



Sources and Complexity of the Intense and Severe Geomagnetic Storms during the Maximum Phase of Solar Cycle 23

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OUTLINE

1. INTRODUCTION

- **Solar particle streams affecting the terrestrial magnetosphere:**
 - Solar Flares → Carrington flare of Sept. 1859;
 - M regions → Coronal Holes (CH) → High Speed Streams (HSSs) ⇒ Co-rotating Interaction Regions (CIRs);
 - Coronal Mass Ejections (CMEs)
- **Solar Cycle:**
 - Solar cycle phases: minimum, ascendant, maximum, descendant;
 - SC 23 maximum
- **Geomagnetic storms (GSs):**
 - Phases;
 - Classification;

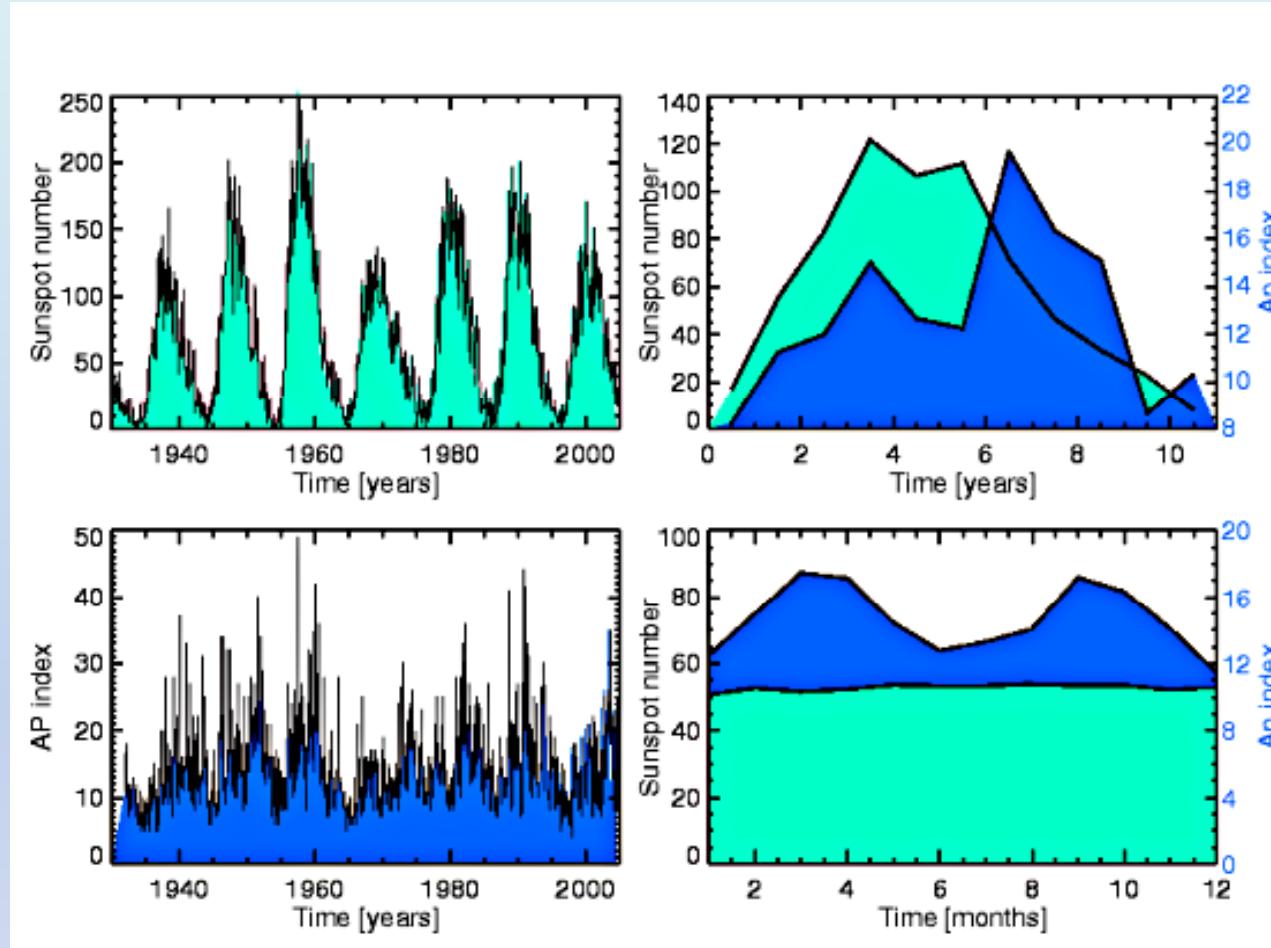
2. MAJOR AND SEVERE GSs OF 1999 – 2002:

- Main phase complexity;
- Solar sources;
- Interplanetary magnetic field: Bz and B

3. REMARKS

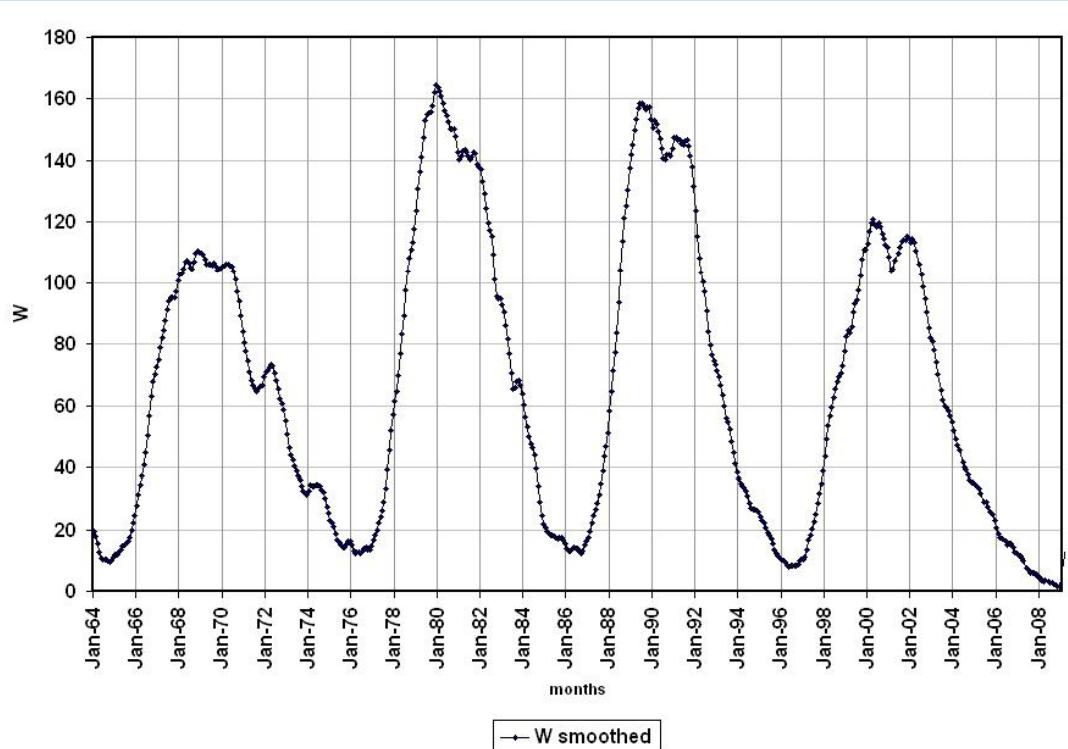
INTRODUCTION

- **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**



Periodicities in solar and geomagnetic activity. The top right panel shows the solar cycle variation present both in the geomagnetic and solar records, showing peak geomagnetic activity during the declining phase of the solar cycle. The bottom right panel shows the semiannual variation in the geomagnetic data not visible in the solar records. (T. Pulkkinen, 2006)

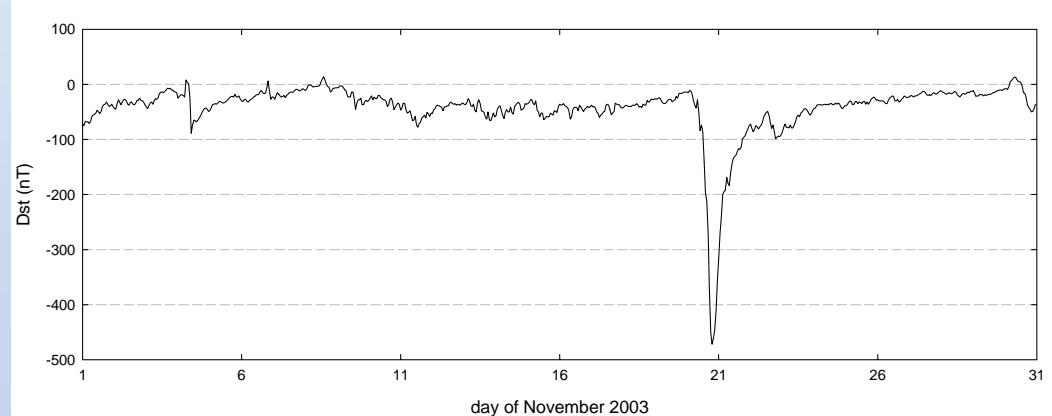
Solar Cycle: phase duration



- **Minimum:** $W < 20$;
- **Maximum:** interval to encompass entirely the “shape” of the SC maximum (prolonged more than one year or having two peaks);
- **Ascendant & Descendant:** intervals placed between them
⇒ **SC 23 maximum phase: September 1999 – July 2002**

Geomagnetic storms

The main feature → a decrease in the horizontal component of geomagnetic field at the equator (Cid et al., 2008) related to the enhancement of the ring current which flows around the Earth from east to west in the equatorial plane; **Dst is drastically decreasing.**

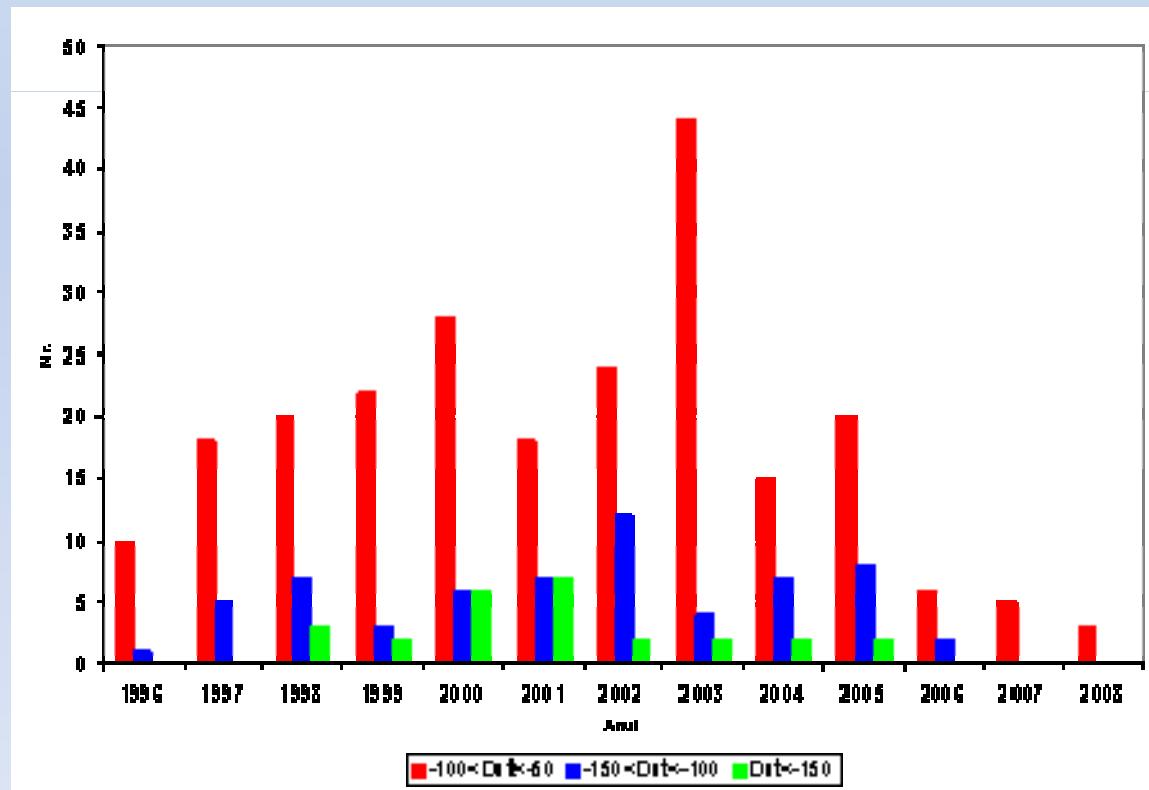


- The **initial phase** –presents a period of enhanced Dst; B_z is oriented primarily northward \Rightarrow little energy is entering the magnetosphere \Rightarrow Dst increases relative to quiet time;
- Some storms have a **sudden commencement** – the effect of a compression of the dayside of the magnetosphere by enhanced solar wind pressure
- The **main phase** is the defining feature of a storm. It represents ring current injection, which results from a southward IMF and the resultant strong convection – Bz is southward; hours.
- The **recovery phase** is due to loss of ring-current ions as a result of: charge-exchange with the neutral exosphere, Coulomb interaction and wave-particle interaction (Kozyra et al, 1997) – Bz is northward; days.

- Initial phase of some geomagnetic storms shows a sudden increase of Dst to positive values up to tens of nT corresponding to the **storm sudden commencement (SSC)**; then it decreases sharply as the ring current intensifies. Other geomagnetic storms begin by a gradual decrease in Dst – **the gradual storm**.
- The geomagnetic storms are also classified as **recurrent** and **non-recurrent**.
- The **Dst** or ***disturbance storm time*** index is a measure of geomagnetic activity used to assess the severity of magnetic storms. It is expressed in nT and is based on the average value of the horizontal component of the Earth's magnetic field measured hourly at four near-equatorial geomagnetic observatories.
- The use of the Dst as an index of storm strength is possible because the strength of the surface magnetic field at low latitudes is inversely proportional to the energy content of the **ring current**, which increases during geomagnetic storms.
- The **intensity of geomagnetic storms** is defined by the **minimum Dst** value, known as **Dst peak value** ⇒ **GS classification**:
 - **-50 < Dst < -30 → minor (small) storm (typically substorm);**
 - **-100 < Dst < -50 → moderate storm;**
 - **-150 < Dst < -100 → intense (strong) storm;**
 - **- Dst < -150 → severe storm.**

Geomagnetic storms (moderate – severe) during SC 23

Dst	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	Total
- 50 > Dst > - 100	10	18	20	22	28	18	24	44	15	20	6	5	3	236
-100 > Dst > -150	1	5	7	3/1	6	7	12/5	4	7	8	2	0	0	62
Dst < - 150	0	0	3	2	6	7	2	2	2	2	0	0	0	26
Total	11	23	30	27	40	32	38	50	24	30	8	5	3	321



The yearly distributions of the geomagnetic storms by their intensity, during SC 23 (Maris & Maris, 2010, Complex Catalogue: GSs-HSSs, 1996 – 2008; at: http://www.spacescience.ro/new1/GS_HSS Catalogue.html)

MAJOR AND SEVERE GSs OF 1999 – 2002

No	Date mm/dd/hh	Dst min (nT)	Bz min (nT)/Δt _{min}	Δt (h) (Bz<0)	B (nT)	SSC	Solar/Heliospheric sources		
							CIR	Flare	CME/ICME
1999									
1	09/22/23	-173	-15,8/-1h	4 h	11	SSC	CH ² / CIR ¹	C2.8	CME/ICME ³
2	10/22/06	-237	-30.7/-1h	8 h	20	SSC	CH ¹ /CIR ¹	-	CME/ICME-CIR ³
3	11/13/22	-106	-11.5/-3h	>10 h	4	GS	CH ²	-	DG/ICME ³
2000									
4	02/12/11	-133	-16.4/-1h	4 h	13	SSC	-	F ² /C7.3	CME/ICME ³
5	04/06/22	-287	-27.3/-1h	7 h	6	GS	CIR ¹	F ² /C9.7	CME/ICME ³
6	05/24/08	-147	-11.1/-1h	2 h	5	SSC	CIR ¹	F ² / C7.6	CME/ICME ³
7	07/16/00	-301	-49.4/-4h	8 h	20	SSC	-	F ² /X5.7	CME/MC ³
8	08/11/06	-106	-11.2/-2h	<10 h	12	SSC	-	F ²	CME/MC ³
9	08/12/09	-235	-29.7/-1h	5 h	18	GS ?	-	F ² /C2.3	CME/MC ³
10	09/17/23	-201	-23.9/-2h	4 h	10	SSC	-	F ² /M5.9	CME/ICME ³
11	10/05/13	-182	-17.5/-2h	3 h	6	SSC	CIR ¹	F ² / ?	CME/ICME ³

No	Date mm/dd/hh	Dst min (nT)	Bz min (nT)/ Δt_{min}	Δt (h) (Bz<0)	B (nT)	SSC	Solar/Heliospheric sources		
							CIR	Flare	CME/ICME
2000 (cont)									
12	10/14/14	-107	-11.5/-1h	>10 h	12	GS	CH ² /CIR ¹	C6.7 ³	CME/MC ³
13	10/29/03	-127	-17.1/-3h	6 h	14	SSC	CH ²	C4.0 ³	CME/MC ³
14	11/06/21	-159	-11.7/-6h	9 h	20	SSC	CH ²	-	CME/MC ³
15	11/29/13	-119	-10.3/-6h	>10 h	9	SSC	-	F ² /X4.0	CME/ICME ³
2001									
15	03/20/13	-149	-18.6/-1h	>10 h	15	SSC	-	F ²	CME/MC ³
17	03/31/08	-387	-44.7/-2h	6h	33	SSC	-	F2/X1.7	CME/ICME ³
18	04/11/23	-271	-20.5/0h	>10 h	14	SSC	-	F ² /X2.3	CME/MC ³
19	04/18/06	-114	-19.6/-3h	>10 h	8	SSC	-	F ² /X14.4	CME/MC ³
20	04/22/15	-102	-12.8/-4h	>10 h	11	SSC	-	F ² / -	?/MC ³
21	08/17/21	-105	-18.1/-3h	9 h	11	SSC	-	F ² /C2.3	CME/MC ³
22	09/26/01	-102	-6.4/-4h	7 h	7	SSC	-	F ² /X2.6	CME/ICME ³
23	10/01/08	-148	-12.7/-1h	9 h	9	SSC	-	F ² /M3.3	CME/ICME ³
24	10/03/14	-166	-20.9/-2h	9 h	12	SSC	CIR ¹	F ² /M1.8	CME/MC ³

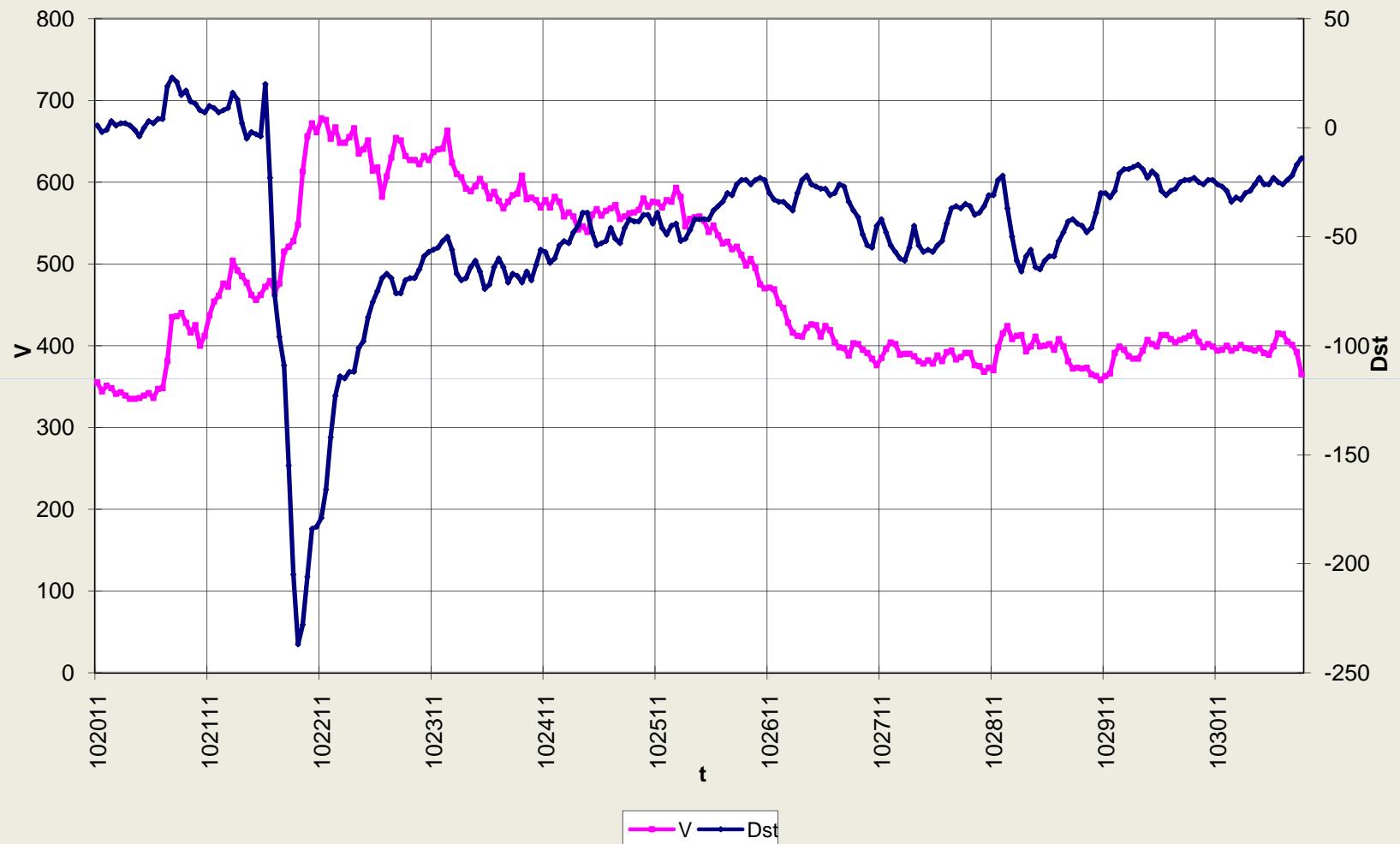
No	Date mm/dd/hh	Dst min (nT)	Bz min (nT)/ Δt_{min}	Δt (h) (Bz<0)	B (nT)	SSC	Solar/Heliospheric sources		
							CIR	Flare	CME/ICME
2001 (cont)									
25	10/21/21	-187	-16.4/-3h	5 h	9	SSC	-	F ² /X1.6	CME/ICME ³
26	10/28/11	-157	-14.5/-6h	>10 h	5	GS ?	-	F ² /X1.3	CME/ICME ³
27	11/01/10	-106	-10.4/-1h	>10 h	11	SSC	-	F ² ?/?	?
28	11/06/06	-292	-64.0/-3h	>10 h	7	SSC	-	F ² /X1.0	CME/ICME ³
29	11/24/16	-221	-27.8/-5h	4 h	14	SSC	-	F ² /M9.9	CME/ICME ³
2002									
30	03/24/09	-100	-9.7/-4h	>10 h	15	SSC	-	F ² /M1.0	CME/ICME ³
31	04/18/07	-127	-12.8/-2h	8 h	14	SSC	-	F ² /M1.2	CME/MC ³
32	04/20/08	-149	-13.0/-5h	8 h	8	SSC	-	F ² /M2.6	CME/MC ³
33	05/11/19	-110	-16.5/-3h	7 h	15	SSC	-	F ² /C4.2	CME/ICME ³
34	05/23/17	-109	-11.6/-1h	2 h	9	SSC	-	F ² /C9.7	CME/ICME ³

1 – Cid, C. et all, 2004, *Sol. Physics* **223**, 231-24

2 – Maris O., Maris G., 2009, HSS Catalog, at: http://www.spacescience.ro/new1/HSS_Catalogue.html

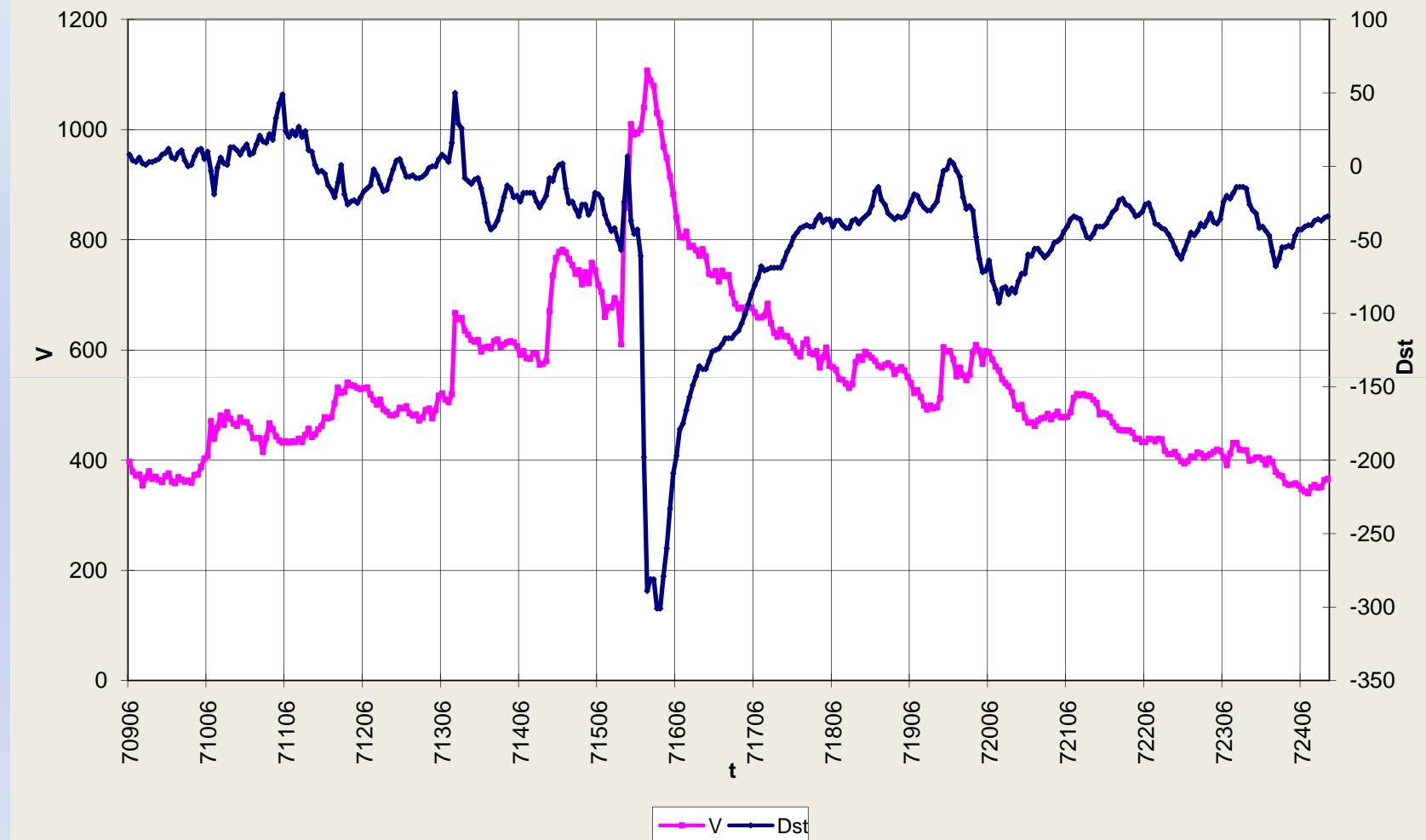
3 – Zang, J. et all, 2007, JGR 112, A10102, doi: 10.1029/2007JA01321

1999_20 Oct

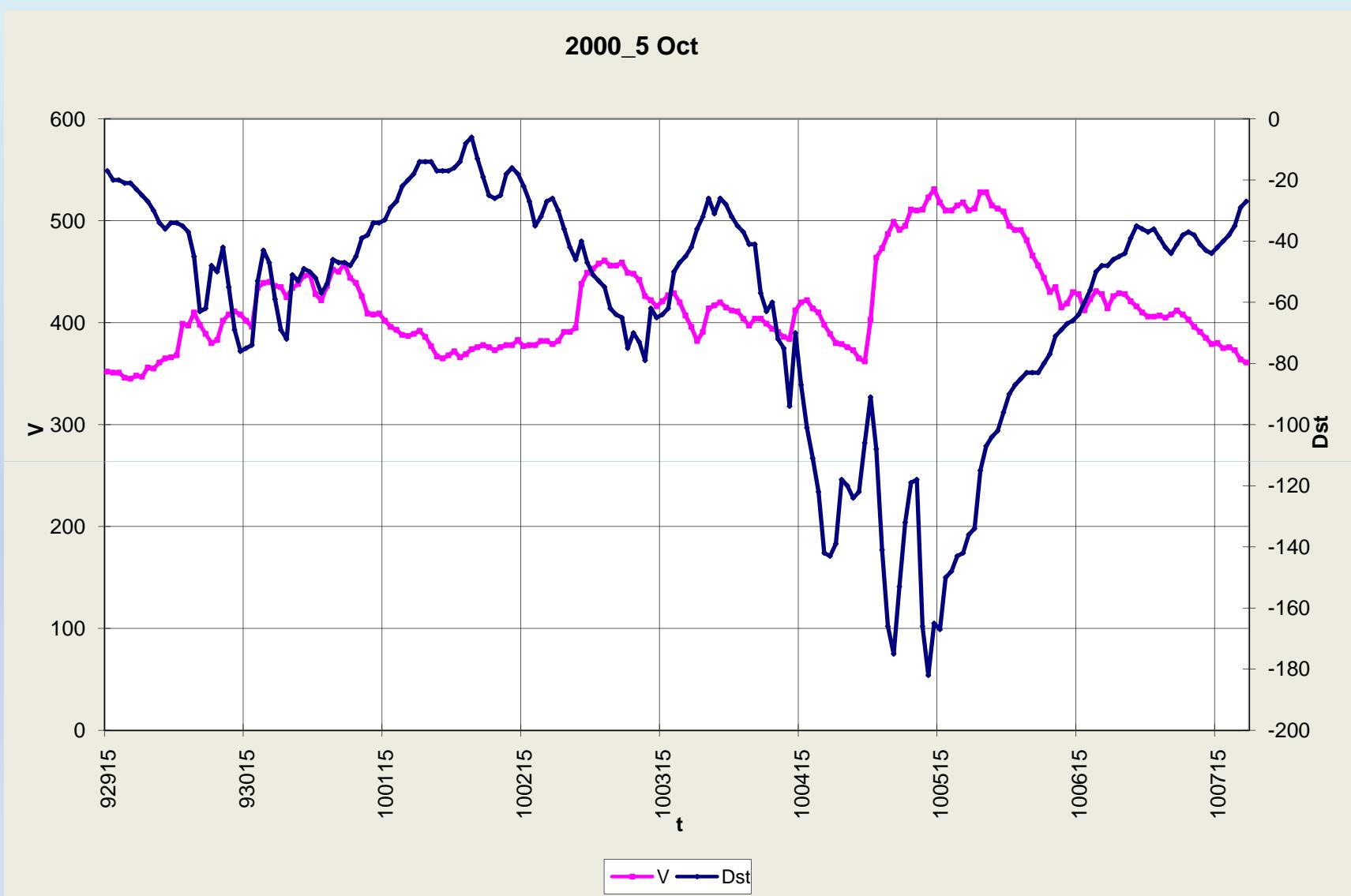


2	10/22/06	-237	-30.7/-1h	8 h	20	SSC	CH^1/CIR^1	-	CME/ICME-CIR ³
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2000_16 Jul

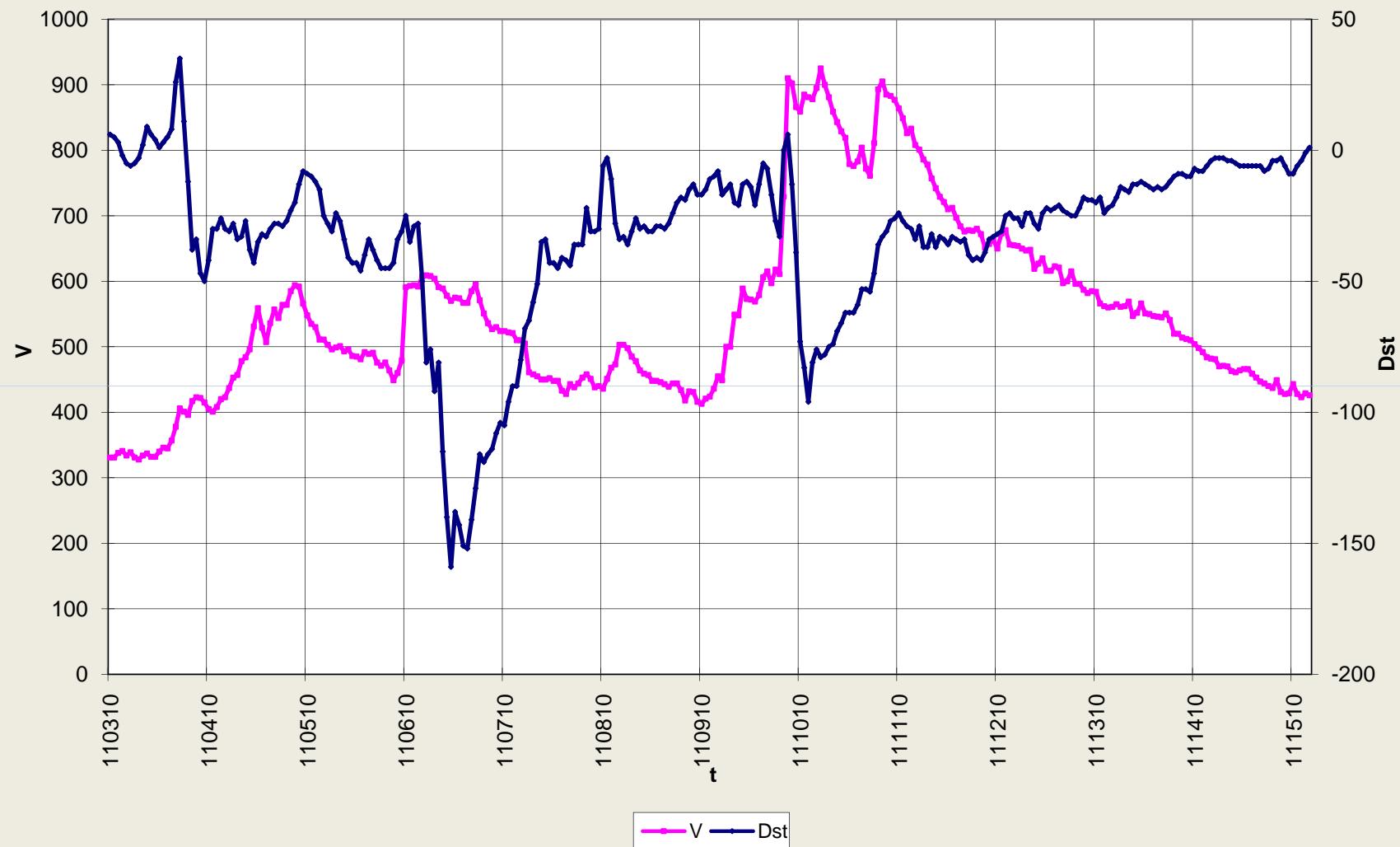


7	07/16/00	-301	-49.4/-4h	8 h	20	SSC	-	$F^2/X5.7$	CME/MC ³
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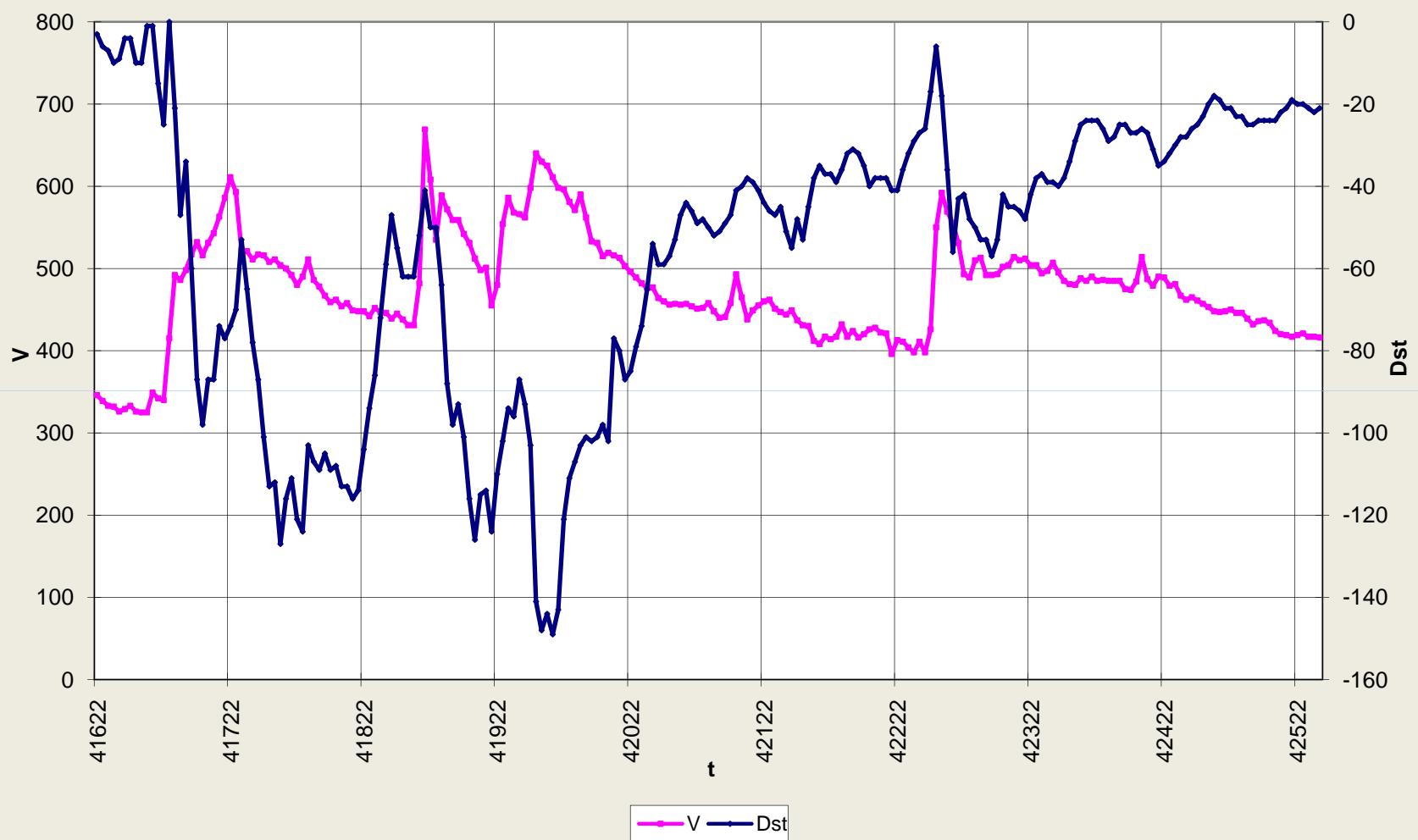
11	10/05/13	-182	-17.5/-2h	3 h	6	SSC	CIR ¹	F ² / ?	CME/ICME ³
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2000_06 Nov



14	11/06/21	-159	-11.7/-6h	9 h	20	SSC	CH^2	-	CME/MC ³
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2002_18 and 20 Apr



31	04/18/07	-127	-12.8/-2h	8 h	14	SSC	-	$F^2/M1.2$	CME/MC ³
32	04/20/08	-149	-13.0/-5h	8 h	8	SSC	-	$F^2/M2.6$	CME/MC ³

Case analysis - Regression analysis

Geomagnetic Storms:

- (1) April 6, 2000;
- (2) August 11, 2000;

Correlations:

- a) (V ; Dst);
- b) ($V \cdot Bs$; Dst) where:

$Bs = |Bz|$ for $Bz < 0$ and

$Bs = 0$ for $Bz > 0$ (Wu & Lepping, 2006)

	Date	$r (V, Dst)$	$r (V \cdot Bs, Dst)$
1	04/06/2000	- 0.78	- 0.9
2	08/10/2000	- 0.12	- 0.94



Combined effect of $Bz < 0$ and V

Remarks ...

1. The “magnitude” (force) of the solar events impact on the magnetosphere depends on solar events contributing to HSSs \Rightarrow **solar cycle phase**.
2. Maximum Phase of SC 23 – 35 months (SC 20 – 33 m; SC 21 – 34 m; SC 22 – 36 m);
3. 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 the processes ultimately derive their energy from the solar wind through the reconnection process**.
4. The **amount of reconnection** at the magnetopause and its consequences **depend strongly on the interplanetary magnetic field orientation, (Bz)**.

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 the forecaster having a **good understanding of how solar and heliospheric disturbances interact and how the magnetosphere works**.