High-latitude Daytime Magnetic Bays as Effects of Strong Positive IMF Bz: Case study

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Abstract We present unusual negative magnetic bay-like disturbances occurred in the dayside polar geomagnetic latitudes under positive IMF *Bz*. The considered events were observed during the recovery phase of the storm of May 30, 2003 and the main phase of the storm of Nov 24, 2001. We call such magnetic disturbances "dayside polar substorms". It is supposed that the development of dayside polar substorms can be represented as a magnetospheric response to a significant change of the IMF *Bz* from negative to high positive values. The vector construction of the geomagnetic data (Scandinavian magnetometer chain IMAGE) demonstrated a clockwise vortex during the storm of Nov 24, 2001, and two opposing vortices in the event of May 30, 2003. These vortices could be regarded as a proxy of an intensification of downward and upward field-aligned currents. This assumption is based on the IZMIRAN model estimations and the simultaneous DMSP and CHAMP satellite data. According to the OVATION model and the electron images from IMAGE satellite, the Scandinavian polar stations that registered these dayside polar magnetic substorms, were mapped into the dayside auroral oval, i.e. inside the closed magnetosphere.

Keywords: solar wind–magnetosphere interactions, polar magnetic disturbances

1. Introduction

Space weather studies deal with various solar and interplanetary phenomena that have a considerable impact on the magnetosphere of the Earth. Solar wind-magnetosphere interaction manifests in different types of geomagnetic disturbances. It is known that the solar wind energy storages in the magnetosphere under the negative *Bz* components of the Interplanetary Magnetic Field (IMF). It induces the development of night-side magnetic substorms.

During the positive IMF *Bz* there is no IMF new energy input, however, under such conditions, bay-like magnetic disturbances could be observed in the dayside of the polar regions (e.g., Iwasaki, 1971; Friis-Christensen and Wilhjem, 1975; Feldstein, 1976). The dayside magnetic bays (we called them «dayside polar substorm») are caused by the high-latitude ionospheric electric current (Feldstein, 1976; Wilhjeim et al., 1978; Feldstein et al., 2006). This current was termed as "polar electrojet" – *PE*.

Under the positive IMF *Bz* the specific system of field-aligned currents (FAC) develops in the polar cap, termed as *NBZ* system (Iijima et al., 1984). When IMF is northward, the magnetospheric configuration changes substantially and it forms a corresponding polar system of field-aligned currents (Antonova and Ovchinnikov, 1999, 2001). The special configuration of the *NBZ* currents is significantly controlled by the sign and the magnitude of the IMF *By* component. Under the IMF *By* ~ 0, the *NBZ* currents flow into the polar ionosphere on the dusk side and flow away on the dawn side (Iijima and Shibaji, 1987). In the Northern Hemisphere, under the IMF *By* > 0, the currents shift toward the morning and under IMF *By* < 0 – toward the afternoon.

The properties of daytime polar substorms are very poorly known. Some of them were mentioned in (Kleimenova et al., 2015; Levitin et al., 2015: Gromova et al., 2016).

The aim of this paper is to study two dayside polar substorms occurred during the magnetic storms of May 30, 2003 and Nov 24, 2001, when the IMF *Bz* suddenly changed the sign and became strongly positive.

2. Observations

Our study is based on the ground-based Scandinavian magnetometer data (IMAGE profile), and observations by the DMSP and IMAGE low orbiting satellites, as well as the IZMIRAN model of field-aligned currents, and the OVATION model of the auroral oval location.

2.1 Event of May 30, 2003

Here we continue study of the event of May 30, 2003 discussed in (Levitin et al., 2015). Figure 1 presents (a): magnetograms from high-latitude stations of Scandinavian magnetometer chain IMAGE (http://www.ava.fmi.fi/MIRACLE/) and (b): *Bz, By* components of IMF, and the solar wind dynamic pressure (*Psw*) on May 30, 2003. (OMNI database http://omniweb.gsfc.nasa.gov). On May 30, 2003 in the daytime sector of the polar latitudes, the bay-like disturbances were observed at high-latitude stations of IMAGE chain from ~03:40 UT to ~09:30 UT (06:40 – 12:30 MLT).

From ~03:40 UT to ~07:00 UT, the *X* component of the magnetic field at high latitude stations NAL, LYR, HOR, and BJN dropped sharply to -450 nT. The onset of this negative magnetic bay coincided with a sudden northward turning of the IMF *Bz* (up to ~ +25 nT), and a simultaneous abrupt sign reversal of the IMF *By* (from +20 nT to –20 nT). At the same time, the dynamic pressure of high-speed solar wind jumped from 20 nPa to 38 nPa. However the velocity of the solar wind remained at the level of ~700 km/s.

At ~07:00 UT, the positive bay (~200 nT) appeared although the IMF *Bz* maintained the same sign and value, but the IMF *By* became high positive (up to 28 nT). This positive bay was observed in a restricted latitudinal region at the most high latitude stations NAL and LYR.

The considered negative bay occurred (from ~03:40 UT to ~07:00 UT) under the negative IMF *By*, and its onset at can be probably caused by the westward polar electrojet. When the IMF *By* changed the sign from negative to positive, the eastward polar electrojet produced the positive bay (from ~07:00 UT to 12:30 UT).

2.2 *Event of Nov 24, 2001*

A rather similar event was observed on Nov 24, 2001, when a daytime magnetic bay was recorded under a strong positive *Bz* (Kleimenova et al., 2015). The magnetograms at high-latitude stations of IMAGE chain are shown in Fig.2 (panel *a*), while the IMF *Bz* and *By* components, and the *Psw* are presented in Fig. 2 (*b*). In the dayside sector of the polar latitudes, a very strong magnetic bay with an amplitude of ~2000 nT was observed from 08:00 to 10:30 UT (11:00 - 13:30 MLT).

At 07:38 UT, the IMF Bz turned northward and reached an extremely high positive value (~+60 nT) at 09:50 UT. During this bay development, the IMF By became negative (~-25 nT), and the solar wind velocity remained invariably high (~800 km/s). A few gaps in the solar wind data between 07:15 UT and 07:37 UT made it impossible to determine the exact time of the solar wind dynamic pressure jump. However, the *Psw* suddenly increased before the gaps, from 34 nPa at 07:08 UT to 96 nPa at 07:14 UT (see Fig. 2). The same *Psw* value was observed at 07:38 UT, when the IMF *Bz* reached to +25 nT. At this moment, the daytime high latitude negative bay appeared.

Thus, both dayside polar substorms, considered in this paper, developed under high positive IMF *Bz* values and an extremely strong solar wind dynamic pressure (~20 nPa and ~50 nPa respectively). It is important to mention that both negative bays started after a drastic jump of the *Psw*. The jump conditions are consistent with their being fast mode shocks.

3. Discussion

3.1 *The rapid magnetospheric compression*

We assume that the rapid magnetospheric compression could trigger the discussed dayside polar substorms. The dayside compression, that can be attributed to the fast shock, launches into the magnetosphere and propagates in the tailward direction. The compression of the night-side magnetosphere/magnetotail under the negative IMF *Bz* (i.e. southward IMF) usually leads to a night substorm that develops as it was discussed in (e.g., Zhou and Tsurutani, 2001; Tsurutani et al., 2015). Interplanetary shocks may induce sudden dayside auroral brightening (e.g., Craven et al., 1986; Zhou et al., 1999), known as «shock aurora».

Our research demonstrates that even under the positive IMF *Bz* (i.e. northward IMF) the magnetic substorm-like disturbances could occur in the magnetosphere. However, it happens in the dayside polar region. We suppose that the necessary energy for this substorm was loaded into the manetosphere due to previous geomagnetic activity associated with the southward IMF. The stored energy could dissipate away coupling with the ionosphere through increase of Field Aligned Currents (FAC).

3.2 *The field-aligned currents*

The substorm ionospheric currents are associated with field-aligned currents. There are several statistical models of the global distribution of high-latitude field-aligned electric currents, (e.g., Mishin et al., 1978; Feldstein and Levitin, 1986; Papitashvili et al., 2002; Lukianova and Christiansen, 2006). The IZMIRAN model (Feldstein and Levitin, 1986) is based on IMF and the solar wind parameters as model input. It allows to calculate the large-scale spatial-temporal distribution of the ionospheric electrical currents (Hall and Pedersen), field-aligned currents and some other parameters in the high-latitude region (60° - 89°) in MLT - corrected geomagnetic latitude coordinate system. Here the IZMIRAN model was applied for estimation of FAC distribution during considered events.

The ground magnetic vortices are caused by FAC. A clockwise direction of the vortex rotation is a signature of the downward FAC, and respectively a counter-clockwise vortex corresponds to the upward FAC. The horizontal vectors of the geomagnetic field were constructed on the base of so called difference magnetograms that represent the magnetic variations compared to the most magneto-quiet 2009 level (Levitin et al., 2014).

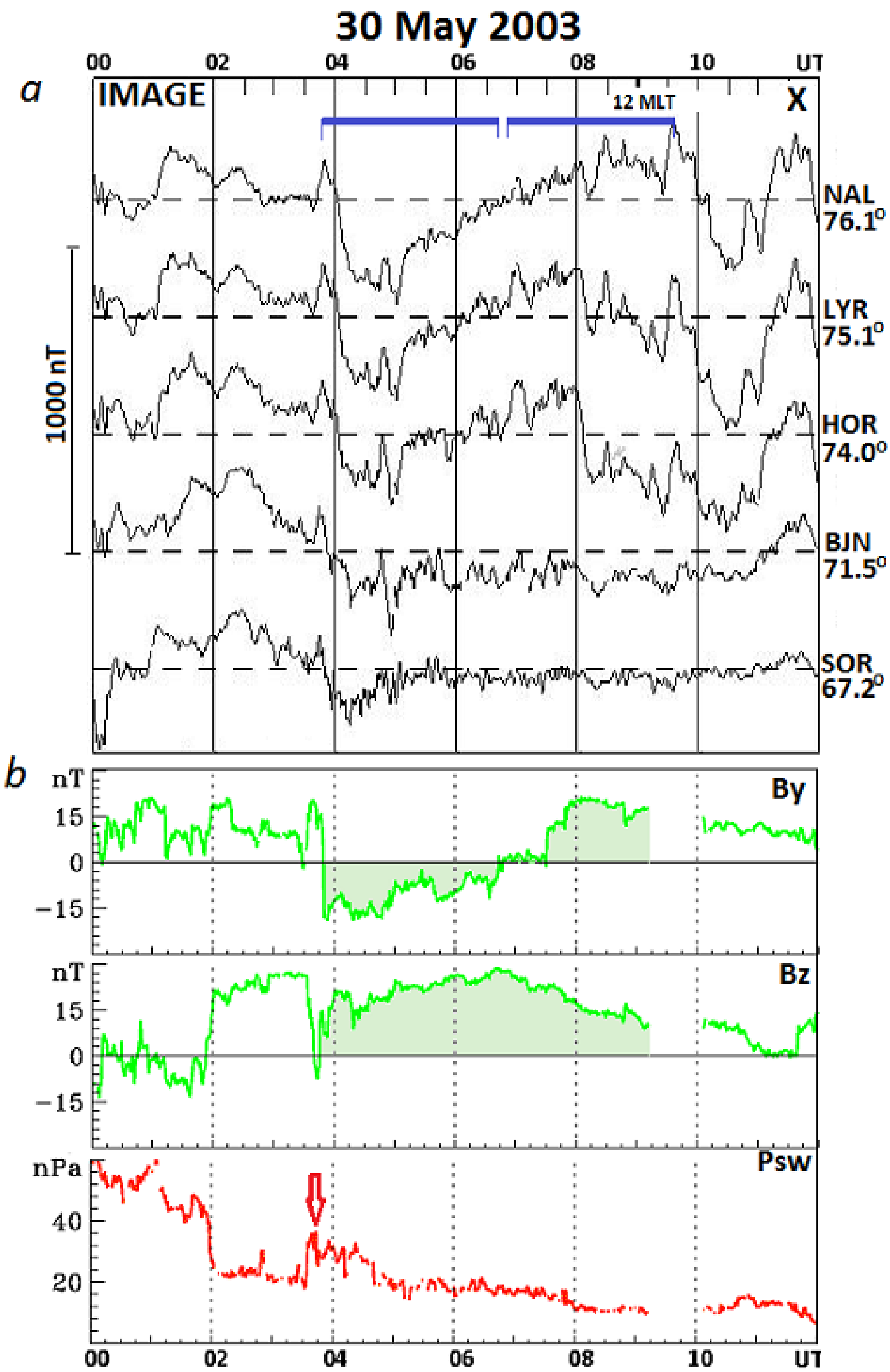

Fig. 1. Event of May 30, 2003. (a): Magnetograms of high-latitude stations of Scandinavian magnetometer chain IMAGE. Blue horizontal bars shows daytime magnetic bays under study. (b): the Bz, By components of IMF, and solar wind dynamic pressure Psw . Arrow marks the dynamic pressure jump

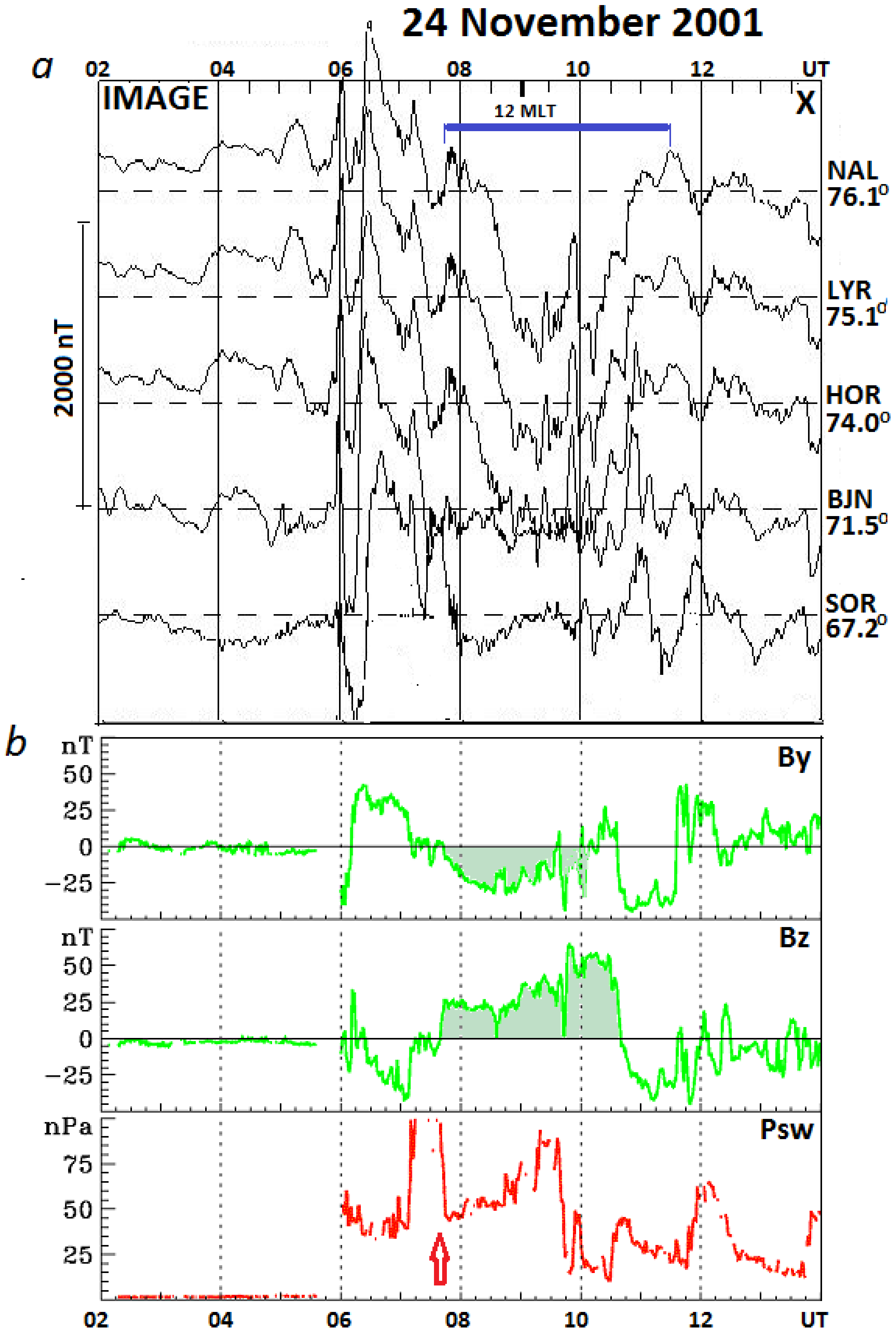

Fig. 2. The same as Fig. 1 but for the event of Nov 24, 2001.

The vectors of the geomagnetic field on May 30, 2003 recorded at the high-latitude IMAGE stations (NAL – SOR), are shown in Fig. 3 (left) to make it evident that there were two vortices rotating in the opposite directions. The center of the clockwise vortex was observed at ~04:00 UT, when a notable *Psw* shock was registered (Fig. 1) simultaneously with a strong negative IMF *Bz* impulse. Since the vortex direction should be interpreted as a signature of the FAC (and its clockwise direction corresponds to the downward FAC) we suppose that under such conditions the intensification of the field-aligned currents produced a dayside negative magnetic bay in the polar latitudes, and subsequently, the development of the westward *PE*.

The centre of the second vortex was observed at ~07:00 UT. Its counter-clockwise direction should be interpreted as a signature of the upward FAC. At this moment, the IMF *By* changed the sign from negative to positive, under the invariable *Psw* and the IMF *Bz*. In Fig. 1, the onset of the positive magnetic bay is shown, we note that it was associated with the development of the eastward *PE*.

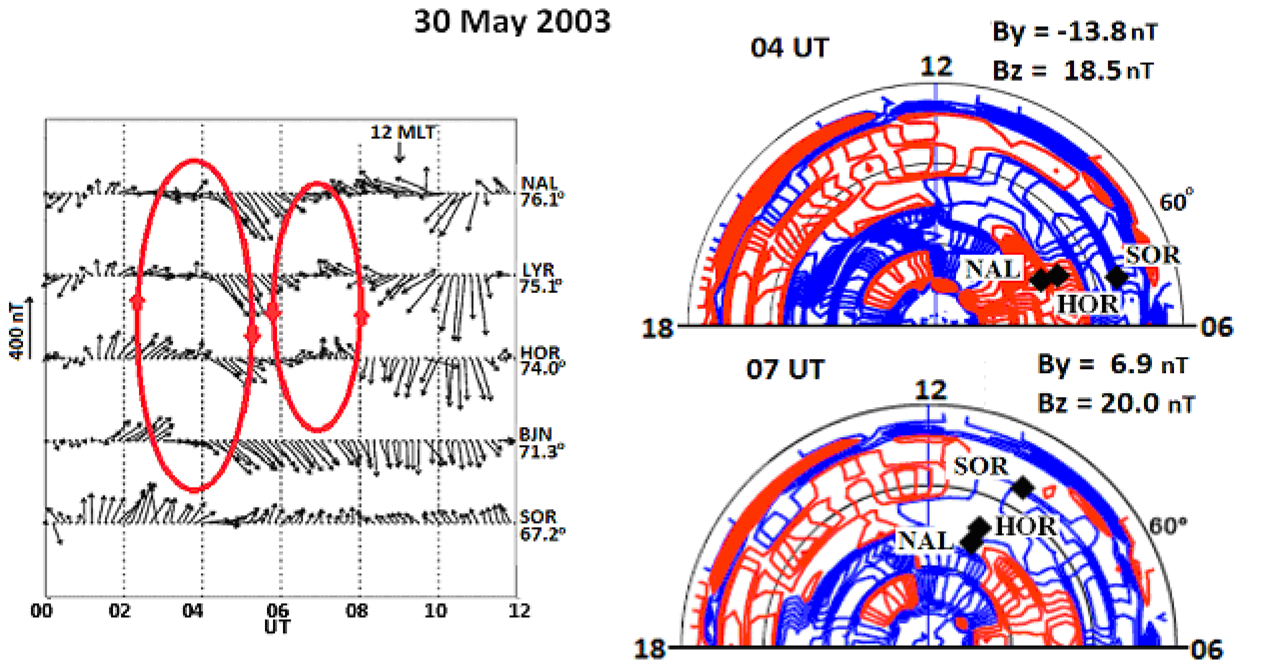

Fig. 3. Event of May 30, 2003. Left: magnetic variation vectors. Right: distribution of the field-aligned currents in the high-latitude region of the dayside sector according to IZMIRAN model in the magnetic local time - corrected geomagnetic latitude coordinates. Red lines shows downward FAC, blue - upward ones.

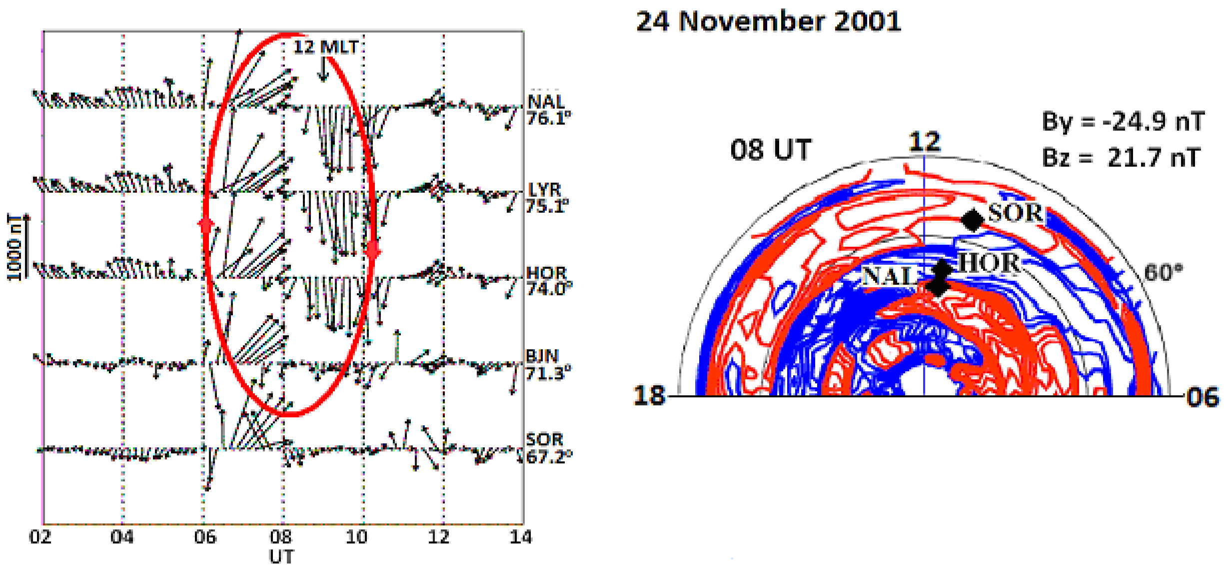

Fig. 4. The same as Fig. 3 but for the event of Nov 24, 2001.

The maps of the FAC patterns (Fig. 3, right) were elaborated on the base of the IZMIRAN model in respect of the center of the vortices at ~04:00 UT and at ~07:00 UT. The FAC distribution at 04:00 UT demonstrates that the IMAGE stations NAL-HOR were mapped into the zone of a downward FAC enhancement (red contours in Fig. 3). At 07:00 UT, the IMF conditions became different and consequently the FAC spatial distribution was modified: the upward FAC (blue contours in Fig. 3) shifted poleward. As a result, the IMAGE stations NAL-HOR were mapped into the zone of upward FAC.

Figure 4 presents the vectors of the geomagnetic field on Nov 24, 2001 recorded at the high-latitude IMAGE stations (NAL – SOR) and the FAC distribution during this substorm calculated on the base of the IZMIRAN model. The strong dayside negative bay during 07:00 UT – 11:00 UT corresponds to the intensive clockwise vortex, it should be interpreted as a signature of the downward FAC (Fig. 4, left). The vortex center was observed at ~08:00 UT after a huge compression shock under the positive IMF *Bz* (Fig. 2). Our mapping of the FAC patterns is presented on the right panel of Fig. 4 and reveals that in this time the IMAGE stations NAL-HOR occurred in the zone of the downward FAC (red contour in Fig. 4).

Thus, we demonstrated that the daytime polar magnetic bay were collocated with polar latitude FAC.

3.3 The aurora oval location

In our study, the aurora oval position was applied from the OVATION model data (http://sd-www.jhuapl.edu/Aurora/ovation) that based on the multiple data sets from the DMSP satellites and Polar UVI imager. The middle panels of Fig. 5 show the auroral oval position at 05:00 UT (the first, negative, magnetic bay) and at 09:00 UT (the second, positive, magnetic bay) on May 30, 2003. The location of the high latitude IMAGE stations (NAL and SOR) is marked on the maps by the stars. It is seen that in the both intervals, the IMAGE stations were mapped into the dayside auroral oval. That was confirmed by the DMSP F13 spectrograms of the precipitating particles (Fig. 5, right panels) and the CHAMP (Fig. 5, left panels) magnetic field data (http://op.gfz-potsdam.de/champ). The particle (ions and electrons) enhancement was observed in the same area as the examined dayside polar magnetic substorms.

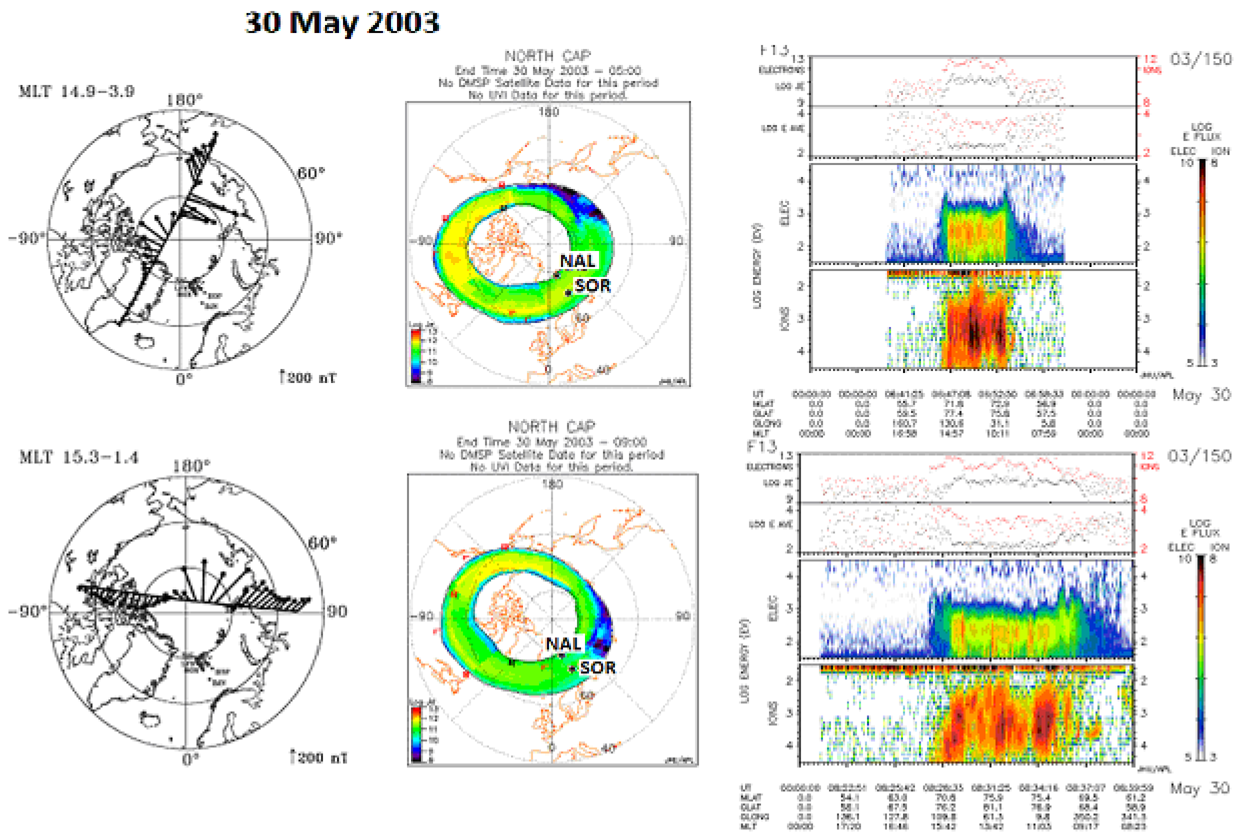

Fig. 5. The auroral oval position according to OVATION model and DMSP F13 precipitating particle data in the time of the first magnetic bay at 04 - 07 UT(top) and the second one at 07 – 09 UT (bottom) for May 30, 2003. The stars show location of the IMAGE high latitude stations NAL – HOR.

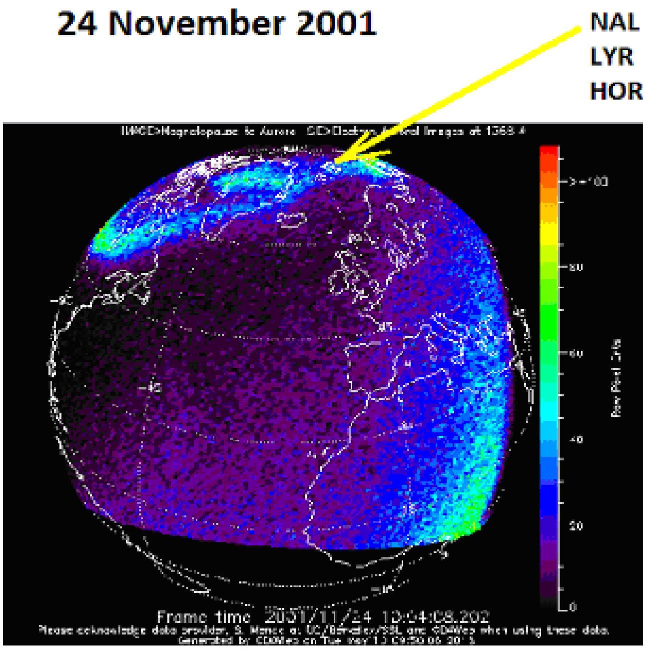

Fig. 6. The electron image from IMAGE satellite for Nov 24, 2001. The arrow shows location of high latitude stations NAL – HOR.

There is no the OVATION data for Nov 24, 2001 during the considered magnetic bay in 08:00 – 11:00 UT, therefore we used the electron image of IMAGE satellite (http://cdaweb.gsfc.nasa.gov/cgi-bin/). The data for 10:00 UT is presented in Fig. 6. It is seen that the high-latitude Scandinavian stations, marked by the yellow arrow, are mapped into the dayside auroral oval.

Thus, the Scandinavian polar stations where the dayside polar magnetic substorms were observed. The data are mapped into the dayside auroral oval, i.e. inside the closed magnetosphere.

4. Summary

1. Our study of two dayside polar substorms shows that the sign of these disturbances is controlled by the sign of the IMF *By*.
2. We found that the daytime polar substorms represent a magnetosphere response to high positive values of the IMF *Bz* under a strong shock of the solar wind dynamic pressure.
3. The daytime polar magnetic bays under consideration were collocated with polar latitude FAC. We suppose this FAC could be referred to the *NBZ* system.
4. The daytime polar substorms are mapped inside the closed magnetosphere into the dayside auroral oval.

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