STUDY OF SUBSTORMS OCCURRENCES AT HIGH LATITUDES DEPENDING ON THE SOLAR WIND CONDITIONS

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Abstract: *All substorm disturbances observed in polar latitudes can be divided into two types: "substorms on contracted oval", which are observed at geomagnetic latitudes higher than 70° in the absence of substorms below 70° and "expanded substorms", which travel from auroral (<70°) to polar (>70°) geomagnetic latitudes. The aim of this study is to compare the conditions in the interplanetary magnetic field (IMF) and solar wind, under which these two types of substorms are observed on the basis of data from meridional chain of magnetometers IMAGE and OMNI database for 1995, 2000, and 2006–2011. It is shown that the main difference between the two types of substorms is related to the solar wind velocity. The "substorms on contracted oval" are observed at low velocity ($v < 500$ km/s) and "expanded substorms" - at higher values of velocity ($v > 500$ km/s). In addition,"expanded substorms" are observed during high temperature and pressure conditions in the solar wind (avg $P\sim > 2$ nPa; avg $T\sim > 2*10^5 K$). "Substorms on contracted oval" are observed mainly during positive values of IMF B_Y. It is shown also that "expanded substorms" are observed during high speed recurrent stream (HSS) in the solar wind. "Substorms on contracted oval", in contrast, are observed at the end of HSS or after HSS, during the late recovery phase of a magnetic storm.*

Introduction

Magnetospheric substorms have long been the focus of solar-terrestrial physics, however, till now the responsible physical process represent an outstanding unsolved problem. The temporal and spatial evolution of magnetospheric substorms remains an important and enduring problem in space plasma physics. It is well known that during the expansion phase of a substorm in the midnight sector, the westward electrojet and auroras can expand rapidly poleward sometimes reaching latitudes well above the typical location of the night side auroral oval (e.g., [1], [2], [3], [4]). Many studies have provided details of the spatial and temporal behavior of substorms and auroras at extremely high latitudes of an expanded oval ([5], [6], [7], [8], [9], [10], [11]). It is noted that "extremely high-latitudes" were called geomagnetic latitudes above 75º up to the geomagnetic pole ([7]). Often substorms which propagate to very high-latitudes, were considered as a separate type of substorms and were called "high-latitude substorms" ([4], [7], [11]) or "substorms with large poleward expansion" ([12]). Sometimes rapid poleward expansion was considered as different substorm phenomenon – "poleward leap" ([13], [14]). Some authors showed that "high-latitude substorms" occur more frequently under high solar wind values and during the solar cycle minimum, when the high speed recurrent streams from coronal magnetic holes prevail ([4], [7], [15], [16], [17]). During the solar cycle maximum when the magnetic clouds become the most typical solar wind disturbances, the so called "high-latitude substorms" are observed rarely and the substorms do not reach the polar latitudes ([15]).

It is known that during "quiet" periods the oval contracts poleward ([18]) and the IMF has in general a northward component. It was found (e.g., [19], [20]) that during such quiet periods, the magnetic disturbances are concentrated in a narrow latitudinal region near the pole, and substorms and auroras can occur along the contracted oval, beyond standard auroral zone. Thus, latitudes above the equatorward boundary of the "contracted" oval, i.e. the geomagnetic latitudes above 70º were called "high" latitudes ([20]).

The search for differences between substorms observed on the "normal", "compressed" and "extended" oval long attracted the attention of researchers ([21], [22], [23]). Often substorms were divided into different types - "confined" and "widerspead" ([20]), "localized" and "normal" substorms ([24]), "contracted oval" and "normal" substorms ([24]), "small" and "normal-size" substorms ([25]). In all these papers, comparisons were made between different substorm types and "normal" substorms. But in our work different types of substorms observed at high latitudes will be compared with each others. As follows from the dynamics of the auroral oval, at latitudes above 70º two types of substorms can be observed - substorms in conditions of “contracted” oval and substorms in conditions of “expanded” oval.

We call “substorm on contracted oval” the magnetic disturbance which starts at the geomagnetic latitudes above ~70º and then slowly propagates poleward, up to the maximal latitudes of observation (75.25º CGMLat - for the meridional chain of IMAGE magnetometers). It should be noted that there are no disturbances at geomagnetic latitudes below ~70º. It should be noted that in some papers the “substorms on contracted oval” are called differently -“confined” substorms ([20]); “small” substorms ([25]), “polar” substorms ([26]). It is shown that “substorms on contracted oval” do not differ from “usual” substorms in their characteristics, both in the vicinity of the auroral breakup substorm feature and in terms of total electrojet current ([22], [23], [24]). The “substorms on contracted oval” have plasma sheet signatures similar but less intense than the “usually” substorms and their activity is usually confined to some local time sector ([22], [20], [25]). It has been shown that “substorms on contracted oval” usually occur during northward IMF B_Z. Furthermore, in [25] is shown also that “substorms on contracted oval” were frequently observed during azimuthal IMF direction. By analogy with the name of the auroral oval position in disturbed conditions (“expanded” oval) we will call ”expanded substorms” the substorms which start in auroral zone and than propagate to very high latitudes. And in the maximum phase of the ”expanded substorms”, the westward electrojet (namely, the “center" of the westward electrojet) can be observed at very high geomagnetic latitudes (above 75º) ([11]).

Since these two types of substorms at high latitudes – “substorms on contracted oval” and ”expanded substorms”- occur at different geomagnetic disturbance, we can assume that they are associated with different conditions in the solar wind and IMF. In our study we compare the solar wind conditions observed for “substorms on contracted oval” and ”expanded substorms”. For this purpose the IMAGE magnetometers data have been compared with the interplanetary medium parameters from OMNI database.

Data

We used the magnetic data of the IMAGE meridional chain Nurmijarvi - Ny Alesund, from 56.9º to 75.25 º of geomagnetic latitudes. To construct the latitudinal profile of the westward electrojet, we used the MIRACLE model of the corresponding electrojet currents development (http://www.space.fmi.fi/MIRACLE/). The solar wind and Interplanetary Magnetic Field parameters measured by Wind spacecraft were taken from OMNI database.

Fig.1 demonstrates the example of the westward electrojet currents extension as it was observed by the IMAGE magnetometer network during a substorm on 29 July 2000. Fig.1 was derived from the one dimensional (1D) equivalent ionospheric currents calculated with the MIRACLE model (http://www.space.fmi.fi/MIRACLE/). The figure shows the poleward motion of the location of both the polar edge and the “center” of the westward electrojet. The "center" of the westward electrojet corresponds to the location of the most intense equivalent ionospheric currents ([3]). It should be noted that the concept of the electrojet "center" is often used as the indication of the latitudinal location of the electrojet, because during the substorm expansion phase, the westward electrojet occupies a large area and can be inhomogeneous ([27]). In our study we used the “center” of the westward electrojet location as the definition of an “expanded substorms” position.

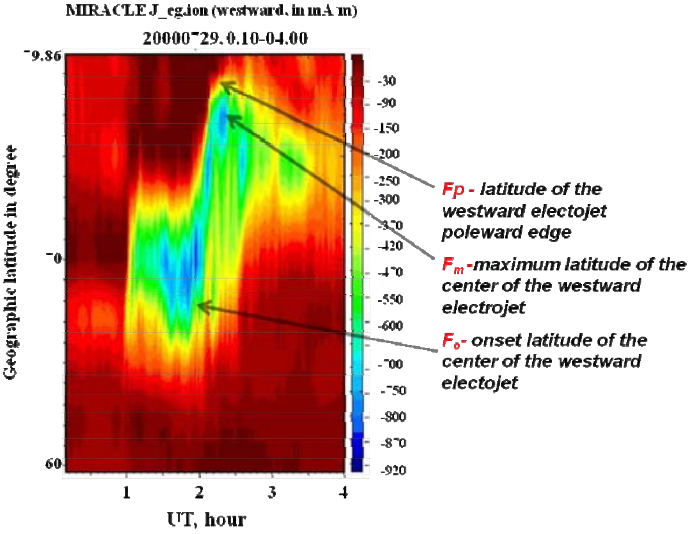

Fig. 1. Example of the westward electrojet development during a substorm on 29 July 2000. The position of the polar edge and the “center” of the westward electrojet during the substorm are shown

Results

Fig. 2 shows the histograms of the solar wind and IMF parameters (B_X, B_Y, B_Z, V_X, E_Y, T, N, P) observed before the onset of the “substorms on contracted oval” and the ”expanded substorms”. All considered parameters were averaged for the 1.5 hour interval preceding the moment of the substorm maximal development. Such interval was chosen to take into account the fact that the energy can be input not only during the growth phase of a substorm (~1 h) but during the expansion phase as well (at $B_Z < 0$). Histograms of the B_X, B_Y, B_Z components of IMF, the V_X component of the solar wind velocity, the E_Y component of the interplanetary electric field, the temperature (T), density (N) and dynamic pressure (P) of the solar wind are shown. The “substorms on contracted oval” events are marked by diamonds, and the ”expanded substorms”- by triangles. It can be seen that the main factor on which the difference between these two types of substorms is clearly expressed is the solar wind velocity. The “substorms on contracted oval” are observed at low velocity (generally ~ 300-400 km/s) and the ”expanded substorms”- at higher values of the solar wind velocity (larger than 500 km/s). It is seen also that “substorms on contracted oval” are observed mainly under positive values of B_Y component of IMF, while ”expanded” ones – under negative values of B_Y component. It should be noted that there were no differences in the distributions of B_Z and B_X component of the magnetic field and solar wind density before observations of both types of substorms. In addition, the ”expanded substorms” are observed under higher values of the temperature and pressure of the solar wind than the “substorms on contracted oval” (averaged T for “expanded substorms” ~$2.8*10^5$ K; averaged T for “substorms on contracted oval” ~ 0.7 $*10^5$ K; averaged dynamic P for “expanded substorms” ~ 2.84 nPa; averaged dynamic P for “substorms on contracted oval”~ 1.39 nPa)

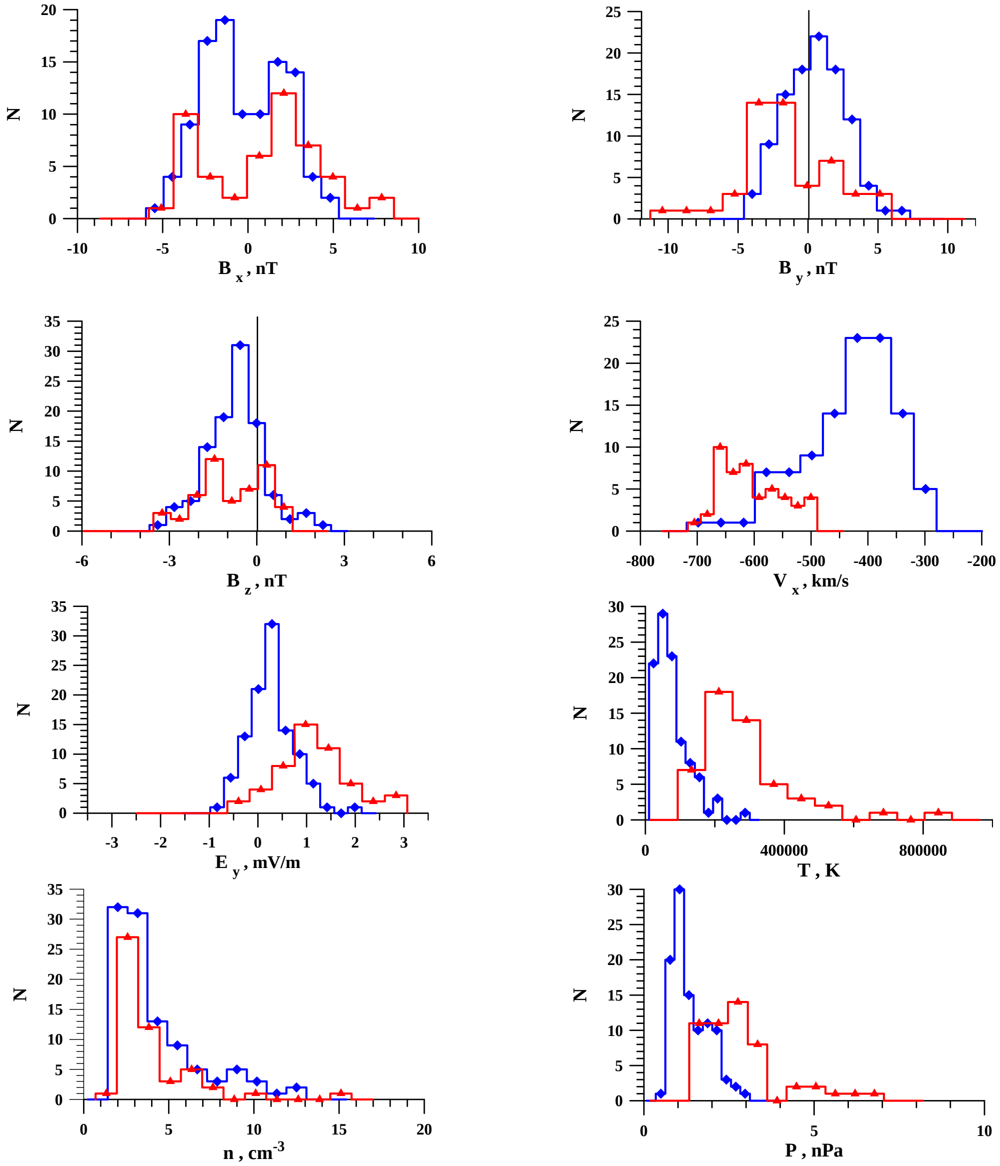

Fig. 2. Histograms of the solar wind and IMF parameters (B_X, B_Y, B_Z, V_X, E_Y, T, N, P) averaged over one and a half hours before the maximal phase of the polar (diamonds) and high-latitude (triangles) substorms

We calculated also the standard deviations of all considered parameters of the solar wind and IMF before the onset of these 2 types of substorms. It is shown that the disturbances (standard deviations) of all considered parameters of the solar wind and IMF are higher before observations of ”expanded substorms” than of “substorms on contracted oval”.

4. Discussion

We have carried out a comparative analysis of the conditions for occurrence of substorms at high geomagnetic latitudes, namely for occurrence of substorm westward electrojet. Both types of substorms - “substorms on contracted oval” and ”expanded substorms”- were compared with the interplanetary conditions, i.e., the presence/absence of high-speed solar wind streams, the presence of a geomagnetic storm, etc. It is shown that the “expanded substorms” were observed under increased temperature and pressure of the solar wind (avg P > 2 nPa; avg T > $2*10^5$K). In addition, “substorms on contracted oval” are observed mainly under positive values of B_Y component of IMF, while “expanded substorms” – under negative values of B_Y component. The last result conforms with the result obtained in paper [27] that “small substorms” were frequently observed during azimuthal IMF direction with dominating IMF B_Y and small fluctuating IMF B_Z. It should be noted that other researchers of “substorms on contracted oval” did not consider the dependence on B_Y component of IMF. In our work it has been shown that a key differentiating parameter on which these two types of substroms are clearly expressed is the solar wind velocity. “Substorms on contracted oval” are observed at a low solar wind velocity (V< 500 km/s), and ”expanded substorms” are observed at a high solar wind velocity (V> 500 km/s). It is being noted that the effect of solar wind velocity on the occurrence of substorms at high latitudes was noted long ago ([4], [6], [7], [11]). However none of the researchers has provided a physical interpretation of this phenomenon. Although different suggestions about the reason of the geo-efficiency of the solar wind speed were considered in earlier works. For example, the suggestion about an increase in the solar wind pressure depending on the velocity was studied in [28]. The authors have shown that a high dynamic pressure is usually observed under high density of the solar wind, which is characteristic for low velocities, despite a square dependence on the velocity. They also have shown that the solar wind pressure (thermal and magnetic and their sum) does not increase with an increase in the solar wind velocity, which leads us to refuse this suggestion.

The suggestion that the solar wind velocity affects the occurrence of high latitude substorms via the magnitude of the solar wind electric field was also verified ([10], [11]). It turned out that, though $E_Y \sim B_Z V_X$, i.e., the electric field is directly proportional to the velocity, the IMF B_Z component mainly contributes to the dependence of substorm latitude on the solar wind electric field.

One possible reason may be the dependence of plasma sheet temperature on solar wind velocity. In work [29] it was shown that with the increasing of the speed the region of hot particles (with energy 5-10 keV) in the plasma sheet expands (up to 50 R_E). From this it follows that the precipitation of energetic electrons from the heated plasma sheet will create a region of increased conductivity at higher latitudes in the ionosphere. As the westward electrojet is Cowling current, which flows in the region of high conductivity, the position of the maximum intensity (“center” of electrojet) is determined by the position of the increased conductivity region. However this interpretation is also not enough. The heating of the plasma sheet can occur not only due to the growth of the solar wind speed, but on the contrary, because during these solar wind conditions substorms propagate to high latitudes.

Thus, the question about the reasons of geo-efficiency of the solar wind speed is an open question.

Conclusions

- “Substorms on contracted oval”, i.e. substorms recorded at latitudes > 70º, are observed after the passage of a high-speed recurrent stream of the solar wind (when the velocity is reduced from high to low values), during the late recovery phase of a geomagnetic storm. ”Expanded substorms”, on the contrary, are observed during the passage of a recurrent high-speed stream of the solar wind.
- The main factor on which the difference between these two types of substorms is clearly expressed is the solar wind velocity. The “substorms on contracted oval” are observed at low velocity (V< 500 km/s) and the “expanded substorms” – at higher values of the solar wind velocity (V> 500 km/s).
- “Expanded substorms” are observed under increased temperature and pressure of the solar wind (P~ > 2 nPa; T~ > $2*10^5$K). In addition, “substorms on contracted oval” are observed mainly under positive values of B_Y component of IMF, while “expanded substorms” – under negative values of B_Y component.

- The variability of solar wind parameters for the ”expanded substorms” is stronger than for the “substorms on contracted oval”.

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