Auroral Activity of the Polar Boundary Arc and the Equatorial Part of an Oval During Substorms

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Abstract. A substorm scheme with independent development of the activity in the inner magnetosphere and at the trapping boundary in the magnetotail regions is discussed. As examples analysis of the auroral TV observations during several substorms is presented.

1. Introduction

After the works of *O.B. Khorosheva* [1961]*, Ya.I Feldstein and G.V. Starkov* [1967] showing, that the instant picture of polar aurora looks like the closed ring or oval, it has passed a half-century, and still there is no established view on three-dimensional structure of an nightside substorm magnetosphere. It has been suggested that the poleward border of the oval corresponds to border of the closed magnetic field lines, while the equatorward border corresponds to inner plasma sheet boundary located in some depth inside the quasi-trapping zone. However this opinion is not commonly accepted. The existing disagreement in the discussion of the geometry and dynamics of the magnetoshperic three-dimensional projection to the auroral oval reflects the diversity in the models of a substorm.

At any specific moment the oval is inhomogeneous - auroral forms in the different parts of the oval can have a different nature. Frequently a double oval is observed with an active aurora on southern and northern boundaries of an oval and with a decrease of a luminescence in between [*Elphinstone*, 1994]. Though in the disturbed time the aurora both at equatorward and poleward boundaries of the oval be active, but the are no synchronization of these activities.

In this work we will summarize characteristics and differences of auroral dynamics inside the oval and at its poleward boundary and we introduce a scheme of a substorm, supposing independence of the associated physical processes in the trapping region and in the tail of the magnetosphere.

2. On the Models of a Substorm

There are many different models of a substorm [see review of *T. Lui,* 2000], but if only the geometry and direction of propagation of substorm activity are considered, there remain two or three model types. Figure 1 can be used to demonstrate the main differences. Point "A" indicates the nightside magnetosphere region or rather several regions with several different names and physical meaning but the same location: the internal magnetosphere, trapping or quasitrapping region, the auroral magnetosphere, inner boundary of a plasma sheet and the geosynchronous region. Similarly "B" point out the gradient boundary of a magnetic field, the trapping boundary, boundary of the closed field lines, braking region, - again the names and

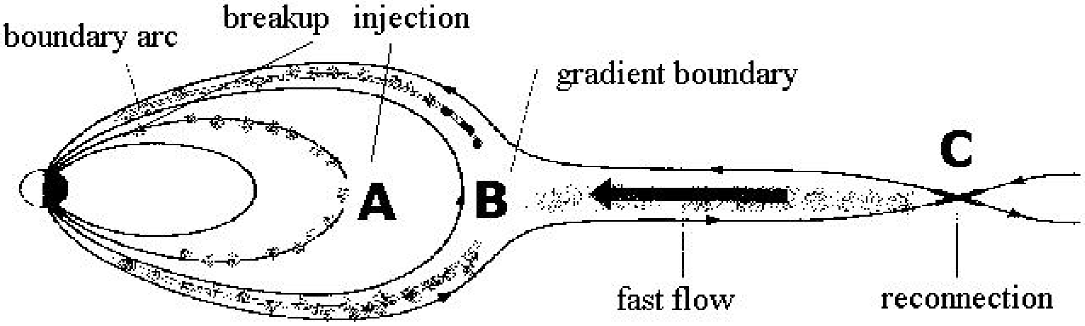

Figure 1. Model of the Earth's magnetosphere

definitions are different, but the geometric position is roughly the same. And the third area "C" specifies position of a near-earth line of a reconnection which supposed to be located at approximately 30 Earth radii. During a substorm certain disturbances are observed in all three areas. The basic disagreement between the two main groups of substorm models relates to the evolution and the propagation direction of the substorm activity.

The first group of models assumes propagation of activity after the beginning of a substorm in a direction "C-B-A". In the near-Earth reconnection model (NENL), the substorm starts with reconnection at distances of 30-50 Re. Then accelerated plasma propagates in two directions - tailward and toward the Earth, and the Earthward movement from a point "C" to "À" results in an acceleration of particles up to hundreds keV, so-called injections. However, detectors at the geostationary orbit register sometimes fast sharp increase of intensity of energetic particles, without energy dispersion and both electron and ion increase occur almost simultaneously. This does not agree with radial injection scheme, because the dispersion due to the differences in speeds and the effects of the magnetic drift are inevitable. Therefore model was updated in such a manner that at gradient boundary (braking region) the fast streams of plasma get decelerated and give back energy to the buildup of a substorm current wedge and acceleration of auroral particles. Then from gradient boundary deep into magnetospheres propagates an impulse of a magnetic field, the wave of compression, which causes dispersionless acceleration of energetic particles. In this model presented by *Reeves* [1998] the injection of energetic particles (in a point A) are displaced in space and in time from the substorm current wedge and auroral breakup (in a point B), which contradicts the convincing experimental evidences of their detailed temporary and space correlation [*Lazutin*, 1999].

The models of a substorm in the inner magnetosphere assume opposite development of events, from "A" to "C". According to this group of models, the explosive substorm instability starts at "A" spontaneously or due to some trigger effect , and the subsequent expansion of activity tailward creates in the tail a configuration of a magnetic field, that is suitable for development of a reconnection.

We do agree that substorm starts in the inner magnetosphere, but it is not necessary to link it directly with substorm activity in magnetotail.
Indeed, during some substorms, which makes about 20 % of the total number, the expansion reaches up to 80° and even 85° geomagnetic latitudes [*Mende et al.,* 1998]. But most often substorm expansion terminates well inside the quasi-trapping region.

In the present paper we propose to overcome the contradictions of the above described approaches by assuming independent development of substorm activity in the inner and outer magnetosphere. It is possible to take for a basis the model of a spontaneous beginning of a substorm in the inner magnetosphere and at the same time independently reconnection and fast flow bursts braking at the trapping boundary. The energy can be transferred to the inner magnetosphere gradually, in several steps and the compressive waves do not play important role in energetic particle acceleration or injections.

3. Polar aurora at the boundary of an auroral zone.

Independence of substorm activity in the inner magnetosphere and magnetotail can be seen in auroral observations. The equatorial part of the double oval has been discussed in the literature more often because the epicenter of the substorm onset in located here. The existence of poleward boundary arcs has been known for a long time, [*S.I. Isaev,* 1968], but their importance for substorms has not been examined. Perhaps, only *Elphinstone* [1996] named polar arcs as one of main substorm modules. We will show several examples to illustrate main features of boundary arcs. We have been using television observations on the Kola Peninsula and all sky cameras recordings made in Finland.

On figure 2-4 we present N-S keograms of polar aurora constructed on the TV auroral records of Loparskaya and Lovozero Observatories. Scanning the sky along the central meridian one can see the boundary arc at geomagnetic latitude 71-74˚. (The latitude scale in a keogram is only approximate, because near to horizon the errors are large). This is the same where the narrow weak auroral arc is visible in magnetically quiet time. It is reasonable to assume, that in a projection to the equatorial plane the boundary arc corresponds to the gradient boundary of a magnetic field, where particles moving from the tail begin to undergo gradient drift and where the braking region is supposed to be located.

The upper section of figure 2 shows the keogram of polar aurora measured at Lovozero during the substorm 1857UT 11.11.1999. During the growth phase, 15-5 minutes prior to the breakup, the boundary arc was visible together with a series of diffuse arcs moving equatorward.

After the beginning of an active substorm phase during the first poleward expansion, the boundary arc continued slow drift to south until the beginning of the second intensification at 1905 UT.

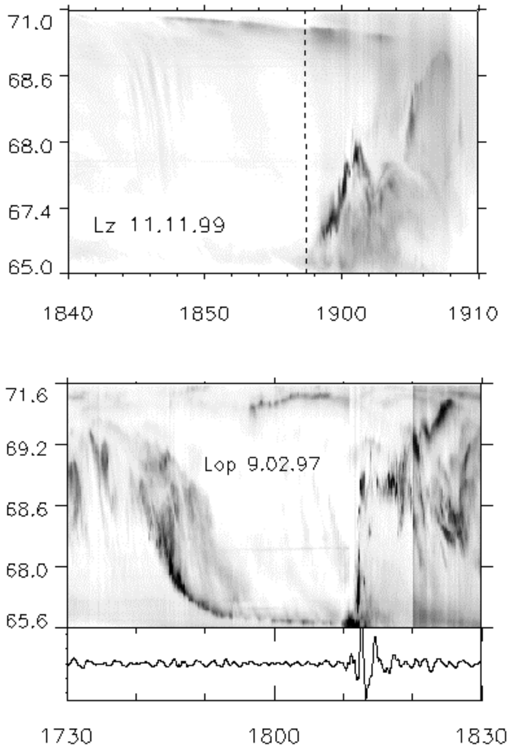

Figure 2. N-S keogramms made from auroral TV records of Loparskaya and Lovozero Observatories of PGI on Kola Peninsula.

During a substorm 1810 UT 9.02.97 (Fig. 2, bottom) the boundary arc was present more than an hour during the growth and expansion phases. Sometimes the arc splitted into two arcs, sometimes it brightened, and thus it behaved differently from the substorm activity in the main auroral oval. Decrease of the arc brightness after a breakup is an artificial effect, the operator in the observatory has reduced sensitivity of the TV camera as the bright active auroras appeared.

The upper section of figure 3 shows the keogram of a substorm of 26.03.98. Again the boundary arc is active during the growth phase, but with the beginning of then expansion the boundary arc disappeared (or became weak). Expansion was large this time and possibly boundary arc was shifted further to the North for a short time, but later it again appeared at its old place.

The independence of activations of the polar and equatorial parts of a double oval is illustrated by the keogram in the bottom part of figure 3. The splitting of the boundary arc into two or three parts visible in this keogram is a typical feature.

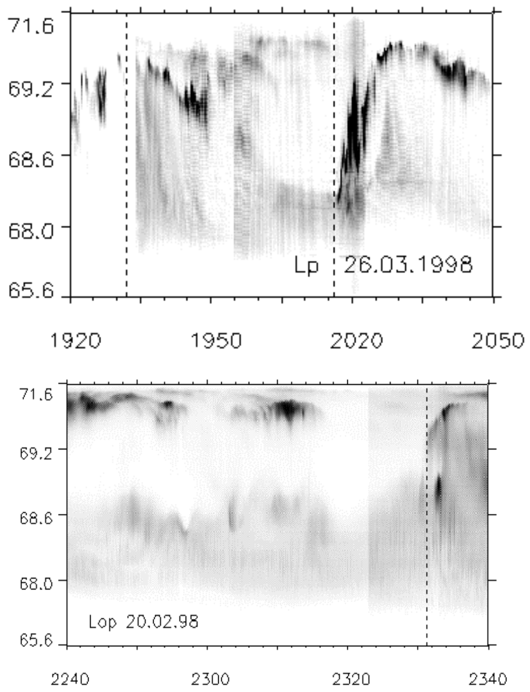

Figure 3. Keograms of the auroral sibstorms of March 26 and February 20, 1998.

As soon as the poleward arc show signs of displacement to the south, there arrives a new boundary arc on its place. Usually the most poleward arc is weak and the displaced arc is more active.

The observations in Lovozero and Loparskaya often do not allow to consider details of the activations of the polar arc when it was too close to the horizon. For this purpose we used measurements on the Finnish stations, in particular Kevo station, where the boundary arcs often occur near the zenith. The activation there was not a simple brightening, but an active process with folds, curving, and occasional explosive breaks of structure, but shorter and local, than in the main auroral zone.

The boundary arc typically stays at the same latitude or is slightly displaced toward equator. However, as it was mentioned before, there are substorms expanding deep into the polar cap and there are some cases with the significant shift of boundary arc to the south (or possibly the real boundary arc is not visible). It is important to note, however, that the double oval configuration often persists and the distance to the equatorward part remains not less than 2 degrees of latitude.

4. Separate development of a substorm at the boundary of trapping region and inside it

According to auroral activity we have two spatially separated areas of substorm activity: internal part of the auroral oval with the equatorial arc and a poleward part of an oval with a boundary arc. Both areas became active during substorm, but activations are independent and are not synchronized. Of couse there are definite links between these two regions displayed to us in a form of auroral arcs drifting from the boundary arc equatorward. During the growth phase the arcs presumably provide energy transport and accumulation. But direct sequence between the events in these two regions are absent.

In the equatorial plane of the nightside magnetosphere also there are two or three separate substorm activity regions, shown as A, B, and C on figure 1. Particle intensity and energy spectrum are different there, as well as character of particle motion and relation with the magnetic field. Significant number of the studies have been published to prove that substorm activity is a single global phenomenom and that there are direct sequence of events propagating from the magnetotail earthward or in the opposite direction. Gathering observational support for this conclusion is difficult, because substorm consists of a sequence of localized activations of 1-2 minute duration and with a data of two satellites, one in the magnetotail, another in the inner region, it is difficult to select proper pair of the events for the comparison. We suppose that fast impulsive substorm events in the inner magnetosphere and magnetotail are independent, and to verify this idea, it is necessary to link the two auroral regions with the regions in the equatorial plane.

There are strong experimental evidences showing that equatorial arc and active aurora are projected to the trapping or quasi-trapping regions. Active aurora during substorms are closely coupled with bremstrahlung X-ray bursts which were registered in stratosphere [*Winckler et al.*, 1958, *Lazutin*, 2000]. X-rays are produced by energetic electrons precipitating into the atmosphere. Injections are the only source of such precipitation. Both individual examples and statistics imply that injections of energetic particles take place in the trapping or quasi-trapping region.

On the other hand, there is plenty of experimental evideence, that during substorms the magnetotail responds by dynamic transformations in the of a magnetic field structure and enhanced plasma flow. What part of the high-latitude polar region may be considered as a magnetotail plasma sheet conjugate area? Auroral and magnetic activity in the polar cap are decreasing during substorm. The central and equatorial part of the auroral oval are projected to the inner magnetosphere. Therefore only the boundary arc region remains, and it is an appropriate candidate for the projection of the magnetotail activity.

The magnetic gradient boundary is the first natural barrier to radial particle transport into the auroral magnetosphere. Reduction of the magnetic field lines length is equivalent to the fast extension of a loss cone and therefore even during the quiet time there always faint auroral arc is present. Arrival and the braking of high-speed particle streams may sharply increase the brightness of auroras and cause activations - derivation folds, curves etc. It was shown by *Nakamura et al.*, [2000] that 60% of the flow burst events observed by Geotail were associated with the auroral high-latitude activations and auroral streamers and therefore directly related to the polar boundary region, while remaining bursts coincide with the auroral activations during substorm expansion and pseudobreakups, when it is difficult to separate the poleward and equatorward oval regions using Polar UVI images.

Therefore we can accept the substorm model of *Reeves* [1998] describing the importance of the braking region as an focus of the magnetotail substorm activity with one exception: it is difficult to agree, that arrival of immediately produce compressive wave which immediately accelerates energetic particles and trigger substorm in the inner magnetosphere.

In the cases analyzed in this study the activations in the boundary arc began well before the substorm onset, and the appearance of the southward moving auroral arcs. If the braking of high-speed streams will develop a wave of the compression accelerating energetic particles, it is naturally to expect, that such wave would cause auroral signatures. The arcs, moving equatorward are the only objects which can be regarded as such signatures. If it is true, then compressive waves occur before the substorm onset and thus they cannot be regarded as a substorm trigger and as a source of the injection of energetic particles. Moreover, it is generally believed that the motion of arcs equatorward during the growth phase is controlled by the convection electrical and is not related to the waves of compression.

There still remains open questions like: why equatorward movement is not continuous but have discrete character? Does the electric field has an impulse nature, or do the source particles occur only from time to time? Surprisingly, but these questions have not attracted attention.

From the basis of auroral observations we conclude that the braking region, conjugated with the boundary arc indeed receive energy from the magnetotail in the form of FFE high-speed streams of particles arriving, probably, from the area of a reconnection in a tail and transmitting energy to the inner magnetosphere. But this transmission is not a single powerful shock wave but several moderate, possibly localized energy impulses. Thus the energy gradually accumulates for the following release with the beginning of the substorm expansion phase.

Such indirect, accumulative link of a substorm in an auroral zone with processes in a tail of the magnetosphere can explain delay of activations in the internal magnetosphere versus to the activations in the magnetotail as reported in a number of experimental studies.

Conclusion

The model of separate development of a substorm activity in the inner magnetosphere and in the magnetotail is discussed. To support this concept the observations of polar aurora were used.

It is shown, that the polar boundary arc behavior is independent from the substorm development in the equatorial region during the growth phase and expansion. It is possible to assume, that the sources and mechanisms of acceleration of the associated particle fluxes are different.

The poleward boundary arc is projected to the magnetic field gradient boundary which is also the boundary of the quasitrapping region. Auroral activations here are connected with arrival and braking of high-speed streams of particles probably born during a reconnection in a tail of a magnetosphere.

Earthward of the poleward boundary arc the equatorward arc and active auroras are observed after the onset of a substorm. They are definitely linked to the injection of energetic ions and electrons and the dipolarization of a magnetic field in the trapping or quasitrapping region.

The energy from boundary of the closed field lines (braking region) is transferred deep into the inner magnetosphere by means of radial drift of plasma or waves of compression. We see this process in aurora both as a movement of separate arcs and as a shift to the south of the area of the luminosity as a whole. Compression waves or convective particle transport seem not to be triggerers of the substorm onset or energetic particles injections. They help to accumulate the energy necessary for the development of explosive instability of a substorm occurring in the inner magnetosphere accompanied by fast energetic particle acceleration.

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