Solar Events Associated With SSCs in 2002: propagation and effects from the Sun to the Earth

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Bocchialini et al 2017, just accepted
Solar Physics in a special issue "Earth-affecting Solar Transients"

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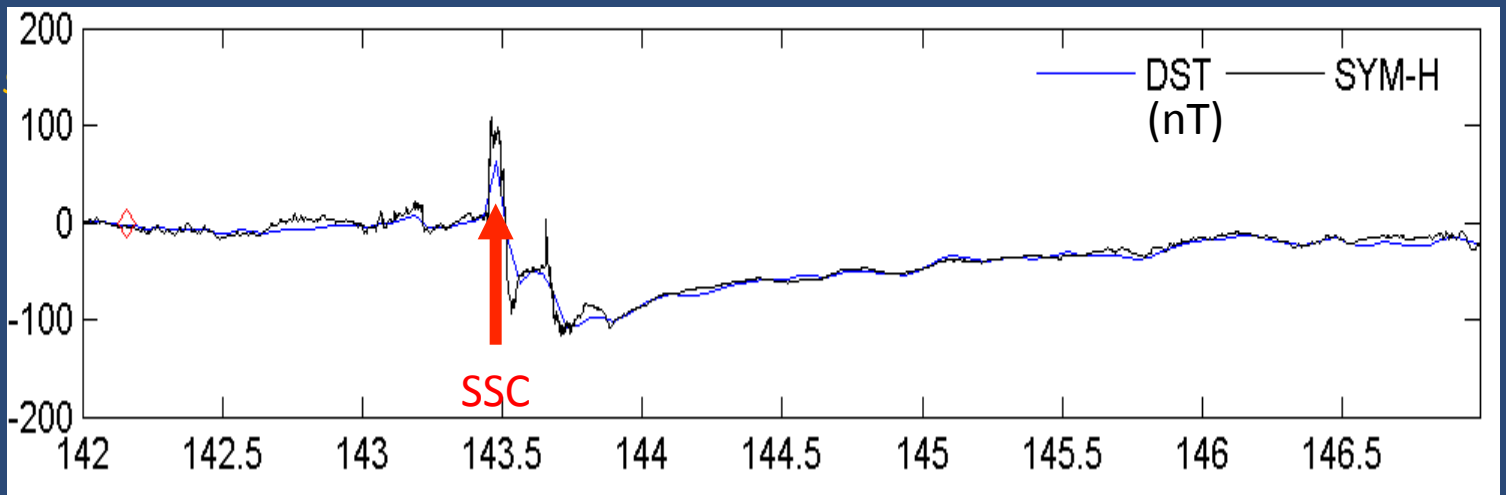
Introduction - Motivation

The aim: to investigate the link between Coronal Mass Ejections (CME) and the geomagnetic storms, related by the occurrence of a Sudden Storm Commencement (SSC),

SSC : sudden growth of the magnetic field strength at the Earth's surface, signature of the impinging of a shock on the magnetopause.

Starting point: the 32 SSCs of year 2002 listed by the observatory de l'Ebre /ISGI.
Identification of the nature of the perturbation at L1, relying on existing catalogues, and characterize it.
Association to a solar source we perform a multi-criteria analysis (velocities, drag coefficient, radio waves, helicity).
---- impact of the solar event studied on the whole chain from Sun to Earth (magnetosphere, ionosphere, thermosphere), as a function of the Dst index value.

Dst (Disturbance ... to the equator).



The Data sets

Multidisciplinary data base, of various origins and regions of the Sun-Earth trajectory, for the period 1996-2007 (www.ias.u-psud.fr/gmi)
Focalisation on 2002, solar activity maximum.

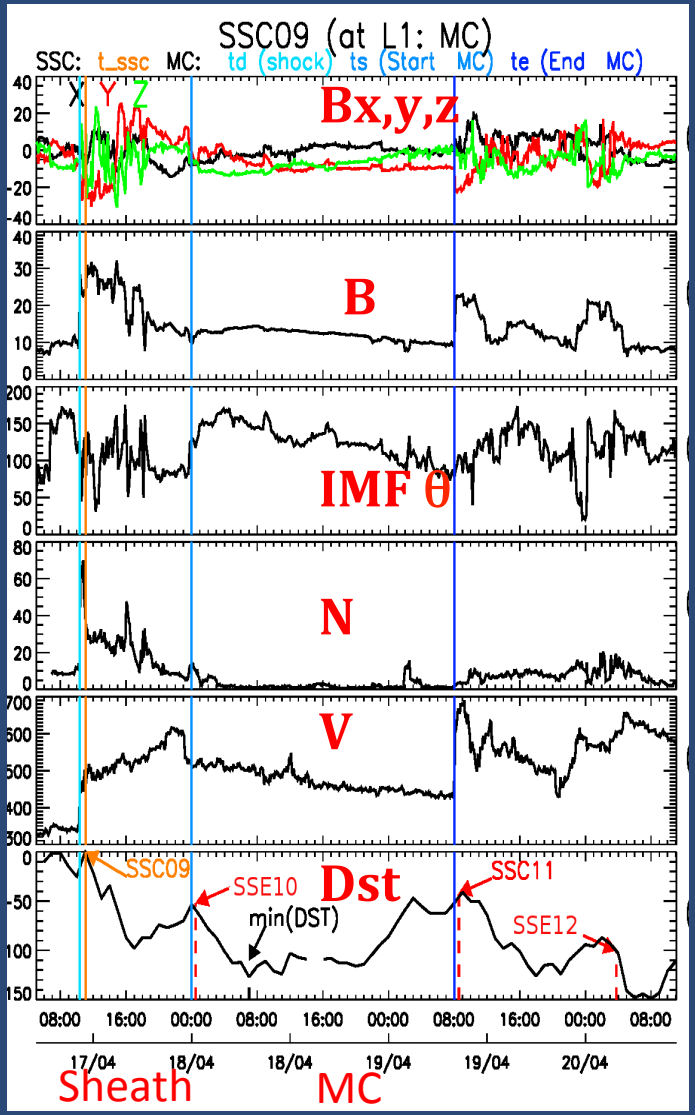
Region	data
Sun	EIT/SOHO and LASCO/SOHO, catalogues of CMEs https://cdaw.gsfc.nasa.gov/CME_list/ + radio observations, WIND, NRH and DAM in Nançay
Interplanetary Observations at L1	ACE, AMDA/CDPP and OMNiWEB/NASA facilities
Magnetosphere	Position of the magnetopause, terrestrial radio emission (AKR and NTC), Cluster (CSDS plots) and Geotail (PWI)
Coupled System magnetosphere / ionosphere	Electrodynamic activity : different **geomagnetic indices** computed from measurements at stations of the worldwide network of geomagnetic observatories ISGI (International Service of Geomagnetic Indices)
Ionospheric response	Super Dual Auroral Radar Network (SuperDARN), giving in particular the variations of the polar-cap potential
Thermosphere	Density variations computed from measurements of accelerometers on-board the CHAMP satellite.

Example of one event: characterization of a MC

Magnetic Cloud (MC) at L1 (17 april – 19 april 2002):

The shock and the sheath causes
-- a SSC: increase of B,N,V
-- followed by a geomagnetic storm and a first decrease of the Dst (min Dst=-100 nT).

The MC causes also
-- a rotation of IMF, a decrease of N and V
-- a fast increase of Dst (-125 nT)
followed by a second decrease of the Dst, that we called Sudden Secondary Event (SSE)



Identification and association of Sun- Earth

- **At L1**

The 32 SSC are due to 31 events sorted as follows :

12 MC (Magnetic Clouds)

6 ICME (Interplanetary CME, non MC)

4 CIR and 1 SIR (Corotating /Streaming Interaction Region)

4 Miscellaneous (not classified)

4 Shock events

Association 1st step: window of 5 days

- **At the Sun**

60 CME with visible source : all 2002 halo CME (28) plus non halo in a 5 days time window from SSC

4 CME halos : no SSC

3 SSC : no CME : are S/CIR at L1

Many CMEs can be the source of a given SSC

→we thus need to use other

Identification and association of Sun- Earth events

- **2nd step : 4 new criteria**

  1. Velocity
  2. Radio waves
  3. MC helicity
  3. Drag based model

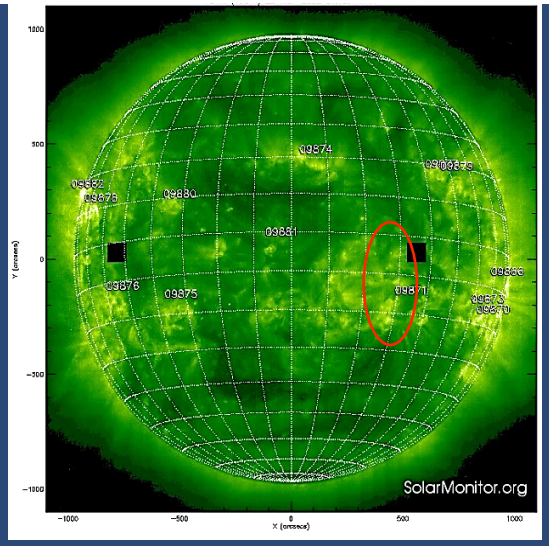
Velocity	Radio Waves	MC helicity	Drag Based Model
$V_{sun} > V_{balistic} > V_{L1}$ priority criterium	Type II ; Type IV	Source: N/S L_1:left/right	10^{-8} < drag coeff < 10^{-5} km^{-1}
Fulfilled for 20/28 SSC Associated with a solar source	27 events (83%) CME-SSC association	MC : 8/12	22/26 (85%)

Identification and association of Sun- Earth

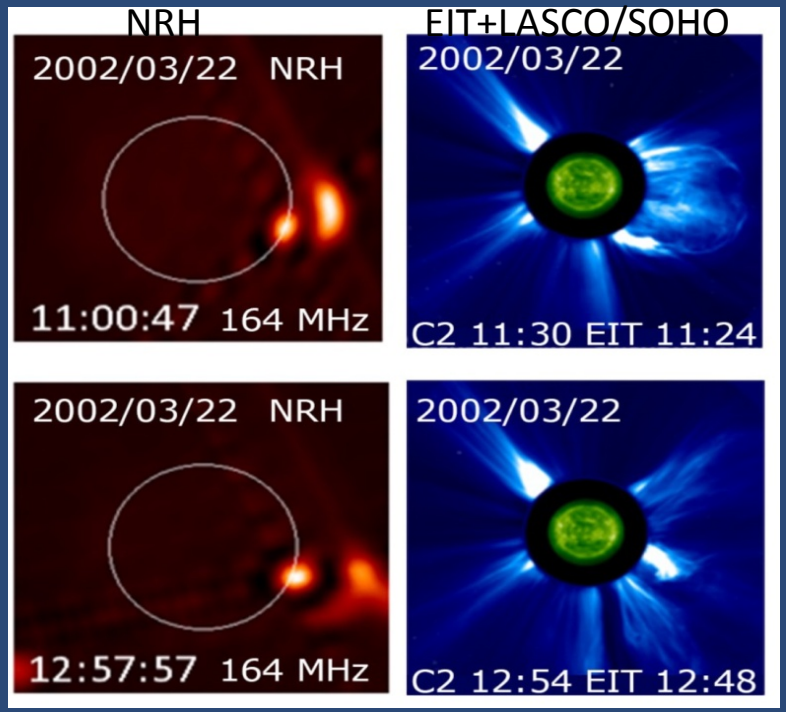
Example of SSC 06

EIT/SOHO

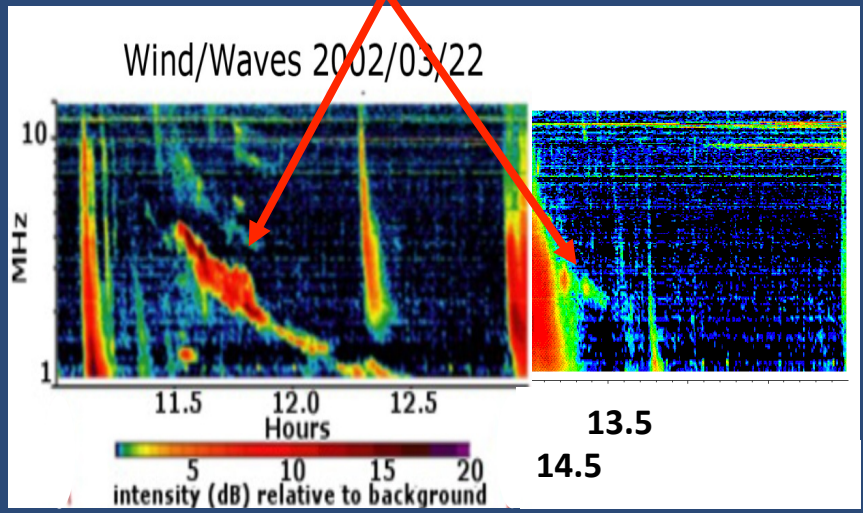
22/03/2002



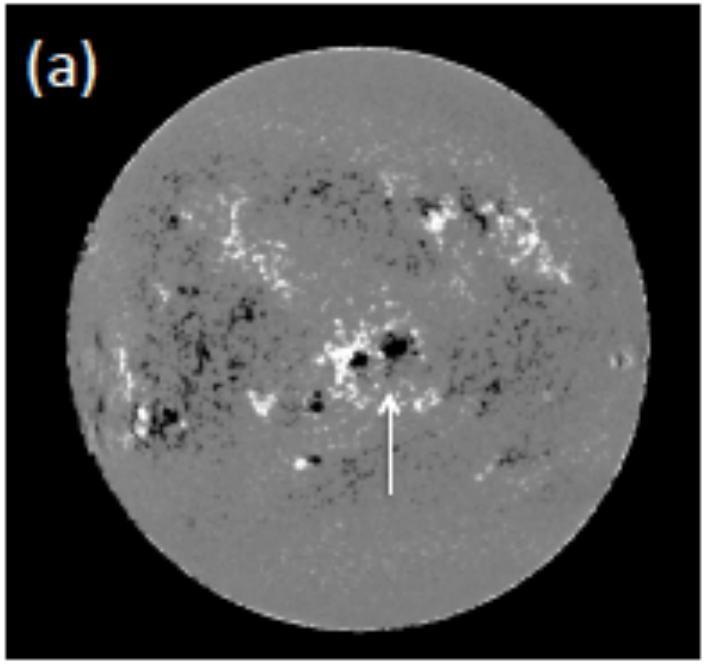
https://sites.lesia.obspm.fr/gmi-radio-cme/

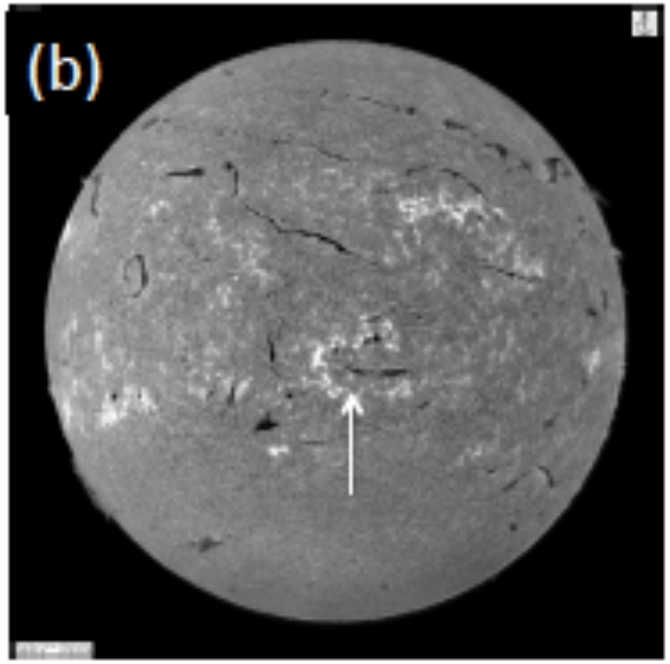


Types II

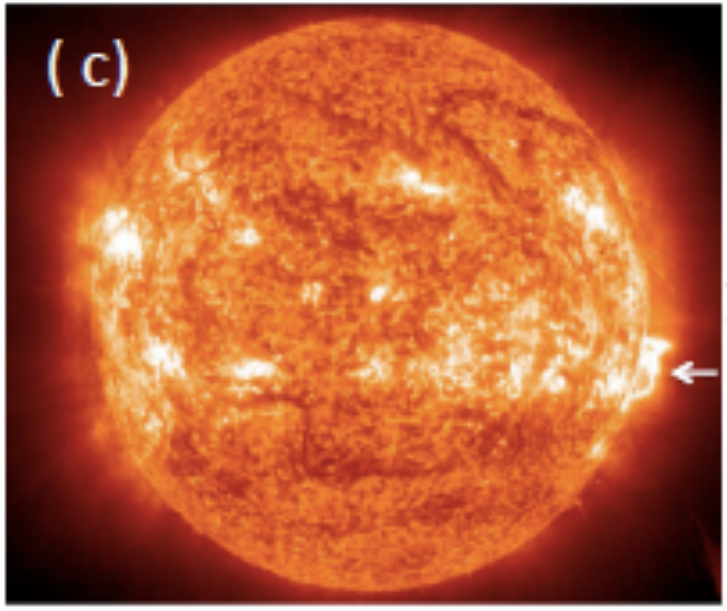


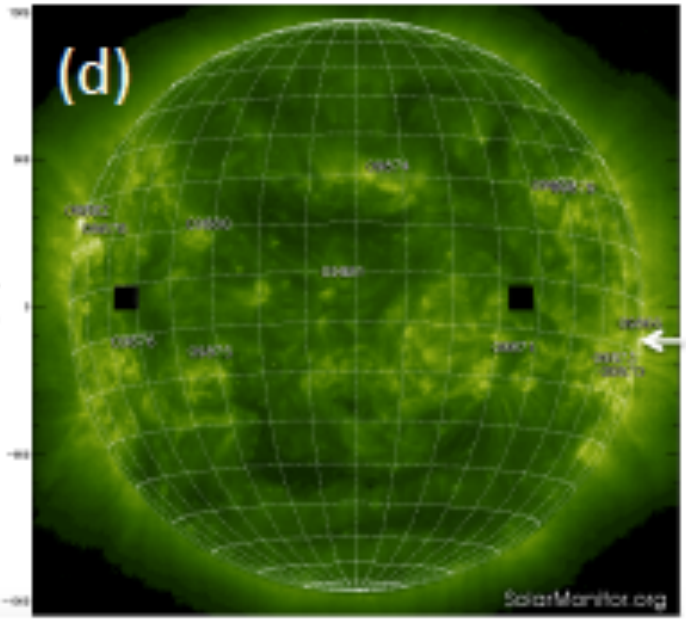
Identification and association of Sun- Earth





15 March 2002





22 March 2002

Identification and association of Sun-Earth

➔ 28 SSCs correlated to 44 CMEs ; 3 SSCs without an identified solar source
➔ 21 halo CMEs among 28 halo CMEs related to 31 SSCs in 2002
➔ 75% of 28 halo CMEs in 2002 (with visible source) are geoeffective
➔ 4% of non-halos (23/~500 in 2002) are geoeffective
➔ 13 events /28 have the contribution of several CMEs, 15/28 the contribution of only one CME :

Events at L_1	single solar source			multisources		no solar source	Total
	CMEH	CMEN	CMEP	CMEH	no CMEH		
12 MC	3	2	0	5	2	0	12
6 ICME	2	0	0	3	1	0	6
4 Misc.	2	0	0	2	0	0	4
4 Shock	1	1+1?	1	0	0	0	4
5 SIR/CIR	1	1?	0	0	0	3	5
Total	9	3+2?	1	10	3	3	31

70% in agreement with the choice of CMEs by Gopalwamy 2010

Identification and association of Sun and Earth

Events at L1 in 2002 associated to an SSC

Structure at L_1	Events in 2002 total	Events in 2002 + SSC	Events in 2002 Efficiency	Well-observed events total	Well-observed events +SSC	Well-observed events Efficiency
MC	17	12	71 %	11	11	100 %
ICME (non-MC)	25	12	48 %	10	6	60 %
SIR/CIR (non-ICME)	41	5	12 %	-	-	-
IP shock (incl. ICME)	35	28	80 %	-	-	-

- ➔ The shocks are good proxies to forecast a SSC
- ➔ MCs are the most efficient "drivers" of SSCs

Well-observed =referenced in more than 2 catalogues

Statistics of the solar sources

44 CMEs, with solar source:

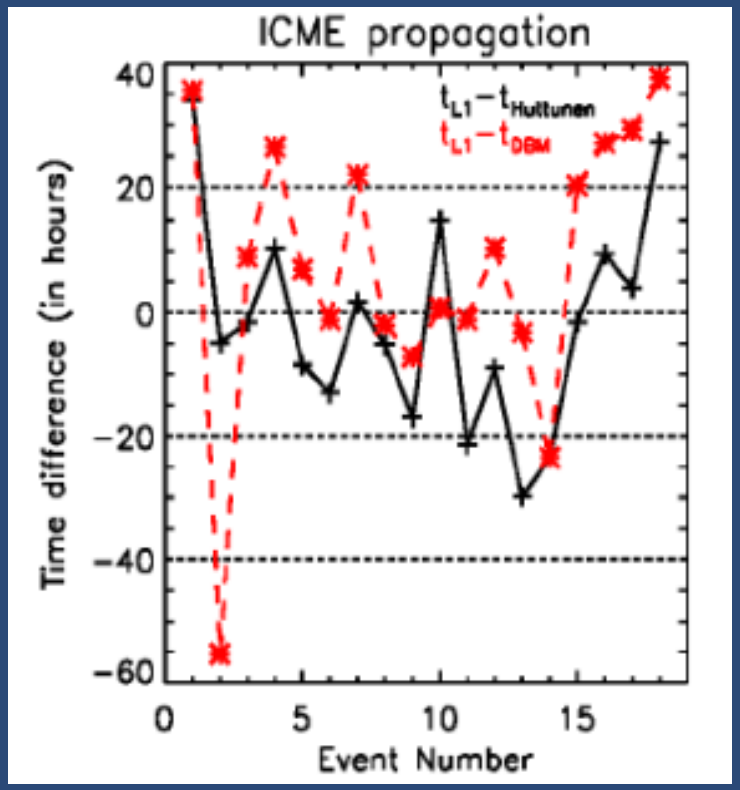
28 « leading » CMEs,

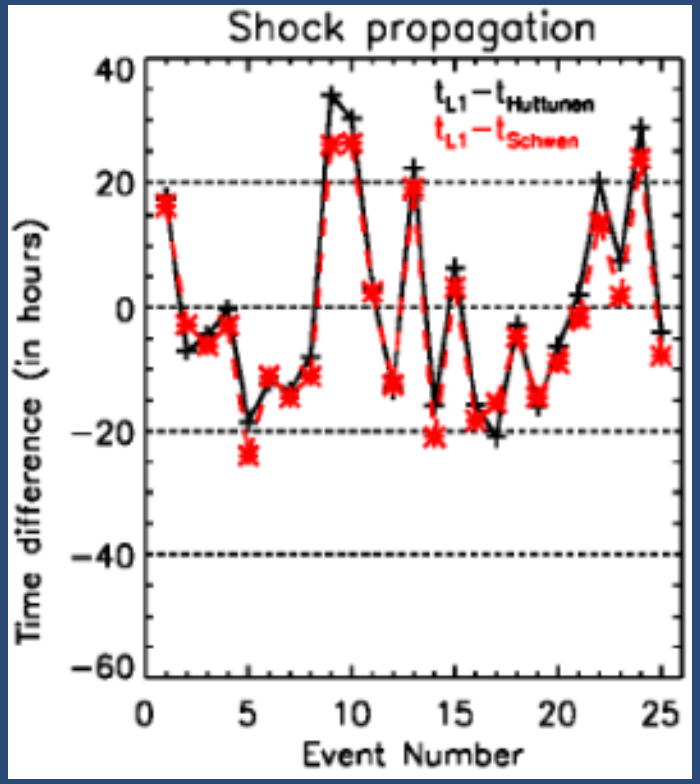
16 « contributing » CMEs

Source of CME :

- 91 % (40/44) from an active region (with or without filament)
- 60 % (26/44) imply the eruption of a filament (in or without AR)
- No relationship with the X class of flare (2 X, 19 M, 15 C)
- 73% (32/44) in the southern hemisphere; 27% (12/44) in the northern ; 36% (16/44) from East ; 64% (28/44) from West. One West Limb AR is responsible of a geoeffective event.
- 75% des halo CME induce SSCs
- (13/14) of the more geoeffective events (min(Dst)<-51nT) are associated type IV radio waves

Propagation time at L1: comparison





Models of Huttunen et al 2005 and DBM for the ICME (MC or not).

Models of Huttunen et al (2005) and Schwenn et al (2005) for the shocks

➔ The agreement is not improved by considering only halo CME or event due to only one CME. There are almost as many negative than positive delays. (Vexp= Vradial/0.88)

Geoeffectiveness of the SSC leaded

- weak $(min(Dst) > -50$ nT)
- moderate $(-100 < min(Dst) < -50$ nT)
- intense $(-200 < min(Dst) < -100$ nT)

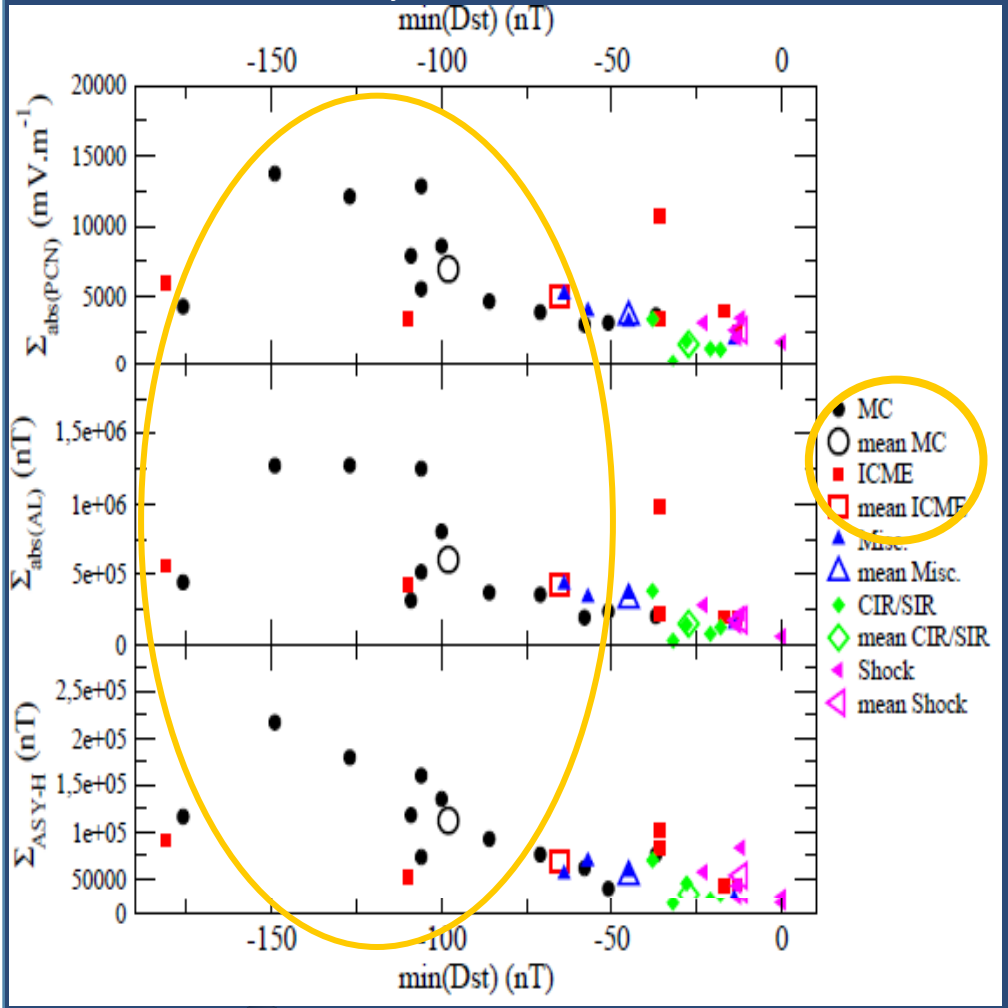
75% of intense storms and 40 % of moderate storms in 2002 are associated to a SSC.

	Intense storm	Moderate storm	No or Weak Storm	Total
MC	7	4	1	12
ICME (non-MC)	2	-	4	6
Miscellaneous	-	2	2	4
Shock	-	-	4	4
CIR/SIR	-	-	5	5
Total	9	6	16	31

92% of the MC lead to moderate to intense storms.
33% of ICME lead to intense storms and 66% weak storms
The shocks and CIR/SIR cause "at best" weak storms.

Regional geomagnetic response

The value of different indices has been integrated, for each event, over the event duration and the integrated value is plotted on the figure as a function of the min of Dst value. A different symbol is used for each kind of event at L1.



➔ ICME/MC are the more geoeffective

➔ One can observe a kind of saturation for Dst values lower than -150nT, may be due to a polar cap saturation, to aurora going toward lower latitude,…

PCN : "northern polar cap" = measurement of E field of the polar convection

Al : magnetic activity due to aurora electrojets

ASY-H : measurement of the asymmetric part of the B field at low latitude

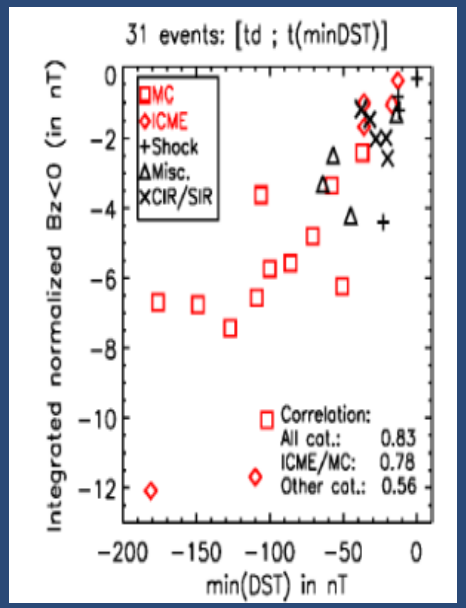
Properties at L1 of geoeffective MC / ICME

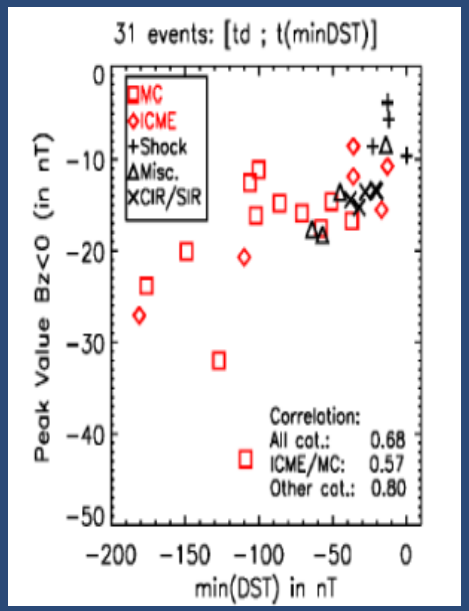
For geoeffective MC and ICME:

- Role of the IMF $B_z<0$

- for intense storms, the integrated $B^*_{z<0}$ value is ($-12 < B^*_{z<0} < -4$ nT) (see figure on the left)

- Bpz ,the Bz<0 peak value, is ($-43 < Bpz < -11$ nT) favoring solar wind-magnetosphere coupling through dayside reconnection (see figure on the right)





Good correlation with the integrated $B^*_{z<0}$ on the duration of ICME/MC

The best correlation between the peak of $B_{z<0}$ and the other events at L1

-low to moderate mean β ($0.03< \beta <1.1$), implying magnetic compression moderate mean Mach number ($3.6 < MA < 6.5$), globally lower than in usual solar wind.

Magnetosphere properties

Magnetopause position (observed within 90 minutes of SCC in only 7 cases) :

-Compression of the magnetosphere

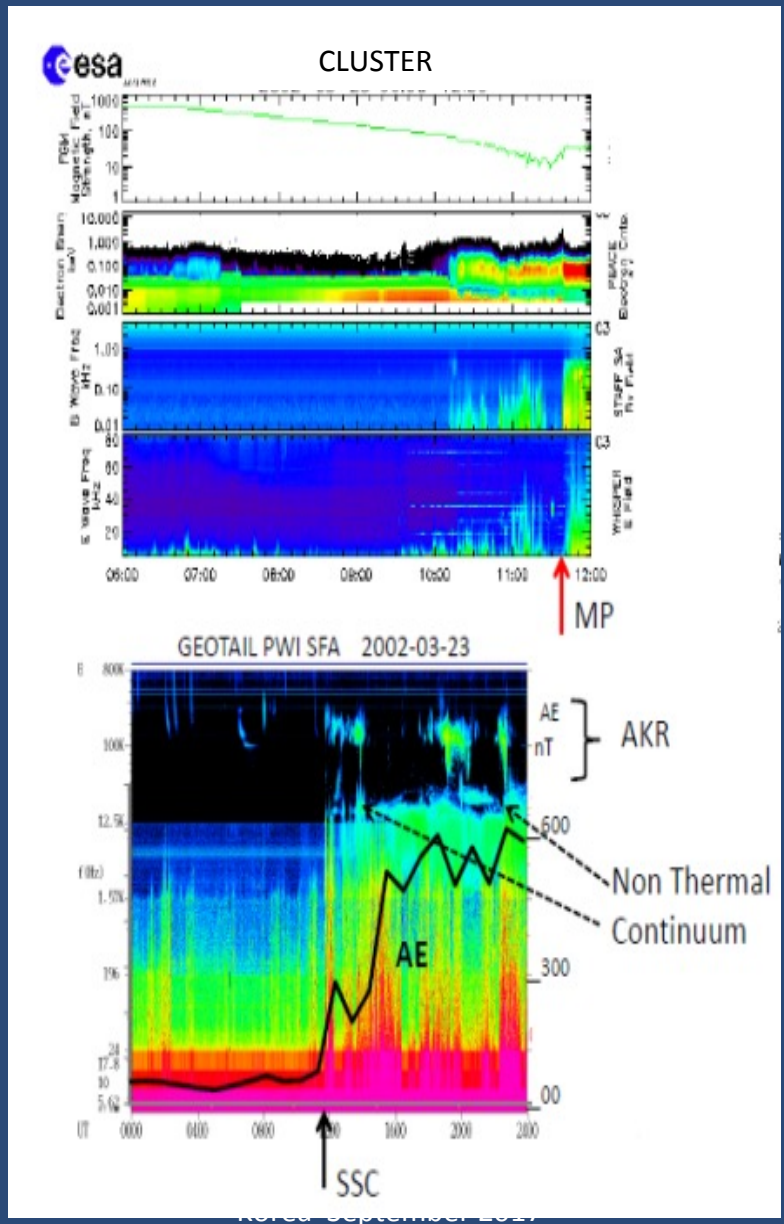
- with $\Delta (R_E) \propto$ SSC amplitude
- the strongest compressions (-3.7< $\Delta (R_E)$ <-2.3) for shocks due to MC

Observation of Earth radio emissions

Injection of energetic particules:

- Auroral Kilometric Radiation AKR : observed for 23/30 events
  When not observed, AE index <800 nT, Dst>-50 nT

- Non Thermal Continuum (NTC) observed for 27/29 events.
  Not observed, Dst ~0



Conclusions

44 CME (including 20 halo CME) are at the origin of 28 of the 32 year 2002 SSCs;

Despite multicriteria for SSC-CME association, including radio wave diagnosis (type IV and type II waves), some cases remain ambiguous.

100% of the well defined Magnetic Clouds induce an SSC

Magnetic Clouds (MC) and ICME (non MC) are the most geoeffective at magnetospheric, ionospheric and thermospheric level.

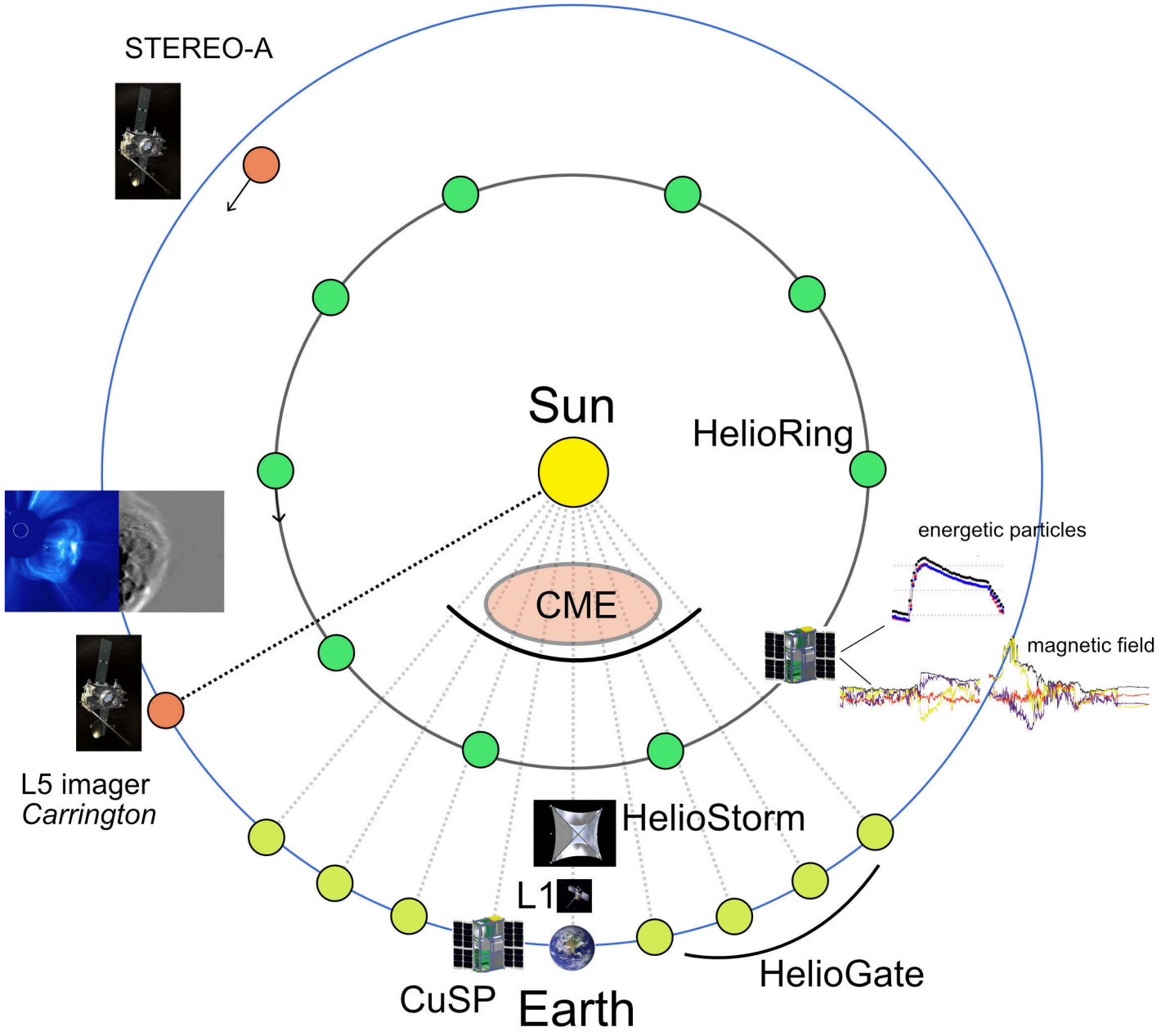
About the geoeffectivity index SSC:

75% of the year 2002 intense storms (Dst <-100nT) are associated with a SSC

40% of the moderate ones (-100nT< Dst < -50nT) are associated with a SSC.

www.ias.u-psud.fr/gmi (login: gmi, password: cme).

Space Weather interplanetary CubeSat mission concepts



6/2016 C. Möstl, SRI Graz, Austria

X-Cube-Sat launched from ISS (goal: O in the thermosphere)

QB50* VKI
David Masutti

AstronautiX +LPP+ LMD (France)r

Korea September 2017

Properties of the Ionosphere and thermosphere Propriétés à l'Ionosphère et à la thermosphère

The ionospheric response for the maximum values PCP (SuperDARN) :
-for the overall 31 SSC-leaded events : 39% for max(PCP) > 95 kV and 51.5% for 75 <max(PCP) < 95 kV

-during the 13 geoeffective ICME-MC and non MC :
PCP > 95 kV (strong response) for 9 events (69%) 75 <PCP9<5 kV (moderate response) for 4 events (31%)

The PCP response, globally stronger for the strongest geomagnetic storms, shows a reinforcement of auroral ionospheric convection during ICME- MC driven storms.

The 13 geoeffective ICME and MC show thermospheric response (100%):

The 3 strong ones among the 31 events (strong = an increase of the nocturnal neutral density of more than a factor of 2) correspond to
3 intense geomagnetic storms.
7 moderate responses (54%) (which correspond to 6 intense and 1 moderate geomagnetic storms), and 3 weak responses (23%) which correspond to 3 moderate geomagnetic storms.

nclude: we confirm that the events with a low Dst have a strong thermospheric

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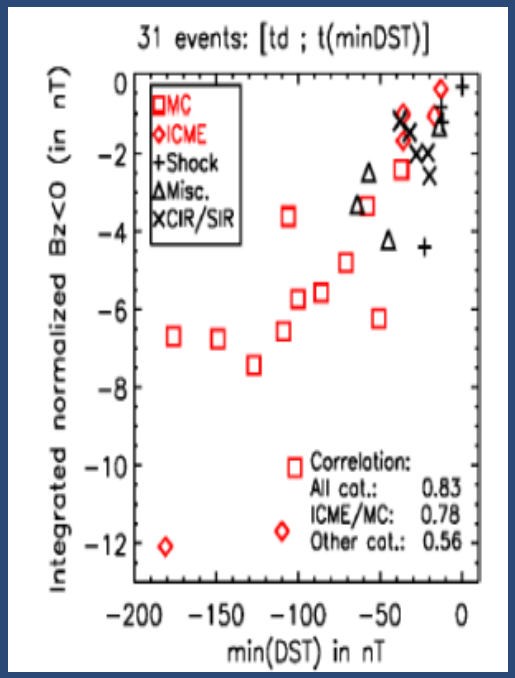

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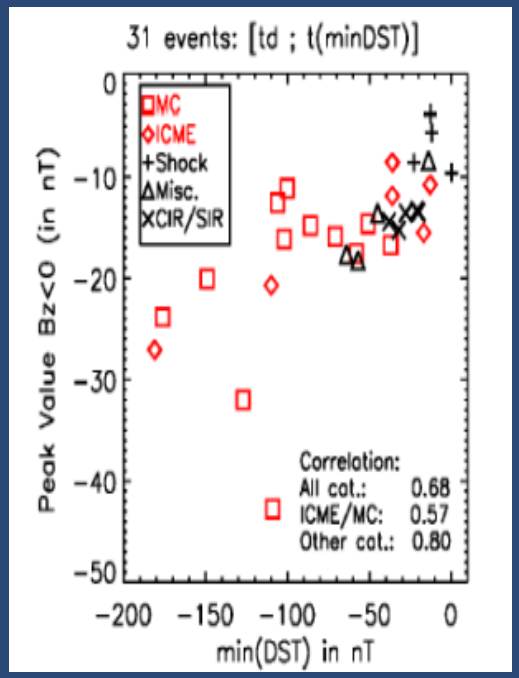

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- B_{pz} ,the $B_z<0$ peak value, is ($-43 < B_{pz} < -11$ nT) favoring solar wind-magnetosph
dayside reconnection (see figure)
- low to moderate mean β (0.03< β <1.1), implying magnetic compression
-moderate mean Mach number (3.6 < MA < 6.5), globally lower than in usual solar

Magnetosphere properties

Magnetopause position, observed in 7 cases:
- Compression of the magnetosphere with DRE ∝ SSC amplitude ; the strongest compressions (-3.7< DRE <2.3) for shocks due to MC

-Injection of energetic particules: Earth radio emissions : AKR (23/30) ;

- **When not observed, AE index <800 nT, Dst>- 50 nT**
- **NTC observed for 27/29 events. Not observed, Dst ~0 (see figure on the right).**