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SUBSTORMS MANIFESTATION AT HIGH AND MID-LATITUDES DURING TWO LARGE MAGNETIC STORMS

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Abstract

The dynamics of magnetic substorms at high and middle latitudes during two severe geomagnetic storms: on 17 March 2015 and on 22–23 June 2015 has been analyzed. The storms were rather similar: both storms were a result of the solar wind Sheath impact and both storms were characterized by a strong intensity ($SYM/H_{min} < -200$ nT). We studied the magnetic substorms during these storms on the base of the INTERMAGNET and IMAGE networks data. The attendant solar wind and Interplanetary Magnetic Field (IMF) parameters were taken from the OMNI database. The spatial-temporal dynamics of three substorms was studied in detail: at 17:29 UT and at 22:55 UT during the first storm and at 18:33 UT during the second storm. The substorms on 17.03.2015 originated during the main storm phase, and the onset of the substorm on 22.06.2015 followed the storm sudden commencement (SSC) of the second storm. All three substorms were characterized by a sharp poleward expansion of the westward electrojet simultaneously with a slower motion to lower latitudes. They were observed also at middle and low latitudes as positive magnetic bays. The westward electrojet reached ~71° CGMLat during the first two substorms and surpassed 75° CGMLat during the third substorm. Therefore, the first two events were "classical" substorms, and the third one – an "expanded" substorm. We suggested that this behavior is related to the different solar wind conditions: the "classical" substorms developed under magnetic cloud (MC) conditions, and the "expanded" – under the Sheath region effect.

Introduction

Substorms are a characteristic event at auroral latitudes. It is well known that during the substorm expansion phase, the westward electrojet propagates fast poleward, usually by a series of jumps. Depending on the magnetic activity, the electrojet could reach latitudes well above the typical location of the night side auroral oval [e.g., 1–10]. Thus, when the electrojet moves to geomagnetic latitudes higher than 75°, the so called "expanded" substorm forms [11]. However, it is generally accepted that under highly disturbed conditions, for example, under enhanced magnitude of the Interplanetary Magnetic Field (IMF) negative B_Z

component, the oval equatorward boundary shifts as well down up to ~50° geomagnetic latitudes. So, in such conditions, the magnetic substorms can be observed at middle and even low latitudes as positive magnetic bays [e.g., 12]. Akasofu, Chapman and Meng [13] assumed that the positive bay was created by the low-latitude return currents from the westward electrojet. Later on Akasofu and Meng [14] and Meng and Akasofu [15] explained the positive bays as a result of the field aligned currents. The mid-latitude positive bays are usually observed in the substorm expansion phase and actually they are caused by the substorm current wedge [16, 17].

The goal of our paper is to study the interplanetary and geomagnetic conditions suitable for the substorms activity at middle and low latitudes and their possible relationship with the substorms at high latitudes analyzing the magnetic disturbances during two large magnetic storms: on 17 March 2015 and 22–23 June 2015.

Data

We used the magnetic data from the IMAGE and INTERMAGNET networks. From the IMAGE set, we considered data from the meridional chain stations Suwalki (SUW) - Ny Ålesund (NAL), situated in the longitudinal range 98° ÷ 112° CGMLon, and covering the latitudinal range from 52º to 75º CGM lat. The list of the IMAGE stations and their coordinates is given at http://space.fmi.fi/image/www/index.php?page=stations. The chosen INTERMAGNET stations are in the longitudinal range of 92° ÷ 104° CGMlon, from 35° to 64° CGMlat. The magnetic observatories names and coordinated can be found at the INTERMAGNET site http://www.intermagnet.org/data-donnee/dataplot-eng.php? type=xyz.

The westward electrojet development was estimated by the time evolution of the equivalent ionospheric currents, computed by the Finish Meteorological Institute (FMI) on-line tool for 22.06° lon. (~112° CGMLon) (http://space.fmi.fi/MIRACLE/iono_1D.php#form). The solar wind and Interplanetary Magnetic Field (IMF) parameters were provided by the OMNI database (https://cdaweb.sci.gsfc.nasa.gov/cgi-bin/eval1.cgi) and by the catalog of large-scale solar wind phenomena (ftp://ftp.iki.rssi.ru/omni/) [18].

Results

Interplanetary and geomagnetic conditions

The interplanetary and geomagnetic conditions during the examined events are presented in Fig. 1. From up to down, the following quantities are shown: the magnitude of the interplanetary magnetic field (IMF) B_T, the IMF B_Z, the flow velocity V_X, the plasma density, temperature, pressure (P), and the AE, SYM/H and K_P geomagnetic indices. The considered storms were the largest ones during the present solar cycle 24.

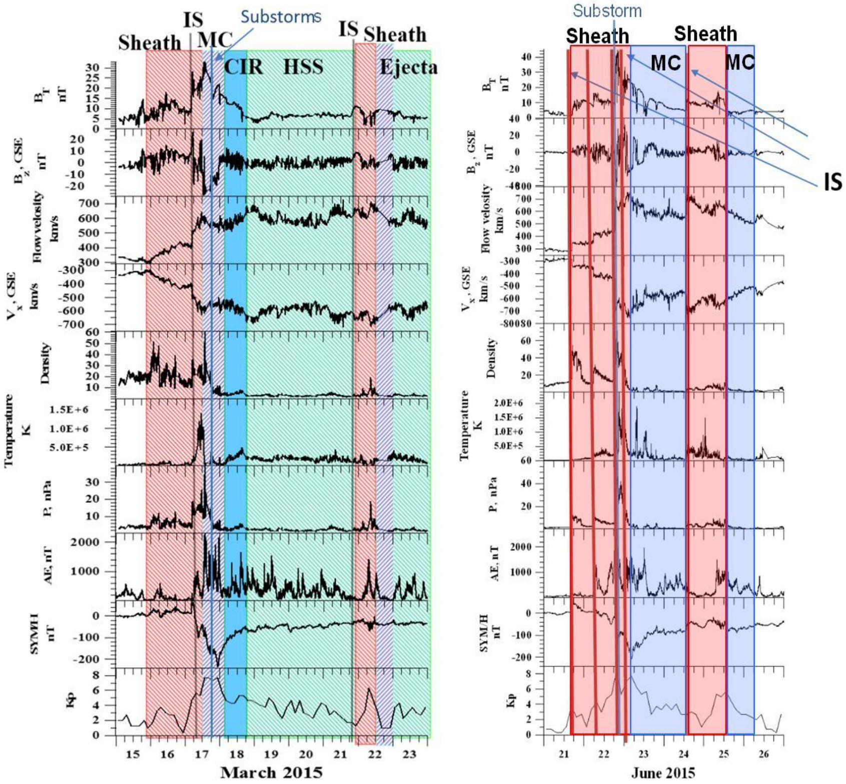

Fig. 1. Interplanetary and geomagnetic conditions during the storms on 15 March 2015 and 22–23 June 2015. The structures in the solar wind are marked by rectangles in different colours and inscribed in the upper part of the figure. The moments of interplanetary shocks (IS) arrivals are indicated by straight vertical lines. The time of the substorms during the main storm phases are marked by blue vertical lines.

The geomagnetic storm on 17 March 2015 (St. Patrick storm) was caused by a solar flare and the associated coronal mass ejections (CMEs) on 15 March 2015. The storm sudden commencement (SSC) was initiated by the formed large interplanetary shock (IS) in the sheath region. SYM/H jumped from 16 to 66 nT.

The storm was a severe one (of level G4), and the G3/G4 conditions were sustained for ~12 hours. The main phase continued ~18 hours. SYM/H fell down to –235 nT. The B_Z component of the IMF reached –30 nT and was retained ~ –20 nT for ~6.5 hours.

The storm on 22–23 June 2015 (the summer solstice storm) originated during variable solar wind conditions, when a consecution of three CMEs reached the Earth. At the third interplanetary shock the IMF B_Z turned from positive to negative and dropped to –40 nT, at that time the storm sudden commencement occurred with a sudden impulse from –20 nT to 69 nT. This storm was also a severe (G4) storm, the level of moderate-severe storm was retained for about 7 hours. The main phase lasted about 9 hours. SYM/H_{min} was –208 nT. The IMF B_Z was sustained ~ –20 nT for about 6 hours.

Both considered storms were similar to each other: they were SHEATH-caused storms, initiated by interplanetary shocks in the SHEATH region, they were very intensive, of level G4, they had clearly expressed storm sudden commencements, two-step main phases and long lasting recovery phases (Fig. 1).

Three substorms have been studied in detail: two substorms, registered during the main phase of the first storm (with their onsets at 17:29 UT and 22:55 UT on 17 March 2015), and one substorm generated during the initial phase of the second storm at 18:33 UT on 22 June 2015. The substorms of 17 March 2015 are presented in Fig. 2 and Fig. 3, and the substorm of 22 June 2015 – in Fig. 4 and Fig. 5. In Fig. 2 and Fig. 4, the equivalent ionospheric currents (upper panels) and the X-component of the magnetic field at the IMAGE latitudinal chain SUW-NAL (bottom panels) are given for the substorms on 17 March 2015 and 22 June 2015, respectively. The upper panels demonstrate the westward electrojet geographic latitude dynamics, estimated at the 22.06° geographic longitude. In Fig. 3 and Fig. 5 the magnetic field X-component at the selected INTERMAGNET stations during the considered substorms is presented. In the figures, the magnetic station location is arranged by the latitude. The substorm onsets are indicated by the red vertical lines (determined by TAR NUR and PEL stations data).

The values of the IMF B_T, IMF B_Z and solar wind parameters were averaged for 1.5 hours before the substorm onsets.

Substorm at 17:29 UT on 17 March 2015

This substorm has originated during the main storm phase, at the time of the magnetic cloud (MC) in the solar wind (see Fig. 1). The averaged parameter values were: B_T = 23 nT, B_Y = 2.0 nT, B_Z = –19 nT, V_X = –570 km/s. At the substorm onset, SYM/H was -176 nT. The westward electrojet moved fast to the Nord from ~56°÷62° to ~69° CGMlat at ~17:50 UT. After that, at ~18:05 UT, a new northward jump occurred and the electrojet reached ~72° CGMlat. A slower movement to the South was observed as well (Fig. 2, upper). The disturbances in the X-component begun at NUR (56.89 CGMlat.). They are clearly expressed to the North, to BJN (71.45° CGMLat) as well as to the South, to BRZ (52.30° CGMlat) (Fig. 2, bottom panel). At the lower latitudes, a positive bay in the X-component was observed at all mid-latitude stations to the South from HLP (50.70° CGMlat) (Fig. 3). It lasted about 20 min.

This positive bay could be seen even at the equatorial latitudes, at the station Adis Abeba (AAE), at 5.22° CGM lat. (not shown in Fig. 3).

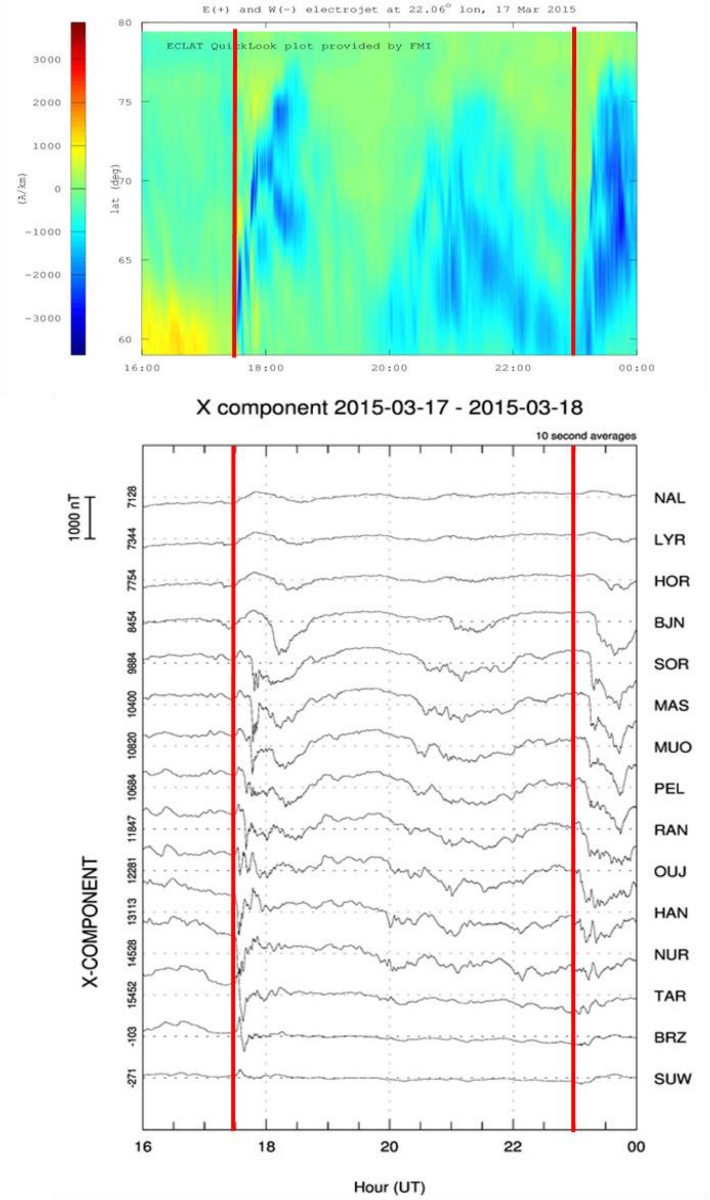

Fig. 2. Equivalent ionospheric currents (blue- negative, red -positive) – upper panel, and the X-component of the magnetic field at the IMAGE latitudinal chain SUW-NAL during the first two examined substorms on 17 March 2015 (bottom panel)

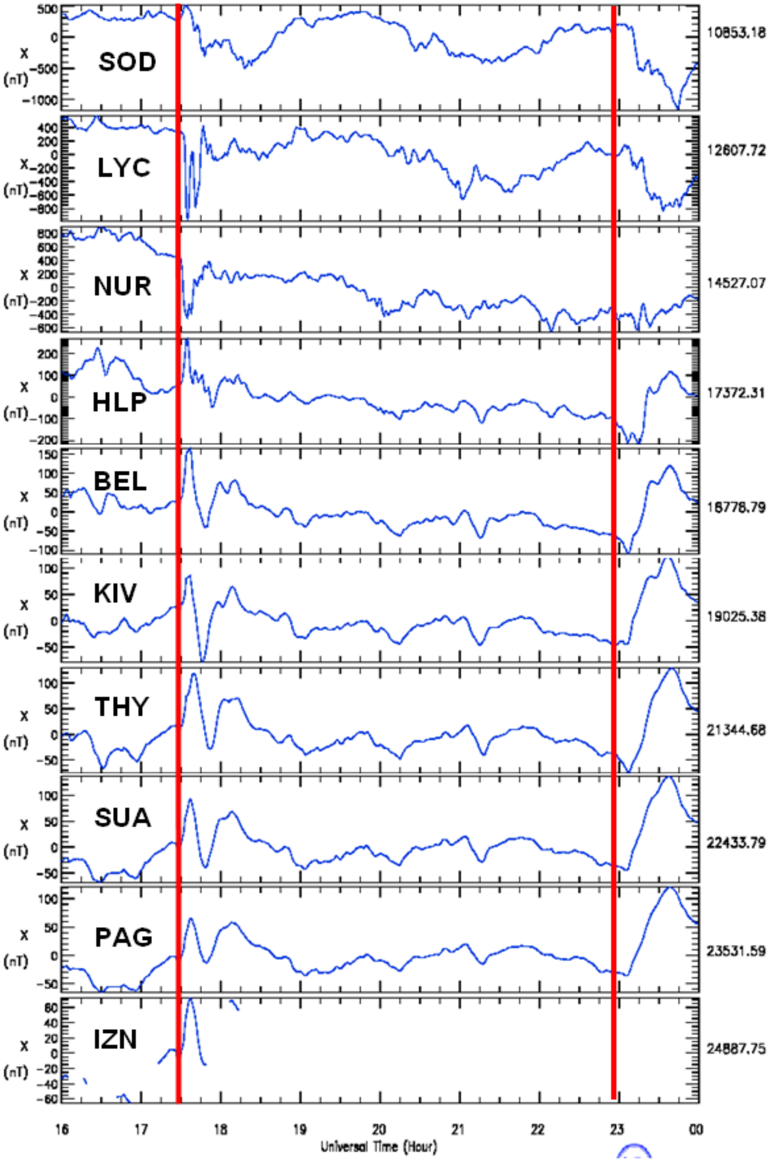

Fig. 3. X-component of the magnetic field at the selected INTERMAGNET stations during the examined substorms on 17 March 2015

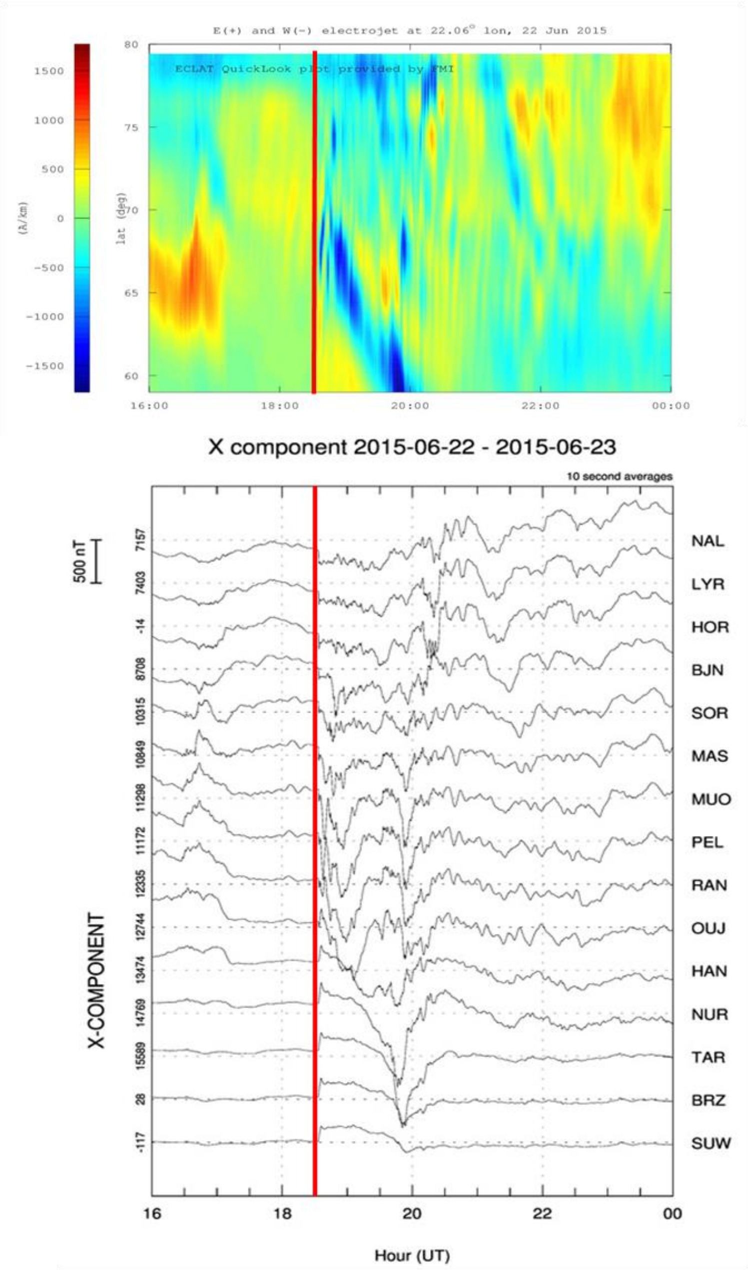

Fig. 4. Equivalent ionospheric currents (blue- negative, red -positive) – upper panel, and the X-component of the magnetic field at the IMAGE latitudinal chain SUW-NAL during the substorm on 22 June 2015 (bottom panel)

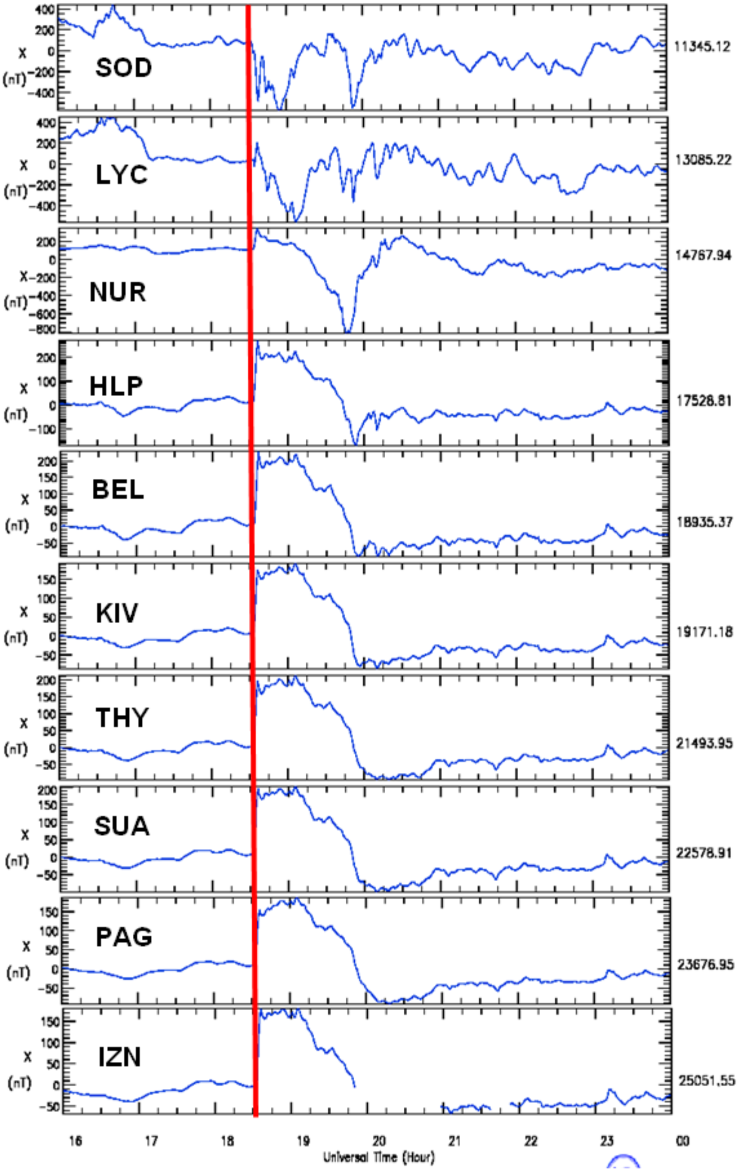

Fig. 5. X-component of the magnetic field at the selected INTERMAGNET stations during the substorm on 22 June 2015

Substorm at 22:55 UT on 17 March 2015

The second examined substorm on 17 March 2015 was developed also during the MC, in the main storm phase, close to the SYM/H_{min}. The following average IMF values were recorded: IMF B_T = 20.45 nT, IMF B_Y = –10 nT, IMF B_Z = –15 nT, V_X = –550 km/s. At the substorm onset, the SYM/H = –161 nT. The westward electrojet drifted fast to the North, from ~54° to ~72° CGMlat (Fig. 2, upper panel). The strong disturbances in the X-component begun at TAR (54.47° CGMlat), reached BJN (71.45° CGMlat) to the North and were observed up to BRZ (52.30° CGMlat) to the South (Fig. 2, bottom panel). A positive magnetic bay was registered at first at HLP (50.70° CGMlat) as well as in all mid-latitude stations to the South from HLP (Fig. 3), and also at the equatorial latitudes (AAE, not presented here). It lasted about 1 hour.

Substorm at 18:33 UT on 22 June 2015

This substorm was originated during SHEATH in the solar wind. Its onset was observed in the time when a shock wave (IS), third in this disturbed period, impacted the magnetosphere (Fig. 1, right panel). The shock arrival was characterized by a sharp increase of the solar wind parameters: the dynamic pressure jump was from 5 to about 60 nPa, the velocity X-component increased from 450 km/s to 700 km/s, the proton density – from 15 to 60 cm^{-3}, and the temperature – from $2*10^5$ to $1.4*10^6$ K. The magnitude of the IMF B_T enhanced from 10 to 45 nT, and the IMF B_Z turned southward at 18:39 UT and reached –40 nT at 19:22 UT. Prior to the onset, the average IMF and solar wind parameter values were: IMF B_T= 9.57 nT, IMF B_Y= –6 nT, IMF B_Z= –1.1 nT, V_X= –435 km/s. The fast decrease of the IMF B_Z and the change of its direction provoked the storm sudden commencement (SSC) at 18:33 UT. The SYM/H value sharply increased from –20 nT to 88 nT, after that decreased and at 19:18 UT became negative. Then the main storm phase began. The substorm onset followed the SSC, its development was in progress during the storm initial phase and continued further in the main phase.

The westward electrojet moved fast to the North from 62° ÷ 67° CGMlat at 18:33 UT and after a jerk reached the CGM latitudes of 75° and more. Simultaneously, the electrojet shifted to the South, to the CGM latitudes < 57° at 19:40–20:00 UT (the upper panel in Fig. 4). The perturbations in the X-component began at PEL (63.55° CGMlat), reached NAL (75.25° CGMlat) to the North and BRZ (52.30° CGMlat) to the South by the IMAGE latitudinal chain (bottom panel in Fig. 4). A positive magnetic bay was seen at the mid-latitude stations (Fig. 5) and equatorial stations (AAE, not presented here). The positive bay was registered at all stations southward from HLP (50.70° CGMLat). The bay lasted about 1.5 hours and was characterized by a sharp increase, followed by a gradual decrease.

Discussion

The considered substorms originated during the rather similar severe geomagnetic storms. One of its resemblances was a noticeable display of positive magnetic bays at middle and low latitudes. However, its onsets and further development have been observed under different interplanetary and geomagnetic conditions, which lead to the different onset locations and the different spatial dynamics of the westward electrojet, as well as to the differences in the substorms extent and the behavior of the middle and low latitude positive magnetic bays.

The substorms of 17 March 2015 occurred during MC, in the time of the main storm phase, under disturbed conditions, as indicated by the corresponding averaged IMF B_Z, V_X, and SYM/H values. The substorm onsets were located at ~57° and ~54° CGMlat, respectively, corresponding to an expanding auroral oval. The third substorm onset of 22 June 2015 has happened during SHEATH, and followed the interplanetary shock and the SSC. The average IMF B_Z and V_X values suggested relatively quiet interplanetary conditions prior the substorm. Perhaps, for that reason, the auroral oval was not so expanded as in the first two events and the substorm onset was at higher CGM latitude, at ~63–64°. (Note, the substorms of 17 March 2015 developed in the main storm phase).

In the first two events, the sharp motion of the west electrojet could be observed to the North direction up to ~70–71° CGMLat (upper panel of Fig. 2). The strong X-component magnetic perturbations on the ground reached 71° CGMlat (bottom panel of Fig. 2), a slower drift to the South was registered simultaneously as well. Such behavior is typical for the "classical" substorms.

During the substorm of 22 June 2015, the considerable movement of the westward electrojet to the South and North was observed (Fig.4, upper panel). The significant travel of the substorm to the South has happened, probably, due to the change of the IMF B_Z sign from positive to negative up to –40 nT. After the second jump of the electrojet to the North, its progress surpassed the 75° CGMlat. The electrojet center reached the station LYR (75.12° CGMlat). Such substorm behavior allows ranking this substorm among the "expanded" substorms [11].

The positive magnetic bays observed at the middle latitudes during the first two substorms, were nearly symmetric, and the duration of the perturbation was about 20 min and 1 hour, correspondingly. The positive bay during the third substorm was characterized by a sharp increase, as a result of the association of the substorm onset with the IS and SSC, and by a gradual decrease later.

The boundary between the negative and positive bays was observed in the latitude range of 50 ÷ 56° CGMlat (between the stations HLP and NUR). According to the McPherron et al. [12] scheme, this boundary could be mapped between the electrojet location and the field aligned currents during the considered substorms.

Conclusion

In this work we analyzed the strongest geomagnetic storm in the current 24th solar cycle – the storm of 17 March 2015 (Ap = 108) [19, 20]. It, together with the storm of 8 September 2017 (Ap = 106), represents the two extreme (G4 – level) manifestations of the geomagnetic activity of the 24th cycle during solar maximum and minimum respectively [19–22].

Also examined is the 2015 summer solstice storm of 22–23 June (Ap = 72), which is the sixth major geomagnetic storm (also G4 – level) of solar cycle 24 https://www.spaceweatherlive.com/.

Our main contributions are as follows:

- The middle and low latitudes substorms demonstrate the positive sign of the magnetic X- component. The magnetic bay sign changed from negative to positive between 50° and 56° CGMlat (between HLP and NUR sta-tions);
- The clear effect of the magnetic storm Sudden Commencement (SSC) was expressed by the rapid substorm shift from the auroral to low latitudes and the sharp increase of the substorm intensity on 22 June 2015. The larger amplitude and longer duration of the positive magnetic bay on 22 June 2015 are, probably, due to its development in the SHEATH versus the development in the MC of the substorms on 17 March 2015.
- It is seen that certain interplanetary conditions (SHEATH + IS) during the storm on 22 June 2015 led to a substorm that manifested itself at low latitudes (positive bays), and also at high latitudes (so called “expanded” substorms);
- The substorms during the storm on 17 March 2015 were observed at low and auroral latitudes too, but without the high-latitude expansion, perhaps, this is connected with the development of these substorms during the magnetic cloud (MC). Thus, they appear “classical” substorms.

The research conducted here will be expanded to other strong storms of the 24th solar cycle, for example the G4 – Severe geomagnetic storm on September 7–8 2017 and other interesting cases.

References

1. Akasofu, S.-I. The development of the auroral substorm, Planetary and Space Science, 1964, 12, 4, 273–82. https://doi.org/10.1016/0032-0633(64)90151-5
2. Feldstein, Y. L. and G. V. Starkov. Dynamics of auroral belt and geomagnetic disturbances, Planetary and Space Science, 1967, 15(2), 209–229.
3. Kisabeth, J. L. and G. Rostoker. The expansive phase of magnetospheric substorms: 1. Development of the auroral electrojets and auroral arcs configuration during substorm, J. Geophys. Res., 1974, 79, 7, 972–84.

4. Wiens, R. G. and G. Rostoker. Characteristics of the devel opment of the westward electrojet during the expansive phase of magnetospheric substorms, J. Geophys. Res., 1975, 16, 2109–28.
5. Sergeev, V. A., A. G. Yakhnin, and N. P. Dmitrieva. Substorms in the polar cap are effect of high-speed streams of the solar wind, Geomag. Aeron., 1979, 19, 1121–22. (in Russian)
6. Wang, H., H. Lühr, S. Y. Ma, and P. Ritter. Statistical study of the substorm onset: its dependence on solar wind parameters and solar illumination, Ann. Geophys., 2005, 23, 2069–79. doi:10.5194/angeo-23-2069-2005
7. Despirak, I. V., A. A. Lubchich, A. G. Yakhnin, and H. K. Biernat. Poleward expansion of the westward electrojet depending on the solar wind and IMF parameters, Geomagnetism and Aeronomy, 2008, 48, 3, 284–92.
8. Tanskanen, E. I., T. I. Pulkkinen, A. Viljanen, K. Mursula, N. Partamies, and J. A. Slavin. From space weather toward space climate time scales: Substorm analysis from 1993 to 2008, J. Geophys. Res., 2011, 116, A00I34. doi:10.1029/2010JA015788
9. Clausen, L. B. N., S. E. Milan, J. B. H. Baker, J. M. Ruohoniemi, K. H. Glassmeier, J. C. Coxon, and B. J. Anderson. On the influence of open magnetic flux on substorm intensity: Ground- and space-based observations, J. Geophys. Res., 2013, 118, 2958–69. doi:10.1002/jgra.50308
10. Despirak, I. V., A. A. Lubchich, and N. G. Kleimenova. Polar and High Latitude Substorms and Solar Wind Conditions, Geomag. Aeron., 2014, 54, 5, 619–26.
11. Despirak, I. V., A. A. Lubchich, and N. G. Kleimenova: High-latitude substorm dependence on space weather conditions in solar cycle 23 and 24 (SC23 and SC24), J. Atmos. Sol. Terr. Phys., 2018, 177, 54–62**.**
12. McPherron, R. L., C. T. Russell, and M. P. Aubry. Satellite studies of magnetospheric substorms on August 15, 1968. 9. Phenomenological model for substorms, J. Geophys. Res., 1973, 78, 3131.
13. Akasofu, S.-I., S. Chapman, and C. I. Meng. The polar electrojet, Journal of Atmospheric and Terrestrial Physics, 1965, 27, 11–12, 1275–1305. doi:10.1016/0021-9169(65)90087-5
14. Akasofu, S.-I. and C. I. Meng, A study of polar magnetic substorms, J. Geophys. Res., 1969, 74, 1, 293–313. doi:10.1029/JA074i001p00293
15. Meng, C. I. and S.-I. Akasofu, A study of polar magnetic substorms .2. 3-dimensional current system, J. Geophys. Res., 1969, 74, 16, 4035–53. doi:10.1029/JA074i016p04035
16. McPherron, R. L., Chu, X., The mid-latitude positive bay and the MPB index of substorm activity, Space Science Reviews, 2017, 206, 1–4, 91–122. doi:10.1007/s11214-016-0316-6
17. McPherron, R. L. and X. Chu, The midlatitude positive bay index and the statistics of substorm occurrences, J. Geophys. Re.: Space Physics, 2018, 123, 2831–50. doi:10.1002/2017JA024766
18. Yermolaev, Yu. I., Nikolaeva, N. S., Lodkina, I. G., Yermolaev, and M. Yu., Catalog of large-scale solar wind phenomena during 1976–2000. Cosmic Research (Engl. Transl.), 2009, 47, 81–94.

19. Tomova, D., P. I. Y. Velinov, and Y. Tassev, Energetic evaluation of the largest geomagnetic storms of solar cycle 24 – on March 17, 2015 and September 8, 2017 during solar maximum and minimum respectively. C. R. Acad. Bulg. Sci., 2017, 70, 11, 1567–78.
20. Tomova, D., P. I. Y. Velinov, and Y. Tassev, Comparison between extreme solar activity during periods March 15–17, 2015 and September 4–10, 2017 at different phases of solar cycle 24, Aerospace Res. Bulg., 2017, 29, 10–29.
21. Tassev, Y., P. I. Y. Velinov, D. Tomova, and L. Mateev, Analisis of extreme solar activity in early September 2017: G4 – Severe geomagnetic storm (07–08.09) and GLE72 (10.09) in solar minimum, C.R. Acad. Bulg. Sci., 2017, 70, 10, 1437–44.
22. Velinov, P. I. Y. and Y. Tassev, Long term decrease of stratospheric ionization near the 24-th solar cycle minimum after G4 – Severe geomagnetic storm and GLE72 on September 8–10, 2017, C.R. Acad. Bulg. Sci., 2018, 71, 8, 1086–94.

ПРОЯВА НА СУББУРИ НА ВИСОКИ И СРЕДНИ ШИРИНИ ПО ВРЕМЕ НА ДВЕ СИЛНИ МАГНИТНИ БУРИ

В. Гинева, И. Деспирак, Н. Клеймьонова

Резюме

Анализирана е динамиката на магнитните суббури на високи и средни ширини по време на две силни геомагнитни бури, на 17 март 2015 г. и 22 юни 2015 г. Двете бури са доста подобни: и двете са резултат от въздействието на Sheath област в слънчевия вятър, и двете се характеризират с висока интензивност ($SYM/H_{min} < -200$ nT). Ние изучихме магнитните суббури по време на тези бури на основата на данните от мрежите станции INTERMAGNET и IMAGE. Съпътстващите параметри на слънчевия вятър и междупланетното магнитно поле (ММП) бяха взети от базата данни OMNI. Пространствено-временната динамика на три суббури беше изучена подробно: суббурите от 17:29 UT и 22:55 UT през първата буря и от 18:33 UT през втората буря. Суббурите на 17 март 2015 г. възникнаха през главната фаза на бурята, а началото на суббурята на 22 юни 2015 г. беше след внезапното начало (SSC) на втората буря. И трите суббури се характеризират с рязко разширяване към полюса на западния електроджет едновременно с по-бавно движение към по-ниски ширини. Те бяха наблюдавани също така на средни и ниски ширини като положителни магнитни „заливи”. Западният електроджет достигна ~71° CGMlat през първите две суббури и задмина 75° CGMLat през третата суббуря. Следователно, първите две събития са „класически” суббури, а третото – „разширена” суббуря. Ние предполагаме, че това поведение е свързано с различните условия в слънчевия вятър: „класическите” суббури се развиват при магнитен облак (MC), а „разширените” – под въздействието на Sheath областта.