Statistical analysis of solar events associated with SSC over one year of solar maximum during cycle 23: propagation and effects from the Sun to the Earth.

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From the Sun to the Earth

Solar Magnetic Activity: sunspots, flares, CME, ICME and magnetic cloud (L1 in situ),

Active Region 486

Emerging Flux tube

2D -3D observations (SOHO-SDO,GBs)

Magnetogram

Measurement in situ (ACE and WIND)

(Démoulin review 2008)

Lasco and NRH

Dst or SSC (magnetometers)
Starting point #1
SSC May 23 2002 at 10:18 UT
By using the geomagnetic indices (Dst, SYM-H...)

SSC Storm Sudden Commencement = compression of the magnetosphere indicating the arrival of the shock.

Date; Amplitude; Quality (23-05-2002 10:18; 78 nT; 2)

Dst (hour) et SYM-H (1 mn) variations related to the annular magnetospheric currents of the horizontal magnetic component at the Earth surface

Value of the minimum; Classification (-109; Intense Storm)
Comparaison of the geomagnetic indices Dst / integrated indices

Linear trend with Exceptions due to saturation effects at the pole

Figure 4. Minimum of Dst in function of integrals of different indices PCN, AU, AL
Back and Forth method

We propose a statistical analysis covering one year (2002) to investigate the link between

• SSC (Storm Sudden Commencement), detected by the magnetic observatories on the ground and

• the Coronal Mass ejection (CME).

• propagation in a time window ~1 to 5 days (ballistic propagation ballistic between 300 km/s and 1500 km/s)

• The method is back and forth to find the correct association of events (step 1, step 2, step 3, step1...)

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Some results obtained in one year of measurements (2002) during the cycle 23 maximum

- From
  - 35 SSC identified in 2002
  - 57 CME with an identified solar source (if no halo CME has been identified we search for a partial CME): 27 halo CMEs +30 non halo CMEs
  - Characterisation of the perturbation ICME recorded at L1 before the SSC
  - Geomagnetic indices
  - Ionosphere (detection with Super Darn, Thermosphere CHAMP)
  - Only a few of in situ magnetosphere observations (Cluster operated until July 2002)
How often are MC, ICME, SIR followed by a SSC?

- Events in 2002 from the literature and us

<table>
<thead>
<tr>
<th></th>
<th>+ SSC</th>
<th>Efficiency</th>
<th>Detected by us</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC</td>
<td>17</td>
<td>12</td>
<td>71%</td>
</tr>
<tr>
<td>ICME</td>
<td>34</td>
<td>9</td>
<td>26%</td>
</tr>
<tr>
<td>CIR/SIR</td>
<td>41</td>
<td>4</td>
<td>10%</td>
</tr>
</tbody>
</table>

We have detected all the MC associated with SSC,
2/3 of the ICME associated with SSC,
the 4 SIR/CIR associated with SSC

CIR corotating interplanetary region due to solar wind sheets
Figure 12. Observations at L1 (ACE data) and ground based observations of the Dst index, related to the SSC06 of the March 23, 2002. The Interplanetary Magnetic Field (IMF) is
From the SSC, and MC at L1 research of the CME halos

2002/03/20 – 2002/03/26

CME Height-Time

NORTH
EAST
SOUTH
WEST

CMEh09 p10
h11 h12

GDES X-Ray

1.0–8.0 Å
2.5–4.0 Å

SSC06
X-ray GOES flare: M class

35% are associated with C class events
43% M class events
12% X Class events

M classe on 22 March 2002 at 11UT
Tracking InterPlanetary structures using radio waves

The shock driven by flux rope (MC) commonly excites electromagnetic waves at the local plasma frequency ($f \sim n_e^{1/2} \sim D^{-1}$)

[From Dasso et al., JGR 2009]
Radio observations with Nançay RH and C2 of LASCO

Two CMEs interaction
Type IV is the signature of a flux rope and loops (Démoülin, Pick 2012)
Comparison between observations and models

-14 hours < t < +14 hours

**Figure 3.** ICME and Shocks propagation
The active region AR 9866

(a) March 15

(b) March 22

(c) March 15

(d) March 22
Complex AR 09866

Reversed - S filament

Surrounding filament

Active regions should be large AND complex (Aulanier et al 2013)
Statistics for 2002

From 35 SSCs, only 5 SIRs or CIRS have given an SSC, all the others come from 44 CMEs with solar sources 50% are very well identified.

Solar sources: active region with or without a filament 90% filament with or without an AR 72%

CME halos 70% chance to have some geoeffectiveness
CME partial or non halo: 1%

Multiple CMEs are geoeffective for 50% of the cases

Velocity: 10% have velocity <500 km (non halo CME)
50% have 500<V<1000 km/s
5% have V>1000 km/s (halo CME)

Good association of MCs with type II and type IV radio bursts
THE END
28 SSC are related to 44 CMEs with 28 leading CMEs (17 halos, 9 non-halos),

- 6 halo CMEs are not associated with any SSC and 3 SSC are not related to any CME of our list (Tables 16 and 2).

- From these 28 events, 11 events are related to multi CMEs and multi solar sources, only 17 events are related to a single CME.
Interplanetary Medium at L1: ACE Satellite

Characteristics of the observations:
ICME (Interplanetary CME) or NOT?

t$_{ssc}$
ICME: increase of $V$
t1: shock
t2: start of the ICME
t3: end of the ICME
Statistics for 2002

For the 44 CMEs listed in Table 16 and associated with an SSC (as leading or participating) in Table 2,

- 12 find their source only in an AR, 4 find their source only in a filament, and 26 find their source in an AR and a filament (including one case near a CH). Thus 90% of the CME find their source in an AR (with or without a filament), 72% in a filament (in or out an AR).
- 76% come from the southern hemisphere of the Sun, and 24% from the northern hemisphere of the Sun.
- 43% come from the eastern side of the Sun, 57% from the western side of the Sun.
- 10% have a velocity smaller than 500 km.s\(^{-1}\) (non halo CMEs), 50% a velocity ranging from 500 km.s\(^{-1}\) to 1 000 km.s\(^{-1}\), 45% a velocity between 1 000 km.s\(^{-1}\) and 2 000 km.s\(^{-1}\) (2/3 are halo CMEs), and 5% a velocity higher than 2 000 km.s\(^{-1}\) (halo CMEs),
- 28% are associated with Types II and 10% to Types IV,
- 35% are associated with C class events, 43% M class events, 12% X class events, measured by GOES. They are all linked to an AR, except one.
Table 2. Major Interplanetary Structures Causing Moderate Storms along the Different Phases of Solar Cycle 23

<table>
<thead>
<tr>
<th>Solar Cycle Phase</th>
<th>Number of Storms</th>
<th>Major IP Structures and Percentage of Storms they Caused</th>
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<tbody>
<tr>
<td>Rising phase (1997–1999)</td>
<td>53</td>
<td>CIR/HSS (30.2 %)</td>
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<td>ICME (24.5 %)</td>
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<td>SHOCK-ICME (17.0 %)</td>
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<td>SHOCK/SHEATH (9.4 %)</td>
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<td>Maximum (2000–2002)</td>
<td>62</td>
<td>CIR/HSS (33.9 %)</td>
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<td>ICME (22.6 %)</td>
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<td>SHOCK-ICME (14.5 %)</td>
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<td></td>
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<td>SHOCK/SHEATH (16.1 %)</td>
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<td>Declining (2003–2005)</td>
<td>75</td>
<td>CIR/HSS (60.0 %)</td>
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<td>ICME (20.0 %)</td>
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<td></td>
<td></td>
<td>SHOCK-ICME (5.3 %)</td>
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<tr>
<td></td>
<td></td>
<td>SHOCK/SHEATH (9.3 %)</td>
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<tr>
<td>Minimum (1996, 2006–2008)</td>
<td>23</td>
<td>CIR/HSS (82.6 %)</td>
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<td></td>
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<td>ICME (8.7 %)</td>
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</table>
For the 35 SSC we see that the Dst can be used as a proxy of the geoeffectiveness.
Ionospheric radars
SuperDARN: Polar Cap potential through the pole

Maximum value of the PCP (85-95)
Maximum time after the SSC (01:15)
Nb of points (quality) (100-200)
Thermosphere:
Measurements of the satellite CHAMP (400 km)

The measurements are normalised by a quiet time model Coef. = 2 => augmentation de 100% of the density.
Weak signal for Dst >-15 otherwise the density increases by a factor 1.5 to 2.5 (good agreement with the study of Krauss et al (2015))
<table>
<thead>
<tr>
<th>Group No.</th>
<th>CME No.</th>
<th>SSC No.</th>
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<tbody>
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<td>SSC32 SSC33 SSC34</td>
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<tr>
<td></td>
<td>Not associated</td>
<td>SSC35</td>
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35 SSC, 27 Halo CMEs, 30 non halo CMEs
Sheath arrival

SSC09