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GEOMAGNETIC STORMS AND THEIR SOLAR ORIGIN IN SOLAR CYCLE 24 (2009 – 2019)

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Abstract. We present a list of 171 geomagnetic storms with Dst index ≤ −50 nT that occurred in the solar cycle 24 (2009−2019) as currently reported by the Kyoto database. Solar origin association is proposed in terms of coronal mass ejections (CMEs), together with the accompanying interplanetary CMEs and shocks close to Earth. Correlation between the strength of the Dst index and the speeds of the solar and heliospheric phenomena is performed and the main results are discussed.

1. INTRODUCTION

Geomagnetic storms (GSs) are disturbances in the magnetosphere of the Earth (Dungey, 1961) which can be detected by a network of magnetometers at the ground level. Different combinations of stations are used to compile various geomagnetic indices. The one used to reflect the strength of the GSs is the disturbance storm time (Dst), measured in negative values, in nT, and used in the present work. It is widely accepted the origin of the GSs to be the interplanetary (IP) counterparts of the coronal mass ejections (CMEs) – ICMEs, or alternatively, fast solar wind streams (Richardson, 2018). CMEs are the magnetized plasma, ejected from the corona due to some large scale reconfiguration, and propagating outwards in the IP medium (Webb and Howard, 2012). Upon the ICME arrival at Earth, shock waves may form, usually detected by in situ measurements. GSs are key players in solar and heliospheric studies. They perturb not only the Earth's atmospheric layers, but may also cause a negative effect on ground-based and satellite technologies and indirectly to humans (these effects are termed as space weather, Temmer, 2021). Thus various forecasting efforts are proposed in the search of practical mitigation strategies (Balan et al., 2019).

The aim of this study is to compile a list of all GSs with Dst index ≤ 50 nT in solar cycle (SC) 24 and to identify the associated CMEs, ICMEs and IP shocks, if possible.

2. DATA

Hourly reports from the World Data Center (WDC) for Geomagnetism, Kyoto, were used for this study. The final version of the reports from this database (https://wdc.kugi.kyoto-u.ac.jp/dst_final/) are available by the end of 2016. For the remaining three years in our list we used the provisional reports (https://wdc.kugi.kyoto-u.ac.jp/dst_provisional/index.html), which are however subject to change.

The CME parameters were collected from the SOHO LASCO CME catalog: https://cdaw.gsfc.nasa.gov/CME_list/

The ICME speed is taken from the online version of the Richardson and Cane list: https://izw1.caltech.edu/ACE/ASC/DATA/level3/icmetable2.htm If reported, we take into consideration the CME identified as the solar origin of the ICME.

IP shock speed is taken from the shock database (available at present only by 2018): http://www.ipshocks.fi/database We select IP shocks (from Wind spacecraft) only in about a one-day period prior to the hour of the minimum Dst (regarded as the GS peak time). In case of multiple shocks in close succession that are reported in this time, we list only the earlier entry of the IP shock speed. In the online version of the presented here GS list (https://catalogs.astro.bas.bg/) we will present the time and hour of the shock at the Wind spacecraft and the speeds calculated at both Wind and ACE satellites. For the purpose of this report, we do not distinguish between fast forward and fast reverse type of the shocks.

3. SOLAR ORIGIN IDENTIFICATION

The association procedure that was followed is presented below. We search for the parent CME giving rise to the GS in a 3 (to about 5) day period prior to the hour of the minimum of the Dst index, as reported. In this time window, we select the fastest and widest CME which is preferably Earth-directed (observed as halo, i.e. 360 degrees in angular width (AW), or partial halo), as the most probable origin of the GS. This procedure, however, cannot differentiate between forward and backward propagations. Thus we use ready to inspect ENLIL animations (http://helioweather.net/) in order to confirm the directivity of expansion of the solar wind or/and CME structures and finally to select a parent CME.

In summary, we could identify 70/171 (41 %) CMEs as the parent of the GSs in SC24, as listed in Table 1, with the majority (48/70, 69 %) being halo CMEs. Furthermore, we found 70/171 (41 %) ICMEs and 67/171 (39 %) IP shocks related to the GSs. We note that there is unavoidable subjectivity in the procedure of solar origin and related phenomena association. The GSs and their proposed associations are listed in Table 1.

4. RESULTS

Table 1: List of GSs in SC24, their parent CME, ICME and IP shock. All times are in UT, speeds are in km/s, AW in degrees, Dst index in nT, u - uncertain.

GS date & time yyyy-mm-dd-hr	|Dst|	CME day/time/speed/AW	ICME speed	IP shock speed
2009-07-21-07	83	u	330	u
2010-02-15-24	59	u	no	338
2010-04-06-15	81	03/10:34/668/360	640	838
2010-04-12-02	67	08/04:54/264/160	410	444
2010-05-02-19	71	u	no	no
2010-05-29-13	80	24/14:06/427/360	360	297
2010-06-04-02	53	31/21:08/406/115	no	no
2010-08-04-02	74	01/u/850/360	530	531
2010-10-11-20	75	07/07:24/417/111	no	no
2011-02-04-22	63	01/23:24/437/360	430	363
2011-03-01-15	88	24/07:48/1186/158	no	no
2011-03-11-06	83	07/20:00/2125/360	no	no
2011-04-06-19	60	04/15:57/2081/109	no	no
2011-05-28-12	80	u	510	no
2011-07-05-01	59	01/13:36/356/112	no	no
2011-08-06-04	115	04/04:12/1315/360	540	789
2011-09-10-05	75	06/23:06/575/360	470	340
2011-09-17-16	72	13/24:00/408/242	430	509
2011-09-26-24	118	24/12:48/1915/360	580	544
2011-10-25-02	147	22/10:24/1005/360	460	542
2011-11-01-16	66	27/12:00/570/360	380	no

2012-01-23-06	71	19/14:36/1120/360	450	443
2012-01-25-11	75	23/04:00/2175/360	no	630
2012-02-15-17	67	09/21:18/659/360	no	no
2012-02-19-05	63	u	no	no
2012-02-27-20	57	24/03:46/800/189	440	no
2012-03-02-02	54	u	no	no
2012-03-04-02	50	u	390	no
2012-03-07-10	88	04/11:00/1306/360	no	485
2012-03-09-09	145	07/00:24/2684/360	550	1245
2012-03-12-17	64	09/04:26/950/360	no	520
2012-03-15-21	88	13/17:36/1884/360	680	711
2012-03-28-05	68	24/00:24/1152/360	no	no
2012-04-05-08	64	02/02:12/350/135	no	no
2012-04-13-05	60	u	no	u
2012-04-24-05	120	u	370	416
2012-06-12-02	67	08/19:48/371/120	no	no
2012-06-17-14	86	14/14:12/987/360	440	486
2012-07-09-13	78	04/17:24/662/360	410	no
2012-07-15-17	139	12/16:48/885/360	490	617
2012-09-03-11	69	01/20:00/1442/360	310	u
2012-09-05-06	64	02/03:09/538/360	500	399
2012-10-01-05	122	29/00:12/947/360	370	452
2012-10-09-09	109	05/02:48/612/284	390	445
2012-10-13-08	90	09/00:48/692/122	490	no
2012-11-02-21	65	27/16:48/317/360	340	391

2012-11-14-08	108	09/15:12/559/276	380	386
2013-01-17-24	52	u	390	no
2013-01-26-23	51	23/14:12/530/185	no	343
2013-03-01-11	55	u	no	no
2013-03-17-21	132	15/07:12/1063/360	520	719
2013-03-29-17	59	u	no	no
2013-05-01-19	72	u	430	423
2013-05-18-05	61	15/01:48/1366/360	no	445
2013-05-25-07	59	22/13:26/1466/360	no	527
2013-06-01-09	124	u	no	410
2013-06-07-06	78	u	430	no
2013-06-29-07	102	28/02:00/1037/360	390	466
2013-07-6-19	87	01/20:24/819/208	350	no
2013-07-10-22	56	u	no	507
2013-07-14-23	81	09/15:12/449/360	430	no
2013-08-05-03	50	u	no	no
2013-08-27-22	59	u	no	no
2013-10-02-08	72	29/22:12/1179/360	470	515
2013-10-09-02	69	06/14:43/567/360	480	264
2013-10-30-24	54	28/15:36/812/360	no	343
2013-11-07-13	50	u	no	no
2013-11-09-09	80	u	420	u
2013-11-11-08	68	u	no	no
2013-12-08-09	66	u	no	369
2014-02-19-09	119	16/10:00/634/360	520	597

2014-02-20-07	80	u	no	821
2014-02-22-02	64	18/01:36/779/360	490	no
2014-02-23-20	55	20/03:12/993/360	no	no
2014-02-27-24	97	25/01:26/2147/360	no	438
2014-03-01-09	52	u	no	no
2014-04-12-10	87	u	350	no
2014-04-30-10	67	u	310	no
2014-08-27-19	79	u	no	no
2014-09-12-24	88	10/18:00/1267/360	600	747
2014-10-09-08	51	u	no	no
2014-10-28-02	65	u	no	no
2014-11-10-18	65	07/18:08/795/293	480	no
2014-11-16-08	59	u	no	no
2014-12-12-17	53	u	no	no
2014-12-22-06	71	u	380	475
2014-12-23-23	57	19/02:00/126/505	no	469
2014-12-24-24	53	u	no	no
2014-12-26-02	57	u	no	no
2015-01-04-22	78	u	no	no
2015-01-07-12	107	u	450	494
2015-02-02-07	55	u	no	389
2015-02-18-01	64	u	no	no
2015-02-24-08	58	u	no	no
2015-03-02-09	64	u	no	no
2015-03-17-23	234	15/01:48/719/360	560	562

2015-04-10-05	60	u	no	409
2015-04-11-10	85	u	380	no
2015-04-16-24	88	u	no	398
2015-05-13-07	82	u	no	u
2015-06-08-09	67	u	no	u
2015-06-23-05	198	21/02:36/1366/360	610	767
2015-06-25-17	81	22/18:36/1209/360	550	720
2015-07-05-06	74	u	no	no
2015-07-13-16	68	u	490	532
2015-07-23-09	72	u	no	no
2015-08-16-18	98	12/14:48/647/204	500	456
2015-08-19-07	64	u	no	no
2015-08-23-09	57	u	no	no
2015-08-27-21	103	22/07:12/547/360	370	no
2015-09-04-07	50	u	no	u
2015-09-07-21	75	u	no	no
2015-09-09-13	105	u	460	no
2015-09-11-15	87	u	no	no
2015-09-20-12	79	18/05:00/823/131	510	608
2015-10-04-10	63	u	no	no
2015-10-07-23	130	u	no	no
2015-10-18-10	56	u	no	no
2015-11-04-13	56	u	640	627
2015-11-07-07	87	04/14:48/578/360	500	943
2015-11-09-17	55	u	no	no

2015-11-10-14	56	u	no	no
2015-12-13-20	55	u	no	no
2015-12-20-23	166	16/09:36/579/360	400	563
2016-01-01-01	116	28/12:12/1212/360	440	404
2016-01-20-17	101	14/23:24/191/360	370	u
2016-02-01-09	53	u	no	no
2016-02-03-03	57	u	no	no
2016-02-16-20	65	u	no	no
2016-02-18-01	62	u	no	no
2016-03-06-22	99	u	no	no
2016-03-15-08	50	u	no	405
2016-03-16-24	56	u	no	no
2016-04-02-24	59	u	no	no
2016-04-07-22	61	u	no	no
2016-04-13-02	56	u	no	366
2016-04-14-21	61	u	420	558
2016-04-16-22	58	u	no	no
2016-05-08-08	95	u	no	no
2016-08-03-16	52	u	no	361
2016-08-23-22	73	u	no	no
2016-09-01-10	57	u	no	no
2016-09-02-03	59	u	no	no
2016-09-28-18	51	u	no	no
2016-09-29-10	65	u	no	no
2016-10-04-10	50	u	no	no

2016-10-13-18	110	u	390	431
2016-10-25-18	65	u	no	no
2016-10-29-04	70	u	no	no
2016-11-10-18	60	05/04:36/403/22	360	344
2017-01-01-22	61	u	no	271
2017-01-27-15	70	u	no	133
2017-04-22-17	51	u	no	no
2017-05-28-08	125	23/05:00/259/243	360	378
2017-07-16-16	72	14/01:26/1200/360	520	no
2017-08-31-12	51	u	no	no
2017-09-08-02	-122	04/20:36/1418/360	590	no
2017-09-28-07	56	u	no	no
2017-10-14-06	53	u	no	no
2017-11-08-02	73	u	no	no
2018-03-18-22	50	u	no	no
2018-04-20-10	60	u	no	no
2018-05-06-03	57	u	no	no
2018-08-26-07	175	20/21:24/126/120	410	u
2018-09-11-11	60	u	no	u
2018-10-07-22	53	u	no	u
2018-11-05-06	53	u	no	u
2019-05-11-22	51	u	350	u
2019-05-14-08	65	u	470	u
2019-08-05-21	53	u	no	u
2019-09-01-07	52	u	no	u

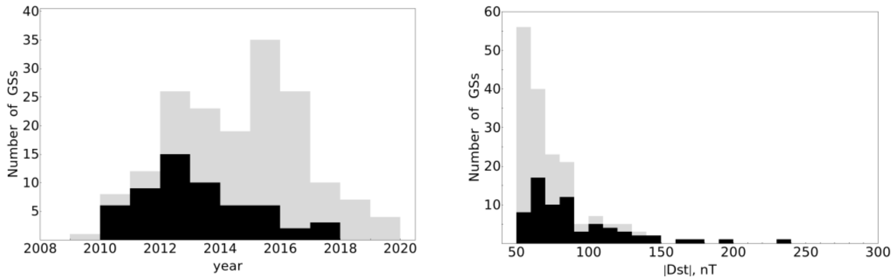

Figure 1: Stacked distribution of the GSs with years (left) and |Dst| (right). Black/Gray color is used for the GSs with/without identified solar origin.

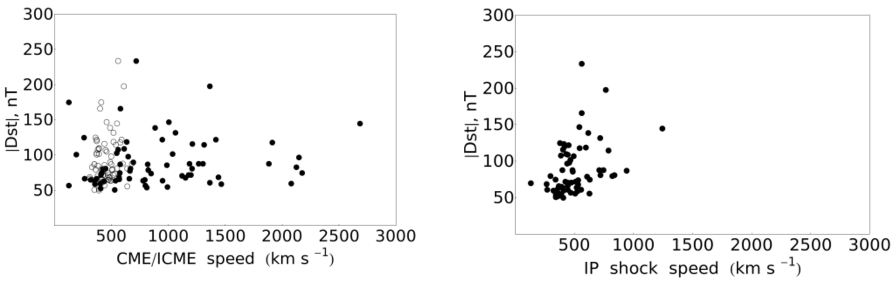

Figure 2: Scatterplots between the Dst index with the CME (with filled) and ICME (empty symbols) speed (left) or with the IP shock speed (right).

In Figure 1 are presented the distributions of the GSs in time (on the left) and of the module of the Dst index (on the right). The length of each color bar reflects the number of cases with (denoted with black color) or lack of (gray color) solar origin (CME) identification. The annual distribution of the GSs follows the sunspot trend. More CME-related GSs are detected in the first half of the SC24. Moreover, nearly all strong GSs (< −100 nT) can be traced back to solar eruptive phenomena, whereas for the majority of the weak GSs (145/171), defined here with Dst index in the range from −50 to −100 nT, it is more difficult to identify with certainty a solar origin (only 50/145, or 34% of them have identified CME).

Figure 2 presents the scatter plots between the strength of the GSs, measured in |Dst| and different speeds of the possible drivers, CME/ICME (left) and IP shock (right plot). For comparative purposes, the plots cover the same ranges. Overall, a large spread is seen with no clear-cut trends. For the ICME speed, we note that the data points are clustered over a very narrow velocity range.

5. CONCLUSIONS

We present a list of 171 GSs with Dst index ≤ −50 nT that occurred in SC24 (2009−2019) together with our proposition for their parent solar identifications and related phenomena. This constitutes a comprehensive scan of the Kyoto data compared to many available partial lists or lists of extreme GSs (e.g., Vennerstron et al. 2016). This catalog is supplemented by the ICMEs and IP shock speeds, as recorded near Earth. In total, 41% of all GSs could be associated with CME at the Sun, where the association decreases for weaker GSs due to the larger amount of uncertainties related to faint events. The parameters of the parent CMEs, together with the ICME and IP shock speeds are also provided. The entire list will be made available for scientific and operational purposes to the solar and space weather communities via the open access platform: https://catalogs.astro.bas.bg/

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