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DIAGNOSTICS OF THE SOURCES OF GEOMAGNETIC VARIATIONS FOR THE SUPERSTORM OF MAY 10–13, 2024

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ABSTRACT. The paper presents the results of the analysis of magnetospheric-ionospheric sources of geomagnetic variations for the superstorm of May 10-13, 2024. This event occurred at the maximum of the 25th cycle of the Wolfe solar activity and at the beginning of the 100-year cycle of geomagnetic activity. During this period, superstorms similar to the storms of October-November 2003 will occur.

To analyze the sources of variations, 1-minute values of Polish and Ukrainian geomagnetic observatories (Table 1) were used. The sources of geomagnetic variations were identified based on the data on the indices of geomagnetic activity D_{st}, K_p, AL, AU, AE and model calculations. The influence of magnetospheric sources and auroral ionospheric electric currents in the middle latitudes is diagnosed. The contribution of each source is calculated.

Keywords: solar and geomagnetic activity, solar cycle, magnetospheric-ionospheric current system.

АНОТАЦІЯ. У роботі викладено результати аналізу магнітосферно-іоносферних джерел геомагнітних варіацій для супербурі 10–13 травня 2024 року. Дана подія відбулась у максимумі 25 циклу сонячної активності Вольфа та на початку 100 річного циклу геомагнітної активності. У даний період будуть відбуватися супербурі подібні до бур жовтня-листопада 2003р. Оскільки геомагнітна активність відстає від сонячної на 1–2 роки, її максимум очікується біля 2026 року.

Для аналізу зовнішніх джерел варіацій використано одномінутні значення польських та українських геомагнітних обсерваторій найбільш інформативної сітки INTERMAGNET.

Ідентифікацію джерел геомагнітних варіацій проведено за даними про зміну горизантальної (східної) компоненти вектора напруженості магнітного поля Землі, спокійної сонячно-добової варіації. Індекси геомагнітної активності D_{st}, AL, AU, AE взяті з міжнародних центрів даних та за модельними розрахунками.

У даній роботі нами використано модель Міда для визначення впливу струмів на магнітопаузі (інші моделі дають співмірні значення). Вплив системи кільцевого магнітосферного струму, струму в хвості магнітосфери і ін. в першому наближенні обчислювався за допомогою D_{st} – індекса та його широтної залежності (у нашому випадку використано закон косинуса широти).

Діагностовано вплив магнітосферних джерел та авроральних іоносферних електроструменів та струмів їх розтікання у середні широти. Вичислено величину вкладу кожного джерела: величина магнітосферної складової для даної бурі становить близько 80%, іоносферної – 20%.

Ключові слова: сонячна і геомагнітна активність, сонячний цикл, магнітосферно-іоносферна система струмів.

1. Introduction

On May 8, 2024, solar flares from sunspot region 3664, solar flare X1.0, which peaked at 05:09 UTC, and solar flare M8.6, which peaked at 12:03 UTC on May 8, 2024 caused asymmetric full halo coronal mass ejections that triggered a large geomagnetic storm on May 10–13, 2024, with a storm sudden commencement (SSC) of (Dst = – 412 nT and Kp = 9).

The diagnostics of the sources of geomagnetic variations has been carried out by many authors (Sumaruk, 2006, Laba, 2010, Grandin, 2024), since each event in the geomagnetic field characterizes a different influence of all sources and takes place in a special way. The superstorm of May 2024 occurred at a time close to the maximum of the 25th 11-year Wolfe cycle, but in our opinion it is not the largest in this cycle, since according to our forecasts (Sumaruk, 2023), the maximum of the cycle is expected in 2025–2026, and superstorms occur at the maximum and at the beginning of the decline of cycles, for example, the superstorm of 2003–2004. One of the reasons for this is the possible coincidence of the directions of the Sun's and Earth's magnetic field in odd solar cycles, the increase in recurrent geomagnetic disturbances (Sumaruk, 2009, Orlyuk 2023) and the beginning of the 100-year cycle (Sumaruk, 2023).

2. Magnetospheric-ionospheric current system

To diagnose the sources of the magnetospheric-ionospheric current system, we used one-minute data of the horizontal (north) component H(X) of the Earth's magnetic field induction vector (*B*) of the Ukrainian and Polish INTERMAGNET observatories (data are presented in Table 1).

Table 1: Observatories whose data were used

IAGA code	*Name*	*Geomag. lat. [deg]*	*Geomag. long. [deg]*
ODE	Odesa	43.720	112.430
LVV	L'viv	47.84	106.8
BEL	Belsk	50.18	104.750
HLP	Hel	53.16	104.060

The horizontal component best reflects variations caused by external sources. The value of irregular field variations can be defined as (Sumaruk, 2006):

$$\Delta = X - S_q, \quad (1)$$

where X – value of the horizontal component of the geomagnetic field. S_q – solar diurnal variation of the horizontal component of the geomagnetic field characterizes the wave radiation of the Sun. Since the amplitudes of S_q – variations change with the season and activity. Seasonal variations of activity caused by changes in the ionospheric conductivity. (Sumaruk, 2004). As a reference level for the field of irregular magnetic variations in middle latitudes, we chose the quiet solar diurnal variation calculated by five internationally quiet days (Sumaruk, 2004; Sumaruk, 2005).

The irregular variation of the geomagnetic field caused by the magnetospheric-ionospheric current system is described by the equation (Fukushima and Kamide, 1973):

$$\Delta = DR + DRP + DT + DCF + DP, \quad (2)$$

where *DR* – the variation from the ring magnetospheric current (including the partial ring current);

DRP – the variation due to the partial ring current;

DT – variation from currents in the magnetosphere tail;

DCF – variation with currents at the magnetopause;

DP – variation from the ionospheric currents in the aurora zone and their reverse currents of spreading to the middle latitudes.

Magnetospheric sources (DR, DT, DRP) are well reflected by the D_{st} index of magnetic activity (Campbell, 1996). D_{st} data are taken from the website *(https://wdc.kugi.kyoto-u.ac.jp).* As a first approximation, the magnitude of the variation from magnetospheric sources (Δ_m) can be calculated by the formula:

$$\Delta_m = D_{st} \cdot \cos\Phi, \quad (3)$$

where Φ –the geomagnetic latitude of the observatory.

3. DCF and DP currents

The magnitude of the variation from the currents at the DCF magnetopause is calculated by model calculations. The most commonly used models are the paraboloidal magnetosphere model, the T02 Tsyganenko magnetosphere model, and the Mead magnetosphere model. The magnitude of DCF variations calculated by different models is commensurate in magnitude. In this work, we used the Mead model (Mead, 1964).

According to this model, the components of the *DCF* field on the Earth's surface are defined as (nT):

$$DCF_x = (25150 \cdot \cos\varphi)/r_b^3 + 21000 \cdot ((2\sin^2\varphi - 1) \cdot \cos t)/r_b^4$$

$$DCF_y = (21000 \cdot \sin\varphi \cdot \sin t)/r_b^4 \quad (3)$$

$$DCF_z = (25150 \cdot \sin\varphi)/r_b^3 + (21000 \cdot \sin\varphi \cdot \cos\varphi \cdot \cos t)/r_b^4,$$

where r_b – the geometric distance to the sub-solar point of the magnetosphere; t – local time, which is counted from the midnight meridian; φ – geomagnetic latitude.

The first term in the formulas for the DCF_x and DCF_z components represents the symmetric part of the field, and the second term represents the asymmetric part. The contribution from the magnetopause currents can be calculated if the distance of the sub-solar magnetopause point to the Earth (r_b) is known. The value of r_b (in km) can be found from the solar wind plasma parameters using the model (Shue, 1998):

$$rb = \{10.22 + 1.29 \tanh[0.184 (Bz + 8.14)]\} (nv^2)\ 1/6.6 \quad (4)$$

where v – the velocity of solar wind, km/s; n – the density, cm^{-3}; Bz – Z-component interplanetary magnetic field. During magnetically quiet periods, $r_b = (11–12) \cdot R_E$, R_E – the radius of the Earth. We calculated the variations of DCF_X for all the studied observatories (data are given in Table 2).

Table 2: DCF_X – variations

ODE, nT		LVV, nT		BEL, nT		HEL, nT	
Max	Min	Max	Min	Max	Min	Max	Min
71.4	11.8	66.8	10.8	64.0	10.3	60.3	9.57

The variation from the auroral ionospheric currents in the aurora zone and their return currents to the middle latitudes (*DP*) is described by the auroral activity indices *AE*, *AU*, *AL*. As is known (Feldstein, 1999), during very large magnetic storms ($D_{st} \leq -150$ nT), the focuses of auroral ionospheric currents are shifted to the middle latitudes. During the onset of a magnetic storm, mid-latitude observatories are affected by reverse ionospheric currents. With the growth of D_{st}, the observatories come under the direct influence of the eastern (AU) or western (AL) electric currents, depending on the local time.

We have calculated the variation of DP (data are presented in Fig. 1):

$$DP = \Delta - \Delta_m - DCF. \quad (5)$$

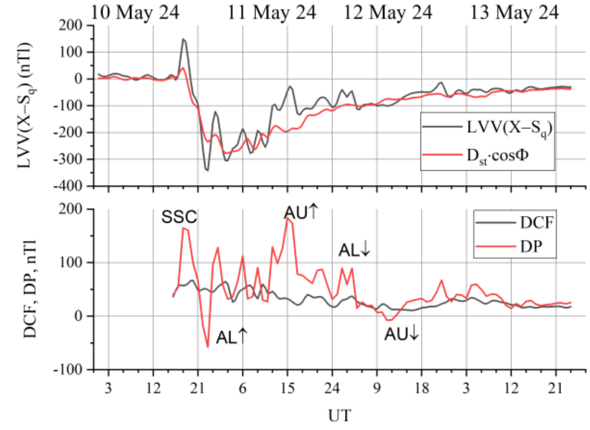

Figure 1 a: Variations of $X - S_q$ and $D_{st}{\cdot}cos\Phi$ (top diagram) and the variations of DCF and DP variations (bottom diagram) for L'viv geomagnetic observatory.

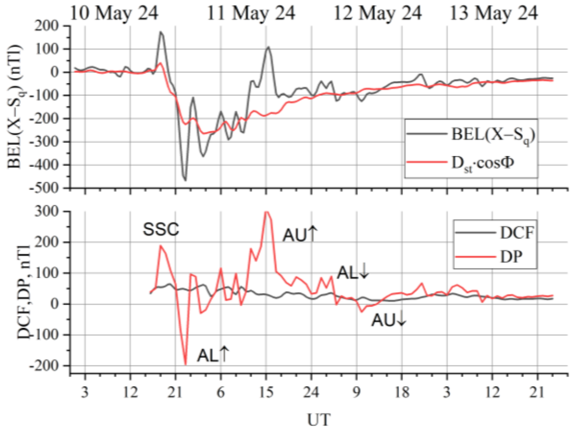

Figure 1 c: Variations of $X - S_q$ and $D_{st}{\cdot}cos\Phi$ (top diagram) and the variations of DCF and DP variations (bottom diagram) for Belsk geomagnetic observatory.

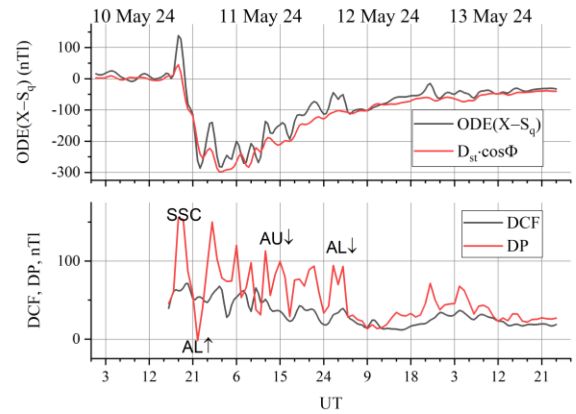

Figure 1 b: Variations of $X - S_q$ and $D_{st}{\cdot}cos\Phi$ (top diagram) and the variations of DCF and DP variations (bottom diagram) for Odesa geomagnetic observatory.

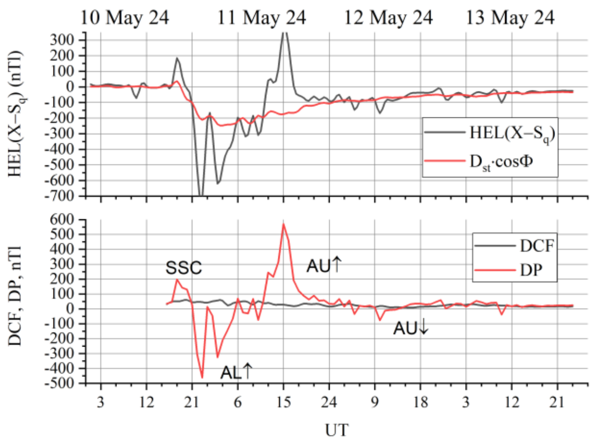

Figure 1 d: Variations of $X - S_q$ and $D_{st}{\cdot}cos\Phi$ (top diagram) and the variations of DCF and DP variations (bottom diagram) for Hel geomagnetic observatory.

Figure 1

4. Discussion

Fig. 1 shows the variations of $X - S_q$ and $D_{st}{\cdot}cos\Phi$ (top panel) and the variations of DCF and DP variations (bottom panel). Identification of ionospheric sources is shown by signs: AL – variation from the western auroral electrojet, AU – from the eastern auroral electrojet. The upward arrow indicates the direct effect of the electric currents, the downward arrow indicates the opposite.

At 18 h 50 min UT on May 10, 2024, the DP-variation is positive, associated with SSC and are ODE–138.5 nT, LVV–14.2 nT, BEL–174.4, nT, HEL–185.1 nT. At 00h UT May 11, 2024 the western auroral electric current sharply increases, the ring magnetospheric current develops, the AL-index increases, and the ring magnetospheric current develops. The D_{st}-variation for the studied observatories are ODE–297.7 nT, LVV–276.5 nT, BEL–263.8 nT, HEL–247.1 nT. The increase in the AL-index means that the currents from the western ionospheric electrojet increased and negative DP values were recorded at the observatories. Further enhancement of the ring current resulted in the movement of the auroral electric currents to mid-latitudes and 15 UT on May 11, 2024, and we observe positive sub-storms (indicated by AU with a upward arrow). On 12–21 UT May 11, 2024, we observe a large positive substorm – generated by the direct action of the eastern auroral jet (AU with an upward arrow). But at this time, the tabulated values of the AE, AL, and AU indices decrease sharply. This decrease is not due to a decrease in the strength of the eastern electrojet but to its shift to subauroral latitudes ($D_{st} \leq -150$ nT), the chain of observatories from which the indices are calculated does not record the maximum current, because the electrojet is located in lower latitudes. Subsequently, the ring magnetospheric current weakens, the auroral electric jets move to the north and the magnetometer registers positive and negative bays caused by the reverse currents of the spreading of the eastern and western electrojet and on May 12–13, 2024.

5. Conclusions

1. We diagnosed the sources of geomagnetic variations, calculated the contribution to the variation of each source, and divided it into components relative to the sources that generate them.

2. It is shown that for the superstorm of May 10–13, 2024, at the studied observatories, magnetospheric sources of variations – the ring magnetospheric current together with the current in the tail of the magnetosphere and the current at the magnetopause during a magnetic storm – give the largest contribution to the field variation of 80%, ionospheric – auroral currents and their reverse currents in the field variation of medium latitudes do not exceed 20%.

3. For diagnostics of irregular geomagnetic variations in the middle latitudes, the S_q-variation can be used as a reference level, taking into account its change with the season and the solar activity cycle, calculated by five internationally quiet days.

4. The geomagnetic variations in the middle latitudes can be divided into components with respect to the sources that generate them.

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