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"POLAR" SUBSTORMS AND THE HARANG DISCONTINUITY

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Abstract. The substorms that we term as "polar" substorms, are recorded in the evening sector of the Earth at the geomagnetic latitudes above 70° MLAT under the absence of negative magnetic bays at the lower latitudes. Like the "classical" substorms, the "polar" substorms are accompanied by aurora arcs brightening, poleward expansion, substorm current wedge formation. The onsets of "polar" substorms are typically located near 70° MLAT at ~19-23 MLT. Other important structure, namely, the Harang discontinuity (the evening narrow latitude-zone between the westward and eastward electrojets), is often observed in the same area and at the same MLT interval. Our aim is to study a possible relationship between the location of the "polar" substorms and the Harang discontinuity (HD). Using the IMAGE geomagnetic data, we found that the "polar" substorm onsets exhibit a tendency to occur near the HD latitude. The longitudinal relationship between the "polar" substorms and the HD was studied basing on the ionospheric AMPERE measurements by the 66 simultaneous satellites. We revealed the ground-based magnetic vortex associated with FACs enhancement near the eastward edge of the Harang discontinuity region separated the evening "polar" substorm development and the after-midnight westward electrojet location. Two typical events of the "polar" substorms are discussed in detail.

Introduction

The high-latitude magnetic substorms observed at geomagnetic latitudes higher 70° MLAT under the absence of negative magnetic bays at the lower latitudes were called the "polar" substorms [*Kleimenova et al.*, 2012, 2023; *Despirak et al.*, 2014, 2022; *Safargaleev et al.*, 2018; 2020]. We found that the onset of a "polar" substorm is typically located near 70° MLAT at ~19-23 MLT [*Kleimenova et al.*, 2023]. It is well known that another important structure, namely, the Harang discontinuity or Harang reversal [*Harang*, 1946; *Heppner*, 1972] is often observed in this area. The Harang discontinuity (HD) represents a narrow latitude-zone between the closely spaced simultaneous westward and eastward electrojets [e.g., *Kissinger et al.*, 2013 and the references there]. It is the region of sharp reversal of the ionospheric convection in the evening sector (around 22-24 MLT). In the terms of auroral electrojets, the Harang discontinuity corresponds to the shear zone where the eastward electrojet (EEJ), equatorward of the shear, and the westward electrojet (WEJ), poleward of the shear, meet. That is, HD is the area separated the positive and negative bay regions. The HD is dynamic in nature. As magnetic activity decreases, it shifts poleward and spreads out in latitudinal width. The schematic picture of the Harang discontinuity is given in Figure 1, adopted from [*Koskinen and Pulkkinen*, 1995].

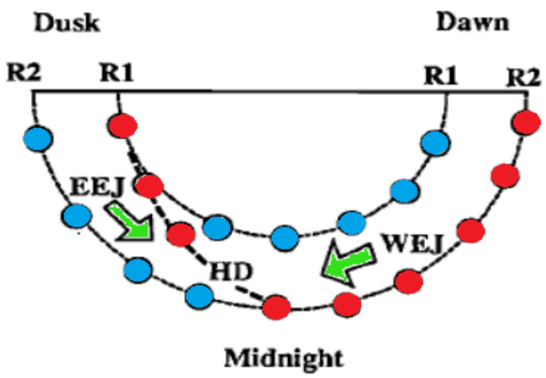

Figure 1. Schematic picture (from Koskinen and Pulkkinen, 1995) of the Harang discontinuity (HD) indicated by the dashed line. The direction of the electrojets is shown by the arrows (EEJ is the eastward electrojet, WEJ is the westward electrojet), the downward FACs are marked by blue and upward FACs are marked by red.

Our aim is to study a possible relationship between the location of the "polar" substorms recorded at Scandinavian IMAGE magnetometer chain and the Harang discontinuity location estimated according to the ionospheric satellite AMPERE data.

Observations and Discussion

Our analysis was based on the magnetic observations at the Scandinavian IMAGE magnetometer chain (https://space.fmi.fi/image/). We have selected the 254 "polar" substorm events recorded during the winter seasons of 2010-2020, and then compared their occurrence with the global distribution of the ionospheric electrojets and field-aligned currents (FACs) obtained from the AMPERE project (https://ampere.jhuapl.edu). The AMPERE project represents the simultaneous magnetic measurements by the 66 low-altitude Iridium communication satellites at the altitude of ~780 km as 10-min averages with the 2 min cadence [e.g., *Anderson et al.*, 2014].

It is well known [e.g., *McPherron et al.*, 1973, *McPherron and Chu*, 2018] that on the meridian of a substorm onset, a mid-latitude positive magnetic bay in the *X* magnetic component is observed indicating the substorm current wedge (SCW) development. The positive deviations in the *Y* component occur if the substorm onset meridian is located far eastward of this station, the negative *Y* values occur due to the westward substorm onset location. As the mid-latitude stations, we used Borok station (BOX, 54.5° MLAT) located close to the IMAGE meridian and Irkutsk station (IRT, 47.8° MLAT) located 65° eastward (https://intermagnet.org/#services). In Figures 2, 3 we present the results of the analysis of two selected events: on 28 January and 5 December 2020.

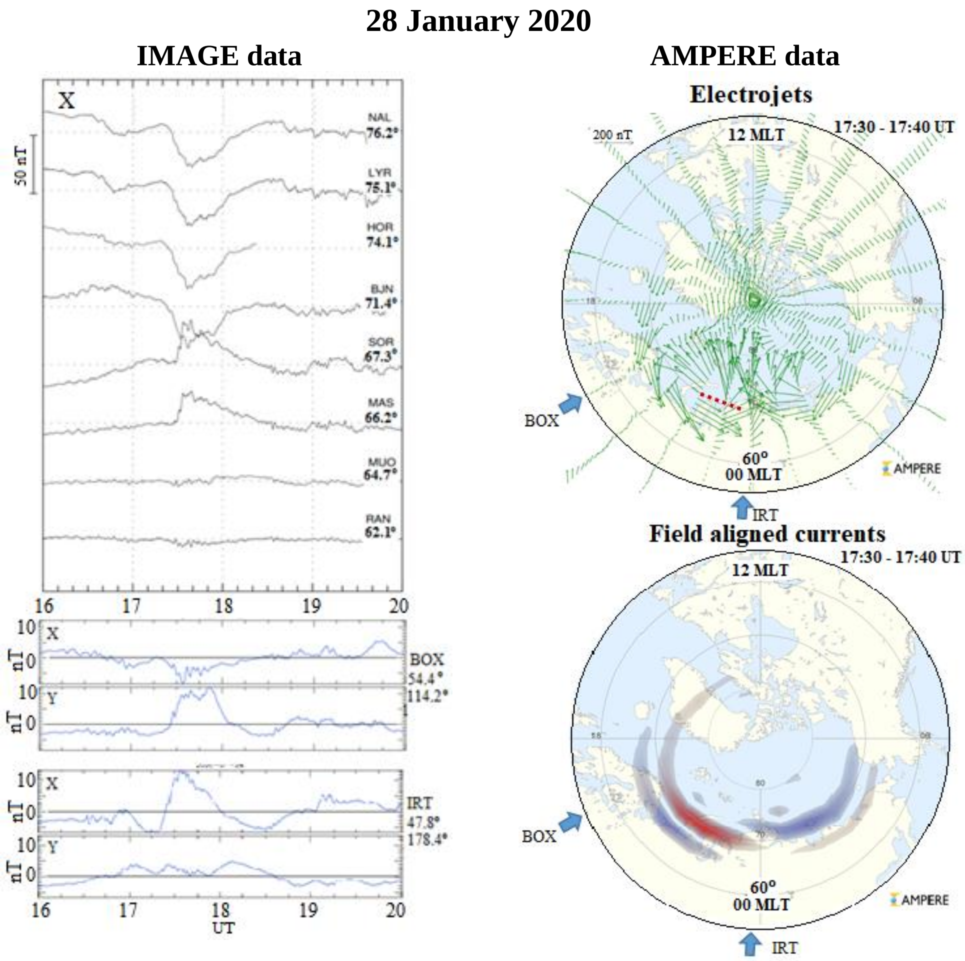

Figure 2. Magnetograms from some IMAGE stations as well as BOX and IRT stations and electrojets and FAC after AMPERE data on 28 January 2020. The Harang discontinuity location is shown by the red dotted line. Blue arrows show the direction of the BOX and IRT meridians.

The "polar" substorm of 28 January 2020 is shown in Figure 2. It was small (< 50 nT) and observed as the negative magnetic bay at BJN-NAL stations at 17:20-18:00 UT. Like a "normal" substorm, it was accompanied by a positive magnetic bay, however, not at the middle but at auroral latitudes (SOR-MAS, ~66-67° MLAT). Due to that, the magnetic *X* component at the mid-latitude BOX station was small negative. The *Y* component at BOX was strong positive like at all IMAGE stations located at 47-67° MLAT (not shown here). It indicates that the IMAGE meridian as well as BOX station was located far westward from the meridian of the "polar" substorm onset.

In this time, the *X* component at IRT station was strong positive, and the *Y* component was near zero. It indicates that this station was located close to the meridian of the "polar" substorm onset. The AMPERE map (Figure 2) of the FAC distribution confirms this conclusion. Moreover, the strong magnetic vortex (see ionospheric current by AMPERE data in Figure 2) indicating the strong local FAC enhancement associated with a polar substorm onset, was observed near IRT longitude.

According to the AMPERE electrojet map and IMAGE magnetograms, the eastward electrojet, represented the equatorward part of SCW, was narrow in latitude and located at much higher latitudes then during the "normal" substorm.

The location of the Harang discontinuity was determined by the data from the IMAGE ground-based magnetometer array and the AMPERE multi-satellite maps of the electrojets and FACs distribution. Figure 2 demonstrates that in the considered event, the Harang discontinuity was located at ~68-70° MLAT (red dotted line) Thus, the "polar" substorm was developed close to the poleward boundary of the Harang discontinuity.

The strong "polar" substorm was observed on 5 December 2020 between 20 and 21 UT (Figure 3). As in the previously discussed event, it was accompanied by the positive magnetic bay at auroral and subauroral stations (SOR-MUO) and at the mid-latitude stations (BOX and IRT) as well. At BOX station, the amplitude of the magnetic *X* component was similar the amplitude of the *Y* component, and both were positive. It indicates that this station was located westward of the meridian of the "polar" substorm onset.

At the mid-latitude IRT station, the *X* component was positive, and the *Y* one was negative. It indicates that this station was located eastward of the meridian of the "polar" substorm. Thus, the onset of this "polar" substorm was located between BOX and IRT. The AMPERE maps confirm this demonstrating the location of the enhancement of upward FACs (red color) in vicinity of the strong vortices in the ionospheric currents (green color).

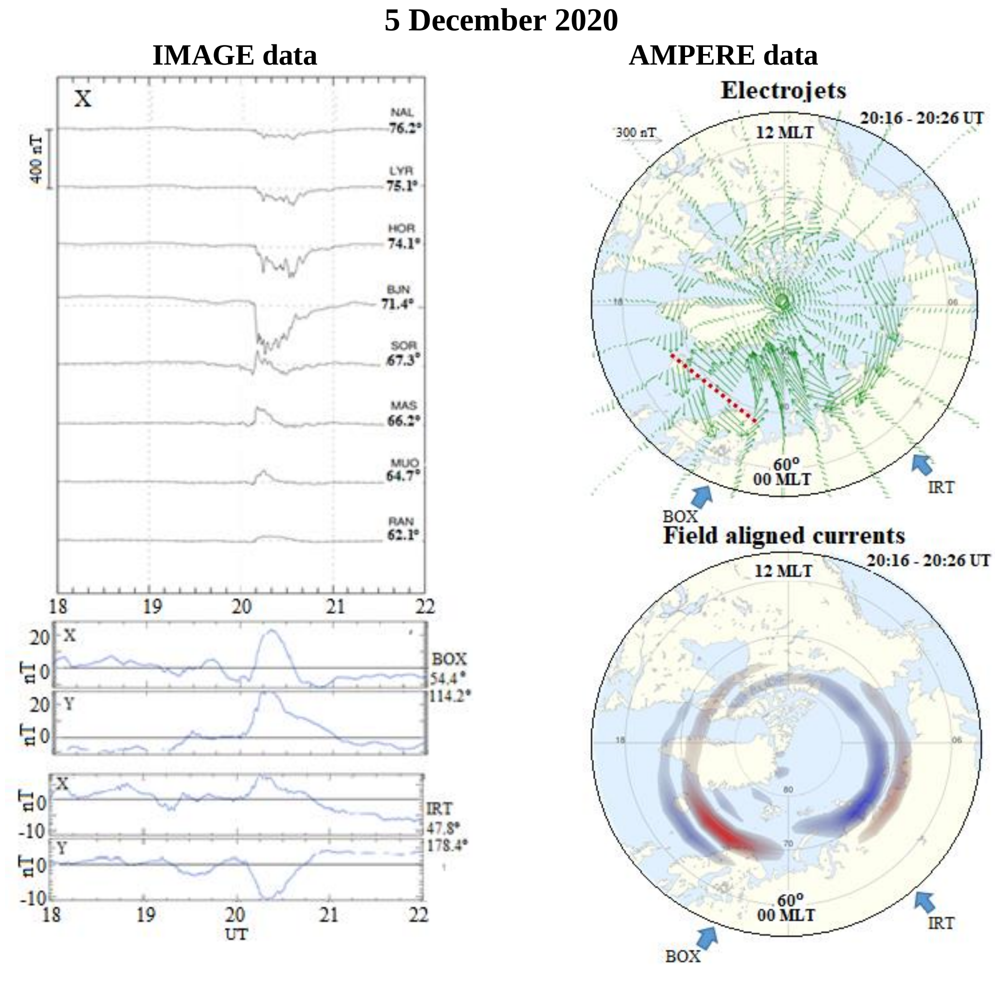

Figure 3. Magnetograms from some IMAGE stations as well as BOX and IRT stations and electrojets and FAC after AMPERE data on 5 December 2020. The Harang discontinuity location is shown by the red dotted line. Blue arrows show the direction of BOX and IRT meridians.

The AMPERE maps of the electrojets and FAC distribution as well as the IMAGE ground-based magnetograms indicate that the Harang discontinuity during this event was located at ~67-69° MLAT, and the onset of the "polar" substorm was in the sea between BJN and SOR station (i.e., between ~68-71° MLAT). Thus, like the first considered event, a "polar" substorm was observed close to the poleward boundary of the Harang discontinuity.

The analysis of the AMPERE electrojet maps allows to reveal the magnetic vortices associated with FAC enhancement close to the eastward edge (the "nose") of the Harang discontinuity region. Figures 2 and 3 demonstrate that the vortices separate the high-latitude area with the evening "polar" substorm development and the auroral latitudes with the after-midnight westward electrojet location.

Summary

- We found that the "polar" substorms location are typically associated with the Harang discontinuity position obtained from the ionospheric AMPERE multi-satellites system measurements and the ground-based IMAGE magnetometer data.
- As a rule, the "polar" substorms were recorded poleward of the Harang discontinuity location and close to its poleward boundary.
- Like the "normal" substorms, the "polar" substorms were accompanied by the SCW (Substorm Current Wedge) development and mid-latitude positive magnetic bay, however, they were observed not only at the middle latitudes, but at subauroral and even auroral latitudes too, demonstrating a narrow latitude distance between the westward and eastward electrojets (narrow latitudinal dimension of the Harang discontinuity).
- The magnetic vortices, associated with FAC enhancement, were found close to the eastward edge of the Harang discontinuity region ("nose") which separated the area of the evening high-latitude "polar" substorm development and the after-midnight area with the westward electrojet location at the auroral latitudes.

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