Interplanetary drivers of the magnetospheric disturbances: 
A brief review of incorrect approaches

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One of the most promising areas of research in solar-terrestrial physics is the comparison of the responses of the magnetosphere-ionosphere-atmosphere system to various interplanetary disturbances (the so-called "interplanetary drivers"). Numerous studies show that different types of drivers cause a different reaction of the system for identical IMF variations. At the same time, the number of incorrect approaches in this direction of research has increased. These errors can be attributed to 4 large classes. (1) The first class includes works whose authors uncritically reacted to previously published works with incorrect driver identification and use incorrect results in their work. (2) Some authors used the wrong criteria and incorrectly determined the types of drivers. (3) Very often, authors associate the disturbance of the magnetosphere-ionosphere-atmosphere system caused by a complex driver (by a sequence of single drivers) with one of the drivers, ignoring the complex nature. For example, magnetic storm are often caused by compression region Sheath in front of the interplanetary CME (ICME), but the authors consider this events as so-called “CME-induced” storm, not “Sheath-induced” storm. (4) Finally, there is a “lost driver” of magnetospheric disturbances: some authors simply do not consider the compression region Sheath before ICME if there is no interplanetary shock (IS) before Sheath, although this type of driver, “Sheath without IS”, generates about 10% of moderate and strong magnetic storms.

1. Introduction

The pioneering studies in the 60s and 70s (Dungey, 1961; Fairfield et al., 1966; Rostoker et al., 1967; Russell et al., 1974; Burton et al., 1975) showed that disturbances in the magnetosphere are mainly associated with the appearance of the southward (Bz <0) component of the interplanetary magnetic field (IMF). IMF lies in the ecliptic plane under steady interplanetary conditions and substantial Bz <0 is observed only in disturbed types of solar wind (SW) such as corotating interaction regions (CIR) between slow and fast SW streams and interplanetary coronal mass ejections (ICME) and compression regions Sheaths in front of fast ICMEs (see reviews Tsurutani et al., 1997; Gonzalez et al., 1999; Yermolaev et al., 2005). There are many studies which shows different magnetosphere response on various types of solar wind, even for close values of IMF Bz (Eselevich et al., 1993; Huttunen et al., 2002, 2006; Huttunen and Koskinen, 2004; Borovsky and Denton, 2006; Pulkkinen et al., 2007; Yermolaev et al., 2007a; Plotnikov and Barkova, 2007; Longden et al., 2008; Turner et al., 2009; Guo et al., 2011; Nikolaeva et al., 2013, 2014, 2015a, 2015b; Yermolaev et al., 2010a, 2010b, 2012, 2014, 2015; Borovsky et al., 2016; Lockwood et al., 2016; Boroyev and Vasiliev, 2018; Despirak et al., 2019 ). Currently, this approach seems very promising, since it allows one to discover new physical connections in solar-terrestrial physics. There is currently a steady upward trend in the number of studies in which some magnetospheric, ionospheric, and atmospheric processes are compared with some specific types of solar wind. However, most researchers are not specialists in the solar wind phenomena and make mistakes in identifying interplanetary
drivers, which often lead to incorrect conclusions. The most common errors are associated with incorrect criteria for identifying the types of solar wind, either by the authors of the erroneous work, or by the authors of those data sources that are used by other researchers. Typical examples of such errors were considered in detail in our works (Yermolaev et al., 2017; Lodkina et al., 2018) and will not be considered in this article.

In this paper, we consider two other incorrect approaches that lead to erroneous conclusions about the relationship of interplanetary drivers and magnetospheric disturbances. Firstly, authors associate the perturbation of the magnetosphere-ionosphere system caused by a complex driver (by a sequence of single drivers) with one of the drivers, ignoring the complex nature. For example, a magnetic storm is often caused by a compression region Sheath in front of an interplanetary CME (ICME), but the authors consider the ICME to be a cause of disturbance, not Sheath. Secondly, there is a “lost driver” of magnetospheric disturbances: some researchers simply do not consider the Sheath compression region before ICME if there is no interplanetary shock (IS) before Sheath, although this type of driver, “Sheath without IS”, can generate moderate and strong magnetic storms.

The structure of this paper is as follows. Section 2 describes data and methods used. Section 3 presents the results of the Sheath measurements. Section 4 discusses and summarizes the results.

2. Data and Methods

In this paper, we use the following data and methods.

The basis of our investigation is the 1-h interplanetary plasma and magnetic field measurements and magnetospheric data of OMNI database (http://omniweb.gsfc.nasa.gov; King and Papitashvili, 2004).

Using threshold criteria for key parameters of SW and IMF, we identified corresponding large-scale types of SW for every 1-h point of the archive during 1976–2018 (see paper by Yermolaev et al., 2009, and site ftp://ftp.iki.rssi.ru/pub/omni/). Our identification of SW types is based on methods similar to ones described in many papers and basically agrees with the results of other authors, but in contrast with other similar studies, we used a general set of threshold criteria for all SW types and made the identification for each 1-h point. To analyze the magnetosphere response on the change of interplanetary conditions, we select the following disturbed types of solar wind, i.e., corotating interaction region (CIR), two types of ICMEs (MC and Ejecta), two types of Sheath (SHMC and SHEJ), and IS forward shocks.

We use the double superposed epoch analysis (DSEA) method with 2 reference time instants at the ends of interval (Yermolaev et al., 2010a). This method involves re-scaling (proportionally increasing/decreasing time between points) the duration of the interval for all SW types in such a manner that, respectively, times of first and last points of all intervals of a selected type coincide.

A magnetic storm is considered to be associated with a solar wind phenomena if the moment of a minimum in the Dst index for the storm falls within the time interval of the SW event or is observed during 1–2 h after this phenomena (2 h correspond to the average time delay between the Dst peak of an intense magnetic storm and the associated peak in the southward IMF Bz component (Gonzalez and Echer, 2005, Yermolaev et al., 2007a,b)).

3. Results

In our papers (Yermolaev et al., 2015; 2017) using the double superposed epoch analysis method, we studied the average behavior of interplanetary and magnetospheric parameters for
the eight usual sequences of SW phenomena: (1) SW/CIR/SW, (2) SW/IS/CIR/SW, (3) SW/Ejecta/SW, (4) SW/Sheath/Ejecta/SW, (5) SW/IS/Sheath/Ejecta/SW, (6) SW/MC/SW, (7) SW/Sheath/MC/SW, and (8) SW/IS/Sheath/MC/SW (where SW means undisturbed solar wind and IS means interplanetary shock) for 1976–2000 and showed that the average temporal profiles of magnetospheric indices have the maxima in intervals between Sheath end and ICME beginning. In particular, the average temporal profiles of measured Dst and density-corrected Dst* indices, which mainly reflect the behavior of the ring current, are divided into two parts (see panels in the first and third rows of Fig.1), i.e., (1) the drop in Dst and Dst* indices is observed in the Sheath (with minima of –50 nT in the early hours in the MC and –35 nT in the Ejecta, respectively, and the Dst* index is systematically 5–10 nT lower than Dst) and (2) the slight increase in Dst and Dst* indices in the MC and Ejecta. For the MC and Ejecta with Sheath and IS, in general, the picture is identical for MC and Ejecta with Sheath and without IS, the only difference being that the Dst and Dst* minima are –70 and –50 nT. The fact that the corrected Dst* index in the Sheath is systematically lower than the measured Dst index is associated with higher values of density and pressure in the Sheath regions compared to the MC and Ejecta.

The panels of the second and fourth rows of Fig. 1 show the time distributions for the Sheath and Ejecta/MC intervals, respectively, of the number of the following events: the onsets of storms with Dst < –50 nT (blue columns) and the Dst minima (red columns). Though the blue and red columns in the figure are shifted with respect to each other for clarity, they were calculated in the 5 identical subintervals. These data show that a great number of magnetic storms began at the beginning of Sheath, and the maximum number of Dst index minima (the maxima of magnetic storms) fell at the end of Sheath to the beginning of Ejecta/MC.
The table and figures 2-5 allow one to compare the Sheath characteristics in 4 variants of the sequence of SW types: IS/Sheath/Ejecta, Sheath/Ejecta, IS/Sheath/MC and Sheath/MC.

The number of Sheath events before Ejecta without IS (432) slightly exceeds the number of events with IS (381), and the number of Sheath before MC with IS (152) significantly exceeds the number of events without IS (28). Although the average values for many parameters of the Table turned out to be close in magnitude to the standard deviations, the statistical error
(standard deviation divided by the square root of the number of points) for some of them turned out to be small, and in this case, the differences in the mean values for different types of Sheath can be considered statistically reliable. In particular, the data in the Table show that the average duration of Sheath events before Ejecta is longer than before MC. The number of magnetic storms generated by Sheath before Ejecta with and without IS is almost the same (61 and 59), and for the MC the difference is more significant (24 and 3), but it was obtained with small general statistics of the MC compared with Ejecta.

Table. Mean values and standard deviations of parameters for 4 types of Sheath.

|                  | S/Sheath/Ejecta | Sheath/Ejecta | IS/Sheath/MC | Sheath/MC |
|------------------|-----------------|---------------|--------------|-----------|
| **Number of events** | 381             | 432           | 152          | 28        |
| **Duration of events, h** | 16.4±9.6        | 14.0±8.8      | 12.4±6.1     | 12.8±9.5  |
| **Number of magnetic storms** | 61              | 59            | 24           | 3         |
| **V, km/s**       | 460±108         | 439±95        | 497±141      | 433±97    |
| **T (10^5), K**   | 1.90±1.78       | 1.70±1.41     | 2.56±3.62    | 1.69±1.69 |
| **T/Texp**        | 2.18±1.24       | 2.29±1.23     | 2.21±1.67    | 2.28±1.29 |
| **N, cm³**        | 12.4±9.5        | 9.7±6.4       | 16.1±11.3    | 13.5±8.3  |
| **B, nT**         | 9.9±4.7         | 8.2±3.6       | 13.6±7.8     | 10.0±5.1  |
| **Kp/10**         | 33±16           | 29±15         | 42.8±18.9    | 31±16     |
| **Dst, nT**       | -19±36          | -18±27        | -24±54       | -17±27    |
| **Dst*, nT**      | -28±39          | -23±29        | -37±55       | -26±26    |
| **AE, nT**        | 329±286         | 278±250       | 458±394      | 303±306   |

Figures 2-5 show the temporal profiles of interplanetary parameters and magnetospheric indices for 4 sequences: (1) SW / IS / Sheath / Ejecta, (2) SW / Sheath / Ejecta, (3) SW / IS / Sheath / MC and (4) SW / Sheath / MC. Each of the four figures contains 10 panels, which depict the average temporal profiles of the analyzed parameters obtained by DSEA method for Sheath regions (for the solar wind before Sheath from 0 to 5 points and ICME after Sheath from 20 to 25 points, the simple method of superposed epoch analysis with reference points was used at the ends of the Sheath interval): a: the ratio of thermal and magnetic pressure β, thermal pressure Pt, the relative density of alpha particles Na / Np, b: proton temperature T * 10^5 K and the ratio of measured and expected temperatures T / Texp, c: the angles of the velocity vector Phi, Theta, d: the component of the IMF Bz, the component of the electric field Ey, e: Dst and Dst * indices, f: the magnitude of the IMF B and the dynamic pressure Pd, g: components of the IMF Bx, By, h: sound and Alfen speeds Vs and Va, i: the ion density N and Kp index, j: the plasma velocity V, index AE.
Fig. 2 The temporal profiles of the solar wind parameters and magnetospheric indices for the IS/Sheath/Ejecta sequence obtained using the SEA and DSEA methods: from 0 to 5 and 20–25 points, SEA was used without re-scaling; from 6–19 points, DSEA was used with re-scaling up to 14 points.
Fig. 3. The same as in Fig. 2 for the Sheath/Ejecta sequence.
Fig. 4. The same as in Fig. 2 for the IS/Sheath/MC sequence.
For “Sheath with IS” events followed by Ejecta, the values of such parameters as the magnitude of the magnetic field $B$, thermal and dynamic pressure $P_t$, $P_d$, plasma velocity $V$, proton temperature $T$ and $T / T_{xp}$, $Dst$ and $Dst^*$ indices are larger than for “Sheath without IS” (Fig. 2 and 3). This is mainly due to a sharper increase in these parameters if the Sheath region...
begins with IS, since in the subsequent time after 2-3 hours after the start of the Sheath region, these parameters change in a similar way. The situation is similar for “Sheath with IS” and “Sheath without IS” events followed by MC (Figs. 4 and 5). For Sheath events with subsequent MS, the values of the parameters B, Pt, Pd, V, T, T / Texp, Dst, Dst * are higher than with the subsequent Eject.

4. Discussion and conclusions

Many studies investigated so-called “CME-induced” storms (or other types of magnetospheric disturbances) as an independent type of storms. In our opinion, there are no CME-induced disturbances, but there are Sheath-induced and MC/Ejecta-induced disturbances, as well as multi-step disturbances, which are excited by a sequence of Sheath/MC or Sheath/Ejecta events. The presented data indicate that the CME-induced disturbances of the magnetosphere can represent the response to absolutely different interplanetary drivers or their successive impact. The region “Sheath without shock” is observed before ICME almost as often as the Sheath region with IS, is sufficiently geoeffective and is the driver of about 10% of all storms. These drivers have different physical natures, possess different efficiencies of the impact on the magnetosphere and may lead to the implementation of different mechanisms of this impact.

The following experimental facts should be mentioned. (1) The average magnitude of IMF B in Sheaths is higher than B in Ejecta and is close to B in MCs (Yermolaev et al., 2015). (2) The efficiency of magnetic storm generation is 50% higher for Sheath than for ICME (MC and Ejecta) (Nikolaeva et al., 2013, 2015; Dremukhina et al., 2018, 2019), i.e. at identical southward components of the interplanetary magnetic field, the magnetic storms are generated ~1.5 times more strongly by Sheaths than by ICMEs.

Thus, it is possible to conclude that, in our opinion, the contribution of compression regions Sheath (including lost driver: Sheath without shock) in the generation of storms is often not taken into account and their role is often underestimated, and this erroneous approach often results in incorrect conclusions during studying the solar-terrestrial links.

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References

Borovsky, J. E., and M. H. Denton (2006), Differences between CME-driven storms and CIR-driven storms, J. Geophys. Res., 111, A07S08, doi:10.1029/2005JA011447.

Borovsky, J.E., Cayton, T.E., Denton, M.H., Belian, R.D., Christensen, R.A., and Ingraham, J.C., The proton and electron radiation belts at geosynchronous orbit: Statistics and behavior during high-speed stream-driven storms, J. Geophys. Res., 2016, vol. 121, no. 6, pp. 5449–5488. doi 10.1002/2016JA022520
Boroyev R.N., Vasiliev M.S., Substorm activity during the main phase of magnetic storms induced by the CIR and ICME events, Advances in Space Research, Volume 61, Issue 1, 2018, Pages 348-354, https://doi.org/10.1016/j.asr.2017.10.031

Burton, R.K., McPherron, R.L., and Russell, C.T., An empirical relationship between interplanetary conditions and Dst, J. Geophys. Res., 1975, vol. 80, pp. 4204–4214.

Despirak, I.V., Lyubchich, A.A. & Kleimenova, N.G. Solar Wind Streams of Different Types and High-Latitude Substorms. Geomagn. Aeron. 59, 1–6 (2019). https://doi.org/10.1134/S0016793219010055

Dremukhina, L.A., Lodkina, I.G. & Yermolaev, Y.I. Statistical Study of the Effect of Different Solar Wind Types on Magnetic Storm Generation During 1995–2016. Geomagn. Aeron. 58, 737–743 (2018). https://doi.org/10.1134/S0016793218060038

Dremukhina, L.A., Yermolaev, Y.I. & Lodkina, I.G. Dynamics of Interplanetary Parameters and Geomagnetic Indices during Magnetic Storms Induced by Different Types of Solar Wind, Geomagnetism and Aeronomy, 2019, Vol. 59, No. 6, pp. 639–650 DOI: 10.1134/S0016793219060069

Dungey, J.W., Interplanetary magnetic field and the auroral zones, Phys. Rev. Lett., 1961, vol. 6, no. 2, pp. 47–48.

Eselevich, V.G. and Fainshtein, V.G., An investigation of the relationship between the magnetic storm Dst indexes and different types of solar wind streams, Ann.Geophys., 1993, vol. 11, no. 8, pp. 678–684

Fairfield, D.H. and Cahill, L.J., The transition region magnetic field and polar magnetic disturbances, J. Geophys. Res., 1966, vol. 71, pp. 155–169.

Gonzalez, W. D., Tsurutani, B. T., and Clua de Gonzalez, A. L.: Interplanetary origion of geomagnetic storms, Space Sci. Rev., 88, 529–562, 1999

Gonzalez, W.D., Echer, E., 2005. A study on the peak Dst and peak negative Bz relationship during intense geomagnetic storms. Geophys. Res. Lett. 32, L18103 https://doi.org/10.1029/2005GL023486.

Guo, J., Feng, X., Emery, B.A., et al., Energy transfer during intense geomagnetic storms driven by interplanetary coronal mass ejections and their sheath regions, J. Geophys. Res., 2011, vol. 116, A05106. doi 10.1029/2011JA016490

Huttunen, K.E.J., Koskinen, H.E.J., and Schwenn, R., Variability of magnetospheric storms driven by different solar wind perturbations, J. Geophys. Res., 2002, vol. 107, no. A7. doi 10.1029/2001JA00171

Huttunen, K.E.J. and Koskinen, H.E.J., Importance of post-shock streams and sheath region as drivers of intense magnetospheric storms and high-latitude activity, Ann. Geophys., 2004, vol. 22, pp. 1729–1738.
Huttunen, K.E.J., Koskinen, H.E.J., Karinen, A., and Mursula, K., Asymmetric development of magnetospheric storms during magnetic clouds and sheath regions, *Geophys. Res. Lett.*, 2006, vol. 33, no. 6, L06107. doi 10.1029/2005GL024894

Lockwood, M., Owens, M.J., Barnard, L.A., et al., On the origins and timescales of geoeffective IMF, *SpaceWeather*, 2016, vol. 14, pp. 406–432. doi 10.1002/2016SW001375

Lodkina, I. G., Yu. I. Yermolaev, M. Yu. Yermolaev, and M. O. Riazantsev, Some Problems of Identifying Types of Large-Scale Solar Wind and Their Role in the Physics of the Magnetosphere: 2, *Cosmic Res.*, 2018, 56, 5, DOI: 10.1134/S0010952518050052

Longden, N., Denton, M.H., and Honary, F., Particle precipitation during ICME-driven and CIR-driven geomagnetic storms, *J. Geophys. Res.*, 2008, vol. 113, A06205. doi 10.1029/2007JA012752

Nikolaeva, N.S., Yermolaev, Yu.I., and Lodkina, I.G., Modeling the time behavior of the Dst index during the main phase of magnetic storms generated by various types of solar wind, *Cosmic Res.*, 2013, vol. 51, no. 6, pp. 401–412.

Nikolaeva, N.S., Yermolaev, Yu.I., and Lodkina, I.G., Dependence of geomagnetic activity during magnetic storms on solar-wind parameters for different types of streams: 4. Simulation for magnetic clouds, *Geomagn.Aeron. (Engl. Transl.)*, 2014, vol. 54, no. 2, pp. 152–161.

Nikolaeva, N., Yermolaev, Y., and Lodkina, I., Predicted dependence of the cross polar cap potential saturation on the type of solar wind stream, *Adv. SpaceRes.*, 2015, vol. 56, pp. 1366–1373.

Nikolaeva, N.S., Yermolaev, Yu.I., and Lodkina, I.G., Modeling of the corrected Dst* index temporal profile on the main phase of the magnetic storms generated by different types of solar wind, *Cosmic Res.*, 2015, vol. 53, no. 2, pp. 119–127.

Plotnikov, I.Y. and Barkova, E.S., Nonlinear dependence of Dst and AE indices on the electric field of magnetic clouds, *Adv. Space Res.*, 2007, vol. 40, pp. 1858–1862.

Pulkkinen, T.I., Partamies, N., Huttunen, K.E.J., Reeves, G.D., and Koskinen, H.E.J., Differences in geomagnetic storms driven by magnetic clouds and ICME sheath regions, *Geophys. Res. Lett.*, 2007, vol. 34, L02105. doi 10.1029/2006GL027775

Rostoker, G. and Falthammar, C.-G., Relationship between changes in the interplanetary magnetic field and variations in the magnetic field at the Earth’s surface, *J. Geophys. Res.*, 1967, vol. 72, no. 23, pp. 5853–5863.

Russell, C.T., McPherron, R.L., and Burton, R.K., On the cause of magnetic storms, *J. Geophys. Res.*, 1974, vol. 79, pp. 1105–1109.

Tsurutani, B. T. and Gonzalez, W. D.: The interplanetary Causes of Magnetic Storms: A Review, in: Magnetic Storms, edited by: Tsurutani, B. T., Gonzalez, W. D., and Kamide, Y., Amer. Geophys. Union Press, Washington D.C., Mon. Ser., 98, 1997, p. 77, 1997;
Turner, N.E., Cramer, W.D., Earles, S.K., and Emery, B.A., Geoefficiency and energy partitioning in CIR-driven and CME-driven storms, *J. Atmos. Sol.-Terr. Phys.*, 2009, vol. 71, pp. 1023–1031.

Yermolaev Yu. I., Yermolaev M. Yu., Zastenker G. N., Zelenyi L.M., Petrukovich A.A., Sauvaud J.A. Statistical studies of geomagnetic storm dependencies on solar and interplanetary events: a review, Planetary and Space Science, 2005. V/ 53/1-3. P. 189-196

Yermolaev, Yu I., Yermolaev, M. Yu, Nikolaeva, N.S., Lodkina, L.G., 2007a. Interplanetary conditions for CIR-induced and MC induced geomagnetic storms. Bulg. J. Phys. 34, 128–135. http://bjp-bg.com/papers/bjp2007_2_128-135.pdf.

Yermolaev, Yu I., Yermolaev, M. Yu, Lodkina, L.G., Nikolaeva, N.S., 2007b. Statistical investigation of heliospheric conditions resulting in magnetic storms: 2. Cosmic Res. 45 (6), 461–470. https://doi.org/10.1134/S0010952507060020 (Kosmicheskie Issledovaniya, 2007, Vol. 45, No. 6, pp. 489–498).

Yermolaev, Yu.I., Nikolaeva, N.S., Lodkina, I.G., and Yermolaev, M.Yu., Relative occurrence rate and geoeffectiveness of large-scale types of the solar wind *CosmicRes.*, 2010a, vol. 48, no. 1, pp. 1–30.

Yermolaev, Y.I., Nikolaeva, N.S., Lodkina, I.G., and Yermolaev, M.Y., Specific interplanetary conditions for CIR-induced, sheath-induced, and ICME-induced geomagnetic storms obtained by double superposed epoch analysis, *Ann. Geophys.*, 2010b, vol. 28, pp. 2177–2186.

Yermolaev, Y. I., N. S. Nikolaeva, I. G. Lodkina, and M. Y. Yermolaev (2012), Geoeffectiveness and efficiency of CIR, sheath, and ICME in generation of magnetic storms, J. Geophys. Res., 117, A00L07, doi:10.1029/2011JA017139.

Yermolaev, Y.I., Lodkina, I.G., Nikolaeva, N.S., and Yermolaev, M.Y., Influence of the interplanetary driver type on the durations of the main and recovery phases of magnetic storms, *J. Geophys. Res.*, 2014, vol. 119, no. 10, pp. 8126–8136. doi 10.1002/2014JA019826

Yermolaev, Y.I., Lodkina, I.G., Nikolaeva, N.S., and Yermolaev, M.Y., Dynamics of large-scale solar wind streams obtained by the double superposed epoch analysis, *J. Geophys. Res.*, 2015, vol. 120, no. 9, pp. 7094–7106. doi 10.1002/2015JA021274

Yermolaev, Y.I., Lodkina, I.G., Nikolaeva, N.S. et al. (2017), Some problems of identifying types of large-scale solar wind and their role in the physics of the magnetosphere, Cosmic Res 55: 178. https://doi.org/10.1134/S0010952517030029