plasma density measurements onboard the CRRES spacecraft, Fraser and Nguyen (2001) found less than 50% of wave events in the plasmapause vicinity ($\Delta L<1$ R_E). In contrast, we found 65% proton aurora spot events in a narrowed vicinity ($\Delta L<0.5$ R_E) of the modeled plasmapause. The apparent contradiction is, obviously, due to the fact that the proton aurora spots relate to the specific type of the EMIC waves seen on the ground as quasi-monochromatic pulsations Pc1, while observations by Anderson et al. (1992) and Fraser and Nguyen (2001) included the EMIC waves of different types. Some of the waves are generated on the dayside as a result of increase of the hot proton temperature anisotropy during magnetosphere compressions. These waves are not necessarily related to the high density of the cold plasma and can be observed well above the plasmapause. A large amount of the events considered by Anderson et al. (1992) and Fraser and Nguyen (2001) are found at high L in the afternoon-evening sector. These events, evidently, relate to the plasmaspheric plume. The morphology of these waves and their ground counterparts (Pc1 bursts, IPDP) significantly differs from that of monochromatic Pc1. This suggests different source characteristics. Respectively, sub-oval proton auroras related to these waves (dayside proton aurora flashes, evening side proton aurora arcs) demonstrate very different characteristics in comparison to the proton aurora spots (e.g. Yahnina et al., 2008; Yahnin et al., 2009; Spasojević and Fuselier, 2009). In particular, co-rotation of a spot (in contrast to dayside flashes and evening arcs) and its location at the same latitude during a long time can be easily explained by connection with plasmapause (Frey et al., 2004; Yahnin et al., 2007).

At the same time, projections of three of the proton aurora spots are found deeper in the plasmasphere, at distances up to ~1 R_E from the modeled plasmapause. For one of such events, 26 November 2001, the comparison with real plasmapause observed with IMAGE EUV instrument showed that in this case the source region (the proton aurora spot projection) is in the cold plasma gradient inside the plasmapause. One may suggest that this holds true for other two similar events. Non-monotonic, sometimes step-wise, decrease of the cold plasma density (multiple plasmapause) is often observed (e.g., Horwitz et al., 1984). Data presented by Mursula et al. (2001) and Usanova et al. (2010) show that multiple sources of Pc1 can be observed in connection with such plasmapause structures. Location of the proton aurora spot projection well inside the modeled plasmapause can be related with such plasmapause structure, which can hardly be reproduced by the model used in this study.

As to those events in which the spots mapped well outside plasmapause, they can relate to the cold plasma structures detached from the plasmasphere. All the three events were observed in the pre-noon sector in accordance with Chappell (1974), who found detached cold plasma structures in the pre-noon sector to be well separated from the plasmasphere. Indirect confirmation of the above statement is the fact that sub-oval proton aurora spot events, independently of their latitudinal position, correlate well with long-term quasi-monochromatic pulsations Pc1, which are, typically, below the equatorial He^+ hyrofrequency (Yahnin et al., 2007). This means rather high percentage of He^+ that reveals the presence of the plasmaspheric material in the source location.

4. Conclusion

In this report, we have compared locations of 17 sub-oval proton aurora spots mapped onto the equatorial plane with the plasmapause position obtained using the numerical model based on the quasi-interchange instability mechanism.

As a result, most of events are mapped within 0.5 R_E from the modeled plasmapause. Since the proton precipitation responsible for the spots closely relates to generation of quasi-monochromatic Pc1, we conclude that the cold plasma gradient is the preferable location for generation of this type of the EMIC waves. We conclude that the rest of the spot events which are at larger distances from the plasmapause are also the result of the ion-cyclotron interaction related either to the gradients of the cold plasma inside the plasmapause or to the detached cold plasma regions.

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