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PLANETARY FEATURES OF WESTWARD AND EASTWARD ELECTROJETS DURING THE STRONG MAGNETIC STORM ON 10-11 OCTOBER 2024

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Abstract. The magnetic storm on 10-11 October 2024 ($Dst_{min} = -333$ nT) was one of the strongest storms in the present 25th solar cycle. Large variations in the intensity of the IMF B_y and B_z (from +40 nT to -40 nT) were observed during the main phase of the storm at the very high solar wind dynamic pressure (P_{sw}) up to ~ 40 nPa. The storm recovery phase developed under the unusual strong (up to -40 nT) and long lasting (~ 12 h) IMF B_z . This led to high substorm activity in the storm recovery phase as well. Thus, at least 8 substorms with AL -index ~ -1500 nT and higher were recorded during the storm main phase and 7 substorms in the recovery phase. In addition, during the main phase of the storm, 7 positive magnetic bays with an amplitude of 500-1000 nT in AU -index were observed, the maximum of which did not coincide with the minimum in AL -index. There were no intense positive magnetic bays (in AU -index) during the storm recovery phase. The planetary features of the configuration of the ionosphere electrojets and field-aligned currents (FAC) were studied by applying the global maps based on the magnetic measurements on 66 LEO satellites of the AMPERE project. The results of our study demonstrated the strong dependence of the electrojet and FAC features on the sign and values on the IMF B_y and B_z as well as on the P_{sw} level. It was shown that the sign of the IMF B_y controls not only the direction of the dayside polar electrojet but also affects the eastward current and the width of the region where it is observed. Rapid simultaneous variations in the IMF components and P_{sw} led to the abrupt changes in the planetary distributions of the electrojets and FACs. This makes it difficult to identify specific effects of each individual component. Further detailed studies are required to understand the observed features.

1. Introduction

The magnetic storm on 10-11 October 2024 ($Dst_{min} = -333$ nT) was one of the strongest storms in the 25th solar cycle. Different aspects of this storm are widely discussed in literature, e.g., [Pierrard *et al.*, 2025; Singh *et al.*, 2025; Xia *et al.*, 2025]. Large variations in the intensity of the IMF B_y and B_z (from +40 nT to -40 nT) were observed during the main phase of the storm under the very high solar wind dynamic pressure (P_{sw}) up to ~ 40 nPa (Fig. 1) (<http://wdc.kugi.kyoto-u.ac.jp/>). It is well known that the most IMF and solar wind geoeffective parameters are the IMF B_z and B_y and solar wind dynamic pressure (P_{sw}), due to this, later only these parameters will be discussed in the text. A good anti-correlation is seen between the AL index and the PC -index variations demonstrating the unloading energy from the magnetotail.

The storm recovery phase developed under the unusual strong (up to -40 nT) and long lasting (~ 12 h) IMF B_z . This led to high substorm activity during both storm phases. At least, 8 strong substorms with the AL -index ~ -1500 nT and higher were recorded during the storm main phase and 7 strong substorms were observed in the recovery phase (Fig. 2). In addition, during the main phase of the storm, there were observed 7 positive magnetic bays with an amplitude of 500-1000 nT in the AU -index. The maxima of the AU -index did not coincide with the minima in the AL -index. There were no intense positive magnetic bays in the storm recovery phase.

Here we study the planetary features of these substorms as the configurations of the ionospheric westward (WE) and eastward (EE) electrojets and field-aligned currents (FAC) in course of this magnetic storm.

2. Data

Our study was based on an analysis of the magnetic measurements on the 66 Iridium satellites simultaneously operating at the altitudes of 780 km of the project AMPERE [e.g., Anderson *et al.*, 2000] presented as the global maps of the ionospheric currents and field aligned currents (<http://ampere.jhuapl.edu/products>). The maps are presented at 2 min cadence over a 10 min window in the geomagnetic coordinates with a spatial resolution of 1° in MLAT and 1 h MLT in the longitude. The magnetic perturbations are given relative to Earth's main magnetic field with automated base line, these data are transmitted to the Earth for a spherical harmonic analysis.

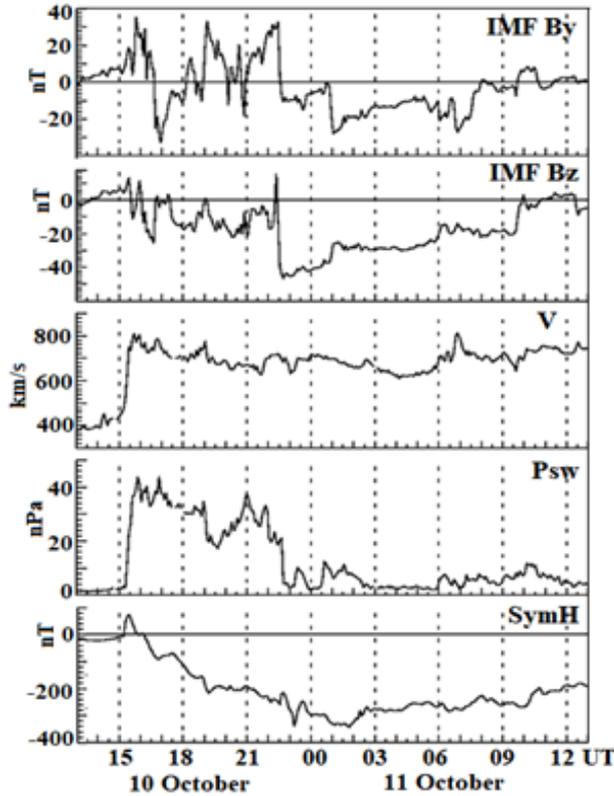


Figure 1. OMNI data: IMF B_y , IMF B_z , V_{sw} , P_{sw} , and $SymH$.

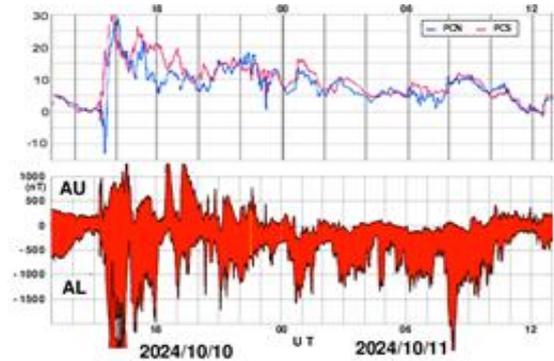


Figure 2. Variations of the PC and AL/AU indexes.

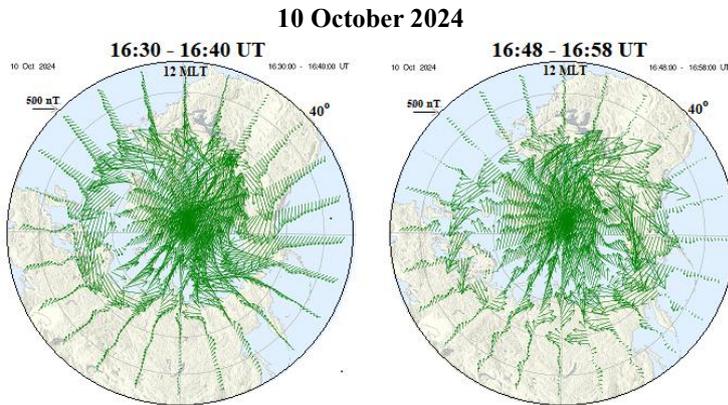


Figure 3. Two maps of ionospheric currents distribution at intervals about 20 min during which the sign of IMF B_y changed from positive to negative.

3. Observation and Discussion

During the storm main phase, there were very significant variations in the values and sign of the IMF B_z and B_y . The strong dependence of the direction of the dayside polar latitude ionospheric currents (EE and WE) on the sign of the IMF B_y was found. The presented in Fig. 3 two AMPERE maps were recorded under very disturbed geomagnetic conditions with similar values of IMF B_z and P_{sw} : IMF $B_z \sim - (20-25 \text{ nT})$ and $P_{sw} = 36 \text{ nPa}$, but with different the IMF B_y directions. The first event (the left map in Fig. 3) was obtained under the strong positive IMF B_y (+30 nT) and the second event (the right map in Fig. 3) which occurred 18 min later, was developed under the strong negative IMF B_y (-25 nT). The

comparison of two AMPERE maps (Fig. 3) allows conclude that at the dayside high-latitudes, the electrojet direction is controlled by the sign of the IMF B_y (note that in the both events, the values of the IMF B_z and P_{sw} were similar). The AMPERE maps in Fig. 3 demonstrate that during studied events, at noon-side polar latitudes, the large-scale ionospheric currents flowed in opposite directions: there were the eastward currents in the first event (16:30 UT) and the westward currents in the second one (16:48 UT). Due to the negative IMF B_z , both the dawn and dusk convection cells were enhanced and expanded.

It is seen that during the storm, the configuration of ionospheric electrojets can change even in few minutes according to changes in the configuration and intensity of FACs caused by the variations in the IMF and solar wind (see Fig.1).

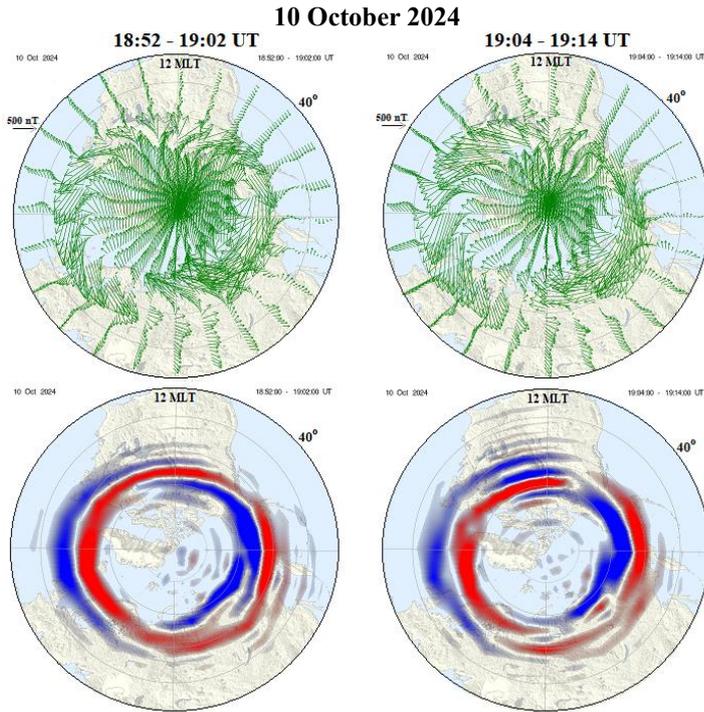


Figure 4. Two maps of the ionospheric (green) and field-aligned (red and blue) currents obtained at intervals of about of 10 min during which the sign and value of the IMF B_y and B_z changed. The upward FACs are shown by red and downward FACs are shown by blue.

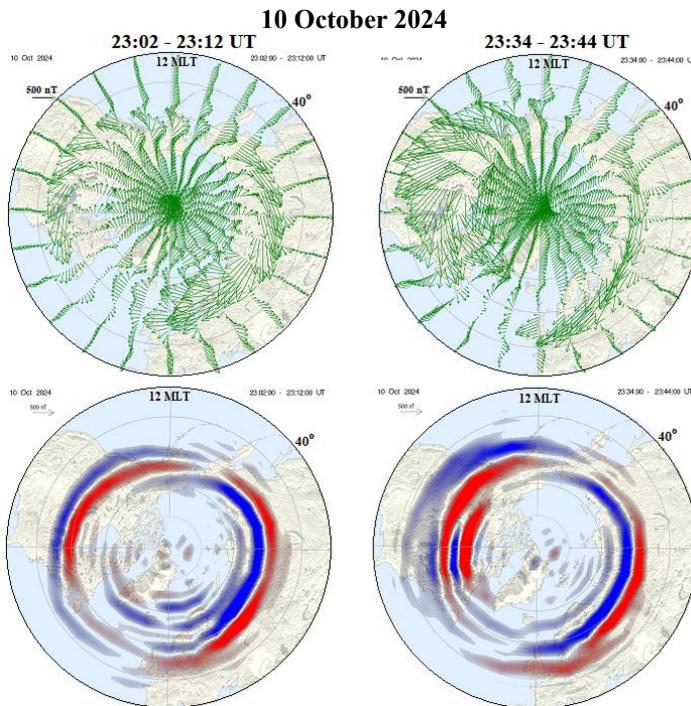


Figure 5. Two AMPERE maps demonstrate how the slight increase in P_{sw} (from 3 to 10 nPa) can change the space configuration of the FACs and, respectively, the location of the eastward and westward electrojets.

The change of the EE, WE and FACs distributions observed as a result of the change of the sign and value of the IMF B_y from negative (-10 nT) to positive ($+25$ nT) under the strong P_{sw} ($\sim 20-30$ nPa) is shown in Fig. 4. One can see that the occurring of the positive and enhanced values of the IMF B_y changed not only the direction of the afternoon polar electrojet but also increase the intensity of the EE (Fig. 4). Note, in the considered event, the midnight WE decreased due to change of the sign of IMF B_z from negative (-10 nT) to positive ($+8$ nT). The additional current, associated with the positive and strong IMF B_y , did not break the structure of the convective cell, but it only supplemented its midday part, there the downward FAC structure became more complicated (right lower part of Fig. 4).

Dramatic changes in the IMF and solar wind have happened at the end of the main phase of this magnetic storm (near 22:30 UT) as it is presented on Fig. 1: the value of the IMF B_z suddenly dropped from $+20$ nT to -45 nT, the value of the IMF B_y dropped from $+36$ nT to -10 nT, and the solar wind dynamic pressure (P_{sw}) collapsed from 32 nPa to 3 nPa. One can see (Fig. 1) that the values of IMF B_z and IMF B_y remained just as high for another 2-3 hours and that the electrojet configuration significantly changed. Due to strong negative value of the IMF B_z , both electrojets (the evening eastward and morning westward ones) shifted to lower latitudes.

About one hour later (at $\sim 23:30$ UT), the P_{sw} increased again up to 10 nPa however the value of IMF B_z remained very strong negative (-40 nT) and the value of the IMF B_y remained strong negative (-10 nT). To show the reaction of the ionospheric currents to this change, we compared the planetary ionospheric current distributions obtained by the AMPERE maps before and after of this slight change in the P_{sw} (Fig. 5). Increase in the pressure P_{sw} (from 3 to 10 nPa) led to a complicated change of the dusk-evening FAC structure and the latitude expansion of the EE area (Fig. 5, right map). The EE significantly enhanced and latitude expended despite the fact that the IMF B_y remained negative. The WE shifted to significant lower latitudes, probably, due to an influence of the very strong negative IMF B_z .

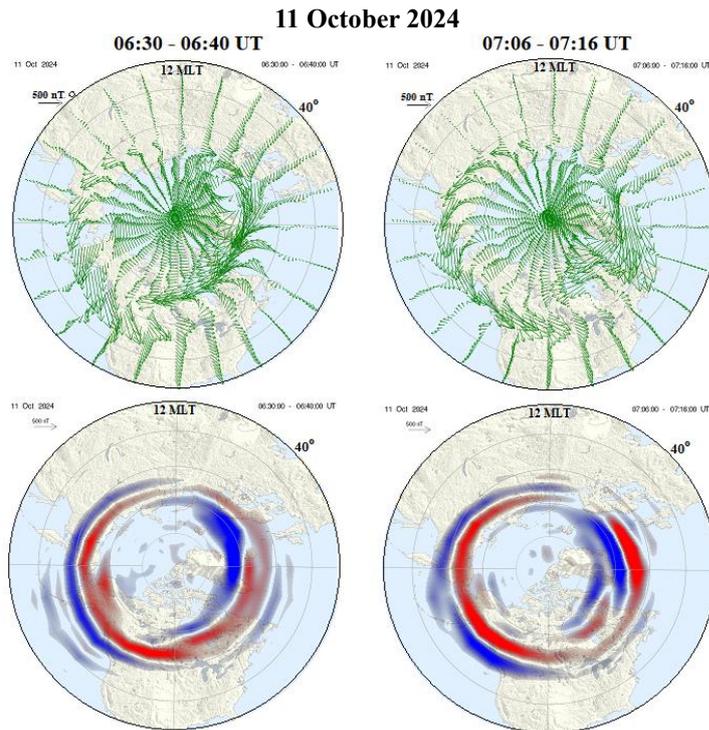


Figure 6. Two AMPERE maps with time interval of about of 30 min demonstrating very variable structure of the electrojets and FACs.

The observations showed that the sign of the IMF B_y controls not only the direction of the dayside polar electrojet, but also affects the eastward current and the size of the region where it is located.

The storm recovery phase developed under the unusual strong negative (up to -40 nT) and long lasting (~ 12 h) IMF B_z . This led to high substorm activity during the storm recover phase as well.

We found that rapid simultaneous values of the P_{sw} led to the complicated rapid changes in the planetary configurations of the eastward and westward electrojets and corresponding FACs depending not only on the instantaneous magnetosphere state but on its previous state too. This makes it difficult to identify specific effects of each individual component. The further detailed studies are required to understand the observed features.

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The storm recovery phase started at 02 UT on 11 October 2024 and developed under unusually strong negative IMF B_z (~ -20 nT) and high V_{sw} values ($\sim 700-750$ km/s). Due to this, there were strong substorm activity ($AL \sim -1000-1500$ nT). Despite the fact that in the storm recovery phase, the IMF and solar wind parameters were not so variable as in the storm main phase, the planetary structure of the FACs and electrojets remained rapidly changing depending not only on the instantaneous IMF values but on its previous state as well. Two AMPERE maps with time interval of about of 30 min (Fig. 6) demonstrate very variable structure of the both electrojets and FACs.

4. Results

We studied the dynamics of the planetary configuration of the eastward and westward electrojets and corresponding field-aligned currents (FACs) during the super-strong magnetic storm on 10-11 October 2024 and found that it depends on the sign and values of the IMF B_y and B_z as well as on the solar wind dynamic pressure (P_{sw}).