Auroral Oval Dynamics in Different Spatial Scales

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The present paper deals with a detail study of the dynamics of the polar cap boundaries. The study involves the data from two satellites of the APEX project, and the data from three DMSP satellites. The APEX (Active Plasma Experiment) satellites moving along the polar orbit provide charged particle measurements in a small spatial scale (due to changeable distance between both spacecrafts), up to 2000 km. The large scale changes are studied by the comparison of the APEX and the DMSP (Defense Meteorological Satellite Program) data. Different regions are identified using the characteristics of the precipitating particles in the energy range 0.1–20 keV which have been registered onboard all satellites. This satellite configuration allows us to determine the evolution of the small structures as well as the motion of the whole precipitating region. The main attention is concentrated on the rising phase of the substorms when the width of the auroral oval decreases with the increasing geomagnetic activity and the velocity of the auroral oval motion can reach 0.2° per minute. The observed phenomena are compared with the changes of the interplanetary magnetic field and the solar wind parameters as provided by the IMP-8 spacecraft.

1. Introduction

The auroral oval dynamics has been intensively studied by many authors during the past decade because all processes in the distant magnetotail are mapped into this region and can be studied by numerous satellites which cross the polar oval in low and middle altitudes. The dayside part of the auroral oval and/or the polar cusp region varies its latitudinal position with the geomagnetic activity and with the \( B_z \) component of the interplanetary magnetic field (IMF) (Burch, 1979). The dayside auroral oval location is at lower latitudes as the geomagnetic activity increases (Burch, 1972); the main effect of the IMF \( B_z \) component is an equatorward shift of the midday auroral oval (or the polar cusp) when the IMF \( B_z \) becomes more negative. A large amplitude of \( \geq 15^\circ \) latitudinal movement of the cusp within a few hours was detected during intense storms. This shift is clearly correlated with ring current intensity (Meng, 1984).

The linear relationships of the equatorward shift of the nightside auroral oval position and the decrease of the IMF \( B_z \) magnitude along with the increase of geomagnetic activity were established. The equatorial boundary position of the night oval is far less sensitive than the polar cusp region to small-scale variations of IMF \( B_z \) and weak substorms (e.g. Kamide and Akasofu, 1974; Holzworth and Meng, 1975). These dependencies—on the geomagnetic activity and on the IMF \( B_z \) component—are not controversial because the southward turn of \( B_z \) is often considered as the initialization mechanism for the substorms or storms. Craven and Frank (1991) reported a rapid poleward motion of the poleward boundary and a less rapid equatorward motion of the equatorward boundary of the nightside oval during the expansion phase of the substorms. The same authors (Craven and Frank, 1987, 1991) have pointed out that the motion of the aurora can begin at relatively localized sites at local time, generally centered at 22–24 hours MLT. The global oval dynamic has been mostly studied by optical observations (Meng and Lundin, 1986) because a similar study of the precipitating particles needs real multipoint measurements. The comparison of the optical imaging of the oval with simultaneous in situ particle measurements is made by Newell et al. (1992). All studies of the oval location take the equatorward boundary position as the measure because the poleward boundary seems to be much less stable and it is a subject of fast random changes. The latitudinal
width of the auroral oval has not been studied separately but it can be derived from the statistical studies of the particle precipitation that there is a general trend of the latitudinal width increasing if the $K_p$ index rises. This trend is independent of MLT but the day-part of the precipitating region is always narrower than the night-part.

Our study is based on the simultaneous measurements of the precipitating particles in the northern hemisphere by five spacecrafts (three DMSP satellites and two APEX satellites) in the beginning of the 1992 year. We have paid attention to the global morphology of the morning and evening sectors of the oval in the large temporal scale (orbit to orbit) as well as in the small scale (few minutes) variations. Similar study of the morning sector has been done by Něméček et al. (1996).

2. Instrumentation and Data Set

The data analyzed in this paper have been obtained by the charged particle spectrometers onboard of two APEX (Active Plasma Experiment) satellites launched into polar orbit at the end of the 1991 year. The charged particle package consisted of several electrostatic analyzers which measured electron and ion fluxes in 16 energy steps placed logarithmically in the range from 0.2 to 25 keV. The spectrometers had narrow angular characteristics and they had been directed into different directions to obtain optimal pitch angle coverage. The data from different directions were measured simultaneously with the time resolution 0.8 sec/spectrum for the subsatellite and 2.6 sec/spectrum for the main satellite. (A more complete description has been published in Něméček et al. (1993).) For our study it is most important that the both satellites moved along the same orbit with the distance between them up to 4 min.

To study the global structures we have combined our measurements with the processed data from three DMSP satellites. These satellites are all polar-orbiting satellites (Hardy et al., 1984) in nearly circular polar orbits of about 840 km altitude. The spectrometers onboard provide the electron/ion distribution once per second in the energy range from 0.03 to 30 keV in twenty logarithmically spaced steps. The detector apertures are always pointed toward the local zenith. For our purpose, we have used the automatically processed data to classify the precipitating particles into seven different regions of their probable source (Newell et al., 1991). We have followed this classification but we have divided the precipitating region into two parts only. The region where the high energy particles are observed and the energy spectrum changes slowly is called the diffuse region and corresponds to the particle precipitation from the central plasma sheet (Newell et al., 1991). Other regions with non-negligible precipitating flows have been named the discrete aurora region. In the night sector of the auroral oval it usually corresponds to the precipitation from the boundary plasma sheet.

The boundary between the discrete and diffuse regions is very clear, it is, as a rule, characterized by the sharp change of the energy of precipitating particles and by the abrupt randomize of the precipitating flows.

The one minute averaged IMF data from IMP-8 were used to complete our data set.

3. Experimental Results

Dynamic properties of the precipitating particles can be studied from many points of view. We suppose that the equilibrium position of the precipitating regions is determined by the solar wind parameters and by the value and the direction of the interplanetary magnetic field. Nevertheless, due to a tremendous volume of the magnetosphere and different kinds of interactions involved, the response to the changes of the IMF and solar wind parameters has many time constants which vary from minutes to days and the magnetospheric system is never fully relaxed. For this reason we have chosen for our detail study the geomagnetic disturbance which occurred on April 4, 1992 and which started from a relatively long period of the weak geomagnetic activity. The other reason for our selection is connected with the fact that during this time there are three DMSP spacecrafts orbiting along the dawn/dusk meridian and thus we have a sufficient temporal resolution of our observation. Moreover, the IMP-8 spacecraft was
operating in the solar wind during the time interval under question and the magnetospheric data are supported by simultaneous solar wind and IMF measurements. The evolution of the auroral oval boundaries on ≈6:00 and ≈18:00 MLT completed with the $K_p$ and $D_s$ indexes and the magnetic field data are summarized in Fig. 1. A plot of the $B_z$ IMF component shows that this component becomes positive for five hours and is negative during following 4 hours. The IMF data after 9:00 UT are not reliable because the IMP-8 is moving probably in the magnetosheath.

The event starts from very quiet geomagnetic conditions ($K_p = 0^+$, IMF $B_z$ positive, and $D_s = 10$). The auroral oval is relatively broad, about 17° of latitude, and its poleward edge reaches 85° of latitude for both

![Fig. 1. Evolution of the geomagnetic disturbance (from top to bottom: IMF modulus, IMF $B_z$ component, $D_s$ index, $K_p$ index, the maximum energy flux carried by precipitating electrons at 06:00 MLT - full line and 18:00 MLT - dashed line, position of the auroral oval-horizontally hatched area corresponds to the diffuse aurora, vertically hatched area corresponds to the discrete aurora).]
MLT. Both the ion and electron precipitating currents are very low. Despite the IMF $B_z$ being positive up to 5:10 UT the auroral oval moves rapidly toward the equator. This fluctuation can be caused by the slight increase of the solar wind dynamic pressure (not shown in figure) which proceeds up to 9:00 UT. After this time no solar wind data are available. The increase of the geomagnetic activity between 3:00 UT and 6:00 UT is connected with the intensification of the ring current intensity as documented by the $D_{st}$ index.

During the rising phase of the substorm the auroral oval continues its equatorward movement until a saturation is reached. This movement is more distinct on the poleward boundary. It results in the decrease of the auroral oval width which is associated with the intensification of the particle precipitation. The total precipitating current peaks at the region of the narrowest oval.

The auroral oval is divided into two parts which correspond to the diffuse and discrete aurora regions in Fig. 1. It should be noted that the boundary between these two regions is more stable than the regions themselves. The equatorward motion of the auroral oval proceeds in the way that the proportions between the diffuse and discrete auroras change in favour of the diffuse region but the position of the boundary between them remains nearly unchanged. The most interesting feature of the described events seems to be the decrease of the width of the auroral oval with the $K_p$ increasing. However, the position of the spacecrafts does not allow us to study this process along a greater part of the auroral oval.

Figure 2 shows two consecutive maps of the night-part of the auroral oval as determined by the APEX and the DMSP spacecrafts. Each map represents a snap-shot of the precipitating regions as all crossings shown in the particular panels in Fig. 2 occurred within a few minutes. In this case the geomagnetic situation is similar to that in Fig. 1 at 6:00 UT (i.e. rising phase of the weak substorm, $K_p=3$, $B_z$ IMF negative). The comparison of the both panels in Fig. 2 shows that the equatorward boundary remains almost stable but the position of the poleward boundary is subject to remarkable changes. In the left panel this boundary has a shape of two circles with diameters which differ by about 10°. The change from one to another is abrupt and occurs at 2:00 MLT. On the next orbit of spacecrafts (right panel of Fig. 2) the change of diameters occurs for a higher MLT. This effect is well known from auroral images and is called auroral bulge (see Lyons (1991) for a review). From the point of view of temporal evolution of the auroral oval position at given MLT this effect will be interpreted as a fast shift of the poleward oval boundary and, because the equatorward boundary remains at the same position, as the latitudinal contraction of the precipitating region. We suppose that by this mechanism the higher dynamics of the poleward boundary, which is demonstrated in Fig. 1, can be explained.

There can be three basic reasons for the auroral oval displacement toward the lower latitude:

1. The change of the source of the precipitating particles to another which is mapped to the lower latitudes.

![Fig. 2. Dynamic changes of the auroral oval as measured by the DMSP and APEX satellites on February 28, 1992 (thick lines - crossings of the auroral oval, numbers - minutes and seconds of the boundary crossing, dashed line - estimated shape of the boundary).](image-url)
(2) The displacement of the same source to lower latitudes (with the same conditions for the magnetic field change).

(3) The position of the particle source and the field geometry remain but the precipitating particles are pushed toward lower latitudes by an external force (i.e. $E \times B$ drift) somewhere along their path to the ionosphere.

These changes should be completed with the decrease of the magnetic field gradient at ionospheric altitudes to allow the observation of these particles at such altitudes.

To distinguish among these possibilities we have studied the spatial and energetic structure of the precipitating particles. Figure 3 shows two consecutive measurements of the electron energy spectra across the dawn part of the auroral oval. The spectra were measured by two APEX satellites on orbit No. 985 (10.03.1992). Both satellites moved along the same orbit and in this particular case the subsatellite was delayed by 244 sec in respect to the main satellite. The geomagnetic situation corresponds to that which occurred at 6:00 UT in the event depicted in Fig. 1 (IMF southward, $K_p = 3$, MLT = 10). If we compare the upper and lower parts in Fig. 3, corresponding fine structures can be clearly identified in the precipitating region despite the fact that the whole region was displaced by 0.7° of latitude toward the

Fig. 3. Spectrograms of the electron precipitation in the morning sector of the auroral oval (horizontal axes of the panels correspond to the same interval of INL, MLT = 10:00, the corresponding structures of the precipitating flow are marked by arrows).
equator and the latitudinal width of the given structures is less than 0.5°. The equatorward shift of the precipitating region follows the increase of the negative value of the IMF $B_z$ component and is more distinct on the equatorward boundary in this particular case. This and all similar cases under study lead to the conclusion that the precipitating region moves as a whole, i.e. the field lines which connect the source of the particles with the observed region are not disrupted during the oval displacement.

4. Discussion

The presented experimental results exhibit many features which are typical for the evolution of the geomagnetic disturbances. We do not use the term "substorm" up to now because it is difficult to connect the observed features with different phases of the substorm activity. We cannot use the traditional definition given by Akasofu (1964) because we have not got optical images of the aurora for the chosen time interval. From Elphistone et al. (1995) who compared the optical images with the simultaneous measurements of precipitating particles under conditions similar to ours it follows that probably the sharp enhancement of the energy flux which occurred after ~ 6:30 UT can be considered as the substorm onset. The other definition of the substorm onset (Rostoker, 1991) is based on the change of the geomagnetic indexes. The most frequently used the $AE$ index is not computed for the time interval under question. If we use the $K_p$ index as an indicator we can note that the rise of this index starts probably before the change of the IMF $B_z$ polarity. However, the southward turn of the IMF is clearly connected with the decrease of the $Dst$ index.

If we follow the idea that substorms are initiated by the southward turn of the IMF we should note that this is true for the geomagnetic indexes and probably for the equatorward shift of the equatorial boundary of the auroral oval. A good correlation between the $Dst$ index and the position of the oval equatorial boundary has been noted by Meng (1984) and suggests that the intensification of the ring current can be the source of the boundary motion (Siscoe, 1979). However, the poleward boundary starts its equatorial motion earlier than $B_z$ becomes negative as is demonstrated by Fig. 1. This boundary probably either follows the slight continuous increase of the solar wind dynamic pressure or moves due to multiple decrease of the IMF $B_z$ component (but not to negative values) which occurs in this time interval. The poleward boundary is a projection of the outer part of the plasma sheet boundary layer and thus should be sensitive to the fluctuation of the solar wind parameters and to the magnetic field reconfiguration which follows each change of the IMF direction.

The way of the motion of the poleward boundary which is shown in Fig. 2 suggests that the shift of the boundary is probably caused by the magnetic field reconfiguration because the increase of the solar wind dynamic pressure would affect the whole boundary. The way of the stepwise expansion is characteristic for the poleward boundary and is likely connected with the fact that the active aurora begins at a relatively localized site during the expansion phase of the substorm (Craven and Frank, 1991).

Another interesting feature of the polar oval expansion is a redistribution between two, clearly distinguishable, types of precipitation. The initial contraction of the auroral oval width is caused by the narrowing of the discrete aurora region. The successive equatorward shift of the equatorial boundary is a consequence of the expansion of the diffuse aurora region. These two effects result in the fact that the boundary between these two types of precipitation is more stable than the oval itself during the expansion phase of the substorm. This boundary is generally accepted as a boundary between the regions with closed and opened field lines. Its stability during the initial phase of the substorm indicated that the small changes of the magnetic field configuration which are connected with the equatorward movement of the polar edge of the auroral oval did not change the magnetic field configuration equatorward of this boundary.

Figure 3 documents that even during a fast displacement of the auroral oval the magnetic field reconfiguration proceeds quasistationarily and the field lines are not disrupted. All possible mechanisms which can cause this displacement lead to the presence of the perpendicular electric field of the order of 10 mV/m for the observed velocity (0.2° per minute). This value of the electric field is in a good agreement with observed values.
5. Conclusion

The present study is based on the comparison of the observations of the charged particle precipitation in different temporal scales. From this study it follows that

- during the rising phase of substorms the width of the precipitating region decreases at all MLT but not at the same time
- the shift of the auroral oval can proceed without the disruption of the field lines
- the velocity of the auroral oval shift can reach for a short time a value of 0.2° per minute
- the behaviour of the regions of the discrete and diffuse auroras during the rising phase of the substorm is different.

These conclusions are based on the comparative study of the events which occurred in the first quarter of 1992 year. In the future, we intend to carry out a statistical study of the mentioned phenomena involving a larger data set.

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