

ФИЗИКА АТМОСФЕРЫ И ГИДРОСФЕРЫ

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AURORAS IN THE CUSP AND ITS POLEWARD VICINITY: A CASE STUDY

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ПОЛЯРНЫЕ СИЯНИЯ В КАСПЕ И ЕГО ПРИПОЛЮСНОЙ ОКРЕСТНОСТИ: ИССЛЕДОВАНИЕ ОТДЕЛЬНОГО СОБЫТИЯ

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Summary

We present a case study of the dayside aurora observed simultaneously with optical instruments from the ground and with auroral particle spectrometers aboard the DMSP F16 and F17 satellites. Optical observations were carried out with an all-sky camera at the Polar Geophysical Institute (PGI) observatory Barentsburg on Svalbard. The aurora as a whole moved equatorward in response to negative turning of the IMF Bz component and then the distinct faint rayed arc intensified, moved to the north and faded. Satellite DMSP F17 crossed the cusp twenty minutes after Bz turned southward. Joint analysis of optical and satellite data showed that faint auroral structures are embedded into the cusp precipitations and correspond to the bursts of electron precipitations with energy below 100 eV. The next satellite crossed the camera field-of-view ten minutes later and the data showed that the source of the faded poleward moving rayed arc was located, most probably, on the non-closed magnetic field lines. This finding and the presence of ion-energy dispersion in the DMSP data allows us to make the conclusion that the dayside reconnection may be considered as the reason for this kind of aurora activity. In this study we also estimated the altitude and horizontal scale of auroral rays in the cusp.

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Исследован редкий случай одновременной регистрации дневных полярных сияний наземной оптической аппаратурой и детектором выпадающих частиц на спутниках DMSP F16 и F17. Оптические измерения проводились камерой полного обзора неба Полярного геофизического института, установленной в обсерватории Баренцбург на арх. Шпицберген. Следуя развороту вертикальной компоненты межпланетного магнитного поля (Vz-компоненты ММП) в область отрицательных значений, система слабых лучистых дуг сместилась к югу, после чего одна из дуг начала дрейфовать обратно к полюсу и пропала. Спутник DMSP F17 пересек касп спустя двадцать минут после разворота Vz-компоненты. Совместный анализ оптических и спутниковых данных показал, что наблюдаемые слабые лучистые структуры находятся в области каспических высыпаний и пространственно связаны с всплеском выпадающих электронов с энергией менее 100 эВ. Следующий спутник DMSP пересек поле зрения камеры спустя десять минут после первого, и анализ его данных показал, что эта дуга в момент исчезновения находилась в области разомкнутых силовых линий. Этот результат, дополненный специфической формой протонных высыпаний в данных спутника DMSP, которую традиционно связывают с пересоединением, позволил нам прийти к выводу, что смещавшаяся к полюсу слабая лучистая дуга могла представлять собой ионосферный след только что пересоединившейся магнитной силовой трубки, уносимой солнечным ветром в антисолнечном направлении. Оценена высота и поперечный размер элемента лучистой структуры в каспе.

1. INTRODUCTION

Investigation of geophysical processes in the cusp and adjacent magnetospheric domains — the mantle (MANT) and the low latitude boundary layer (LLBL) — is important for understanding the physical mechanisms responsible for solar-terrestrial interaction. Magnetic conjugation of these parts of the dayside magnetosphere with the high-latitude ionosphere allows us to study solar-wind/magnetosphere interaction via the ionospheric phenomena observed from the ground. In this paper we concentrate on dayside auroras observed above Svalbard and aurora-related particle precipitations measured on board the DMSP satellites.

As a research tool, the optical aurora has obvious advantages compared with other kinds of ionospheric manifestations of magnetospheric processes since the modern all-sky cameras, as well as the large field of view, have high spatial and temporal resolution. On the other hand, optical observations depend greatly on the weather conditions and may be conducted only during darkness, only. Probably, this is a reason why we still poorly understand how the solar wind/magnetopause interaction is displayed by dayside auroras.

Expanding the set of observational instruments in Spitsbergen allows the use of a wide range of data instead of the optical data alone. Although such a multi-instrumental approach reduces the number of “optical events” suitable for analysis and turns them into so-called “case-studies”, it makes the interpretation of observations less uncertain (e.g. [1]).

Long study of low-altitude satellite data yielded the statistical MLAT/MLT distribution of the ionospheric projections of dayside magnetospheric domains ([2]) showing that the ionosphere above Svalbard is magnetically conjugated with all the above mentioned domains of interest (MANT, cusp and LLBL). To interpret the dayside aurora dynamics in the frame of solar wind/magnetopause interaction, one should correctly define the location of the dayside aurora’s origin in the magnetosphere. For example, if auroras originate in the cusp then move poleward and disappear in the mantle, the hypothesis about their association with reconnecting flux tubes suggested in [3] seems to be a probable one. However, the location of aurora origin is not simple. The typical way is the use of one of the Thyganenko models ([4]). In [5], the conclusion about the association of the early-evening arc (16 MLT) with the inner edge of LLBL was done in the absence of satellite measurements on precipitating particles. The only argument was how far away from the magnetopause the arc is projected in the Tsyganenko

T89 model. The same approach was used in [6] to infer that the post-midday arc (13:40 MLT) originated from the magnetopause. The results of a case study of conjugated satellite (Polar at $\sim 09:30$ MLT and Cluster at ~ 16 MLT, respectively) and optical observations of the dayside aurora were presented in [7, 8]. Including the auroral particle data in these analyzes resulted in a more correct projection of auroras to magnetospheric domains. Nevertheless, the conclusion about the location of the arc's origin in LLBL (see [8]) may not be regarded as indisputable because the Cluster satellite footprint is projected on the edge of the camera field-of-view where distortion due to using of fish-eye lens is very high. In [7] the auroral form positions in the vicinity of the Polar footprint were supposed from the characteristics of precipitating particles while optical observations were used for very general information about auroras. Probably, the approach was conditioned by understanding how critical an ambiguity of mapping of high altitude satellites into the ionosphere is for interpretation. An inaccuracy of Cluster mapping was estimated in [9]. The authors showed that different modifications of the Tsyganenko models yield an uncertainty of Cluster projection to the ionosphere about 100 km that is of the same order as the scale of auroral pulsating patches considered in [9], as well as the meridian extension of cusp and LLBL projections in the present study. The altitude of DMSPs is ~ 840 km and for mapping one can use the IGRF model which, in contrast to the Tsyganenko models, does not depend on geomagnetic activity.

Indirect comparison of the location of auroras with regions of dayside precipitation was done in [10]. Using statistical distribution both of auroras and particle precipitation regions, the author showed that discrete dayside auroral forms are embedded into the boundary plasma sheet whereas diffuse luminosity is associated with rather hard precipitations from the central plasma sheet (CPS). Note that for their analysis they used the approximating formulas ([11]) instead of the direct simultaneous measurements. Later, the former result was confirmed by direct comparison of electron precipitations onboard DMSP with optical observations in the late morning and early evening MLT-sectors ([12] and [13], respectively). The result of the above-mentioned case study in [7] inferred from Polar measurements is also in agreement with these observations.

An analysis of the literature shows that direct simultaneous optical/satellite measurements aimed at locating of the near-noon auroras relative to magnetospheric domains (cusp, LLBL, MANT) are very rare, and the nature of near-cusp auroras, as well as the drivers of aurora dynamics, are still uncertain issues of solar wind/magnetopause interaction. A few of the simultaneous near-noon observations may be easily explained by weather conditions and horizon sun highlight even during the darkest days. There are several case studies (e.g. [14, 15, 1]) demonstrating the possible association of auroras with some domains but reliable statistics are not available so far. The situation can not be clarified using aurora observations from satellites such as Viking, Polar or Image because they give only an overview of auroral activity due to low spatial/temporal resolution, as well as low sensitivity of onboard optical instruments.

Our investigation aims to expand the statistics on the association of dayside auroras with magnetospheric domains adjacent to the magnetopause using conjugated satellite and ground-based observation of the dayside aurora. The conjugation took place under negative IMF B_z conditions due to which the cusp was shifted southward from its statistical position ([2]) and was detected by the DMSP F17 satellite in the central part of the field-of-view of all-sky camera operating at the Barentsburg observatory on Svalbard (78.093°N , 14.208°E).

The most important part of the investigation is the precise collocation of optical and satellite measurements. The procedure will be shortly described in the next section.

2. INSTRUMENTATION AND METHODOLOGICAL ISSUES

The optical data used in our investigation were obtained with the high sensitive CCD-camera installed at the observatory of the Polar Geophysical Institute “Barentsburg” in November 2011. The camera is equipped with a fish-eye lens, has a resolution of 512×512 pixels and monitors the auroral activity in visible light at a temporal resolution of one frame per second.

The satellite data used for this study come from the Defense Meteorological Satellite Program (DMSP) series of satellites, using the SSJ/4 detector. The DMSP F16,F17 satellites are in circular, 840 km, Sun-synchronous orbits at an inclination of 98.3. The reader is referred to [16] and references therein for details on the SSJ/4 detector and its capabilities.

Location of the boundaries of different types of auroral precipitation was inferred from the DMSP satellite data by the method described in [17] and realized as on-line procedure on the website of the Johns Hopkins University (http://sd-www.jhuapl.edu/Aurora/dataset_list.html).

A very important part of our investigation is matching (in space) optical and satellite measurements as accurate as possible. The traditional way of conjunction of optical and satellite measurements is the projection along geomagnetic field lines (mapping) of both auroras and satellite trajectory onto the same surface with a definite geographic/geomagnetic coordinate system. In our study for aurora mapping we used the AIDA-tools package developed by Bjorn Gustavsson ([18]) for processing of the aurora optical data provided by the Auroral Large Imaging System, ALIS ([19]). The AIDA-tools package is available on http://www.alis.irf.se/~bjorn/AIDA_tools/Documentation/index.html. Like many other methods, the AIDA procedure is based on star recognition in the sky image. However, for transformation of “coordinates” on digital image (numbers of column and row) into the physical coordinates on the mapping surface (latitude and longitude), the procedure uses the matrix instead of traditional one-dimensional dependence of coordinates on the zenith angle.

For DMSP mapping we used IGRF magnetic field model and coordinates of the sub-satellite points taken from http://sd-www.jhuapl.edu/Aurora/dataset_list.html. The altitude of the spherical surface where the satellite measurement points were matched with auroras was assumed to be the height of the low border of luminosity (height of auroras). The latter was inferred from the altitude profile of aurora luminosity. Note that the height of auroras is the most uncertain parameter. In the study [12] the height of the dayside auroras was assumed to be 150 km. The value was obtained from triangulation measurements ([20]) based on the photo registration which is more sensitive for the green emission than for the red one whereas it is just red auroras that are the typical form of near-cusp auroral activity.

To estimate the possible error caused by an uncertainty of the aurora height, we carried out a special investigation which showed that the variation of the aurora altitude near zenith in the range 200–250 km introduces an uncertainty of about 8 km in the process of auroras/satellite trajectory matching. This is four times more than the uncertainty due to satellite movement and data temporal resolution and almost ten times more than spatial resolution of optical data. The error increases with moving away from zenith and rises up to 100 km at the distance ~ 200 km from zenith. This means that in a situation similar to that described in [8], the error of association of auroral arc with some domain is of the order of the width of the domain. To reduce the uncertainty in our study, we estimated the aurora height from the characteristics of precipitating particles detected by DMSP at the moment of conjugation with the auroral form under consideration.

3. OBSERVATION

3.1. IMF variations and aurora response

A keogram in Fig. 1a shows (in negative representation) the aurora dynamics above Barentsburg in response to the variations in B_z and B_y components of the interplanetary magnetic field, IMF. Variations of IMF are time-shifted to the Earth's bow shock nose. The keogram is inferred from the sequence of the all-sky camera frames at 10 s resolution and presents variations of integral luminosity of the sky in the NS oriented band of the 20 pixel width that at an altitude of 250 km corresponds to 10 km in the zenith and 25 km at the zenith angle of 60 degrees.

Variations in the B_z component of IMF are commonly considered to be a driver of the many magnetospheric processes through the dayside reconnection. The beginning of

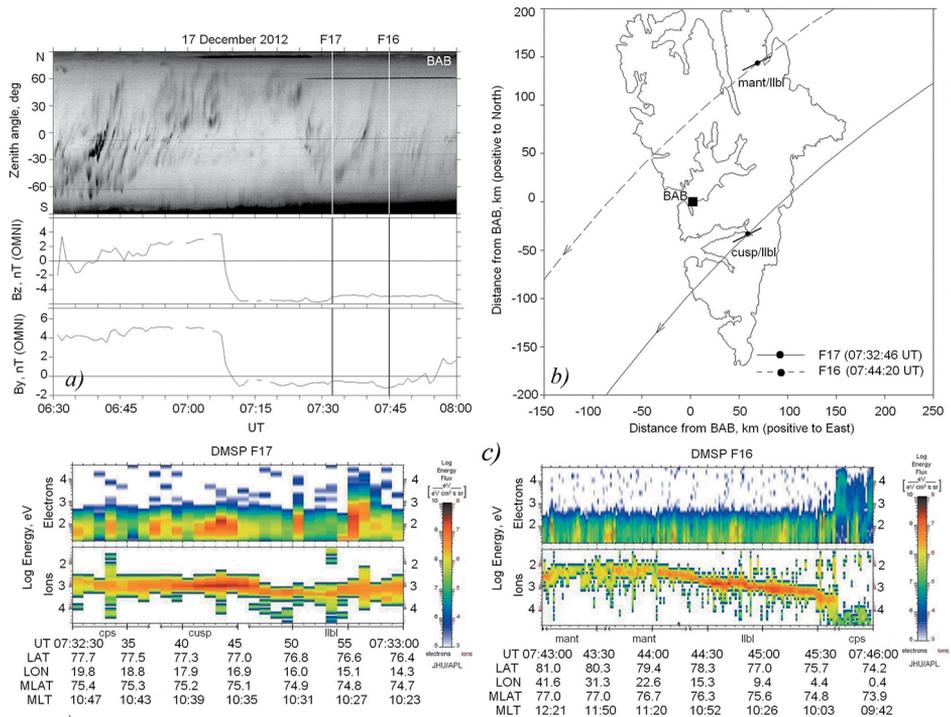


Fig. 1. (a) Aurora response to IMF variations. Vertical lines show the moments of DMSP flight through the field-of-view of the all-sky camera in Barentsburg. (b) Satellite trajectories mapped at the altitude of auroras. Black circles indicate the satellite location at the moment of crossing the boundary between cusp, mantle and LLBL precipitations. Tick orientation on the trajectories is approximately along the geomagnetic latitude. (c) Spectrograms from the DMSP F17 and F16 satellites showing the structure of particle precipitations in the region of optical observations

Рис. 1. а) — отклик сияний на вариации межпланетного магнитного поля. Вертикальными линиями отмечены интервалы пролета спутников DMSP через поле зрения камеры полного обзора неба в Баренцбурге. Черные кружки — положение спутника в момент пересечения границы высыпаний, свойственных каспу, мантии и низкоширотному пограничному слою; б) — проекции траекторий спутников в ионосферу на высоту сияний; в) — спектрограммы спутников DMSP F17 и F16, показывающие структуру высыпаний над областью оптических наблюдений

the interval in Fig. 1*a* is characterized by the gradual B_z rising toward the positive values while B_y is positive and stable. In the middle of the event B_z turned to the negative values and stayed relatively stable so that both the satellites conduct the measurements in conjunction with the optical auroral observations under the negative B_z conditions. The interesting feature of the interval is the vanishing of B_y component, indicating that the IMF lines are anti-parallel to the geomagnetic field lines during both the satellite passes. This creates favourable conditions for reconnection right near the noon meridian.

Auroras during the intervals of interest represent the so-called poleward moving auroral forms (PMAF) that are a typical kind of activity for high latitude dayside auroras. The equatorward shift of PMAF started at 07:20 UT, i.e. 10 minutes after B_z changed sign to negative. This time lag is not exactly the responding time to the B_z variation because it also includes also the propagation time of the solar wind through the magnetosheath. Note that the curves in Fig 1*a*, lower panels, show the IMF variations at the Earth's bow shock nose which, according to the OMNI WEB estimation, was at a distance of 13.2 RE from the Earth.

One more feature of auroral activity inferred from the keogram in Fig 1*a* is the appearance and poleward drift of the auroral arc 10–15 minutes after the beginning of PMAF equatorward displacement. Just before the arc appearance and a few minutes after its disappearance, two DMSP satellites passed through the all-sky camera field-of-view. The moments are indicated with vertical lines in Fig. 1*a* and satellites trajectories are presented in Fig. 1*b*. Note that the tick orientation on the trajectories is approximately along the geomagnetic latitude. The features of particle precipitations during these passes are presented in Fig. 1*c*. They show that before the single arc appearance the F17 satellite detected precipitations typical for the cusp (upper panel in Fig 1*c*). After arc disappearance, the boundary between mantle and LLBL which we consider as a boundary between open and closed magnetic field lines was detected by satellite within the all-sky camera field-of-view (see spectrograms on the lower panels in Fig. 1*c*). A detailed analysis of the satellite/aurora conjugation is presented in the next sections.

3.2. Rayed auroral structures in the cusp and corresponding precipitations

For correct matching of satellite measurements with auroras we need to know the altitude of the spherical surface above the Earth on which both auroras and satellite trajectory with markers of precipitation boundaries will be mapped. As it was shown above, the largest error in the location of satellite measurements relative to auroras may be caused by the ambiguity in choice of the aurora height. To diminish the uncertainty in the aurora altitude we defined this parameter from in situ satellite measurements by the method which was used earlier in the study [1].

Altitude profiles of the luminosity were inferred from the characteristics of electron precipitations along the fragments of satellite trajectories shown in Fig 2*a* and are presented in Fig 2*b* as altitude – UT diagram. In Fig. 2*a*, similar to the keogram, the higher intensity corresponds to the darker areas. Intensity of the red emission (650.0 nm) was calculated according to the model developed in [21]. For green emission (557.7 nm) we used the model described in [22]. The rates of excitation and ionization of the atmospheric species used in the emission intensity calculations were calculated according to method presented in [23]. Altitude profiles for the moments corresponding to precipitation bursts in satellite data (and, hence, the bursts of emission intensity) are shown in Fig. 2*c*.

Results of calculations in Fig. 2*c* show that luminosity in the red emission is more intense than in the green emission that is the expected result for the near-cusp aurora. For

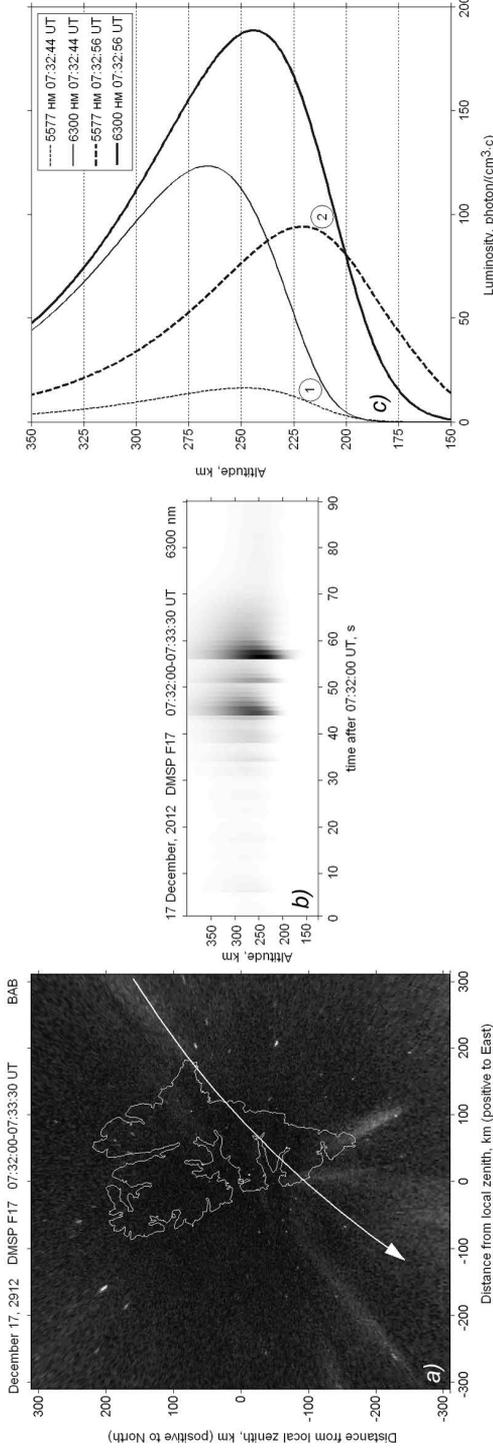


Fig. 2. (a) Rayed auroras in the cusp vicinity mapped onto the spherical surface together with fragments of satellite trajectory. (b) Altitude vs time plot showing the variation of luminosity in red line along the fragment. The larger intensity corresponds to the darker area on the plot. (c) Altitude distribution of luminosity at the moment of the most intensive precipitations in the cusp (1) and in the low latitude boundary layer (2)

Рис. 2. а) — лучистые сияния в области каспа, спроектированные на сферическую поверхность вместе с фрагментами траектории спутников; б) — диаграмма, показывающая интенсивность свечения неба в красной спектральной линии как функцию высоты и времени. Темные участки на диаграмме соответствуют большей интенсивности свечения; в) — высотный профиль в момент наиболее сильных высываний в каспе (кривая 1) и в низкоширотном пограничном слое (кривая 2)

further analysis we assume that all auroras registered by the all-sky camera in Barentsburg during the interval are red auroras. The red luminosity profiles have a maximum in the 230–270 km altitude range (ionospheric F region) and decrease rapidly with altitude decrease. Aurora registration in Barentsburg is carried out by a non-calibrated camera, so we do not know the threshold of camera sensitivity in physical units (Rayleigh) and can not define the height of auroras directly from the curves in Fig. 2. On the other hand, the accurate identification of this parameter on the aurora images is also laborious because it depends on such subjective factors as the method of data visualization and the eye's ability to distinguish the gradation of gray. It may be inferred from Fig. 2*b* that the lower edge of auroras might be several tens of kilometers below the area of maximum luminosity. So, as a height of the spherical surface which will be used further for mapping both auroras and satellite track, we accept the altitude of maxima minus 25 kilometers. We noted in section 2 that for the matching of optical and satellite measurements in the F-region near zenith an uncertainty of $\Delta h \sim 50$ km in height definition gives an uncertainty in the matching of not more than 10 km in the case under consideration.

Auroras were represented as a series of rays which are (*a*) very elongated along the magnetic field lines and (*b*) have a cross section much smaller than the distance between them. At large zenith angles the property (*a*) complicates the identification of the small faint structures against the rather strong background rays. The property (*b*) can also lead to the loss of important information in the case of only satellite measurements because the satellite may pass between the rays. This again points out the importance of coordinated satellite-optical measurements and mapping of auroras and satellite tracks as correctly as possible.

The spectrogram of DMSP F17 in Fig. 1*c* shows that the satellite was inside the cusp precipitations from 07:32:38 to 07:32:45 UT and detected the enhanced electron flux just before entering LLBL. Our calculation shows that this burst produced the red luminosity with altitude profile plotted as the thin line in Fig. 2*c*. Although the maximum of luminosity is at an altitude of ~ 265 km, we accept the altitude of the corresponding auroral structure to be 240 km in accordance with the above reasoning. Results of matching the satellite track with the auroras observed by the BAB all-sky camera at the moment of the satellite crossing the electron enhancement is presented in Fig. 3*a*. The original frame is on the left and the result of its mapping onto the spherical surface is presented on the right. Note that East on the original frame is on the left whereas on the mapped frame it is in its correct position — on the right. The solid line indicates the fragment of the satellite trajectory where cusp precipitations were detected.

It is seen that at the moment of interest the satellite (shown with a white circle) is conjugated with a very faint ray. This can mean that a rayed auroral arc-like structure was located in the cusp, i.e. its source was, most probably, on the open magnetic field lines.

One more precipitation burst was detected at 07:35:56 UT when the satellite was in the precipitations related to LLBL. According to our calculations the red emission maximum was at an altitude of ~ 240 km, so, as a height of the lower edge of the auroras, we accept the altitude of 215 km. The result of the matching is shown in Fig. 3*b*. For a better visualization of structures after mapping we emphasized their lower border on the central image with thin white curves. (Note the important feature of the fish-eye images of auroras: the bottom edge of auroral structure in the ionosphere corresponds to the bright area on the image most distant from zenith edge). The curve A corresponds to

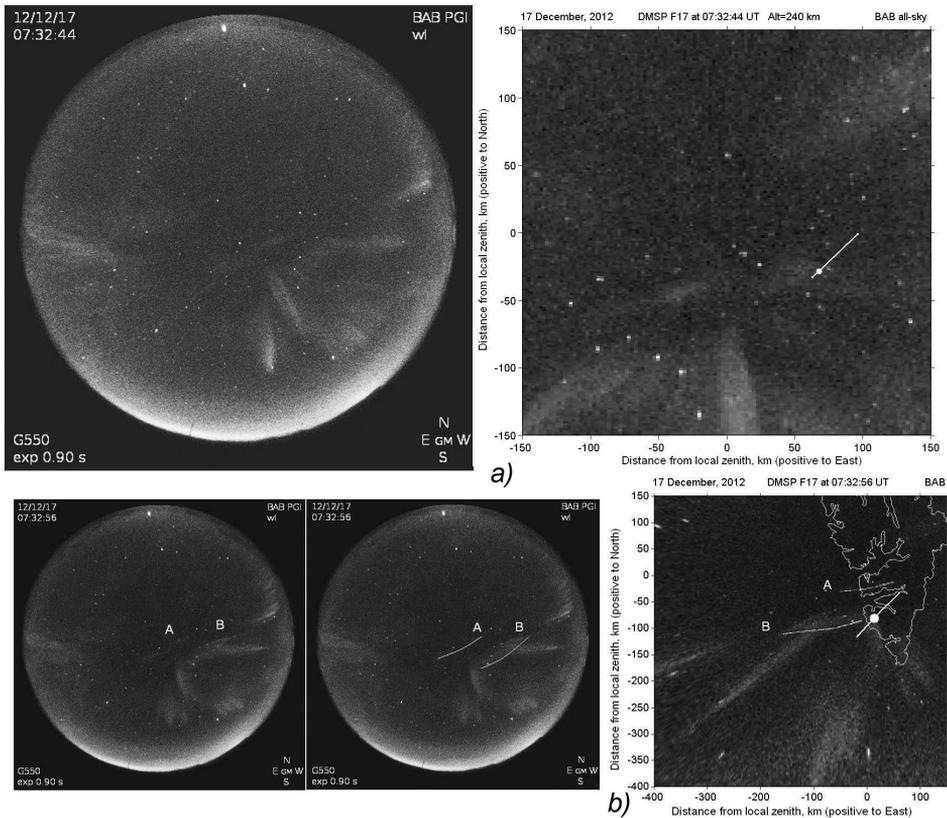


Fig. 3: From left to right: original all-sky frames showing auroras in the cusp (a) and in LLBL (b) and result of mapping them together with the corresponding fragments of the satellite trajectory. White circle indicates the satellite location at the time of precipitation enhancement. More details in the text

Рис. 3. Слева направо: оригинальные снимки камеры, показывающие сияния в каспе (a) и низкоширотном пограничном слое (b) и их проекции в ионосферу вместе с фрагментами спутниковой траектории. Детали в тексте

the above-mentioned faint rayed arc in the cusp which the satellite was conjugated with just before the entry into LLBL. The faint arc B was partly superimposed onto the rather bright rays belonging to the another auroral structure. This structure obscures the east edge of the arc B where the satellite was mapped at the moment of precipitation burst detection (white circle in Fig. 3b, right panel). The satellite then flew in the BPS and its trajectory was mapped between the rays thus not allowing to obtain the emission altitude profile and to make a correct matching of optical and satellite data.

The comparison of proton and electron precipitations presented on spectrograms in Fig. 1c (top panels) gives important information about possible generation mechanism of the rayed auroras in the cusp. It is seen that during the satellite conjugation with the auroral structures in the cusp, proton precipitations do not decrease in response to the electron enhancement but even increase. It is not consistent with our previous result regarding LLBL auroras ([1]) showing that at the moment of satellite-aurora conjugation the proton precipitations were stopped almost completely which we connect with the

existence of anomalous resistance or a double layer above the arc. Since no signature of the particle acceleration was observed in the event considered, one can suppose that the generation mechanism of the rayed structure in the cusp is connected rather with the loss-cone electron scattering than with the electron field-line acceleration.

Just after F17 crossed the cusp, the auroral activity represented a typical poleward moving auroral form (PMAF), i.e. enhancement of auroras southward zenith, poleward drift through camera field of view and fading. In the next section we discuss the possible location of the PMAF relatively magnetospheric domains inferred from F17 measurements.

3.3 Presumed location of the PMAFs during and at the end of their poleward displacement

The keogram in Fig. 1a shows that between the F17 and F16 passages over the BAB all-sky camera (interval confined by two white vertical lines) the auroral activity represented a single PMAF event. The event started near the moment of the F17 cusp crossing in the area of enhanced auroras southward zenith and faded ten minutes later close to the northern edge of the camera field-of-view. An important feature of the event is the short-term intensification of the drifting auroras just before 07:40 UT slightly southward of the local geographical zenith.

The shape of auroras for the moment of brightening is presented in Fig. 4a. One can distinguish several stretched rays which are the elements of the rayed auroral arcs and at least two patches, one of which is located directly in the local magnetic zenith (Fig. 4b). On the one hand, the patch may be the cross-section of one of the auroral rays drifting poleward. On the other hand, it can be treated as the cross-section of a just reconnected magnetic flux tube moving poleward. We clarify the last assumption below.

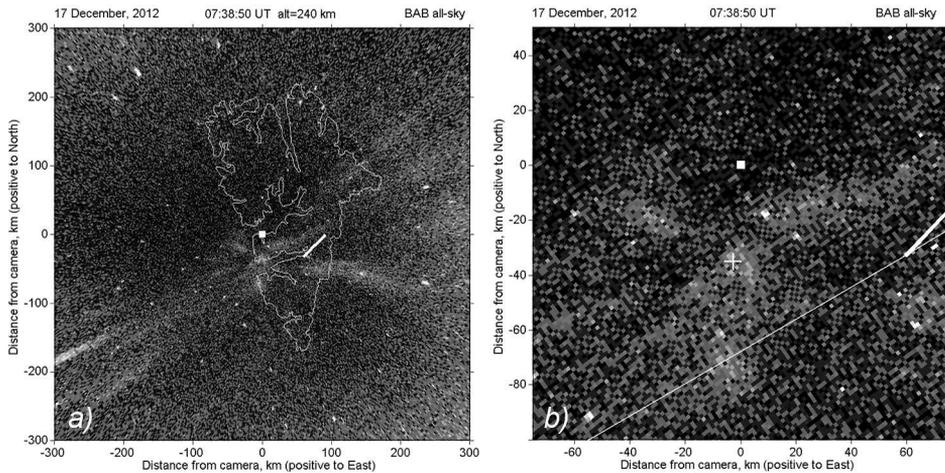


Fig. 4. (a) Complex structure of PMAF at the moment of intensification. (b) Auroral patches above Brentsburg. Local geographic and magnetic zeniths are marked with white square and cross, respectively. Bold white line shows the cusp position six minutes before the moment, thin white line is presumed location of the boundary between cusp and LLBL

Рис.4. *a*) — сложная структура системы дрейфующих к полюсу дуг в момент их интенсификации; *b*) — сияния над Баренцбургом в форме пятен. Географический и магнитный зенит отмечены белым квадратом и крестиком соответственно. Жирной линией показано положение каспа за шесть минут до этого момента, тонкая белая линия — предполагаемое положение границы между каспом и низкоширотным пограничным слоем

The bold white line on the images in Fig. 4 is a fragment of the F17 trajectory where cusp precipitations were detected six minutes before the image was taken. Note that the PMAF development preceded the interval of almost constant IMF (see Fig.1a, central panel). This allows us to assume no global reconstruction of the dayside magnetosphere and, as a sequence, no significant displacement of the ionospheric boundaries of magnetospheric domains at least within a few minutes after cusp detection. As inferred from Fig.1c, top panel, the satellite F17 flew almost along the geomagnetic latitude that is shown with a thin white line in Fig. 4b. Based on the spectrogram in Fig.1c (top panel), this geomagnetic latitude may be regarded as the boundary between the cusp and LLBL. So, the patches poleward of the line may be located in the cusp, thus supporting the above hypothesis about the nature of the auroral patch in the local magnetic zenith as the cross-section of a just reconnected magnetic flux tube.

The next DMSP satellite (F16) flew through the camera field-of-view ten minutes after the first one (F17) and on leaving the MANT precipitations at 07:44:20 UT (see Fig. 1c, bottom panel) was mapped poleward zenith close to latitude where the drifting arcs disappeared. Unfortunately, the arc disappeared completely about four minutes before the moment. So, taking into account the stable IMF condition and the location of the fading arc in respect to the MANT/LLBL boundary which is assumed to be at the geomagnetic latitude of the F16 projection, we can only suggest that it happened in the mantle. The auroras in the mantle have been reported earlier [24].

4. DISCUSSION

The poleward moving auroral form (PMAF) is a typical form of the dayside auroral activity. Investigation into them started several decades ago but no commonly accepted explanation was elaborated. In the early publications that studied this phenomenon it was suggested that the dayside reconnection under negative IMF Bz conditions can be the possible reason for PMAF events (e.g. [3]). While subsequent studies showed that PMAF occur during both negative and positive Bz and that they may be observed far away from the noon meridian [25, 13], the reconnection remains the most popular hypothesis to explain PMAF.

To associate PMAF with just reconnected magnetic flux tube drifting from the cusp in anti-sunward direction, first of all it should be confirmed that the origin of PMAF is on the non-closed magnetic field lines (i.e. in the mantle or in the cusp, at least). Unfortunately, sometimes the researcher does not pay enough attention for reliable arguments of this. For example, in [6] a conclusion regarding the position of the source of PMAF in the magnetopause was based on the Tsyganenko model. In accordance with [9], the use of the Tsyganenko models for aurora conjugation with high-orbiting satellites (Cluster) yields a large uncertainty even in the inner magnetosphere ($L \sim 4.5$) where the shape of the magnetic field lines seems to be more predictable and not so much distorted by the external currents as just near the cusp. As additional argumentation, it was pointed in [6] to the similarity of PMAF and FTE (flux transfer event) timescales. Indeed, the FTE are attributed by many authors to a signature of reconnection but FTE was not reported as actually occurring during the event considered.

In order to locate the source of PMAF in the dayside magnetosphere in our study we used the data of the low-orbiting satellites DMSP series. Note that in contrast to any Tsyganenko models which are based on statistics and, hence, refer to some “averaged” geophysical situation, the position of the magnetospheric domains inferred from the DMSP

measurements is directly related to the moment of the optical observations above Svalbard. The location of the auroras in space was defined as accurately as possible. Firstly, for aurora mapping we used the position of stars on all-sky images which minimized the possible mistakes caused by inaccurate manual installation of the camera. Secondly, to estimate the height of specific auroral forms we do not use a-priori information but calculate it from the characteristics of precipitating electrons directly measured by DMSP just over the auroral form. Therefore the association of the faint auroras on the all-sky images with the cusp precipitations (section 3.2) may be accepted as a proven fact if the on-line procedure of domain identification at the APL website is correct.

A credible conclusion but less supported by direct measurements, is that the PMAF source is located on the non-closed magnetic field lines (section 3.3). Up to the moment when F16 crossed the MANT/LLBL boundary, the PMAF have faded completely. So, our assumption that they were in the mantle is based on the F16 measurements which were made a few minutes after the arc disappearance and the fact that the MANT/LLBL boundary did not shift poleward during the interval.

If the arcs are really on the non-closed magnetic field lines and move poleward at the same time, it is reasonable to associate them with just reconnected magnetic field lines drifting tailward from the cusp. Recall that attributing PMAF to reconnection in [6] was inferred from the similarity of the PMAF and FTE timescales despite the fact that FTE themselves were not detected. In our case the reconnection hypothesis was supported by the DMSP F16 data, in particular by the shape of ion precipitations shown on the bottom panels in Figs. 1c, time interval 07:43:05–07:44:35 UT. First, the spectrogram shows the increase of ion energy while the satellite F16 moves from high latitudes to south (ion-energy dispersion), which is usually considered as a signature of reconnection during negative B_z (e.g. [26]). Second, the dispersion structure crosses the MANT/LLBL boundary, which may be interpreted as penetration of the reconnecting flux tubes from LLBL to the mantle. As an alternative to reconnection, the interchange instability might be the possible mechanism for penetration of PMAF into the mantle (e.g. [27, 28]).

The keogram in Fig. 1 shows the tendency for the PMAF intensity to increase in the course of movement toward zenith. The apparent increase of the luminosity on the flat image may be caused by the pass of the auroras, which actually are three-dimensional structures, exactly through the magnetic zenith. The PMAF which we relate to reconnection has a complex configuration and consists of both rays and patch-like auroras (see Fig. 4). The set of available instruments does not allow us to conclude whether the local spot in the magnetic zenith in Fig. 4 is the cross-section of an auroral ray or is different auroral phenomenon. So, the size of the spot of about 10×20 km at an altitude of 240 km might be the transverse scale of both the ray and the reconnected flux tube.

5. CONCLUSION

A case study of aurora dynamic in the cusp region has been analyzed using ground-based optical measurements and data from the DMSP F17 and F16 satellites crossing the camera field-of-view one after the other within a 10 minute interval. An auroral keogram showed that the aurora development was conditioned by the IMF variations. Sharp changing of the IMF B_z component from positive to negative values caused the partial reconstruction of the dayside magnetosphere so that the aurora activity of a PMAF-like type was shifted southward and the cusp moved to the zenith of the all-sky camera at the

Barentsburg observatory, i.e. southward of its statistical position ([2]). On the other hand, the large negative B_z and $B_y \sim 0$ create favorable conditions for dayside reconnection.

For correct matching of the optical and satellite measurements we used the package of procedures developed for the multi-camera project ALIS (Swedish Institute of Space Physics) as well as the altitude of the auroras inferred directly from the precipitating electron data measured on board the DMSP satellites instead of a-priori information. It was shown that the weak bursts of electron precipitations detected by the F17 satellite inside the cusp are conjugated with the faint red auroras. The auroras look like rayed arcs and are located at the equatorial edge of the cusp-related precipitation. The spectrograms from the F17 satellite show that the auroras were generated by scattered rather than accelerated particles.

The single event of so-called poleward moving auroral forms was observed after the flights of the first satellite. We suggest that at the end of the event the source of the PMAFs was located in the mantle, i.e. on the non-closed magnetic field lines, and dayside reconnection could be responsible for the PMAF formation. The “reconnection hypothesis” is supported also by the presence of ion-energy dispersion on the satellite spectrogram. Note, however, that this assumption does not refer to the PMAFs that occurred before the F17 passage. In accordance with [28], the interchange-like instability might be a possible mechanism for the PMAF formation in this MLT sector, for example.

We also estimated the spectrum and altitude of the rayed arcs in the cusp, the energy of precipitating electrons responsible for the arc generation and the probable reason for that precipitation, as well as the transverse size of the auroral ray/reconnected flux tube that may be of practical value for further investigation of the dayside auroras.

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**Полярные сияния в каспе и его приполюсной окрестности:
исследование отдельного события
(расширенный реферат)**

Процессы взаимодействия солнечного ветра с дневной магнитосферой являются важным звеном формирования космической погоды, поскольку именно посредством этих процессов осуществляется перенос энергии и вещества из межпланетной среды в околоземное космическое пространство. При отрицательных значениях межпланетного магнитного поля (ММП) его силовые линии становятся антипараллельными силовым линиям геомагнитного поля в окрестности подсолнечной точки на магнитопаузе. Такая ситуация неустойчива и приводит к пересоединению силовых линий ММП с силовыми линиями, формирующими магнитопаузу. Пересоединившиеся силовые трубки сносятся солнечным ветром в хвост магнитосферы, где скапливаются, увеличивая тем самым магнитную энергию хвоста. Магнитная энергия высвобождается в ходе магнитосферной суббури — одного из наиболее сильных катаклизмов космической погоды. В процессе сноса в магнитосферный хвост пересоединившаяся силовая трубка пересекает магнитосферный домен, называемый каспом. Геометрия геомагнитного поля такова, что в околополуденные часы основание каспа оказывается над Шпицбергенем, и высыпавшиеся из пересоединившейся трубки частицы теоретически могут оставлять в ионосфере над Шпицбергенем «след» в виде дрейфующих к полюсу слабых форм дневных полярных сияний.

В зимнее время года, когда на широте Шпицбергена темно даже в полуденные часы, эти слабые сияния могут быть обнаружены наземной оптической аппаратурой. Проблема заключается в том, чтобы в сложной картине дневных сияний выделить те, которые «произведены» высыпавшимися из каспа электронами. Откуда сыплются электроны, можно понять, анализируя данные низкоорбитальных спутников серии DMSP. Вторая сложность обусловлена тем, что наземному наблюдателю требуется в относительно короткий период времени, когда оптическим наблюдениям не препятствует ни солнечный, ни лунный свет, в безоблачный полдень, при отрицательных значениях ММП зафиксировать сияния при условии, что спутник DMSP пролетал не просто через поле зрения камеры, но пересекал при этом область каспенных высыпаний. Понятно, что такое стечение обстоятельств встречается крайне редко даже при регулярных оптических наблюдениях на Шпицбергене. По этой причине теоретическая гипотеза о том, что результат пересоединения можно «увидеть» с земной поверхности оптической аппаратурой, хотя и была предложена более пятидесяти лет назад, до сих пор остается дискуссионной.

В работе исследован редкий случай одновременной регистрации дневных полярных сияний наземной оптической аппаратурой и детектором высыпавшихся

частиц на спутниках DMSP F16 и F17. Оптические измерения проводились камерой полного обзора неба Полярного геофизического института (ПГИ), установленной в обсерватории Баренцбург на арх. Шпицберген. Особое внимание уделялось точности сопряжения участков траектории спутников с областями, занятыми свечением. Для этих целей использовался пакет программ, разработанных в Шведском институте космической физики, позволяющий по расположению звезд на снимке камеры каждому пикселу изображения сопоставить физические координаты на плоскости, где располагался максимум свечения и на которую затем спутниковый фрагмент траектории «проектировался» вдоль силовой линии геомагнитного поля.

Следуя развороту вертикальной компоненты межпланетного магнитного поля (B_z -компоненты ММП) в область отрицательных значений, система слабых лучистых дуг сместилась к югу, после чего одна из дуг начала дрейфовать обратно к полюсу и пропала. Разворот B_z привел к тому, что подошва каспа тоже сместилась к югу от своего статистического положения (над поселком Нью-Олесунн) и оказалась в центре поля зрения камеры в Баренцбурге. Спутник DMSP F17 пересек касп спустя двадцать минут после разворота B_z -компоненты. Положение и сияний, и спутника в центре изображения, даваемого камерой, позволило снизить искажения, вносимые объективом типа «рыбий глаз» на больших расстояниях от зенита (в частности, над Нью-Олесунном).

Совместный анализ оптических и спутниковых данных показал, что наблюдаемые слабые лучистые дуги находятся в области каспённых высыпаний и пространственно связаны с всплеском высыпающихся электронов с энергией менее 100 эВ. Следующий спутник DMSP пересек поле зрения камеры спустя десять минут после первого, и анализ его данных показал, что эта дуга в момент исчезновения находилась в области разомкнутых силовых линий. Этот результат, дополненный специфической формой протонных высыпаний в данных спутника DMSP, которую традиционно связывают с пересоединением, позволил нам прийти к выводу, что смещавшаяся к полюсу слабая лучистая дуга могла представлять собой ионосферный след только что пересоединившейся магнитной силовой трубки, уносимой солнечным ветром в антисолнечном направлении. Результат подтверждает теоретическую гипотезу о том, что в некоторых ситуациях дневные полярные сияния могут представлять ионосферный след пересоединения. С этой позиции регулярные оптические наблюдения на Шпицбергене можно рассматривать как один из способов мониторинга космической погоды, создающий предпосылки для ее прогнозирования.