INVESTIGATING AND CATALOGUING HIGH SPEED STREAMS IN THE SOLAR WIND DURING SOLAR CYCLE 24

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ABSTRACT

The High Speed Streams (HSSs) in the solar wind are travelling through the heliosphere towards the orbit of Earth and beyond. They induce a lot of interplanetary disturbances that could cause geomagnetic storms (GSs), polar auroras and malfunctions in spatial and even terrestrial technological systems.

We present our method of investigating and cataloguing HSSs used for events of the 24th solar cycle. **A complex catalogue of HSSs and their effects in the terrestrial magnetosphere as geomagnetic storm was compiled (from 2009 up to 2016) and has been made available at www.geodin.ro/varsiti.**

An analysis of some specific HSS-GS event pairs is also presented, underlying how the HSS features could influence the GS characteristics (the storm magnitude, its main phase structure and the energy transfered from solar wind to magnetosphere during the storm).

Some history …

- **March 1716** – the first interpretation of an '**aurora**' based on exact sciences → as a terrestrial phenomenon which involved geomagnetism (magnetic thunderstorms);
- **1859 – solar flare in white light** → geomagnetic storm;
- **Solar M regions** → recurrent geomagnetic storms (27 days);
- **Solar wind (Parker) 1956** → spatial era 1957→ terrestrial magnetosphere, Van Allen radiation belts . ...;
- **May 1973 – Skylab** (corona in X-ray and white light) → **Coronal Holes** (***recurrent GSs***) and **Coronal Mass Ejections** (***major GSs***);
- **Heliosphere – planetary magnetospheres;**

Solar activity variability ⇒ Geomagnetic variability

In addition to the academic interest in how magnetized plasmas behave, it is important to study the solar wind interaction with the magnetosphere because THIS INTERACTION CONTROLS SPACE WEATHER PHENOMENA IN THE TERRESTRIAL ENVIRONMENT. The ability to develop accurate space weather forecasts depends very much on a good understanding of how solar and heliospheric disturbances interact and how the magnetosphere works.

OUTLINE

1. **INTRODUCTION**
   - **HSSs in the solar wind:**
     - Definition, selection criteria;
     - HSS Catalogues for Solar Cycles (SCs) 20-23;
2. **HSS – GS Catalogue SC 24 (2009 – 2016)**
   - **HSS parameters**
   - **GSs parameters**
3. **Case analysis**

HSS definitions

HSS – a large increase in the SW velocity lasting several days

- Intriligator (1973) – HSS as a stream having a rapidly rising increase in solar wind speed and a peak velocity ≥ 450 km/s;
- Bame et al. (1976) and Gosling et al. (1976) define a HSS as an observed variation of solar wind speed characterized by an **increase of at least 150 km/s within a 5-day interval**;
- Broussard et al. (1977) define a HSS as wind period in which **the solar wind speed is ≥ 500 km/s averaged over a day;**
- Lindblad, B.A., Lundstedt, H. (1981) – **HSS is a stream with ΔV1 ≥ 100 km/s lasting for two days, where: ΔV1 – the difference between the smallest 3-hr velocity mean value for a given day (V0) and the largest 3-hr value the following day (V1).**

Catalogues of HSSs; Selection Criteria

- **SCs. 20; 21: $\Delta V_1 \geq$ 100 km/s lasting for two days, where: DV_1 – the difference between the smallest 3-hr velocity mean value for a given day (V_0) and the largest 3-hr value the following day (V_1);**
  - Lindblad, B.A., Lundstedt, H., 1981, Sol. Phys. 74, 197-206; 1983, Sol. Phys. 88, 377-382;
  - Lindblad, B.A., Lundstedt, H., Larsson B., 1989, Sol. Phys. 120, 145-152;
- **SC 22 : Difference between the maximum daily speed and the mean value between the speeds immediately preceding and following the stream is ≥ 100 km/s lasts for at least two days.**
  - Mavromichalaki, H., Vassilaki, A., Marmatsouri, E., 1988, Sol. Phys. 115, 345-365;
  - Mavromichalaki, H., Vassilaki, A., 1998, Sol. Phys. 183, 181-200.

Catalogues for SC 23

- Gupta, V., and Badruddin, 2010, High-Speed Solar Wind Streams during 1996 - 2007: Sources, Statistical Distribution, and Plasma/Field Properties, Solar Phys. 264, 165-188.
- Maris, O., Maris G., 2012, Cap. 7, "High speed streams in the solar wind during the 23rd solar cycle", pp. 97-134 in: Advances in Solar and Solar-Terrestrial Physics, Research Signpost, India, (Editors: G. Maris and C. Demetrescu), ISBN: 978-81-308-0483-5.

PN2 HELIOTER (Contract no. 81-021/2007)

http://www.spaceweather.eu/, in Cap. "Data Data Catalogs for SW" or at:
http://www.spacescience.ro/00-old/new1/HSS_Catalogue.html (old version)

(now, also available at: http://www.geodin.ro/hss-sc23/

- Xystouris, G.,Sigala, E., Mavromichalaki, H., 2014, A Complete Catalogue of High-Speed Solar Wind Streams during Solar Cycle 23, Sol. Phys. 289, 995-1012.

Complex Catalogue HSS_GS for SC 24 (2009-2016) →VarSITI Grant 2017

DATA SOURCES

- **Solar wind velocity and proton density:**
  - **OMNI2 Data, GSFC/SPDF OMNI Web interface – multi-source intercalibrated web data (http://omniweb.gsfc.nasa.gov);**
- **Coronal Hole data:**
  - **http://www.solen.info/solar/coronal_holes.html**
  - **http://www.spaceweather.com**
  - **http://www.dxlc.com/solar/coronal_holes.html**
- **IMF Data:**
  - **IMF polarity, Bz polarity – OMNI Data,**
- **Geomagnetic Data:**
  - **ftp://ftp.ngdc.noaa.gov/STP/GEOMAGNETIC_DATA**
  - **http://www.geomag.bgs.ac.uk/gifs/aaindex.htm**
  - **http://swdcwww.kugi.kyoto-u.ac.jp/dst_final/index.html**

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Complex catalogue of high speed streams and geomagnetic storms during solar cycle 24

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A complex catalog of the High Speed Streams (HSSs) produced by Coronal Holes (CHs) and their effects in terrestrial magnetosphere as geomagnetic storms for Solar Cycle (SC) 24, from 2009 to 2016 is presented here. The HSSs in the solar wind have a lot of definition given by different authors; the simplest is often the best: a large increase in the solar wind velocity lasting for several days. We selected as „high-speed stream" a solar wind flow having $\Delta V_1 > 100$ km/s that lasted for two days, where: ΔV_1 is the difference between the largest 3-hr mean plasma velocity for a day (V_1) and the smallest three-hours (3-hr) mean plasma velocity for the previous day (V_0). The HSSs were determined using software developed by Ovidius Mariș (Institute of Space Science) during a previous national collaboration (HELIOTER, Contract nr. 81-021/2007) and improved by our team (with special thanks to Daniela Lacatus și Alin Paraschiv), using C and IDL. We thank Ovidiu Mariș for making this software available to our team.

The first part of the catalog lists basic parameters of the high speed streams: start time (calendar date by year, month, and day), the initial (V_0) and V_1 – maximum velocity in the second day of the stream (km/s), Δt_1 – time interval between V_0 and V_1 (in number of 3-hr intervals), the maximum (V_{max}) speed (in km/sec), the duration (in days), the maximum gradient of the plasma speed (in km/s): $\Delta V_1 = V_1 - V_0$, $\Delta VM = V_{max} - V_0$ – maximum gradient of the plasma velocity, the intensity of the stream defined as $I = \Delta V_{max} \times d$,(d-duration of HSS) and, their solar CH (Coronal Holes) sources. The main interplanetary magnetic field polarity during streams is also mentioned.

The second part of the catalog contains all geomagnetic storms (GS) having Dst minimum value less or equal to –30 nT (from minor to strong GS) associated to each HSS, by listing their Dst minimum value, the moment of this minimum given by the calendar date format: month, day and hour

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Catalogue structure

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															-39	03:23:21	-1.7	03:23:20				-43	03:23:21:19
12	2015	3	31	1	320	426.3	14	570.7	13.9	106.3	250.7	3484.73	CH661	+									
13	2015	4	14	1	297.7	597.3	14	696.7	6.2	299.6	399	2473.8	CH663	-	-37	04:14:22	-5.4	04:14:21				-46	04:14:22:32
															-79	04:16:23	-6	04:16:23		5.85E+15	1.51E+17	-88	04:16:23:29
14	2015	4	20	3	380	570.3	10	570.3	4.4	190.3	190.3	837.32	CH664	+									
15	2015	4	30	2	288.3	440	13	440	5.5	151.7	151.7	834.35	CH665	+									
16	2015	5	12	2	342	466.3	6	720.3	6.4	124.3	378.3	2421.12	CH667	-	-76	05:13:06	-8.9	05:13:05		8.59E+13	1.16E+16	-98	05:13:06:59
17	2015	5	18	5	351.3	531.3	9	531.3	4.4	180	180	792	CH668	+	-44	05:19:03	-4.4	05:19:02				-64	05:19:02:55
18	2015	5	28	1	290.7	401.3	15	401.3	7.1	110.6	110.6	785.26	CH670	+									
19	2015	6	7	2	299.7	652	12	652	7	352.3	352.3	2466.1	CH671	-	-73	06:08:08	-14.4	06:08:06		5.62E+15	4.95E+16	-105	06:08:07:45
															-42	06:09:18	-1.7	06:09:17				-60	06:09:18:49
20	2015	6	14	2	453.7	576.7	4	590.7	3.8	123	137	520.6	CH672	+	-44	06:17:15	-5.7	06:17:14				-36	06:17:15:52
															-32	06:18:15	-2.8	06:18:13				-30	06:18:15:53
21	2015	6	24	4	556	700.6	6	754.3	4.5	144.7	198.3	892.35	CME, CH673	+	-86	06:25:15	-6.7	06:25:13		1.46E+16	2.13E+17	-82	06:25:14:39
															-55	06:28:07	-5.4	06:28:05		8.35E+14	1.61E+16	-63	06:28:06:22
22	2015	7	4	1	310.7	538.7	7	538.7	6.2	228	228	1413.6	CH675	-	-67	07:05:05	-10.1	07:05:05		1.54E+17	1.27E+18	-87	07:05:04:52
23	2015	7	10	3	318	626	9	626	10.5	308	308	3234	CH676	+	-61	07:13:15	-4.8	07:13:12		1.71E+16	6.12E+17	-63	07:13:15:33
24	2015	7	20	1	284.3	390.7	14	495.3	10.5	106.4	211	2215.5	CHs677, 678	+	-63	07:23:07	-11	07:23:05		1.47E+14	2.78E+16	-83	07:23:07:28
															-36	07:26:00	-4.2	07:25:23				-39	07:25:23:59
25	2015	7	30	5	342	579.3	10	603	6.4	237.3	261	1670.4	CH679	-									
26	2015	8	5	8	371.3	555	6	557.7	6.4	183.7	186.4	1192.96	CHs680, 681	+									
27	2015	8	14	3	323	497.7	13	572	8.1	174.7	249	2016.9	CH682, 683	+	-84	08:16:07	-8.4	08:16:06	08:15:08	2.41E+17	2.10E+18	-94	08:16:07:37
															-38	08:17:16	-3.7	08:17:14				-32	08:17:16:33
															-50	08:19:06	-6.2	08:19:04		2.35E+15	1.06E+17	-57	08:19:06:14
28	2015	8	22	4	363	569	10	569	5	206	206	1030	CH684	+	-43	08:23:08	-8.5	08:23:07				-62	08:23:08:34
29	2015	8	28	4	335.3	471.3	12	491.3	8.9	136	156	1388.4	CH685	-	-92	08:27:20	-10.8	08:27:18		7.44E+14	2.90E+16	-101	08:27:20:32
30	2015	9	6	3	435.7	589	11	589	2.8	153.3	153.3	429.24	CH687	+	-70	09:07:20	-8.2	09:07:18		2.75E+15	1.20E+17	-73	09:07:20:16
31	2015	9	10	3	385.3	623.3	10	623.3	4	238	238	952	CH688	+	-98	09:09:12	-10.2	09:09:08		1.47E+17	1.22E+18	-100	09:09:12:18
															-81	09:11:14	-0.3	09:11:14		2.21E+16	3.17E+17	-95	09:11:14:26
32	2015	9	14	3	415.7	521.7	9	521.7	3.8	106	106	402.8	CH689	+	-41	09:14:16	-4.4	09:14:14				-47	09:14:16:15
33	2015	9	19	7	391	551.7	8	631	8.2	160.7	240	1968	CHs690, 691,CME	+	-75	09:20:15	-3	09:20:12	09:20:06	5.16E+16	8.01E+17	-70	09:20:15:49
															-37	09:23:17	-6.7	09:23:16				-37	09:23:17:30
34	2015	10	3	6	372.3	479.3	8	479.3	2.9	107	107	310.3	CH*	+	-55	10:04:09	-7.7	10:04:04		9.78E+15	2.55E+17	-52	10:04:07:33
35	2015	10	6	5	380	762.7	11	764.3	5.8	382.7	384.3	2228.94	CH694	+	-124	10:07:22	-6.4	10:07:20		2.69E+17	3.21E+18	-124	10:07:22:23
36	2015	10	12	3	437	568.7	7	568.7	3.4	131.7	131.7	447.78	CH695	+	-42	10:12:18	-6.5	10:12:16				-39	10:12:18:29
															-46	10:14:06	-4.9	10:14:04				-52	10:14:06:05
37	2015	10	17	6	344	456.3	8	456.3	3.5	112.3	112.3	393.05	CH695 partII	+	-48	10:18:09	-11	10:18:08				-46	10:18:10:00
38	2015	10	21	2	351.3	476	5	495	6.8	124.7	143.7	977.16	CH696	-									
39	2015	11	2	8	311.3	691.7	7	714	3.8	380.4	402.7	1530.26	CH697	+	-55	11:03:12	-2.9	11:03:11	11:03:01	3.50E+16	2.20E+17	-60	11:03:12:43
															-60	11:04:12	-3.2	11:04:11		1.08E+16	3.00E+17	-67	11:04:13:01
40	2015	11	8	5	462.3	599	11	713	4.2	136.7	250.7	1052.94	CH698	+	-58	11:10:13	-6.2	11:10:11		5.32E+16	7.78E+17	-47	11:10:13:19
41	2015	11	13	3	373.7	479.3	7	479.3	3.5	105.6	105.6	369.6	CH699	+	-32	11:14:07	-2.2	11:14:04				-35	11:14:07:12
42	2015	12	4	8	359.7	461.7	7	639.3	5	102	279.6	1398	CH704	+									
43	2015	12	9	8	440.7	633	8	658.7	4.1	192.3	218	893.8	CHs704, CH*	+									
44	2015	12	14	4	391.3	537.3	9	588	4.9	146	196.7	963.83	CH705	-	-47	12:14:19	-12.2	12:14:16	12:14:13			-60	12:14:19:04

Earthquakes

- M6.6 Papua New Guinea 22 hours ago
- M6.4 Indonesia 1 day ago
- M6.3 Southeast Indian Ridge 3 days ago
- M6.3 Papua New Guinea 3 days ago
- M4.66 CA 4 days ago

Last update : Tue 08:01:59 (UTC)

No. crt.	Year	Month	Day	3-H	V0 (km/s)	V1 (km/s)	Δt1	Vmax (km/s)	Dur (days)	ΔV1 (km/s)	ΔVM (km/s)	I	Source	IMF
1	2015	1	4	6	395.7	518.3	9	518.3	2.5	122.6	122.6	306.5	CH648	-
2	2015	1	10	1	397.3	560	10	560	4.1	162.7	162.7	667.07	CH649	+
3	2015	1	20	7	283	474.7	8	476	5.4	191.7	193	1042.2	CH*	-
4	2015	1	26	2	335.3	488	12	501	5.8	152.7	165.7	961.06	CH*	-
5	2015	1	31	8	399	646.7	8	685.7	5.1	247.7	286.7	1462.17	CH*	-
6	2015	2	7	8	399.7	551.3	6	551.3	1.9	151.7	151.7	288.23	CH652	+
7	2015	2	17	1	343	460.7	12	460.7	3.5	117.7	117.7	411.95	CH654	-
8	2015	2	22	6	303	431	9	480.3	5.2	128	177.3	921.96	CH655	+

PART 1 – HSSs Columns 1-15

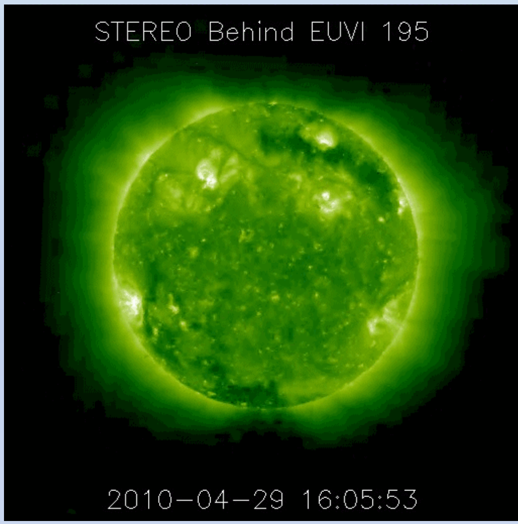
- The start data of the streams by: Year; Month; Day (calendar data); 3-H–3-hr interval of the start day;
- V0–minimum (pre-stream) velocity;
- V1–maximum velocity in the second day of the stream;
- Δt1–time interval between V0 and V1 (in number of 3-hr intervals);
- Vmax–maximum velocity of the stream;
- Dur – duration of the stream, in days;
- ΔV1= V1-V0–gradient of the velocity;
- ΔVM = Vmax-V0–maximum gradient of the plasma velocity;
- HSS importance (or intensity) – $I = \Delta V_{max} \times d$;
- Source – solar source of the stream: CH –coronal hole; CME– coronal mass ejection;
- IMF–the dominant polarity of the IMF for the duration of stream (+/- or -/+ means a magnetic sectorial border).

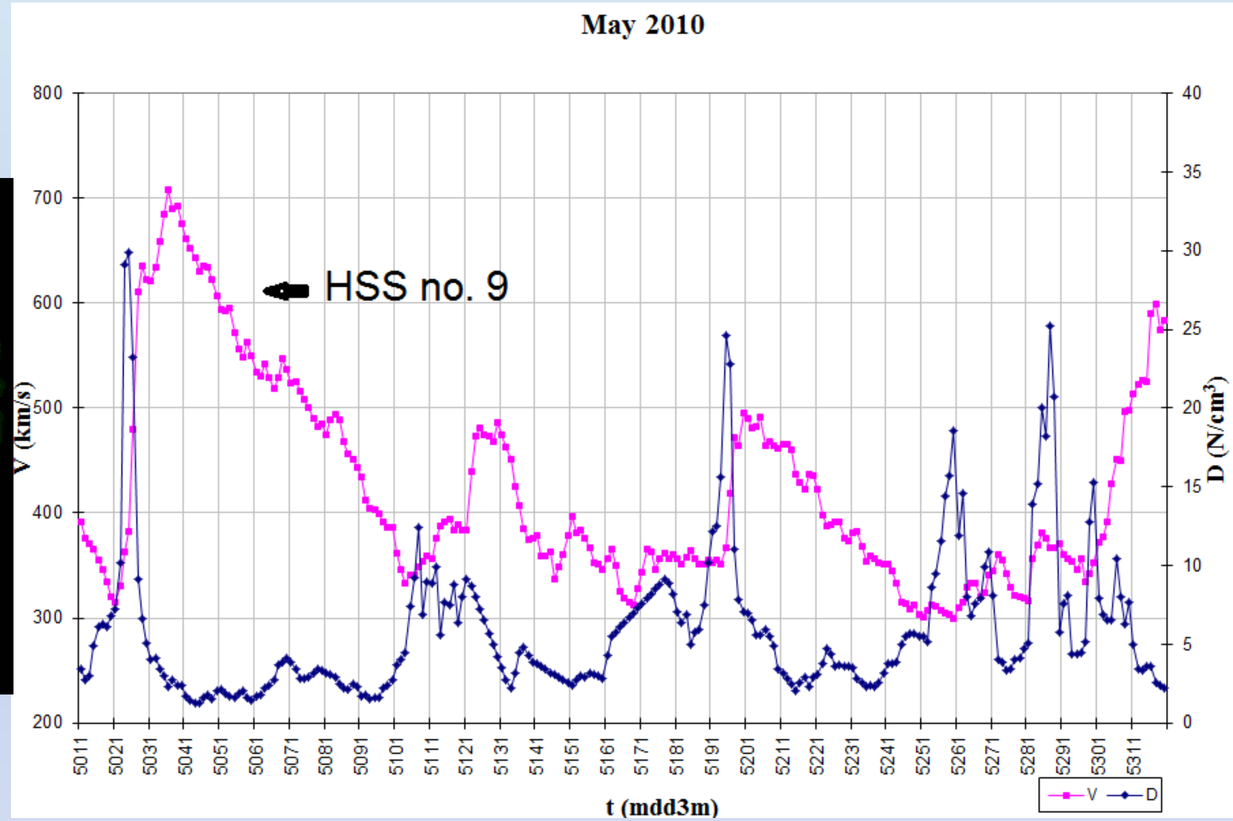
PART 2 – GSs (Dst ≤ - 30 nT) Columns 16-24

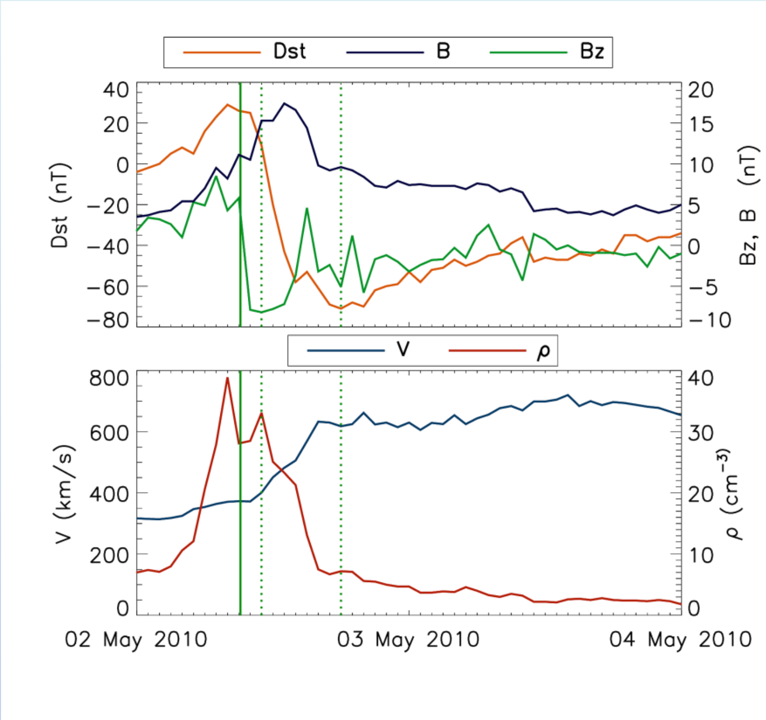
No. crt.	Dst_min (nT)	Dst_date (mm:dd:hh)	Bz_min (nT)	Bz_date (mm:dd:hh)	SSC_date (mm:dd:hh)	Energy estimates ε (J/S)	Energy estimates W (J/S)	SYM_min (nT)	SYM_min date
1	-71	01:04:21	-6.4	01:04:20		1.01E+15	1.49E+17	-75	01:04:21:46
	-42	01:06:09	-6.6	01:06:08				-48	01:06:10:04
2	-30	01:10:01	-2.9	01:09:23				-36	01:10:01:17
	-30	01:11:13	-1.8	01:11:12				-36	01:11:13:30
3									
4	-34	01:26:10	-10.9	01:26:09				-54	01:26:10:30
5									
6	-38	02:07:10	-5.3	02:07:08				-45	02:07:10:12
7	-64	02:18:00	-12	02:17:21		1.70E+15	3.32E+16	-70	02:17:23:58
	-32	02:19:04	-5.2	02:19:03				-34	02:19:04:08
8	-56	02:24:07	-5.6	02:24:05		2.49E+16	2.13E+17	-62	02:24:07:02

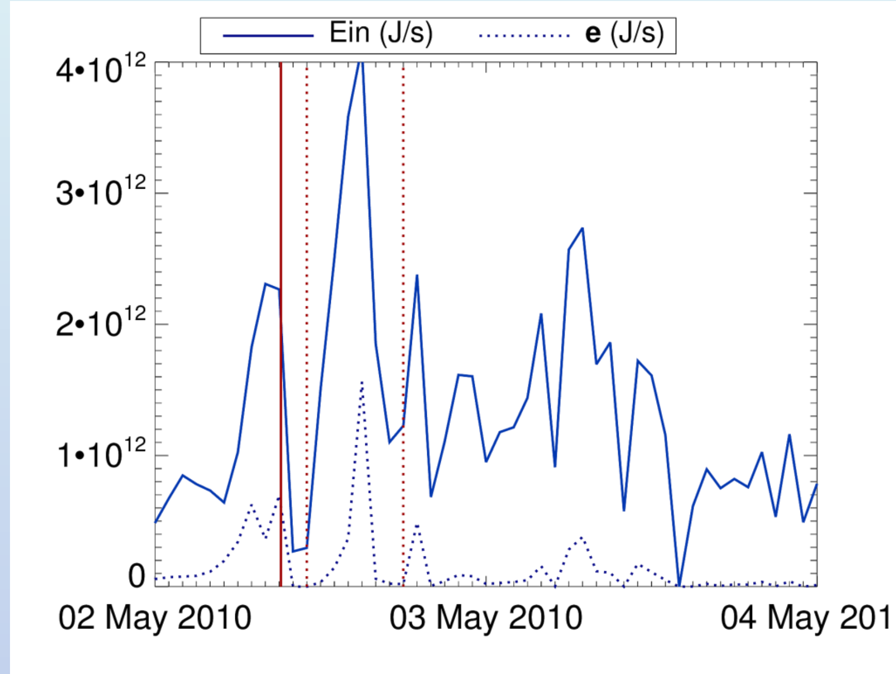
- Dst minimum value;
- Time of minimum Dst;
- Bz minimum value;
- Time of minimum Bz;
- Time of SSC (Sudden Storm Commencement);
- ε – energy coupling function (Akasofu ,1981);
- W – energy coupling function (Wang et al., 2014);
- SYM minimum value;
- Time of minimum SYM.

Case 1: HSS no. 9/2010







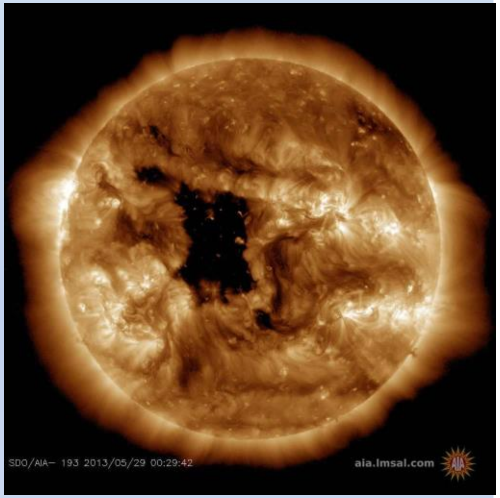


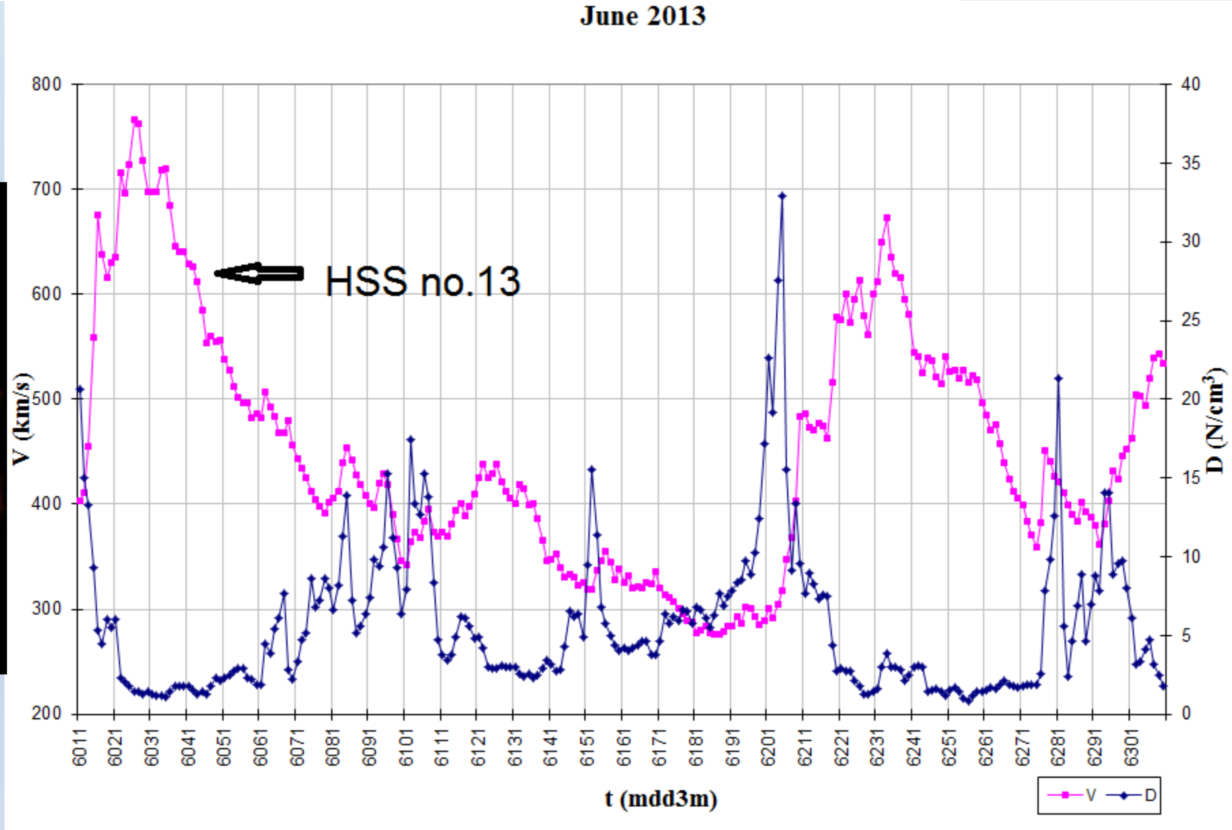
No.	Year	Month	Day	3-H	V0 (km/s)	V1 (km/s)	Δt1	Vmax (km/s)	Dur (days)	ΔV1 (km/s)	ΔVM (km/s)	I	Source	IMF	Dst_min (nT)	Dst_date (mm:dd:hh)	Bz_min (nT)	Bz_date (mm:dd:hh)
9	2010	5	2	1	315.3	635	6	708	9	319.7	392.7	3534.3	CH402	-	-71	05:02:17	-8.2	05:02:11

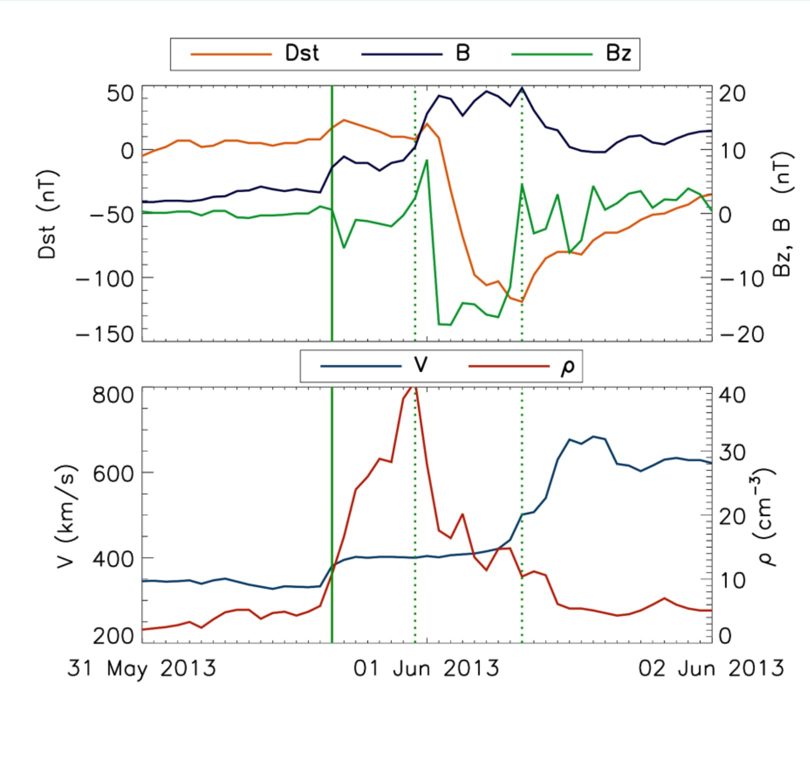
Vmax = 708 km/s
Dst= -71

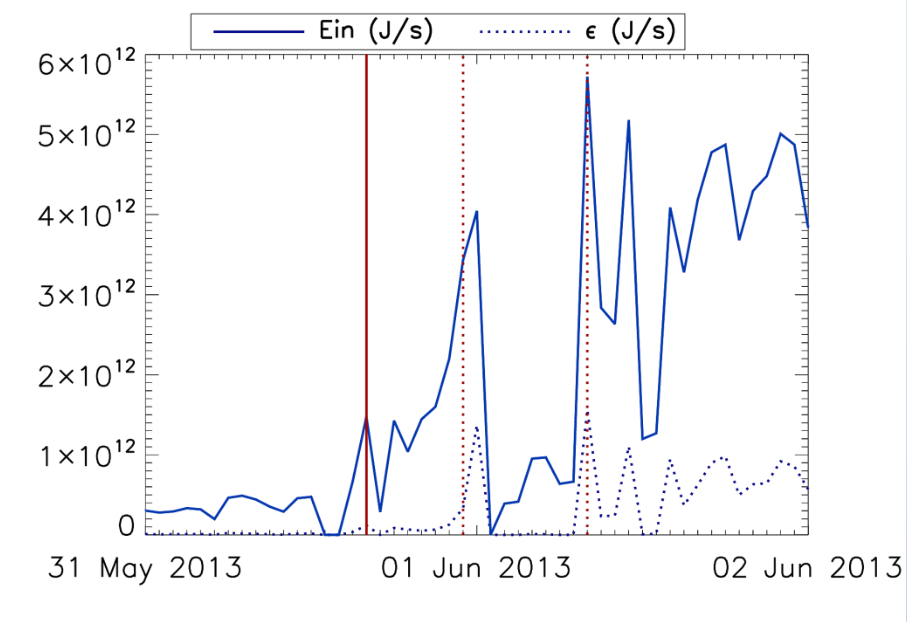
Bz < 0 during 20 h;
$T_{Dst} - T_{Bz} = 6h$

Case 2: HSS no. 13/2013









No.	Year	Month	Day	3-H	V0 (km/s)	V1 (km/s)	Δt1	Vmax (km/s)	Dur (days)	ΔV1 (km/s)	ΔVM (km/s)	I	Source	IMF	Dst_min (nT)	Dst_date (mm:dd:hh)	Bz_min (nT)	Bz_date (mm:dd:hh)
13	2013	5	31	5	332	676	8	766	9.5	344	434	4123	CH571	+	-119	06:01:08	-16.2	06:01:06

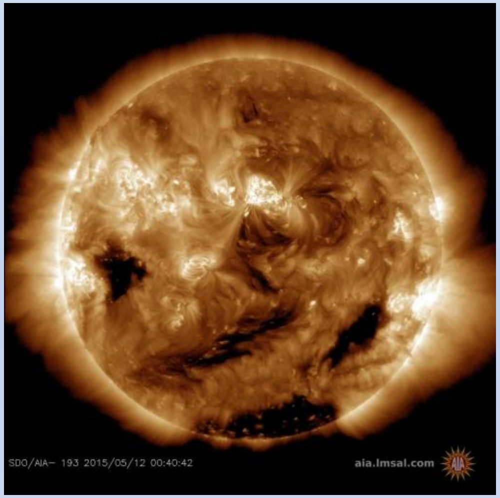
Vmax = 766 km/s

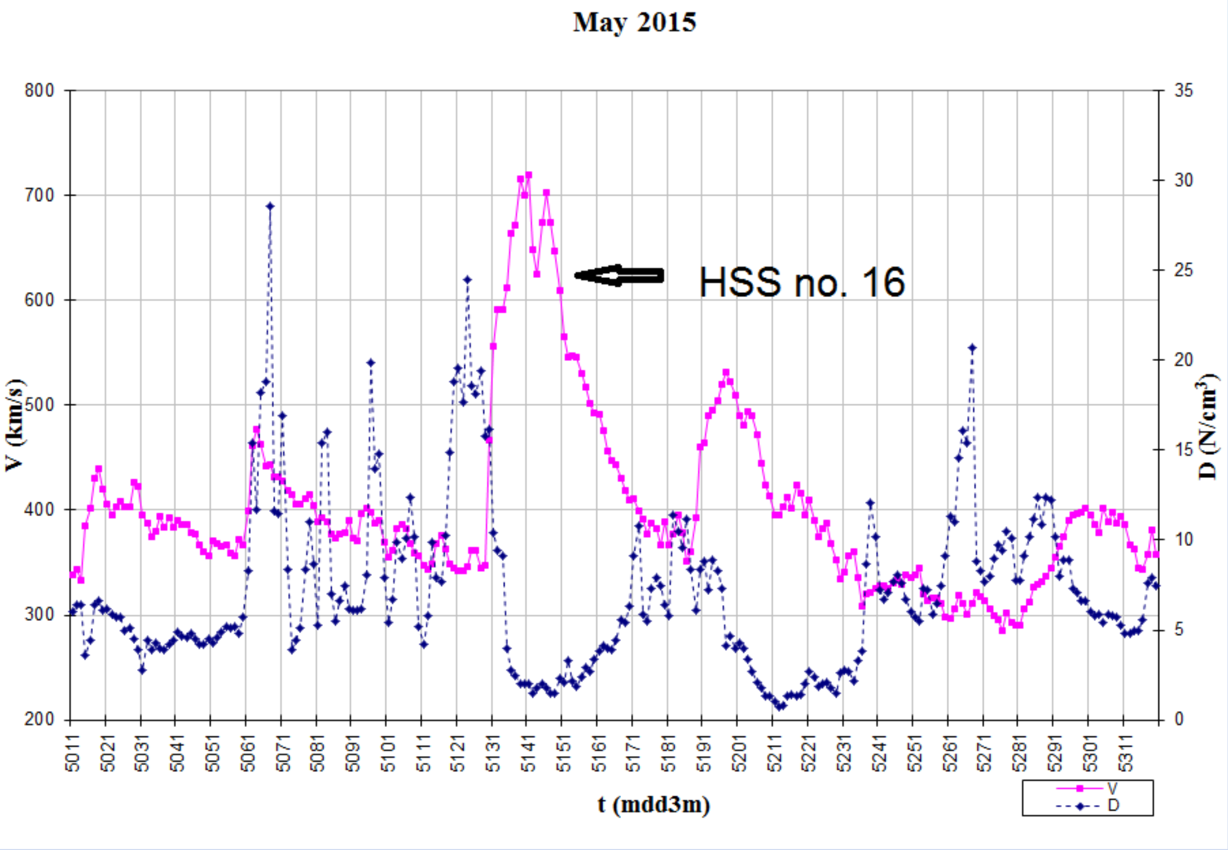
Dst= -119

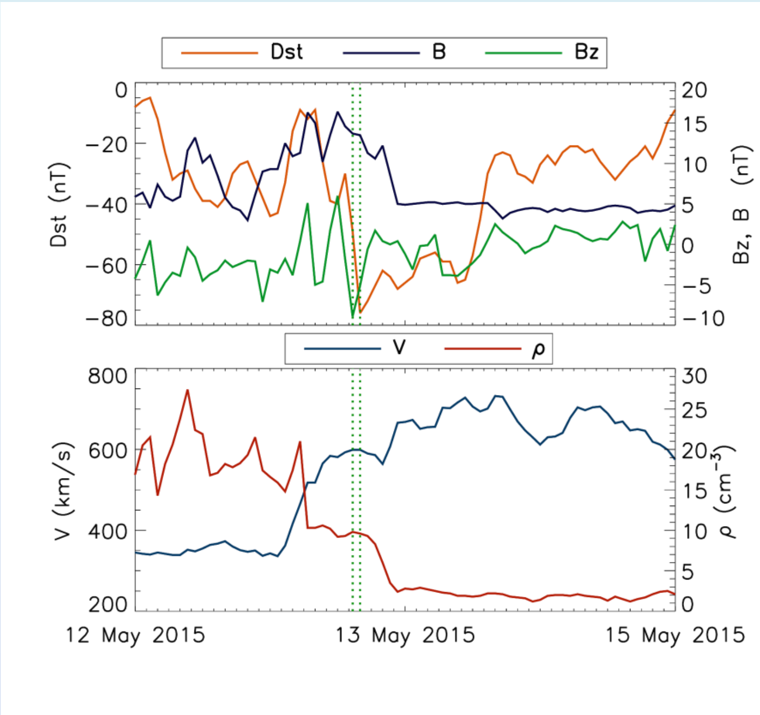
Bz<0 during 12 h (2 values near 0)

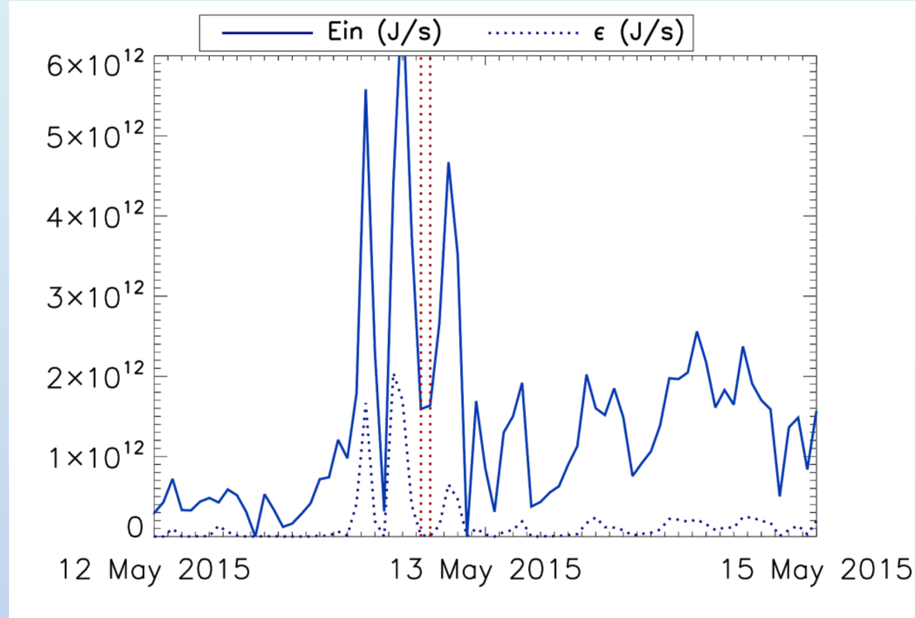
$T_{Dst} – T_{Bz}$=2 h

Case 3: HSS no. 16/2015









No.	Year	Month	Day	3-H	V0 (km/s)	V1 (km/s)	Δt1	Vmax (km/s)	Dur (days)	ΔV1 (km/s)	ΔVM (km/s)	I	Source	IMF	Dst_min (nT)	Dst_date (mm:dd:hh)	Bz_min (nT)	Bz_date (mm:dd:hh)
16	2015	5	12	2	342	466.3	6	720.3	6.4	124.3	378.3	2421.12	CH667	-	-76	05:13:06	-8.9	05:13:05

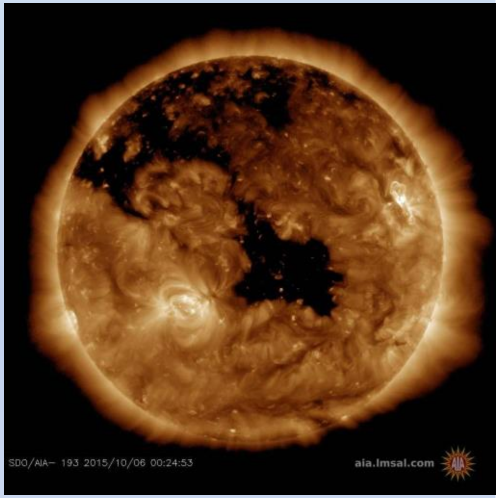
Vmax = 720.3 km/s

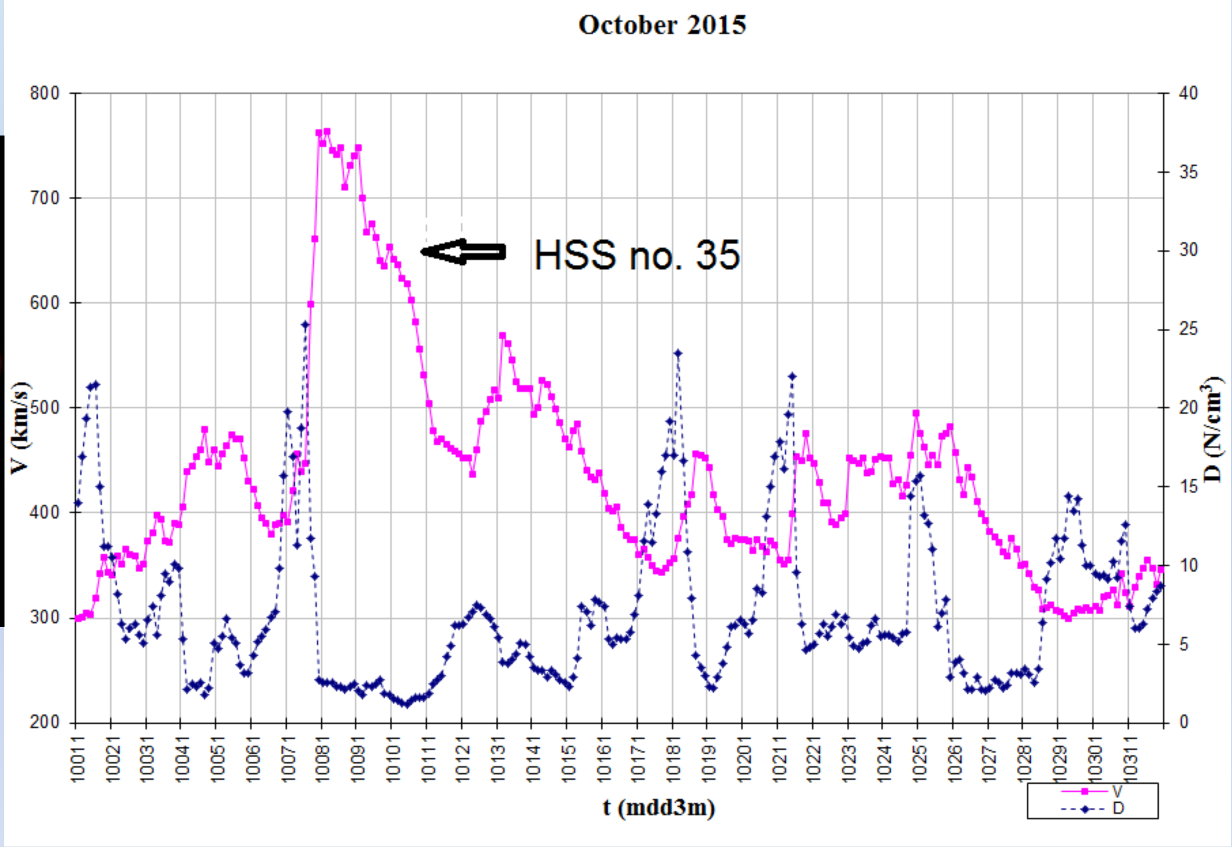
Dst= -76

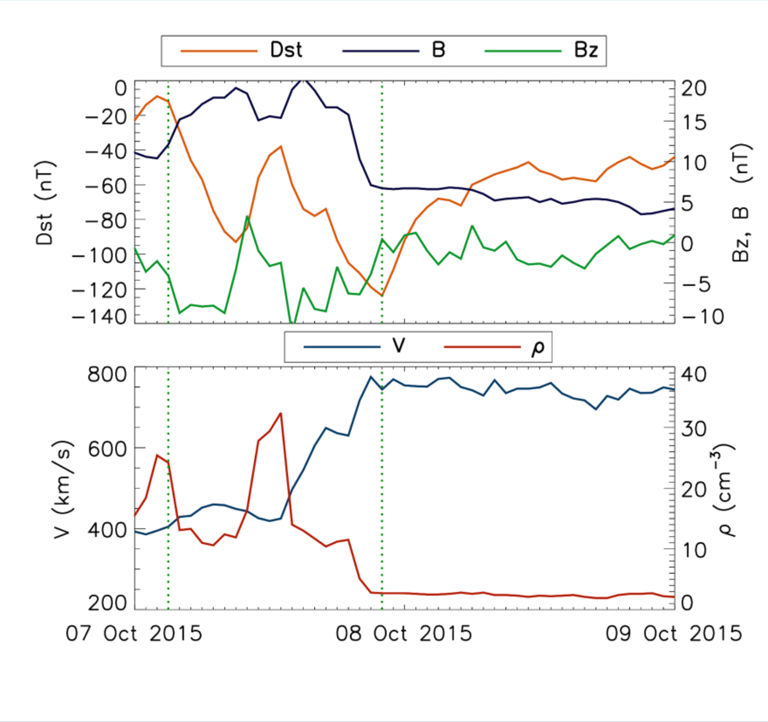
Bz<0 during 4 h

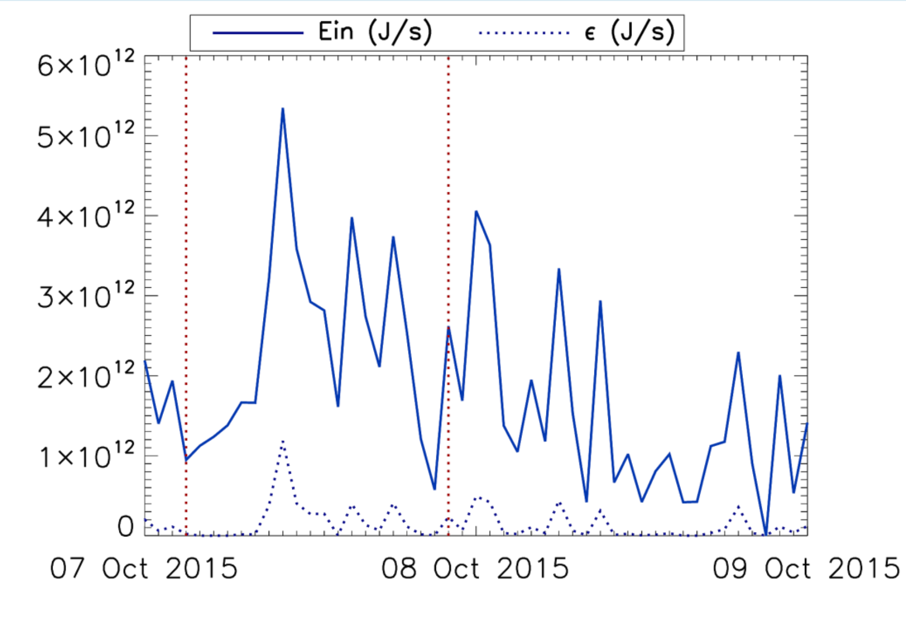
$T_{Dst} – T_{Bz}$=1 h

Case 4: HSS no. 35/2015









No.	Year	Month	Day	3-H	V0 (km/s)	V1 (km/s)	Δt1	Vmax (km/s)	Dur (days)	ΔV1 (km/s)	ΔVM (km/s)	I	Source	IMF	Dst_min (nT)	Dst_date (mm:dd:hh)	Bz_min (nT)	Bz_date (mm:dd:hh)
35	2015	10	6	5	380	762.7	11	764.3	5.8	382.7	384.3	2228.94	CH694	+	-124	10:07:22	-6.4	10:07:20

Vmax = 764.3 km/s

Dst= -124

Bz<0 during ~24 h

$T_{Dst} - T_{Bz} = 2$ h

Summary

1. The “magnitude” of the HSS impact on the magnetosphere depends on solar events contributing to HSSs (heliographic position, structure);
2. Although we do not have a complete understanding of all the processes in the magnetosphere during a geomagnetic storm, it is clear that the majority of them ultimately ***derive their energy from the solar wind through reconnection processes;***
3. The reconnection at the magnetopause and its consequences strongly ***depend on the interplanetary magnetic field orientation (Bz negative).***
4. We hope that this catalogue will be useful to stimulate and carry out further studies in space weather field. It will be completed with HSSs during the end of the 24th solar cycle.

Aknowledgments

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The data used for compiling this catalog was taken from:

- GSFC/SPDF OMNIWeb interface at https://omniweb.gsfc.nasa.gov
- http://wdc.kugi.kyoto-u.ac.jp/aeasy/index.html
- http://www.solen.info/solar/coronal_holes.html The report has been prepared by Jan Alvestad. It is based on the analysis of data from whatever sources are available at time the report was prepared.

We acknowledge all of the above for making the data available.

The HSSs were determined using software developed by dr. Ovidiu Maris using C and IDL (Institute for Space Sciences, Bucharest) in the frame of a national project PN2 HELIOTER (Contract no. 81-021/2007) and improved by our team (with special thanks to Daniela Lacatus and Alin Paraschiv). We thank dr Ovidiu Maris for making this software available to our team.

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Thank You
for Your kind attention !

Energy injected into magnetosphere

Akasofu coupling function, ε [J/s]:

$$\varepsilon = 10^7 \, V \, B^2 \, l_0^2 \sin^4 \frac{\theta}{2} \; [J/s]$$

where: $l_0 = 7R_E$, θ= tan-1 (By/Bz).

Wang coupling function, Ein [J/s]:

$$E_{IN} = 3.78 \times 10^7 \, n_{SW}^{0.24} \, V_{SW}^{1.47} \, B_T^{0.86} \left(\sin^{2.7} \frac{\theta}{2} + 0.25\right) \; [J/s]$$

Total energy injected into Earth's magnetosphere is obtained by integrating over the main phase of GS, from to (time of the main phase beginning) to tm (time of minimum Dst).