DOI: 10.31401/WS.2024.proc.08

Analysis of Substorms Related to Strong MPB at Panagjurishte Station in 2022

Guineva V.[1], *Werner R.*[1], *Bojilova R.*[2], *Raykova L.*[1], *Atanassov A.*[1], *Valev D.*[1]

[1]Space Research and Technology Institute (SRTI) – Bulgarian Academy of Sciences, Stara Zagora Department, Bulgaria; v_guineva@yahoo.com
[2]National Institute of Geophysics, Geodesy and Geography (NIGGG) - Bulgarian Academy of Sciences, Sofia, Bulgaria

Abstract

Substorms developed over Europe are often accompanied by midlatitude positive bays (MPB) which represent peaks in the X magnetic component at midlatitudes. The present study aims at revealing the interplanetary and geomagnetic conditions under which develop magnetospheric substorms responsible for strong MPB at the Bulgarian magnetic station Panagjurishte. In this purpose, the 153 MPB's in 2022 determined as appreciable effect of auroral substorms, are examined. 14 MPB's with maximal X values greater than 20 nT are taken into account. The beginning times of these MPB's are close to the substorm onsets determined from the SML index by Newell and Gjerloev (2011), Forsyth et al. (2015) and Ohtani and Gjerloev (2020). The interplanetary and geomagnetic conditions during the studied substorms have been verified. It was found out that these substorms occurred against the background of different structures in the solar wind related to high speed streams from coronal holes or coronal mass ejections. Under such disturbed interplanetary conditions, in all studied cases magnetic storms developed, the majority of which are between the top 50 geomagnetic storms of 2022.

Keywords: Midlatitude positive bays; Interplanetary and geomagnetic conditions; Panagiurishte magnetic station

Introduction.

Magnetospheric substorms are a substantial element of the space weather. The principle disturbances of the Earth's magnetosphere are due to the substorms development. After the present-day theory, during magnetospheric substorms, a current system forms, namely the so-called Substorm current wedge (SCW) [e.g. McPherron, 1972; McPherron et al., 1973a], by the deviation of the tail current along the magnetic field lines through the ionosphere and the formation of auroral electrojets, in the east and west direction. The auroral electrojets have been investigated since 1970s [e.g. McPherron et al., 1973b, Kisabeth and Rostoker, 1974]. The substorm current wedge is responsible for the main disturbances in the Earth magnetic field: negative bays of the X-component at auroral latitudes and positive bays of X at midlatitudes (midlatitude positive bays – MPB), which accompany the expansion of the magnetospheric substorms [e.g. McPherron, 1972; Kepko et al., 2014]. The magnetic disturbances at the Earth surface have been used in a number of studies of the magnetospheric substorms. The midlatitude magnetic variations are a powerfull tool for the magnetospheric substorms investigation. The MPB's are a good indicator of the substorm onset [McPherron and Chu, 2017], and the sign of Y component was used to estimate the direction of the field aligned currents at a given longitude [Meng and Akasofu, 1969].

The magnetospheric substorms may be accompanied or not with magnetic disturbances at midlatitudes. The presence and strength of the midlatitude magnetic disturbances aroused by magnetospheric substorms, depend on the substorm strength, the measuring point location (distance from the substorm meridian and geomagnetic latitude), and also on the interplanetary and geomagnetic conditions.

The purpose of this work is to verify the interplanetary and geomagnetic conditions during substorms, which caused strong MPB at the Bulgarian magnetic station Panagjurishte. For this, the detected MPB's in 2022 based on the Catalog of the magnetic variations at the Panagjurishte station [Guineva et al., 2023a, Guineva et al., 2023b, Guineva et al., 2023c] have been used.

Data used.

For the study, data from the Catalog of the magnetic variations at the Panagjurishte station (PAG) (~37° GMLat, ~97° GMLon), created at the Space Research and Technology Institute of the Bulgarian Academy of Sciences, have been used. The catalog is available at: http://space.bas.bg/Catalog_MPB/. Data from 2022 were examined.

The interplanetary and geomagnetic conditions have been verified by data of OMNI database of the Coordinated data analysis Web (https://cdaweb.gsfc.nasa.gov/) and the Catalog of large scale solar wind phenomena (http://www.iki.rssi.ru/pub/omni/catalog/).

To compare the results for the substorms by the MPB's, registered at PAG, with other results of substorms over Europe at the same time, the substorm lists by Newell and Gjerloev (2011), Forsyth et al. (2015) and Ohtani and Gjerloev (2020) have been used, available in the SuperMAG database (https://supermag.jhuapl.edu/substorms/?tab=description), as well as IL index data from IMAGE database (https://space.fmi.fi/image/www/il_index_panel.php).

1.1.Data from the Catalog of the magnetic variations at PAG.

For the study, data from the section "Data about MPB", namely from the subsections "Yearly lists", "MPB parameters" and "MPB graphs" of the Catalog for 2022 have been used [Guineva et al., 2023b]. The time interval from 18 UT to 24 UT (approximately 21 MLT – 03 MLT for PAG) was examined. The MPB's, included in the yearly lists, have to fulfil the following conditions:

- The IL index computed by data from the PPN-NAL IMAGE chain has a minimum smaller than -200 nT;
- In the vicinity of this minimum at time distance no more than 30 min., a peak of the X magnetic field component at PAG was registered;
- The maximal value of the peak is greater or equal to 5 nT.

In 2022, 153 midlatitude positive bays were detected, meeting the above criteria. For the investigation, we used the strongest of them, with maximal value greater than 20 nT, which are 14 (about 10% of the whole number).

From subsection "MPB parameters", the MPB beginning time, the MPB maximal value and the MPB amplitude have been used for the chosen substorm cases [Guineva et al., 2023a].

Results.

Interplanetary and geomagnetic conditions in the time of MPB under examination.

Some characteristics of the examined MPB's and the peculiarities of the interplanetary and geomagnetic conditions at the same time are summarized in Table 1. The consecutive columns of the table are as follows: case number, date, the beginning time of MPB at PAG, MPB maximal value, MPB amplitude, observed structure in the solar wind, SYM/H index minimal value, the time of SYM/H minimum, SYM/H value at the MPB beginning time, the phase of the geomagnetic storm at the MPB beginning time (if a geomagnetic storm was developed at the same time).

Table 1. *Interplanetary and geomagnetic conditions in the time of strong MPB's.*

№	date	MPB beginning time	MPB_{max} nT	Amplitude nT	Solar wind structure	SYM/H_{min} nT	Time of SYM/H_{min}	SYM/H nT	Storm phase
1	04.02.2022	17:44	27.63	40.13	EJECTA	-71	20:58	-51	Main phase
2	10.02.2022	20:14	21.57	30.19	MC	-68	19:00	-60	Max development
3	11.02.2022	19:39	28.94	42.87	CIR	-46	00:30 (12.02)	-5	Main phase
4	05.03.2022	20:26	27.30	33.80	HSS	-60	19:41	-57	Max development
5	02.04.2022	18:14	23.50	31.29	HSS	-59	07:07	-25	Late recovery
6	14.04.2022	18:29	27.11	43.66	MC	-86	22:40	-64	Main phase
7	27.05.2022	23:21	21.74	33.49	HSS	-59	07:16 (28.05)	-40	Main phase
8	19.07.2022	19:00	31.15	39.23	EJECTA	-65	12:20	-58	Max development
9	19.07.2022	21:27	30.06	38.63	EJECTA	-65	12:20	-63	Max development
10	08.08.2022	21:59	20.53	33.00	HSS	-69	07:42	-30	Recovery phase
11	11.08.2022	18:30	23.48	32.42	HSS	-69	07:42	-36	Late recovery
12	23.10.2022	20:21	23.32	32.71	CIR	-85	16:36 (22.10)	-16	Late recovery
13	07.11.2022	19:07	24.79	52.63	SLOW	-117	17:20	-110	Max development
14	22.12.2022	19:54	20.74	27.09	SLOW	-33	17:01	-14	

As it seen from Table 1, in almost all 14 cases, structures in the solar wind were registered (5 HSS's, 2 CIR's, 3 Ejectas, 2 MC's, and only 2 Slows), and geomagnetic storms developed (except in the last case). Most of the storms are between the 50 top geomagnetic storms in 2022. 2022 is at about the middle of the ascending phase of SC25, which is expected to be a weak cycle, same as SC24, Sn number didn't exceed 100 in 2022, so the maximal Ap index for the 13 storms is 40, the maximal kp is 6+, and the minimal SYM/H value is -117 nT.

Comparison of the obtained results with results about the same substorms by SML index.

To compare the substorm results by PAG magnetic data, we used the substorm lists by Newell and Gjerloev (2011), Forsyth et al. (2015) and Ohtani and Gjerloev (2020) from the SuperMAG database. At first, the AL index has been used to identify substorm events. Nowadays, several techniques are using the SuperMAG version of the AL index (SML index) to identify substorm events. The substorm events are identified and the substorm onsets are determined by several different techniques. It should be taken into account, that all existing substorm onset identification techniques have limitations. By reason of the applied technique and its assumptions, there may be some differences in the identified substorms and in the determined onsets. The substorm lists contain the time and the location of the substorm onset, comprising the following coloumns: the date, the substorm onset time (UT), magnetic local taime (MLT), magnetic latitude (Mlat), geographic longitude (Glon), and geographic latitude (Glat). For our comparison, we constructed 3 tables, Table 2, 3 and 4, including our data and corresponding data from the Newell and Gjerloev (2011), Forsyth et al. (2015) and Ohtani and Gjerloev (2020) lists, respectively.

Table 2. *Comparison of the obtained beginnings of the examined MPB's with the results of identified substorms over Europe at the same time by Newell and Gjerloev (2011).*

№	date	UT	MLT	MLAT	MLON	GLAT	GLON	station	MPB beginning time (this work)	Δt, min.	Y_{PAG}
1	04.02.2022	17:56	20.25	73.69	111.41	76.51	25.01	HOP	17:44	12	15.8
2	10.02.2022								20:14		9.56
3	11.02.2022								19:39		19.0
4	05.03.2022	20:28	22.37	61.41	104.43	64.52	27.23	OUJ	20:26	2	13.0
5	02.04.2022								18:14		13.0
6	14.04.2022	18:47	21.00	62.87	104.32	65.9	26.41	RAN	18:29	18	1.7
7	27.05.2022	23:23	1.76	62.87	104.30	65.9	26.41	RAN	23:21	2	-2.2
8	19.07.2022								19:00		-11.3
9	19.07.2022	21:34	22.94	62.28	90.90	64.94	10.99	RVK	21:27	7	6.9
10	08.08.2022	22:00	0.27	64.40	105.18	67.37	26.63	SOD	21:59	1	-5.9
11	11.08.2022	18:50	20.47	63.64	96.59	66.4	16.98	JCK	18:30	20	-9.4
12	23.10.2022	20:23	22.71	64.41	105.15	67.37	26.63	SOD	20:21	2	6.8
13	07.11.2022	19:13	21.53	64.41	105.14	67.37	26.63	SOD	19:07	6	0.756
14	22.12.2022	19:54	21.58	66.32	101.20	69.06	20.77	KIL	19:54	0	12.09

Table 3. *Comparison of the obtained beginnings of the examined MPB's with the results of identified substorms over Europe at the same time by Forsyth et al. (2015).*

№	date	UT	MLT	MLAT	MLON	GLAT	GLON	MPB beginning time (this work)	Δt, min.	Y_{PAG}
1	04.02.2022							17:44		15.8
2	10.02.2022							20:14		9.56
3	11.02.2022	20:15	22.58	68.66	104.69	71.43	22.85	19:39	36	19.0
4	05.03.2022							20:26		13.0
5	02.04.2022							18:14		13.0
6	14.04.2022	18:47	21.16	62.54	102.50	65.55	24.47	18:29	18	1.7
7	27.05.2022	23:20	1.85	62.00		65.54	24.25	23:21		-2.2
8	19.07.2022							19:00		-11.3
9	19.07.2022	21:34	22.81	62.00	88.87	64.59	8.72	21:27	7	6.9
10	08.08.2022	22:00	0.15	64.60	103.3	67.51	24.31	21:59	1	-5.9
11	11.08.2022	18:50	20.32	63.24	94.29	65.95	14.49	18:30	20	-9.4
12	23.10.2022	20:15	22.42	62.74	102.7	65.56	24.70	20:21	-6	6.8
13	07.11.2022	19:13	21.41	64.78	103.47	67.52	24.44	19:07	6	0.756
14	22.12.2022	19:32	21.10	66.63	99.29	69.13	18.26	19:54	-22	12.09

Table 4. *Comparison of the obtained beginnings of the examined MPB's with the results of identified substorms over Europe at the same time by Ohtani and Gjerloev (2020).*

№	date	UT	MLT	MLAT	MLON	GLAT	GLON	station	MPB beginning time (this work)	Δt, min.	Y_{PAG}
12	23.10.2022	20:21	22.14	61.69	97.15	64.61	18.75	LYC	20:21	0	6.8
13	07.11.2022	19:11	21.41	66.64	103.89	69.46	23.7	MAS	19:07	4	0.756
14	22.12.2022	19:30	21.12	67.00	100.09	69.66	18.94	TRO	19:54	-24	12.09

The columns in Table 2, 3 and 4 are as follows: case number after Table 1, event date, substorm onset time by the respective list, magnetic and geographic coordinates of the onset (MLT, MLAT, MLON, GLAT, GLON), station name (in case, if the onset geographic coordinates correspond to a station location), the beginning time of the midlatitude positive bay (MPB) at PAG, the difference between the substorm onset time and the MPB beginning time (Δt), and the value of Y at PAG at the moment of the MPB maximum (Y_{PAG}).

From Tables 2, 3 and 4 it is seen, that almost all substorm events, identified by local (European) data, have been identified by techniques, using SML index. The time difference Δt in most cases is small, but there are also cases when Δt is much greater than expected. The MPB beginning at PAG doesn't coincide with the substorm onset, unless the substorm meridian coincide with the PAG location. In all other cases it should be nearly after the substorm onset. That means, that Δt in the tables above is expected to be small and negative. In our previous studies [Guineva et al., 2023a] we have supposed, that the slightly earlier MPB beginning at PAG than the substorm onset time determined based on SML index may be due to the difficulty to estimate whether the smaller disturbances before the sharp decrease of X are the result of localized or global events in the magnetosphere, especially under disturbed conditions or when the substorms are not isolated. The obtained greater differences between the determined substorm onsets and the MPB beginning at PAG in some cases are maybe result of the assumptions made and the conditions set in the processing tools of the different techniques.

A case with great difference between the substorm onset determined by SML, and the MPB beginning at PAG.

To clarify the reasons for greater differences Δt in Tables 2, 3 and 4, we examined in detail these cases. In Figure 1 peculiarities of such a case are given, namely case number 6, the substorm on 14.04.2022 with onset at 18:47 UT by Newell and Gjerloev (2011) and Forsyth et al. (2015). This is an event in the presence of magnetic cloud, during the main phase of a geomagnetic storm. During this substorm a strong midlatitude positive bay was registered at Panagjurishte (PAG), with maximal value 27.11 nT and amplitude 43.66 nT. In Figure 1a the SML index from 17 to 21 UT on 14.04.2022 is shown. The red vertical line indicates the time of the substorm onset determined by SML, and the green one – the time of the MPB beginning at PAG, which is 18 minutes earlier than the onset. In Figure 1b the magnetic field components at the Ranua station (RAN) are presented, which coordinates coincide with the substorm onset location given in the substorm lists. The red and green vertical lines match the

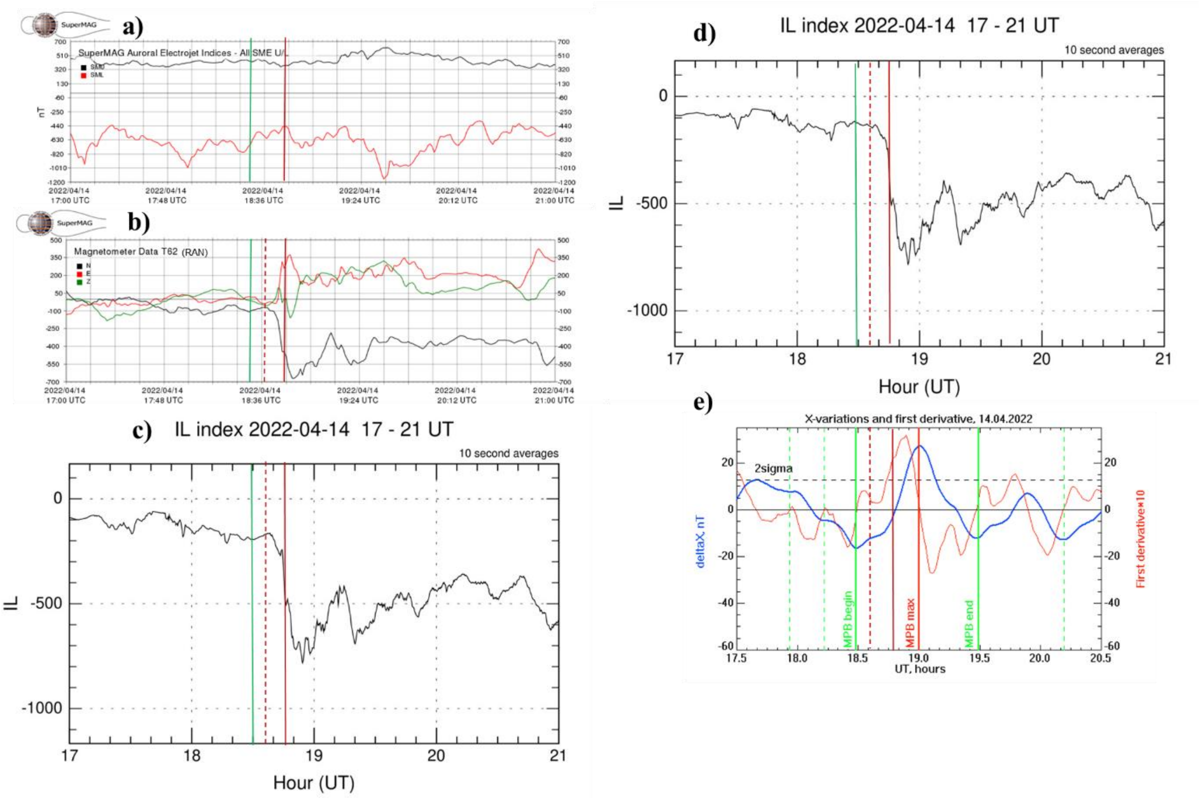

Figure 1. *An event for which greater difference between the determined by SML data substorm onset time and the estimated MPB beginning time at PAG (Δt), the substorm on 14.04.2022: a) SML index from 17 to 21 UT; b) magnetic field data from the station Ranua (RAN) from the same time interval; c) IL index based on all IMAGE stations; d) IL index based on PPN-NAL chain stations; e) MPB registered at Panagjurishte (PAG).*

same moments as in Figure 1a, and the red dotted line – the onset time based on RAN X component, estimated by eye inspection (about 18:37 UT). It is seen that in this case, there is also difference between the onset times determined by SML index and the magnetic variations at the onset location. Figure 1c and 1d show the IL index by all IMAGE stations and by the PPN-NAL stations chain, respectively. The vertical lines indicate the same times as in Figure 1b. It can be seen some difference between Figure 1c and 1d only near the time of the substorm onset. There is a plateau of small disturbances from about 18:20 to 18:40 UT and maybe the disturbances after the green line, pointing the MPB beginning at PAG, belong to global events in the magnetosphere. As Ranua is part of the PPN-NAL chain, this meridian can be considered roughly as the substorm meridian. Panagjurishte is at about 5° distance by GMLON from Ranua, therefore the MPB beginning at PAG is very close to the onset time. It is known, that the MPB's are less sensitive to interference from small details in the electrojet and are a good indicator of the substorm onset [McPherron, 1972]. We assume that in this case, the substorm onset was between 18:20 and 18:29 UT. The exact onset time could be determined by examination of the MPB's of the European stations in the region.

Conclusions.

The strong midlatitude bays (MPB) (Xmax>20 nT) registered at Panagujrishte (PAG) in 2022 were related to substorms, developed during disturbed interplanetary and geomagnetic conditions. The obtained MPB beginning times are close to the substorm onsets determined from the SML index except a few cases.

The obtained small differences may be due to some distance of PAG station from the substorm meridian, as well as to the complicated conditions, when some smaller magnetic perturbations just before the sharp decrease of X are related to the beginning of the global magnetospheric disturbances. We presume, that the substorm onsets could be more easily and accurately determined by the midlatitude positive bays data from a global or regional set of midlatitude magnetic stations.

The obtained greater differences between the determined substorm onsets and the MPB beginning at PAG in some cases are maybe result of the assumptions made and the conditions set in the processing tools of the different techniques. The contributions of stations far from the substorm meridian, in such cases may lead to significant discrepancies between the substorm onset, determined by global (SML) and regional (IL, European MPB index) indices, so all results have to be verified for every concrete case.

Acknowledgements: We acknowledge the substorm timing list identified by the SOPHIE technique (Forsyth et al., 2015), the substorm timing list identified by the Newell and Gjerloev technique (Newell and Gjerloev, 2011), the substorm timing list identified by the Ohtani and Gjerloev technique (Ohtani and Gjerloev, 2020), the SMU and SML indices (Newell and Gjerloev, 2011); and the SuperMAG collaboration (Gjerloev et al. 2012)**.** The authors are grateful to the creators of the databases IMAGE (http://space.fmi.fi/image/), OMNI (https://cdaweb.gsfc.nasa.gov/) and the solar wind large-scale phenomena catalog (http://www.iki.rssi.ru/omni/) for the opportunity to use them in this work.

References

Forsyth, C., Rae, I. J., Coxon, J. C., Freeman, M. P., Jackman, C. M., Gjerloev, J., Fazakerley A. N. (2015). A New Technique for Determining Substorm Onsets and Phases from Indices of the Electrojet (SOPHIE), J. Geophys. Res. Space Physics, Vol. 120, DOI:10.1002/2015JA021343.

Gjerloev, J. W. (2012), The SuperMAG data processing technique, J. Geophys. Res., Vol. 117, A09213, DOI:10.1029/2012JA017683.

Guineva V.H., R. Werner, A.M. Atanassov, R.Ts. Bojilova, L.N. Raykova, D.T. Valev, (2023a). Determination of the parameters of midlatitude positive bays caused by magnetospheric substorms, Proceedings of the Fifteenth Workshop "Solar Influences on the Magnetosphere, Ionosphere and Atmosphere", Primorsko, Bulgaria, 05 - 09 June 2023, pp.56-63, DOI: 10.31401/ws.2023.proc, https://www.spaceclimate.bas.bg/ws-sozopol/pdf/Proceedings2023.pdf

Guineva V., R. Werner, I. Despirak, N. Klejmenova, A. Lubchich, P. Setsko, A. Atanassov, R. Bojilova, L. Raykova, D. Valev, (2023b). Results from the bulgarian-russian project on investigation of the geomagnetic disturbances propagation to mid-latitudes and their interplanetary drivers identification for the development of mid-latitude space weather forecast, Proceedings of the Nineteenth International Scientific conference SES2023, 24-26.10.2023, Sofia, Bulgaria, pp.47-56, http://space.bas.bg/SES/archive/SES%202023_DOKLADI/1_Space%20Physics/2_Guineva.pdf

Guineva V., R. Werner, I. Despirak, N. Klejmenova, A. Lubchich, P. Setsko, A. Atanassov, R. Bojilova, L. Raykova, D. Valev, (2023c). Basic results from the project "Investigation of the geomagnetic disturbances propagation to mid-latitudes and their interplanetary drivers identification for the development of mid-latitude space weather forecast", Proc. 46th Annual seminar "Physics of Auroral Phenomena", 13-17 march 2023, Apatity, Russia, pp.23-29, http://pgia.ru/seminar/archive/

Kepko L., R.L. McPherron, O. Amm, S. Apatenkov, W. Baumjohann, J. Birn, M. Lester, R. Nakamura, T.I. Pulkkinen, V. Sergeev, (2014). Substorm current wedge revisited, Space Sci. Rev., Vol.190, pp. 1–46, DOI: 10.1007/s11214-014-0124-9.

Kisabeth, J.L., G. Rostoker, (1974). The expansive phase of magnetospheric substorms: 1. Development of the auroral electrojets and auroral arcs configuration during substorm, J. Geophys. Res., Vol.79, No7, pp.972–984, DOI: 10.1029/JA079i007p00972.

McPherron, R.L., (1972). Substor related changes in the geomagnetic tail: The growth phase, Planet. Space Sci., Vol. 20, No. 9, pp. 1521-1539, DOI: 10.1016/0032-0633(72)90054-2.

McPherron, R. L., Russell, C. T., Aubry, M. (1973a). Satellite studies of magnetospheric substorms on August 15, 1968, 9: phenomenological model for substorms, J. Geophys. Res., Vol. 78, No. 16, pp. 3131–3149, DOI: 10.1029/JA078i016p03131.

McPherron R.L., C.T. Russell, M.G. Kivelson, P.J. Coleman, Jr., (1973b). Substorms in space: The correlation between ground and satellite observations of the magnetic field, Radio Sci., Vol.8. No.11, pp. 1059-1076, DOI: 10.1029/RS008i011p01059.

McPherron, R.L., Chu, X., (2017). The midlatitude positive bay and the MPB index of substorm activity, Space Sci. Rev., Vol. 206, pp. 91-122, DOI: 10.1007/s11214-016-0316-6.

Meng, C.-I., Akasofu, S.-I., (1969). A study of polar magnetic substorms. 2. 3-dimensional current system, J. Geophys. Res., Vol. 74, pp. 4035–4053, DOI: 10.1029/JA074i016p04035.

Newell, P. T., Gjerloev, J. W., (2011). Substorm and magnetosphere characteristic scales inferred from the SuperMAG auroral electrojet indices, J. Geophys. Res., Vol. 116, A12232, DOI:10.1029/2011JA016936.

Ohtani, S., Gjerloev, J.W., (2020). Is the substorm current wedge an ensemble of wedgelets?: Revisit to midlatitude positive bays, Journal of Geophysical Research: Space Physics, Vol. 125, No. 9, p. e2020JA027902, DOI:10.1029/2020JA027902.