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Statistic study on the geomagnetic storm effectiveness of solar and interplanetary events

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Abstract

In the literature on the solar–terrestrial relations there are different estimations of storm effectiveness of solar and interplanetary events – from 30% up to 100%. We made a review of published results and found that different results arise due to differences in the methods used to analyze the data: (1) the directions in which the events are compared, (2) the pairs of compared events, and (3) the methods of the event classifications. We selected papers using: (1) the analysis on direct and back tracings of events, and (2) solar (coronal flares and CMEs), interplanetary (magnetic clouds, ejecta and CIR) and geomagnetic disturbances (storms on *Dst* and *Kp* indices). The classifications of magnetic storms by the *Kp* and *Dst* indices, the solar flare classifications by optical and X-ray observations, and the classifications of different geoeffective interplanetary events are compared and discussed. Taking into account this selection, all published results on the geoeffectiveness agree to each other in each subset: "CME → Storm" (40–50%), "CME → MC, Ejecta" (60–80%), "MC, Ejecta → Storm" (50–80%), "Storm → MC, Ejecta" (30–70%), "MC, Ejecta → CME" (50–80%), "Storm → CME" (80–100%), "Flare → Storm" (30–40%) and "Storm → Flare" (50–80%).

Keywords: Coronal mass ejections; Solar flares; Solar wind; Geomagnetic storms

1. Introduction

Estimation of geoeffectiveness (ability to generate magnetic storms on the Earth) of solar and interplanetary events is one of the most important problems of solar–terrestrial physics and, in particular, its practical part – space weather prediction. Although general concept on sources of geomagnetic storm does not change during many years (Russell and McPherron, 1973; Akasofu, 1981; Crooker and Cliver, 1994; Gonzalez et al., 1999; Crooker, 2000) in the literature on the solar–terrestrial relations there are different estimations of storm effectiveness of solar and interplanetary events from 30% up to 100%. For example, estimations of CME geoeffectiveness change from 35–45% (Plunkett et al., 2001; Berdichevsky et al., 2002; Wang et al., 2002; Yermolaev and Yermolaev, 2003a) up to 83–100% (Brueckner et al., 1998; St. Cyr et al., 2000; Srivastava, 2002; Zhang et al., 2003). The reasons of these discrepancies may be differences in used methods of: (1) magnetic storm identification, (2) interplanetary space event identification, (3) solar event identification, and (4) correlation between geomagnetic, interplanetary and solar events. The aim of our report is to compare different methods of solar–terrestrial physics and to explain existing discrepancies in published results.

2. Magnetic storms

The state of magnetosphere is described by different indices and *Dst* and *Kp* indices are usually used for identification of magnetic storm (Mayaud, 1980).

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Dependence of *Kp* index on *Dst* index for 611 magnetic storms with $-300 < Dst < -60nT$ during 1976–2000 (Yermolaev and Yermolaev, 2003b) is presented in Fig. 1. As shown in Fig. 1, several storm intervals according to *Dst* measurements may be identified as quiet intervals on the basis of *Kp* index. There are also many observations (see, for example, 15–23 UT on 24 October, 2003 (Veselovsky et al., 2004)) when at high *Kp* index *Dst* index shows quiet conditions.

Kp and *Dst* indices are measured at different geomagnetic latitudes (see Fig. 2) and sensitive to different currents systems (magnetospheric phenomena): auroral electrojet (magnetic substorms) and ring current (magnetic storms). It is necessary to use *Dst* index to exclude auroral phenomena from analysis and to study the magnetic storm effectiveness.

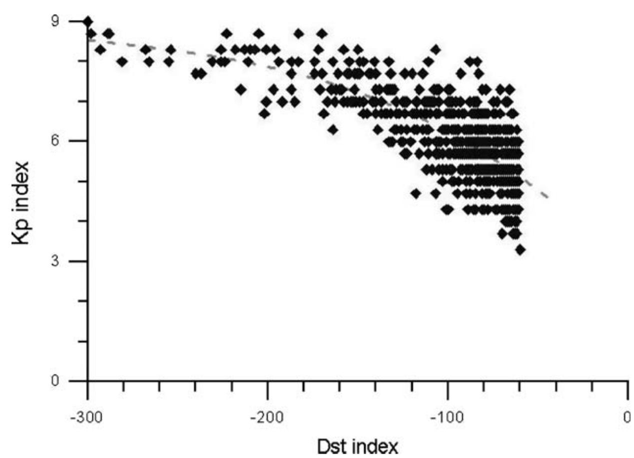

Fig. 1. Dependence of *Kp* index on *Dst* index for 611 magnetic storms during 1976–2000 (Yermolaev and Yermolaev, 2003b).

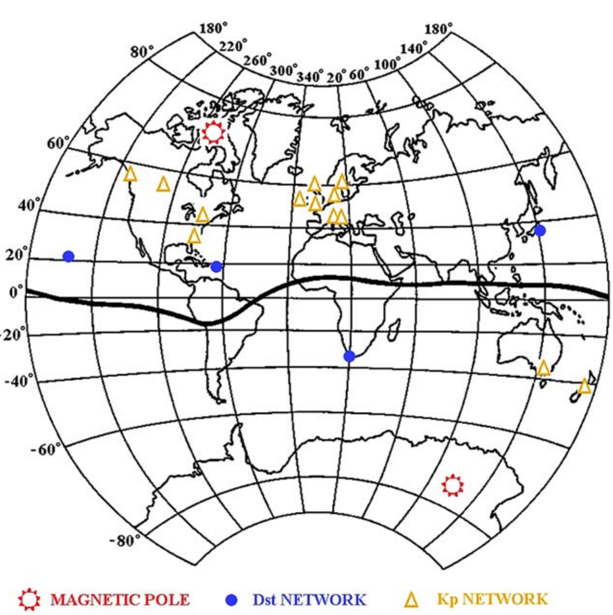

Fig. 2. Locations of ground magnetic stations of *Kp* and *Dst* networks.

3. Interplanetary events

According to numerous observations there are six large-scale types of interplanetary phenomena (see Fig. 3): 1 – heliospheric current sheet; 2 – slow solar wind from coronal streamers; 3 – fast solar wind from coronal holes; 4 – compressed streams of solar wind (corotating interaction region, CIR, and streams ahead magnetic clouds, MC), 5 – magnetic clouds (ejecta), and 6 – decompressed streams of solar wind but only 4th and 5th types are geoeffective because they may include long southward *Bz* component of IMF (Gosling and Pizzo, 1999; Gonzalez et al., 1999; Crooker, 2000; Bothmer, 2004).

There is no unique method of identification of interplanetary phenomena: different researchers use different sets of parameters as well as different numerical criteria of their analysis. For example, to identify magnetic cloud the methods include from 2 to 10 parameters (see Yermolaev and Yermolaev, 2003b and references therein). Recently several researchers began to use $T/T\text{exp}$ parameter (where T is measured proton temperature and $T\text{exp}$ is proton temperature calculated on the basis of average T dependence on velocity V) to select ejecta ($T/T\text{exp} < 0.5$) and compressed streams ($T/T\text{exp} > 2$) (Richardson et al., 2001; Vennerstroem, 2001; Cane and Richardson, 2003). Fig. 4 presents OMNI data for October 7–26, 1974: 2–4th panels – intensity, polar and azimuthal angles of magnetic field; 5th panel compares T (solid line) and $T\text{exp}$ (dotted line) with shading $T < 0.5T\text{exp}$; bottom panels – the plasma

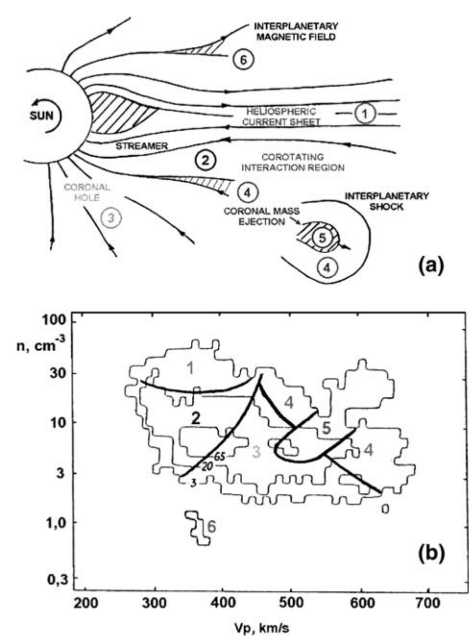

Fig. 3. Schematic view of 6 types of interplanetary event (a) and location of these types on "density-velocity" plane on the basis of Prognoz 7 measurements (b) (Yermolaev, 1990, 1991; Yermolaev and Stupin, 1997).

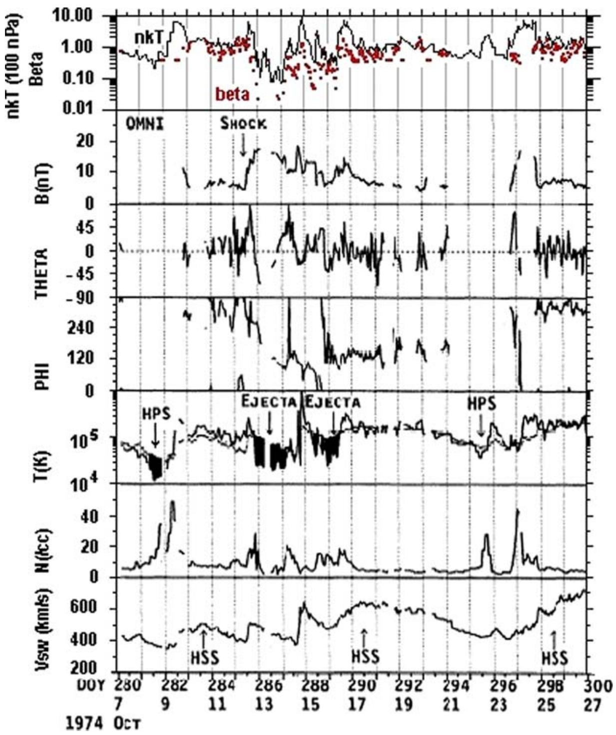

Fig. 4. Solar wind data for October 7–26, 1974 (2–6 panels from Richardson and Cane, 1995, see text).

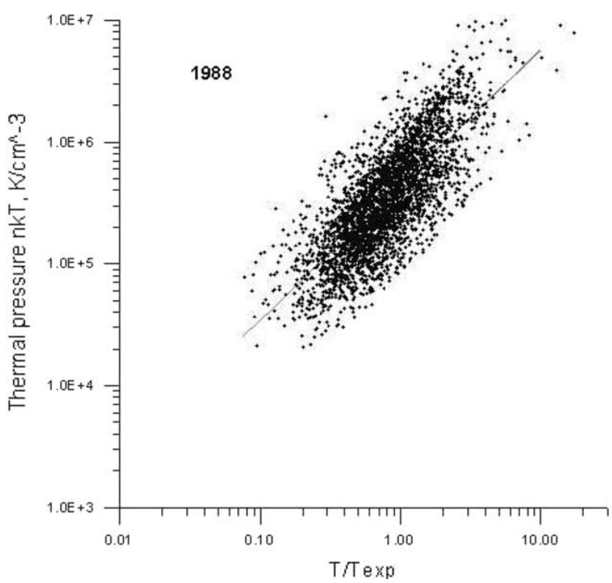

Fig. 5. Dependence of nkT on T/Texp obtained on the basis of OMNI data in 1988.

density n and solar wind speed; the low-T regions on October 12–16 are associated with ejecta, while that on October 8 is an encounter with the heliospheric plasma sheet (HPS) (Richardson and Cane, 1995).

We added 1st panel in Fig. 4: thermal proton pressure nkT (solid line) and proton beta-parameter (points). Time variations of nkT and T/Texp are similar (because

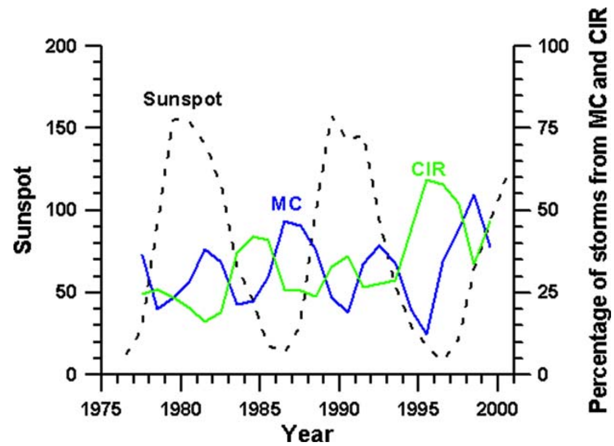

Fig. 6. 3-Year spline smoothed variations of percentages of storms generated by magnetic clouds (MC, black line) and corotating interaction regions (CIR, grey line).

on the average the relations $T\text{exp} \sim V^2 \sim n^{-1}$ are correct (Yermolaev, 1996), see Fig. 5) but use of nkT and beta-parameters is more reliable because this allows one to exclude heliospheric current sheet (HPS as shown in Fig. 4) from magnetic cloud intervals.

Our analysis of interplanetary sources of 404 magnetic storms with $Dst < -60nT$ during 1976–2000 shows that 33% storms were generated by magnetic clouds, 30% by CIR, 6% by interplanetary shocks, and percentage of strong ($Dst < -100nT$) storms generated by MC increases upto 52%. It is important to note that the curves for percentages of storms generated by MC and CIR have two maxima per solar cycle and change in antiphase (see Fig. 6 (Yermolaev and Yermolaev, 2002)).

4. Solar events

The solar flares were discovered before other active processes on the Sun and during long time all distur-

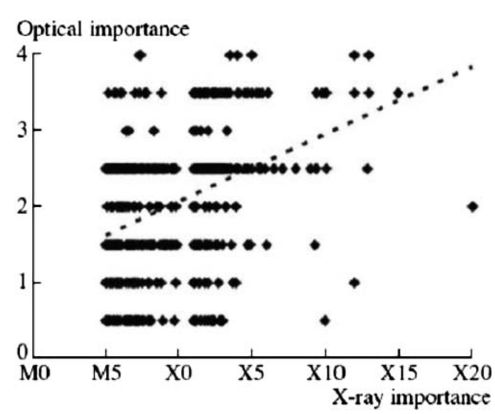

Fig. 7. Dependence of optical importance on X-ray importance for 643 solar flares with X-ray importance $>M5$ during 1976–2000.

Table 1
Correlation between solar, interplanetary and magnetospheric phenomena

N	%	Number of events	Remarks	Reference
I: CME → Storm				
1	50	38	Kp	Webb et al. (1996)
2	71	7	$Dst < -50$	Webb et al. (2000), Crooker (2000), Li et al. (2001)
3	35	40	$Kp > 6$	Plunkett et al. (2001)
4	45	20	$Kp > 5$	Berdichevsky et al. (2002)
5	35–92	?	$Dst < -50$	Webb (2002)
6	45	132[a]	$Kp > 5$	Wang et al. (2002)
	20	132[a]	$Kp > 7$	
7	35	125[a]	$Dst < -60$	Yermolaev and Yermolaev (2003a)
	40	125[a]	$Dst < -50$	Yermolaev and Yermolaev (2003b)
8	64	70[b]	$Dst < -50$	Zhao and Webb (2003)
	71	49[c]	$Dst < -50$	
9	42	218[a]	$Dst < -50$	This paper
II: CME → Magnetic cloud, Ejecta				
1	63	8	Earth-directed halo-CME	Cane et al. (1998)
2	60–70	89	Frontside halo-CME	Webb et al. (2001)
3	80	20	Halo-CME	Berdichevsky et al. (2002)
III: Magnetic cloud, Ejecta → Storm				
1	44	327 E	$Kp > 5$	Gosling et al. (1991)
2		28 MC		Gopalswamy et al. (2000)
	67		$Dst < -60$	Yermolaev and Yermolaev (2002)
3	63	30 MC	$Dst < -60$	Yermolaev et al. (2000)
4		48 MC		Gopalswamy et al. (2001)
	57		$Dst < -60$	Yermolaev and Yermolaev (2003b)
5	82	34 MC	$Dst < -50$	Wu and Lepping (2002a)
6	73	135 MC	$Dst < -50$	Wu and Lepping (2002b)
7	50	214 E	$Dst < -50$	Cane and Richardson (2003)
	43	214 E	$Dst < -60$	
8	77	149 MC	$Dst < -50$	Echer and Gonzalez (2004)
IV: Storm → CME				
1	100	8	$Kp > 6$	Brueckner et al. (1998)
2	83	18	$Kp > 6$	St. Cyr et al. (2000), Li et al. (2001)
3	94	?	?	Srivastava (2002)
4	96	27	$Dst < -100$	Zhang et al. (2003)
V: Storm → Magnetic cloud, Ejecta				
1	73	37	$Kp > 7-$	Gosling et al. (1991)
2	67	12	$Dst < -50$	Webb et al. (2000)
3	25	?	Dst (corr)	Vennerstroem (2001)
4	19	1273 E	$Kp > 5-$, Solar minimum	Richardson et al. (2001)
	63	1188 E	$Kp > 5-$, Solar maximum	
5	33	618	$Dst < -60$	Yermolaev and Yermolaev (2002)
	25	414	$-100 < Dst < -60$	
	52	204	$Dst < -100$	
6	32	90	$-100 < Dst < -50$	Huttunen et al. (2002)
	21	100	$7- > Kp > 5$	
	76	21	$-200 < Dst < -100$	
	38	21	$8 > Kp > 7-$	
7	70	30	$Dst < -100$	Watari et al. (2004)
8	24	150	$Dst < -50$, 1978–1982	Li and Luhmann (2004)
	32	187	$Dst < -50$, 1995–2002	
VI: Magnetic cloud, Ejecta → CME				
1	67	49 E	CME	Lindsay et al. (1999)
2	65	86 E	CME	Cane et al. (2000)
	42	86 E	Earth-directed halo-CME	
3	82	28 MC	CME	Gopalswamy et al. (2000)
4	50–75	4 MC	Halo-CME	Burlaga et al. (2001)
	40–60	5 E	Halo-CME	
5	56	193 E	CME	Cane and Richardson (2003)
6	48	21 MC	Halo-CME	Vilmer et al. (2003)

Table 1 (*continued*)

N	%	Number of events	Remarks	Reference
VII: Flare → Storm				
1	44	126[d]	$\geqslant M0$	Yermolaev and Yermolaev (2002)
2	40	653	$\geqslant M5$	Yermolaev and Yermolaev (2003a)
3	33	571	$\geqslant 3(optic)$	Ivanov and Miletsky (2003)
VIII: Flare → SSC				
1	35–45	4836	$\geqslant M0$	Park et al. (2002)
IX: Storm → Flare				
1	59	116	$Kp > 7-$	Krajcovic and Krivsky (1982)
2	88	25	$Dst < -250$	Cliver and Crooker (1993)
3	20	204	$Dst < -100$	Yermolaev and Yermolaev (2003a)

[a] Earth-directed halo-CME.
[b] Frontside halo CME.
[c] Centered frontside halo CME.
[d] With solar energetic particle events.

bances in the solar wind and the Earth's magnetosphere were connected only with the solar flares. Later, in the beginning of 1970, other powerful solar processes such as coronal mass ejections (CMEs) were discovered. However only after the landmark paper by Gosling (1993) the situation has significantly changed, and now CME is considered almost as the unique cause of all interplanetary and geomagnetic disturbances (see discussion by Harrison, 1996; Cliver and Hudson, 2002). Nevertheless, in the literature there is large number of studies on "flare–storm" and "CME–storm" correlations. Optical and X-ray importances are used for identification of solar flares. As shown in Fig. 7, the correlation between these indices is very low (Yermolaev and Yermolaev, 2003b).

In contrast to the flare, very important problem of CME geoeffectiveness is determination of location of CME on the solar disk and first of all on what side of the Sun: visible or back. To solve this problem the white light observations of CME out of solar disk are compared with UV observations on the disk (see for example, paper by Gopalswamy (2002)). It is necessary to keep in mind that CME location obtained by method above is only hypothesis (not experimental fact) because researchers must use measurements made: (1) by different instruments; (2) in different frequency ranges; (3) in different spatial places and (4) at different time. So we should only statistically consider CME location on the solar surface obtained on the basis of UV images.

5. Correlation between events

We selected published results on CME, flare and interplanetary effectiveness using: (1) direct and back tracings and (2) different pairs of event types: "CME → Storm", "CME → MC, Ejecta", "MC, Ejecta → Storm", "Storm → MC, Ejecta", "MC, Ejecta → CME", "Storm → CME", "Flare → Storm" and "Storm → Flare". Results of the selection are presented in Table 1 and schematically shown in Fig. 8 (Yermolaev and Yermolaev, 2003b; Yermolaev et al., 2005).

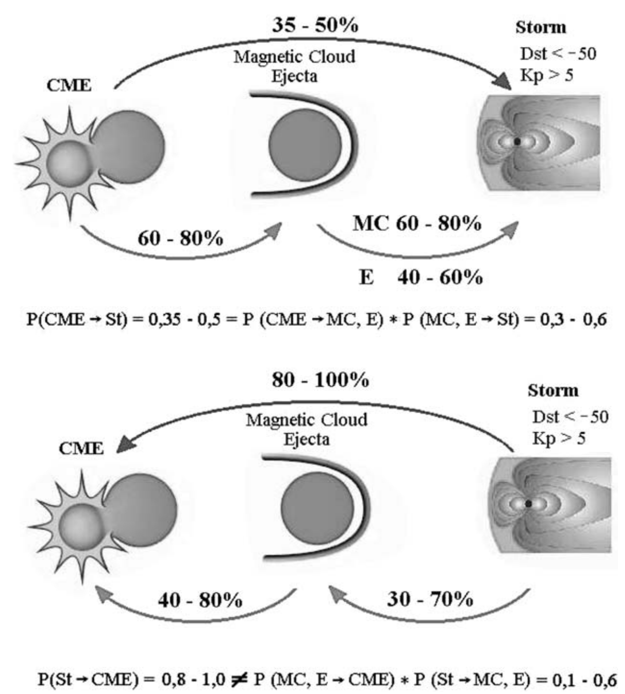

Fig. 8. Schematic view of correlations between CME, MC/ejecta and magnetic storms for direct (top panel) and back (bottom panel) tracings. Relations of probabilities for 1- and 2-step tracings are shown below each panel.

6. Discussion and conclusions

The present comparison of methods and results of the analysis of the phenomena on the Sun, in the interplanetary space and in the Earth's magnetosphere shows that:

- used methods of event selection are different;
- direction of data tracing is of great importance for research of the entire chain of solar–terrestrial physics;
- the obtained estimations of CME influence on the storm both directly (by one step "CME → Storm") and by multiplication of probabilities of two steps ("CME → Magnetic cloud, Ejecta" and "Magnetic cloud, Ejecta → Storm") are close to each other and equal to 40–50% (Webb et al., 1996; Cane et al., 1998; Yermolaev et al., 2000; Gopalswamy et al., 2000; Plunkett et al., 2001; Wang et al., 2002; Berdichevsky et al., 2002; Wu and Lepping, 2002a,b; Yermolaev and Yermolaev, 2002, 2003a,b; Cane and Richardson, 2003; Echer and Gonzalez, 2004);
- CME effectiveness obtained in papers by Webb et al. (2000), Webb (2002), Zhao and Webb (2003) is likely to be overestimated (see the Table 1);
- value of 83–100% was obtained in papers by Brueckner et al. (1998), St. Cyr et al. (2000), Srivastava (2002), Zhang et al. (2003) by searching for back tracing correlation and strongly differs from direct tracing results;
- values of 83–100% are not confirmed by the two-step analysis of sources of storms since at steps "Storm → Magnetic cloud; Ejecta" and "Magnetic cloud; Ejecta → CME" these values are (25–73%) (Gosling et al., 1991; Vennerstroem, 2001; Yermolaev and Yermolaev, 2002; Huttunen et al., 2002) and ~40% (Cane et al., 2000) each of which is less than the value obtained by the one-step analysis "Storm → CME";
- obtained estimations of CME geoeffectiveness (40–50%) are close to estimations of geoeffectiveness of solar flares (30–40%) (Park et al., 2002; Yermolaev and Yermolaev, 2002, 2003a; Ivanov and Miletsky, 2003) and exceed them slightly;
- and, therefore, the forecast of geomagnetic conditions on the basis of observations of the solar phenomena can contain high level of false alarm (Yermolaev and Yermolaev, 2002).

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References

Akasofu, S.-I. Energy coupling between the solar wind and the magnetosphere. Space Sci. Rev. 28, 121, 1981.

Berdichevsky, D.B., Farrugia, C.J., Thompson, B.J., Lepping, R.P., Reames, D.V., Kaiser, M.L., Steinberg, J.T., Plunkett, S.P., Michels, D.J. Halo-coronal mass ejections near the 23rd solar minimum: lift-off, inner heliosphere, and in situ (1 AU) signatures. Ann. Geophys. 20, 891, 2002.

Bothmer, V. The solar and interplanetary causes of space storms in solar cycle 23. IEEE Transactions on Plasma Science 32 (4), 1411, 2004.

Brueckner, G.E., Delaboudiniere, J.-P., Howard, R.A., Paswaters, S.E., St. Cyr, O.C., Schwenn, R., Lamy, P., Simnett, G.M., Thompson, B., Wang, D. Geomagnetic storms caused by coronal mass ejections (CMEs): March 1996 through June 1997. Geophys. Res. Lett. 25, 3019, 1998.

Burlaga, L.F., Skoug, R.M., Smith, C.W., Webb, D.F., Zurbuchen, T.H., Reinard, A. Fast ejecta during the ascending phase of solar cycle 23:ACE observations, 1998–1999. J. Geophys. Res. 106, 20957, 2001.

Cane, H.V., Richardson, I.G., St. Cyr, O.C. The interplanetary events of January–May, 1997, as inferred from energetic particle data, and their relationship with solar events. Geophys. Res. Lett. 25 (14), 2517, 1998.

Cane, H.V., Richardson, I.G., St. Cyr, O.C. Coronal mass ejections, interplanetary ejecta and geomagnetic storms. Geophys. Res. Lett. 27 (21), 3591, 2000.

Cane, H.V., Richardson, I.G. Interplanetary coronal mass ejections in the near-Earth solar wind during 1996–2002. J. Geophys. Res. 108 (A4), 1156, 2003.

Cliver, E.W., Crooker, N.U. A seasonal dependence for the geoeffectiveness of eruptive solar events. Solar Phys. 145, 347, 1993.

Cliver, E.W., Hudson, H.S. CMEs: How do the puzzle pieces fit together? J. Atmos. Sol–Terr. Phys. 64, 231, 2002.

Crooker, N.U. Solar and heliospheric geoeffective disturbances. J. Atmos. Sol–Terr. Phys. 62, 1071, 2000.

Crooker, N.U., Cliver, E.W. Postmodern view of M-regions. J. Geophys. Res. 99, 23383, 1994.

Echer, E., Gonzalez, W.D. Geoeffectiveness of interplanetary shocks, magnetic clouds, sector boundary crossings and their combined occurrence. Geophys. Res. Lett. 31, L09808, 2004.

Gonzalez, W.D., Tsurutani, B.T., Clua de Gonzalez, A.L. Interplanetary origin of geomagnetic storms. Space Sci. Rev. 88, 529, 1999.

Gopalswamy, N. Space weather study using combined coronographic and insitu observations. in: Lyu, Ling-Hsiao (Ed.), Space Weather Study Using Multipoint Techniques. Pergamon Press, p. 39, 2002.

Gopalswamy, N., Lara, A., Lepping, R.P., et al. Interplanetary acceleration of coronall mass ejections. Geophys. Res. Lett. 27, 145, 2000.

Gopalswamy, N., Lara, A., Yashiro, S., Kaiser, M.L., Howard, R.A. Predicting the 1-AU arrival times of coronal mass ejections. J. Geophys. Res. 106, 29207, 2001.

Gosling, J.T. The solar flare myth. J. Geophys. Res. 98, 18937, 1993.

Gosling, J.T., McComas, D.J., Phillips, J.L., Bame, S.J. Geomagnetic activity associated with Earth passage of interplanetary shock disturbances. and coronal mass ejections. J. Geophys. Res. 96, 7831, 1991.

Gosling, J.T., Pizzo, V.J. Formation and evolution of corotating interaction regions and their three-dimensional structure. Space Sci. Rev. 89, 21, 1999.

Harrison, R.A. Coronal magnetic storms: a new perspective on flares and the 'Solar Flare Myth' Debate. Solar Phys. 166, 441, 1996.

Huttunen, K.E.J., Koskinen, H.E.J., Schwenn, R. Variability of magnetospheric storms driven by different solar wind perturbations. J. Geophys. Res., 107, 2002.

Ivanov, V.G., Miletsky, E.V. Space and time factors of solar flare geoeffectiveness, in: Proceedings of the Climatic and Ecological Aspects of Solar Activity, St. Petersburg, Russia, p. 183, 2003.

Krajcovic, S., Krivsky, L. Severe geomagnetic storms and their sources on the Sun. Astronom. Inst. Czech., Bull. 33 (N 1), 47, 1982.

Li, Y., Luhmann, J. Solar cycle control of the magnetic cloud polarity and the geoeffectiveness. J. Atmos. Sol–Terr. Phys. 66, 323, 2004.

Li, Y., Luhmann, J.G., Mulligan, T., Hoeksema, J.T., Arge, C.N., Plunkett, S.P., St. Cyr, O.C. Earthward directed CMEs seen in large-scale coronal magnetic field changes, SOHO LASCO coronagraph and solar wind. J. Geophys. Res. 106, 25103, 2001.

Lindsay, G.M., Luhmann, J.G., Russell, C.T., Gosling, J.T. Relationship between coronal mass ejection speeds from coronagraph images and interplanetary characteristics of associated interplanetary coronal mass ejections. J. Geophys. Res. 104, 12515, 1999.

Mayaud, P.N. Derivation, meaning and use of geomagnetic indices. AGU Geophys. Monogr. vol. 22, 1980, 1980.

Park, Y.D., Moon, Y.-J., Kim, I.S., Yun, H.S. Delay times between geoeffective solar disturbances and geomagnetic indices. Astrophys. Space Sci. 279, 343, 2002.

Plunkett, S.P., Thompson, B.J., St. Cyr, O.C., Howard, R.A. Solar source regions of coronal mass ejections and their geomagnetic effects. J. Atmos. Sol–Terr. Phys. 63, 402, 2001.

Richardson, I.G., Cane, H.V. Regions of abnormally low proton temperature in the solar wind (1965–1991) and their association with ejecta. J. Geophys. Res. 100, 23397, 1995.

Richardson, I.G., Cliver, E.W., Cane, H.V. Sources of geomagnetic storms for solar minimum and maximum conditions during 1972–2000. Geophys. Res. Lett. 28, 2569, 2001.

Russell, C.T., McPherron, R.L. Semiannual variation of geomagnetic activity. J. Geophys. Res. 78, 241, 1973.

Srivastava, N. Can geoeffectiveness of CMEs be predicted?. Bull. Astronom. Soc. India 30, 557, 2002.

St. Cyr, O.C., Howard, R.A., Sheeley Jr., N.R., Plunkett, S.P., et al. Properties of coronal mass ejections: SOHO LASCO observations from January 1996 to June 1998. J. Geophys. Res. 105, 18169, 2000.

Vennerstroem, S. Interplanetary sources of magnetic storms: Statistic study. J. Geophys. Res. 106, 29175, 2001.

Veselovsky, I.S., Panasyuk, M.I., Avdyushin, S.I., et al. Solar and heliospheric phenomena in October–November 2003: causes and consequences. Kosmicheskie Issledovaniia 42 (5), 453, 2004 (in Russian, translated Cosmic Research 42, 5, 435).

Vilmer, N., Pick, M., Schwenn, R., Ballatore, P., Villain, J.P. On the solar origin of interplanetary disturbances observed in the vicinity of the Earth. Ann. Geophys. 21, 847, 2003.

Wang, Y.M., Ye, P.Z., Wang, S., Zhou, G.P., Wang, J.X. A statistical study on the geoeffectiveness of Earth-directed coronal mass ejections from March 1997 to December 2000. J. Geophys. Res., 107, 2002.

Watari, S., Vandas, M., Watanabe, T. Formation of a strong southward IMF near the solar maximum of cycle 23. Ann. Geophys. 22, 673, 2004.

Webb, D.F., Jackson, B.V., Hick, P. Geomagnetic Storms and Heliospheric CMEs as Viewed from HELIOS. in: Solar Drivers of Interplanetary and Terrestrial DisturbancesASP Conference Series, vol. 95, p. 167, 1996.

Webb, D.F., Cliver, E.W., Crooker, N.U., et al. Relationship of halocoronal mass ejections, magnetic clouds, and magnetic storms. J. Geophys. Res. 105, 7491, 2000.

Webb, D.F., Crooker, N.U., Plunkett, S.P., St. Cyr, O.C. The solar sources of geoeffective structure. in: Space WeatherAGU Geophys. Monogr., vol. 125, p. 123, 2001.

Webb, D.F. CMEs and the solar cycle variation in their geoeffectiveness, in: Wilson, A. (Ed.), Proceedings of the SOHO 11 Symposium on From Solar Min to Max: Half a Solar Cycle with SOHO, 11–15 March 2002, Davos, Switzerland. A symposium dedicated to Roger M. Bonnet, ESA SP-508, pp. 409–419, 2002.

Wu, C.-C., Lepping, R.P. Effects of magnetic clouds on the occurrence of geomagnetic storms: The first 4 years of wind. J. Geophys. Res. 107, 1314, 2002a.

Wu, C.-C., Lepping, R.P. Effect of solar wind velocity on magnetic cloud-associated magnetic storm intensity. J. Geophys. Res. 107, 1346, 2002b.

Yermolaev, Yu.I. A new approach to study of large scale structure of solar corona on basis of measurements of solar wind parameters. Kosmicheskie Issledovania 28 (6), 890, 1990 (in Russian).

Yermolaev, Yu.I. Large-scale structure of solar wind and its relationship with solar corona: Prognoz 7 observations. Planet. Space Sci. 39 (10), 1351, 1991.

Yermolaev, Yu.I. Transport of mass, momentum and energy from the Sun to the Earth by different types of solar wind streams. ASP Conference Series vol. 95, 288–299, 1996.

Yermolaev, Yu.I., Stupin, V.V. Helium abundance and dynamics in different types of solar wind streams: the Prognoz 7 observations. J. Geophys. Res. 102 (A2), 2125, 1997.

Yermolaev, Yu.I., Zastenker, G.N., Nikolaeva, N.S. The Earth's magnetosphere response to solar wind events according to the INTERBALL Project Data. Kosmicheskie Issledovaniia 38 (6), 563, 2000 (in Russian, translated Cosmic Research 38, 6, 527).

Yermolaev, Yu.I., Yermolaev, M.Yu. Statistical relationships between solar, interplanetary, and geomagnetic disturbances, 1976–2000. Kosmicheskie Issledovaniia 40 (1), 3, 2002 (in Russian, translated Cosmic Research 40, 1, 1).

Yermolaev, Yu.I., Yermolaev, M.Yu. Statistical relationships between solar, interplanetary, and geomagnetic disturbances, 1976–2000, 2. Kosmicheskie Issledovaniia 41 (2), 115, 2003a (in Russian, translated Cosmic Research 41, 2, 105).

Yermolaev, Yu.I., Yermolaev, M.Yu. Statistical relationships between solar, interplanetary, and geomagnetic disturbances, 1976–2000, 3. Kosmicheskie Issledovaniia 41 (6), 574, 2003b (in Russian, translated Cosmic Research 41, 6, 539).

Yermolaev, Yu.I., Yermolaev, M.Yu., Zastenker, G.N., Zelenyi, L.M., Petrukovich, A.A., Sauvand, J.A. Statistical studies of geomagnetic storm dependencies on solar and interplanetary events: a review. Planetary and Space Science 53 (1), 189, 2005.

Zhang, J., Dere, K.P., Howard, R.A., Bothmer, V. Identification of solar sources of major geomagnetic storms between 1996 and 2000. Astrophys. J. 582, 520, 2003.

Zhao, X.P., Webb, D.F. Source regions and storm effectiveness of frontside full halo coronal mass ejections. J. Geophys. Res. 108, 1234, 2003.