Solar Physics
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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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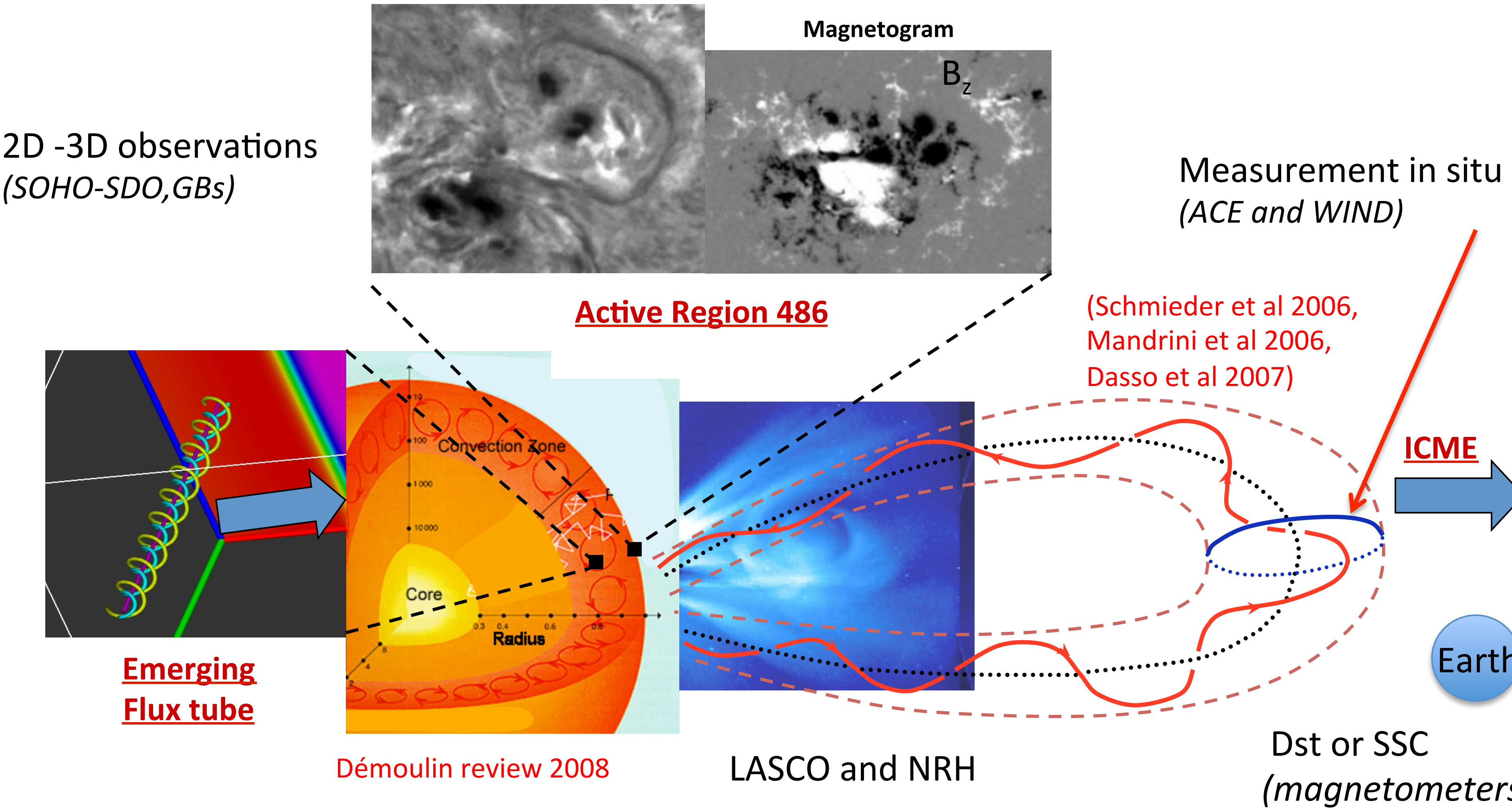
From the Sun to the Earth

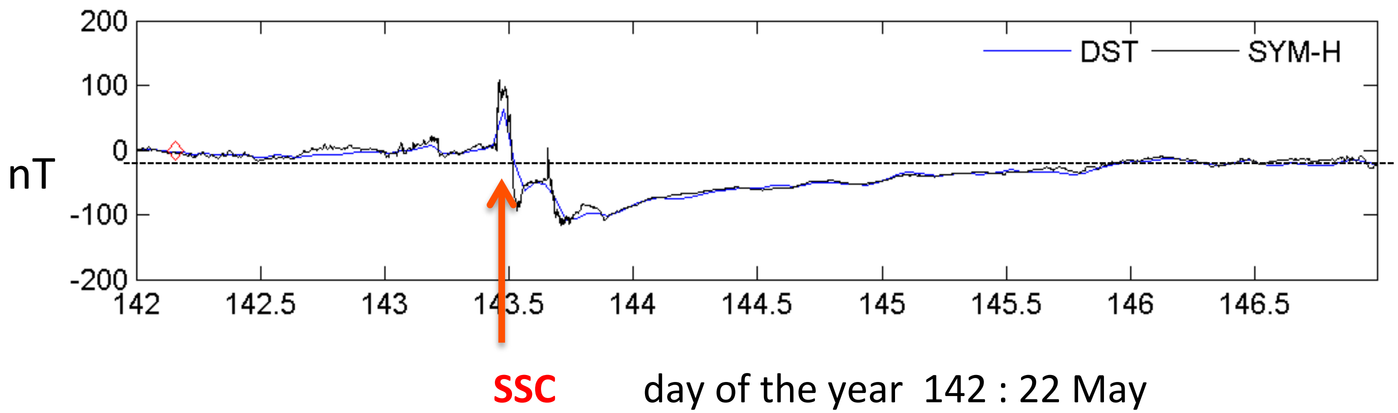
Solar Magnetic Activity: sunspots, flares, CME, ICME and magnetic cloud (L1 in situ),



Starting point #1

SSC May 23 2002 at 10:18 UT

By using the geomagnetic indices (Dst, SYM-H…)



day of the year 142 : 22 May

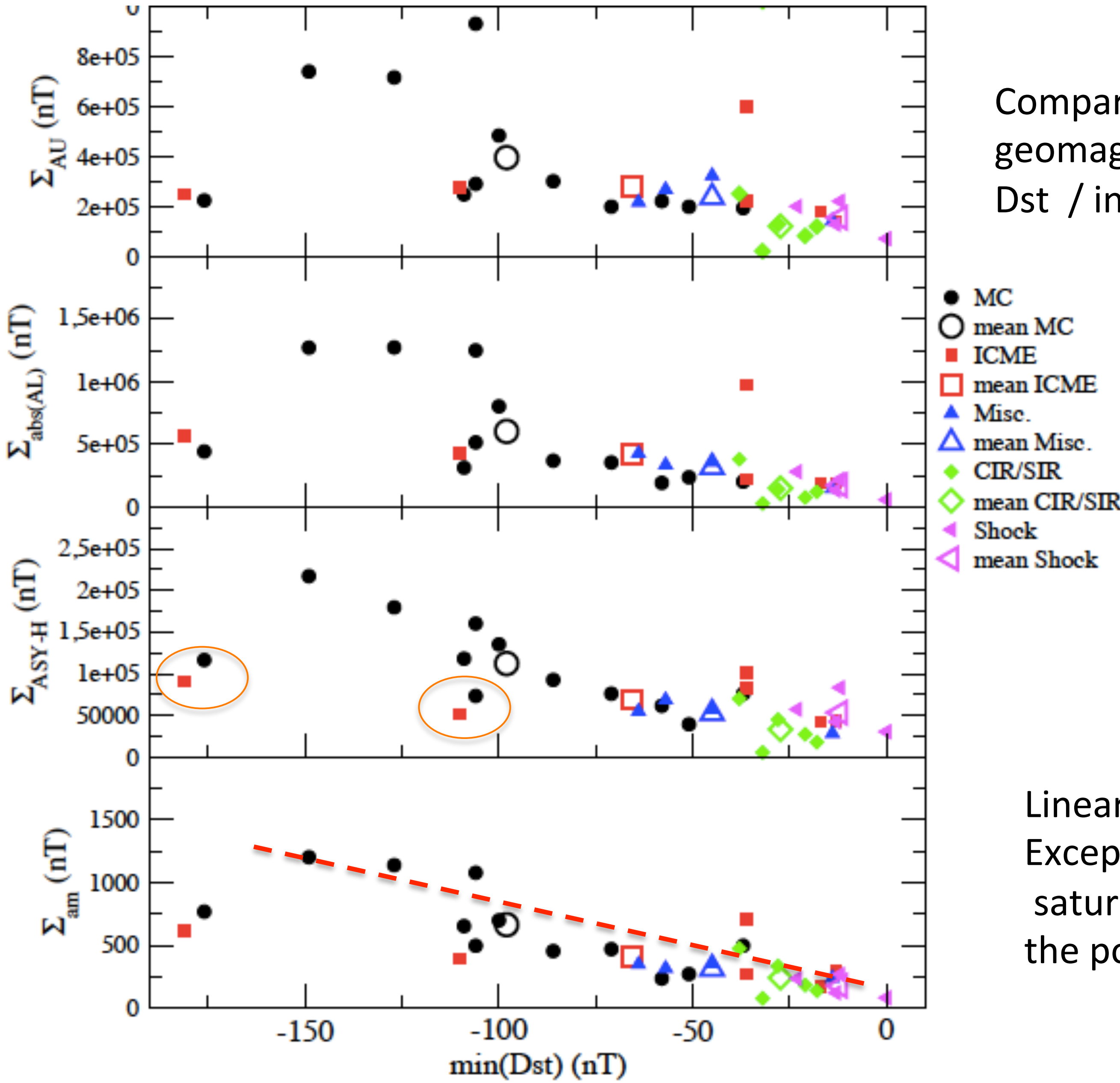
SSC Storm Sudden Commencement = compression of the magnetosphere indicating the arrival of the shock.

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…)

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 ?

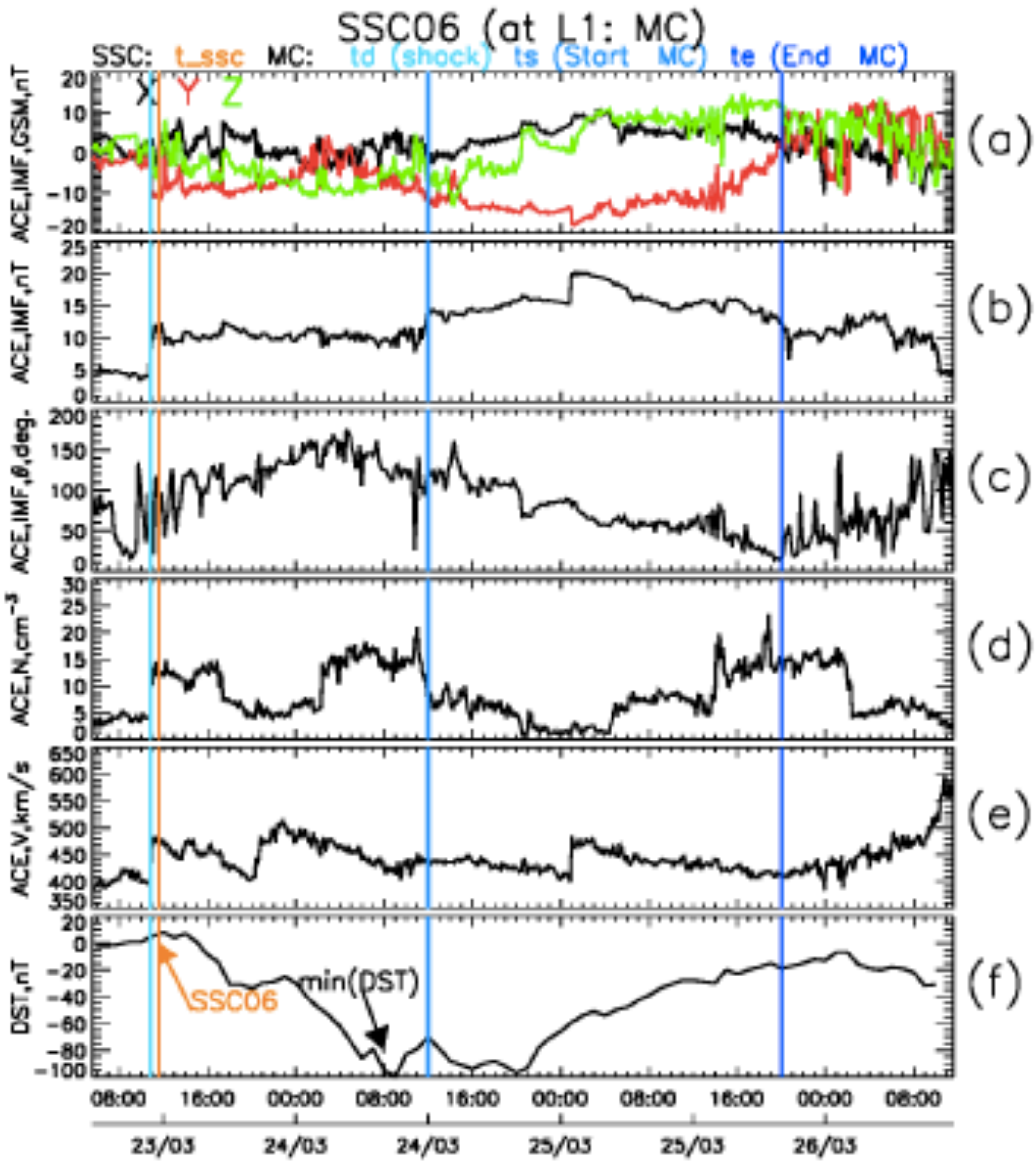
- Events in 2002 from the literature and us

		+ SSC	efficiency	Detected by us	
MC	17	12	71%	12	OK
ICME	34	9	26%	6	<9
CIR/SIR	41	4	10%	4	OK

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

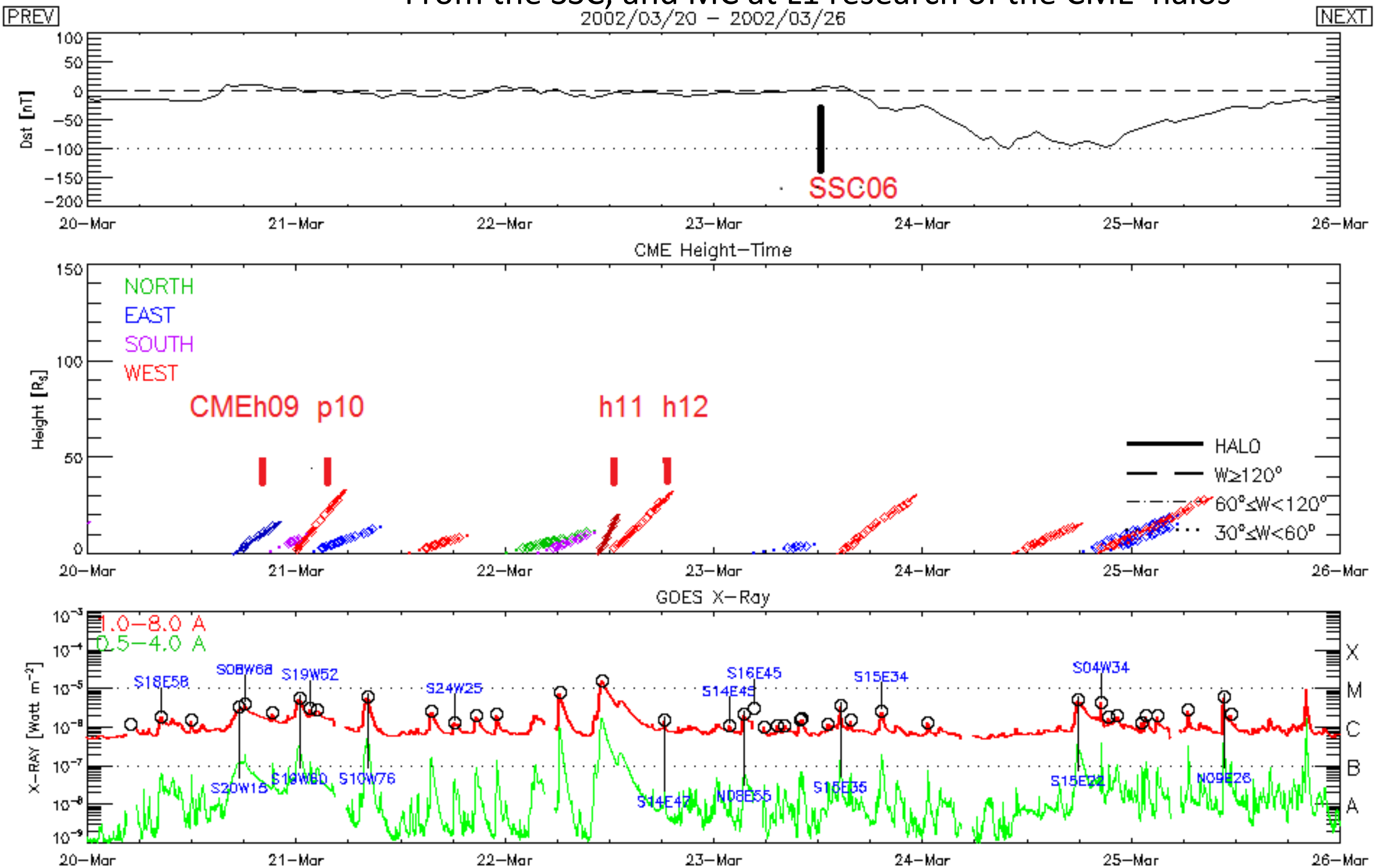
CIR corotating interplanetary region due to solar wind sheets

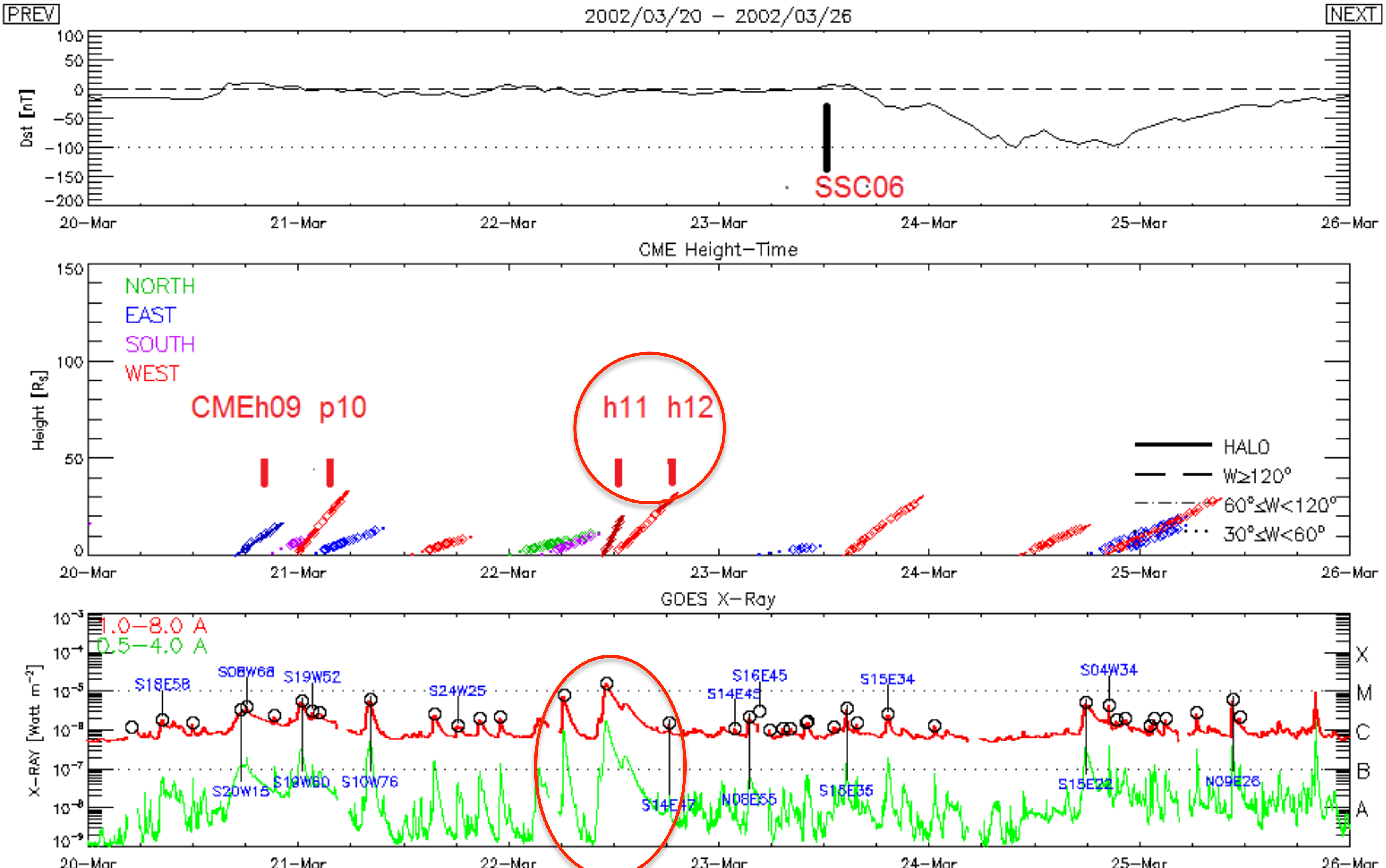
ONE EXAMPLE



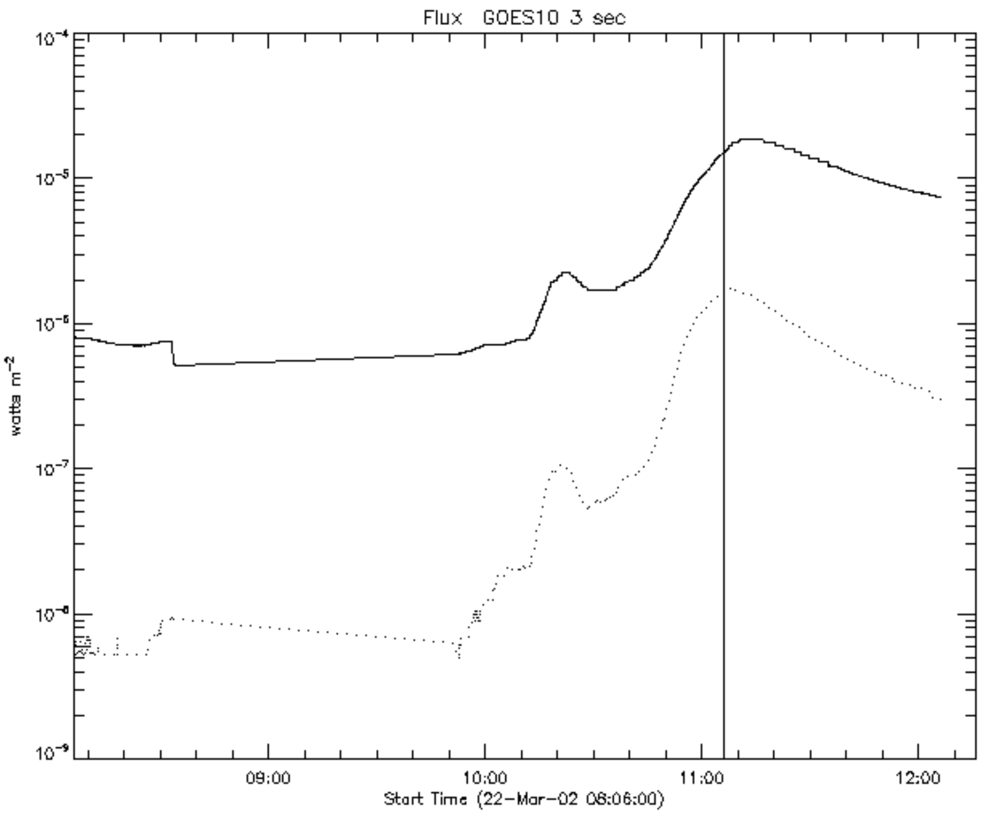
'igure 12. Observations at L1 (ACE data) and ground based observations of the *Dst* index, 'elated to the SSC06 of the March 23, 2002. The Interplanetary Magnetic Field (IMF) is

From the SSC, and MC at L1 research of the CME halos




PREV
2002/03/20 – 2002/03/26
NEXT
Dst [nT]
SSC06
CME Height–Time
NORTH
EAST
SOUTH
WEST
CMEh09 p10
h11 h12
HALO
W≥120°
60°≤W<120°
30°≤W<60°
Height [Rs]
GOES X-Ray
1.0–8.0 A
0.5–4.0 A
X-RAY [Watt m^-2]
S18E58
S08W68
S19W52
S24W25
S16E45
S14E49
S15E34
S04W34
S20W15
S19W60
S10W76
S14E47
N08E55
S15E35
S15E22
N09E26
X
M
C
B
A
20–Mar
21–Mar
22–Mar
23–Mar
24–Mar
25–Mar
26–Mar

X –ray GOES flare : M class

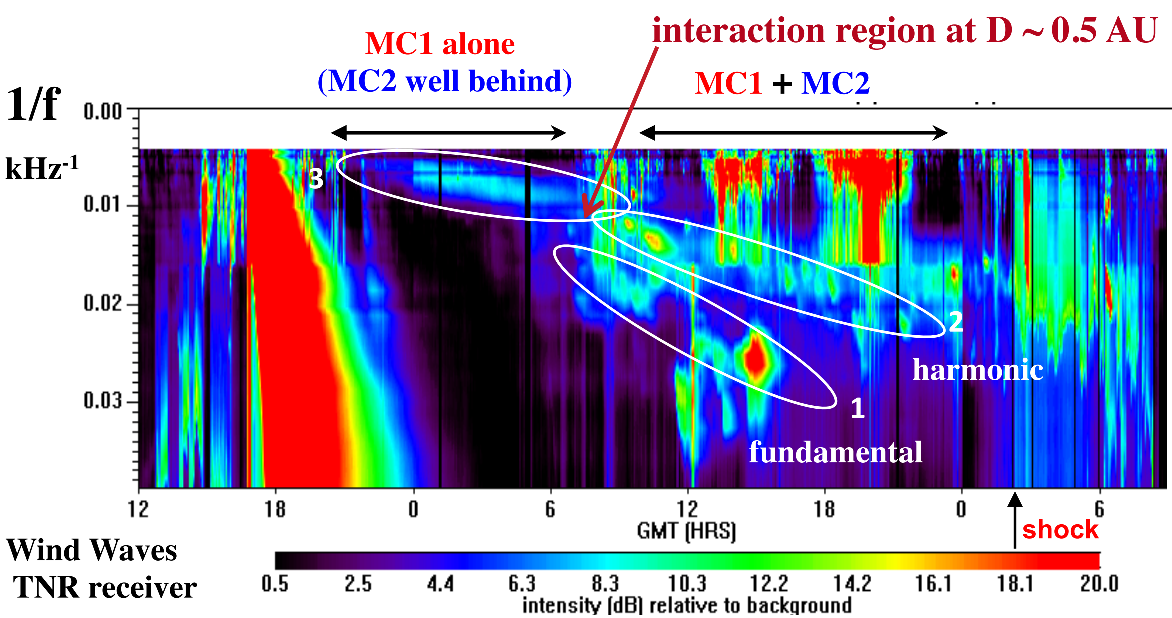


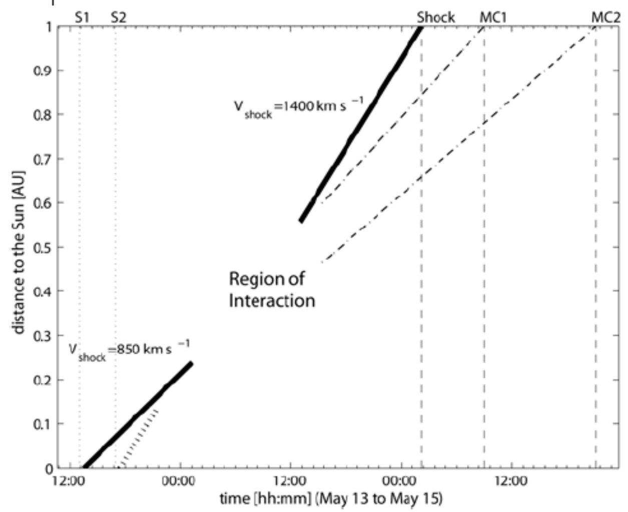
M classe on
22 March 2002 at 11UT

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

Tracking InterPlanetary structures using radio waves

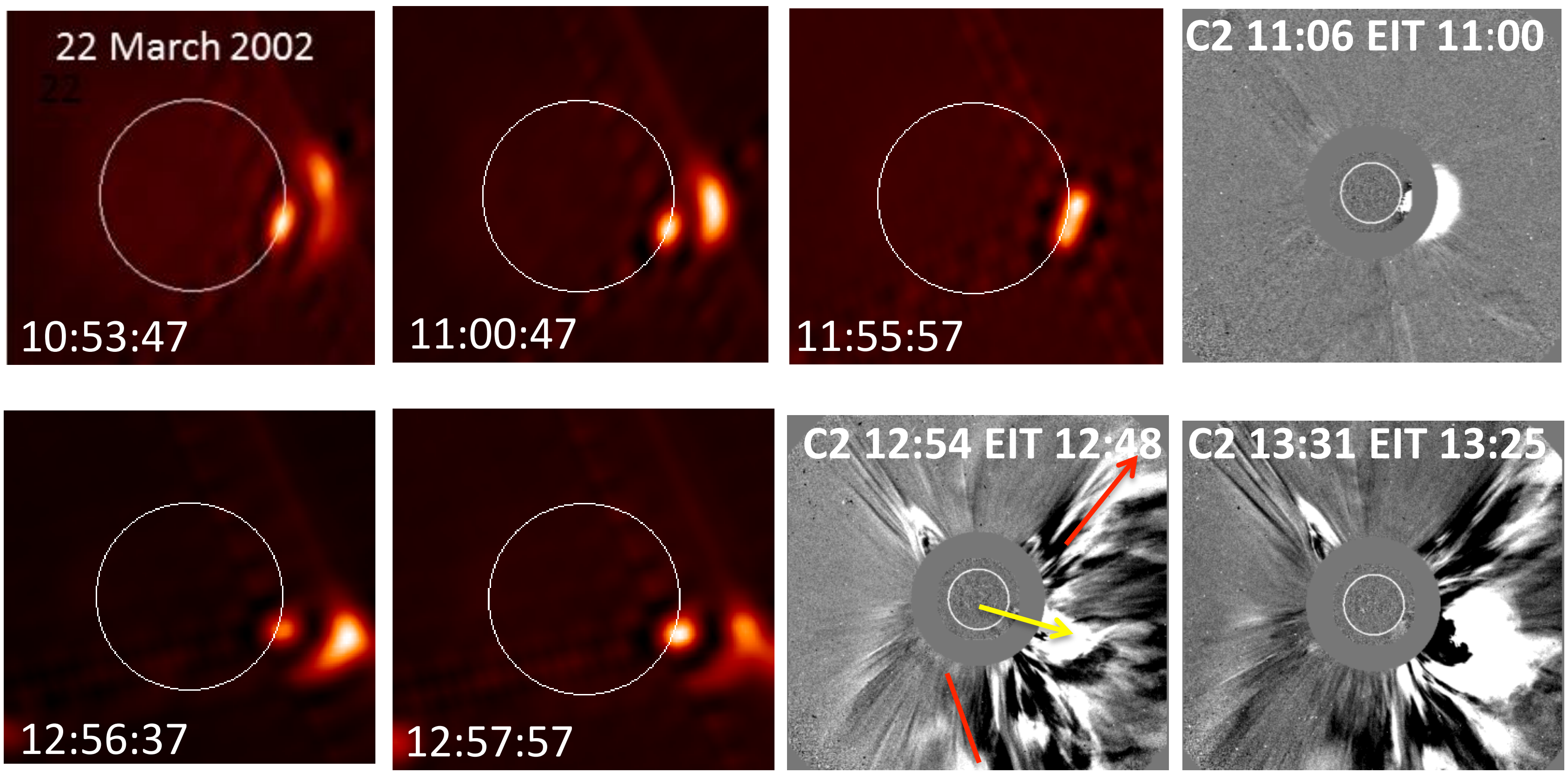
The shock driven by flux rope (MC) commonly excites electromagnetic waves at the local plasma frequency ($f \sim n_e^{1/2} \sim D^{-1}$)





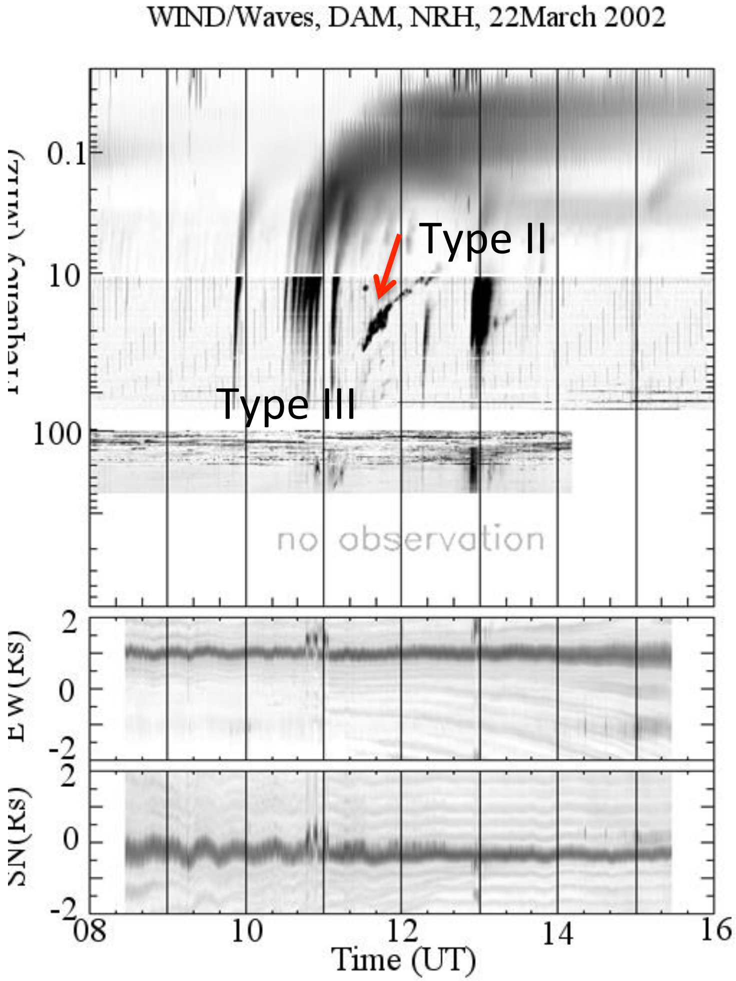
[From Dasso et al., JGR 2009]

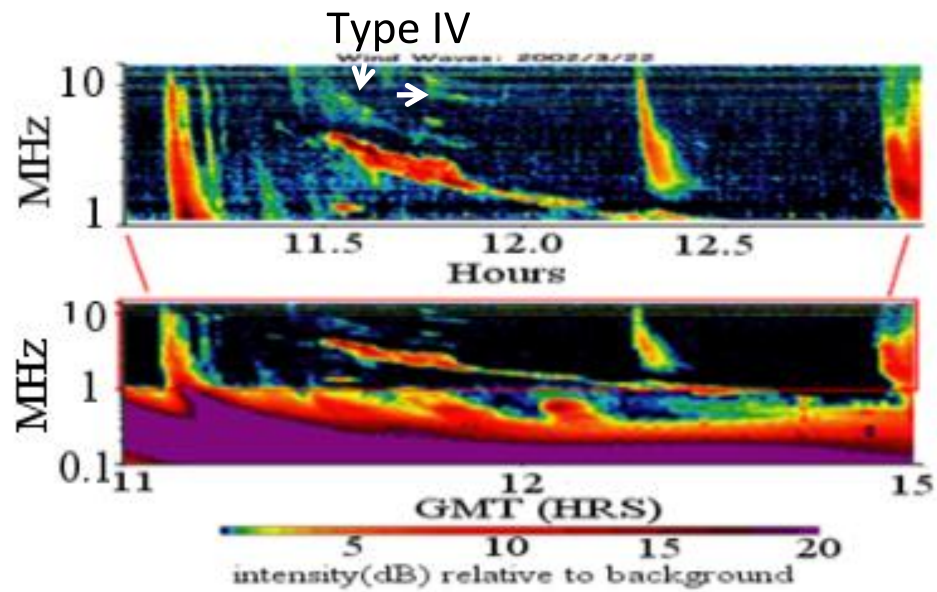
Radio observations with Nançay RH and C2 of LASCO

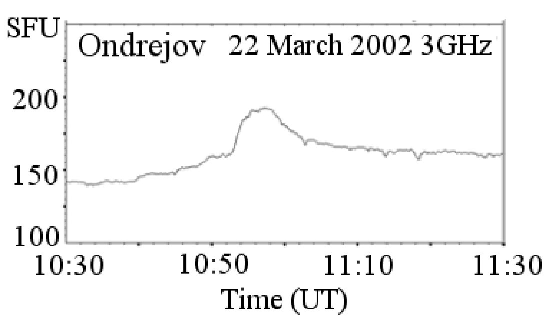


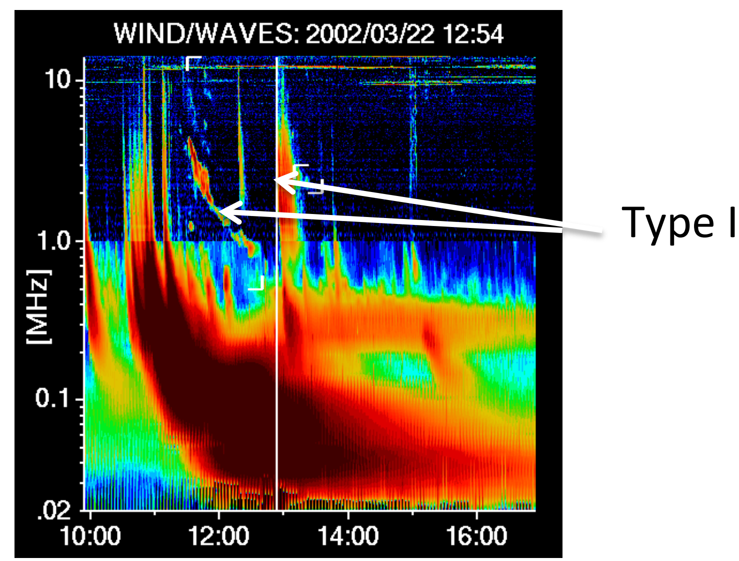
Two CMEs interaction

From Wind/waves satellite type II and IV



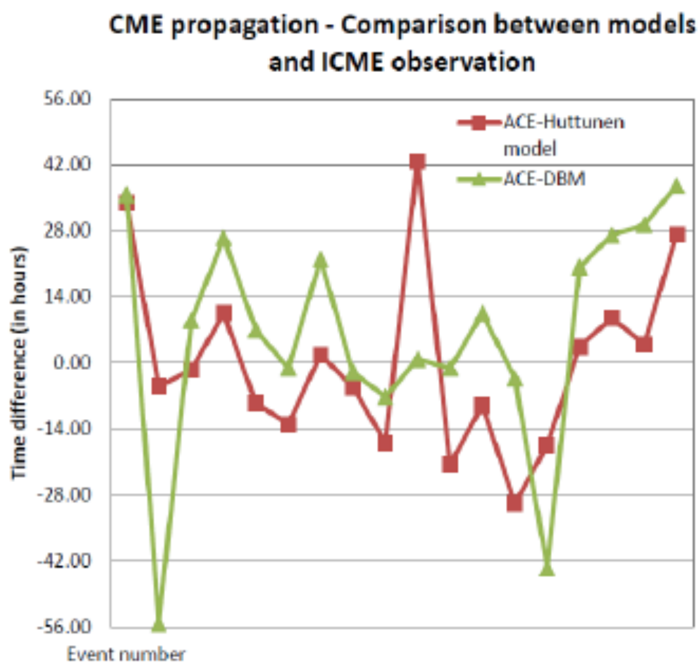


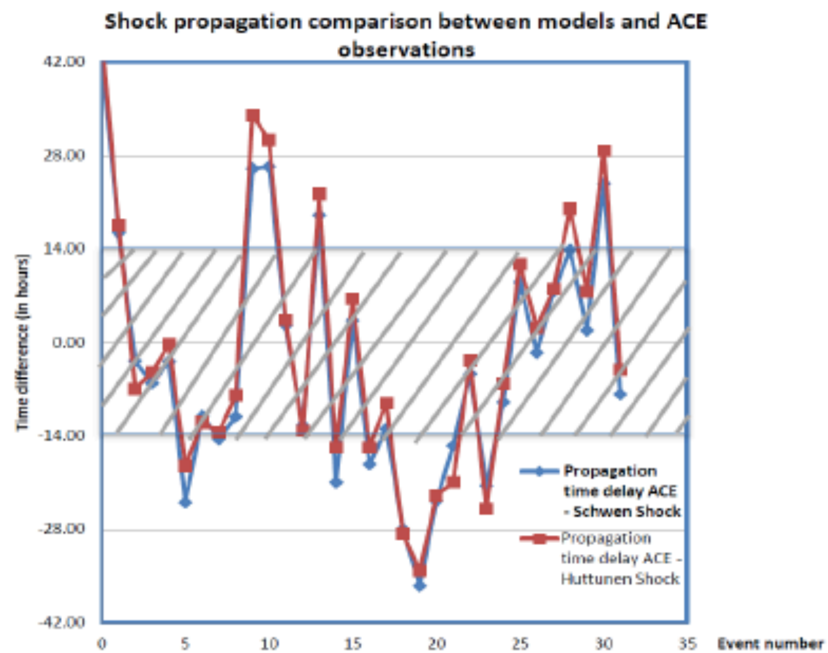




Type IV is the signature of a flux rope and loops (Démoulin, Pick 2012)

Comparison between observations and models

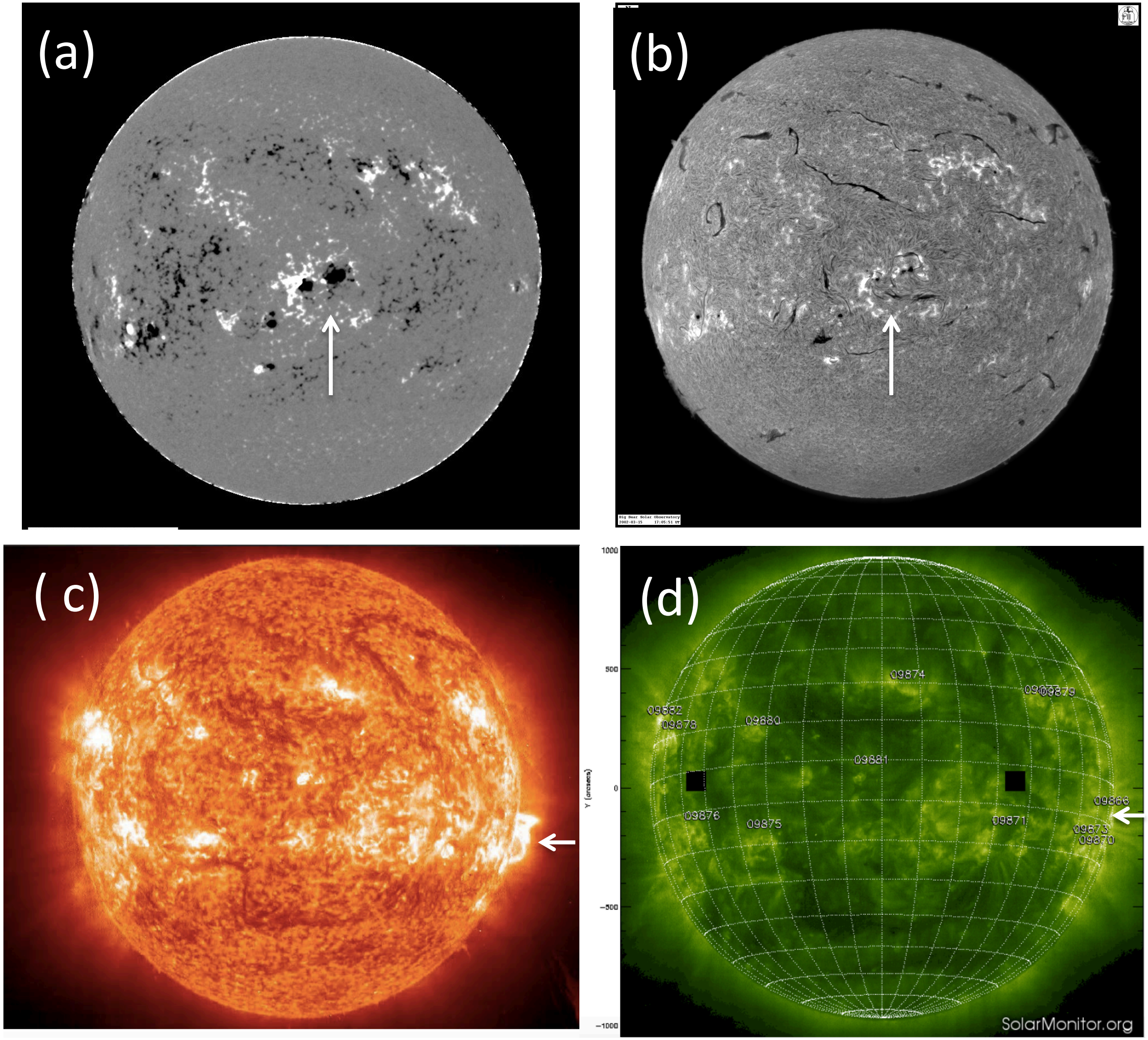




-14 hours < t < +14 hours

Figure 3. ICME and Shocks propagation

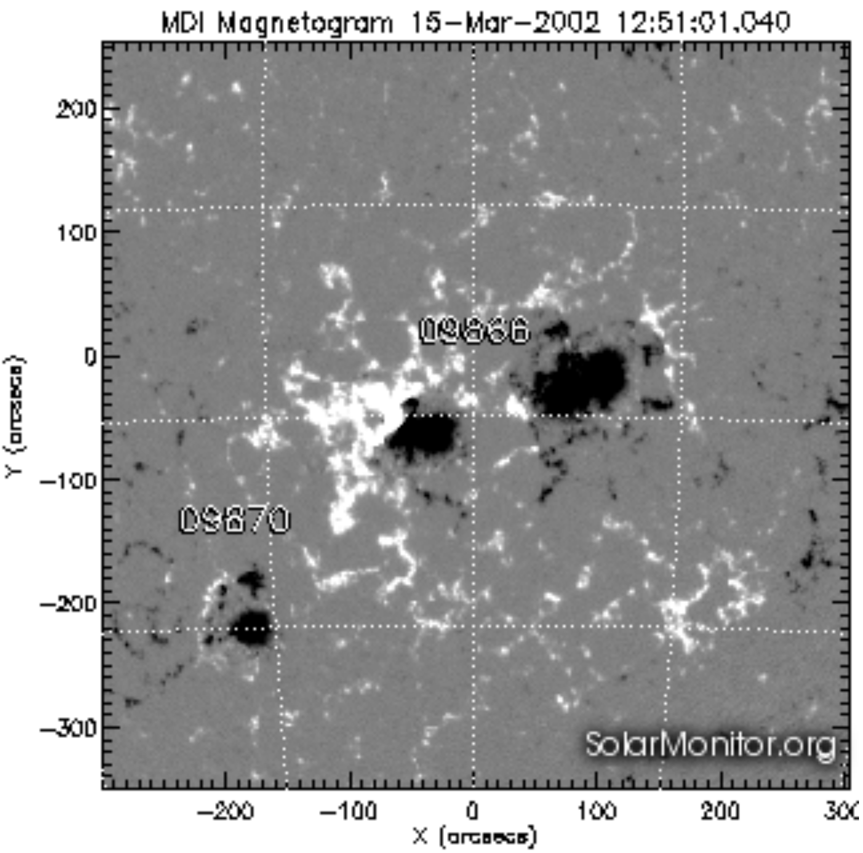
The active region AR 9866



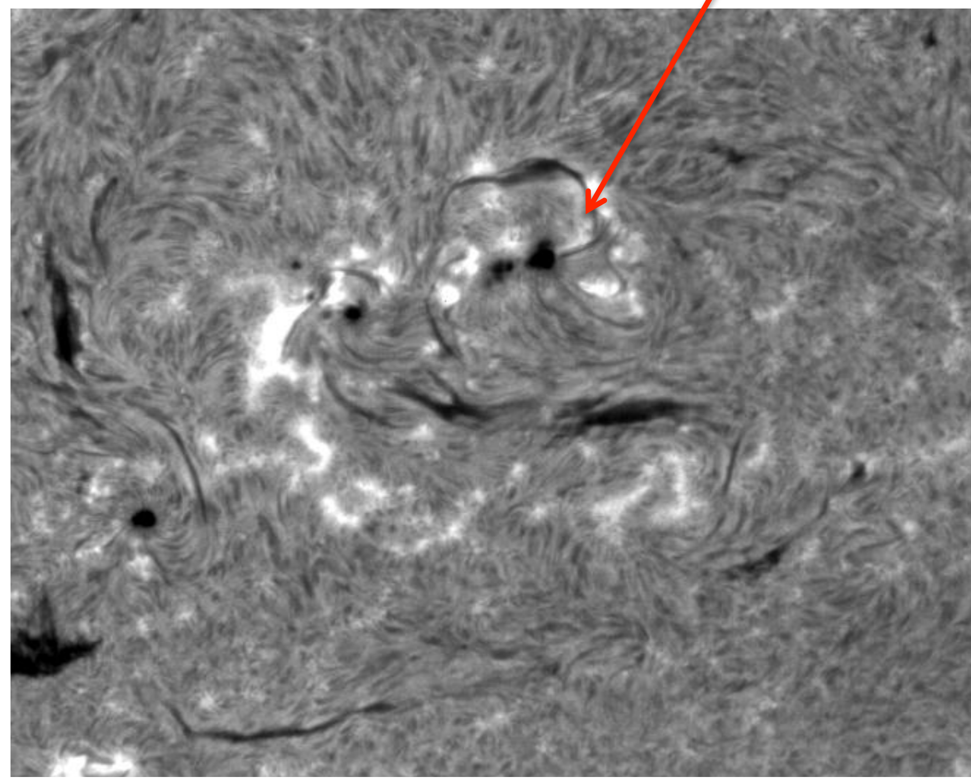
March 15

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 idetified.

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

Table 6. SSC sources: MC, ICME, Misc., Shock, SIR/SIR. The total of sources is 31/35 SSCs because 4 pairs of SSCs have the same sources.

SSC source Type	1 source CMEh	CMEn	CMEp	multisources with CMEh	no CMEh	not-assoc.	Total
12 MC	3	3	0	5	1	0	12
6 ICME	2	1	0	3	0	0	6
4 Misc.	2	0	0	2	0	0	4
4 Shock	1	1+1?	1	0	0	0	4
5 CIR/SIR	1	1	0	0	0	3	5
Total	9	6+1 ?	1	10	1	3	31

All the SSCs (-3) are related to a solar source

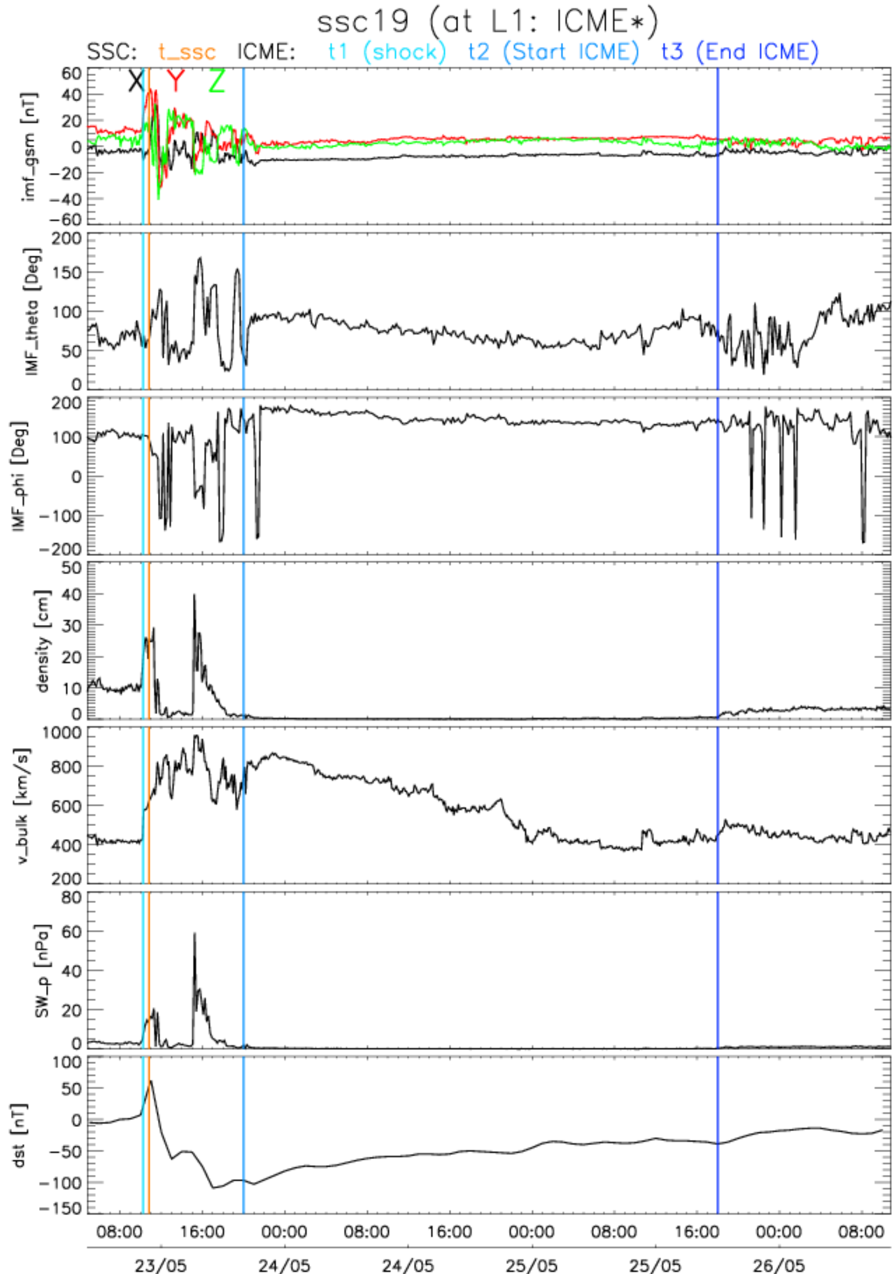
- **28 SSC are related to 44 CMEs with 28 leading CMEs (17 halos, 9 non-halos),**
- **6 halo CMEs are not associated with any SSC and 3 SSC are not related to any CME of our list (Tables 16 and 2).**
- From these 28 events, 11 events are related to multi CMEs and multi solar sources, only 17 events are related to a single CME.

Starting point #3

Interplanetary Medium at L1 : ACE Satellite

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

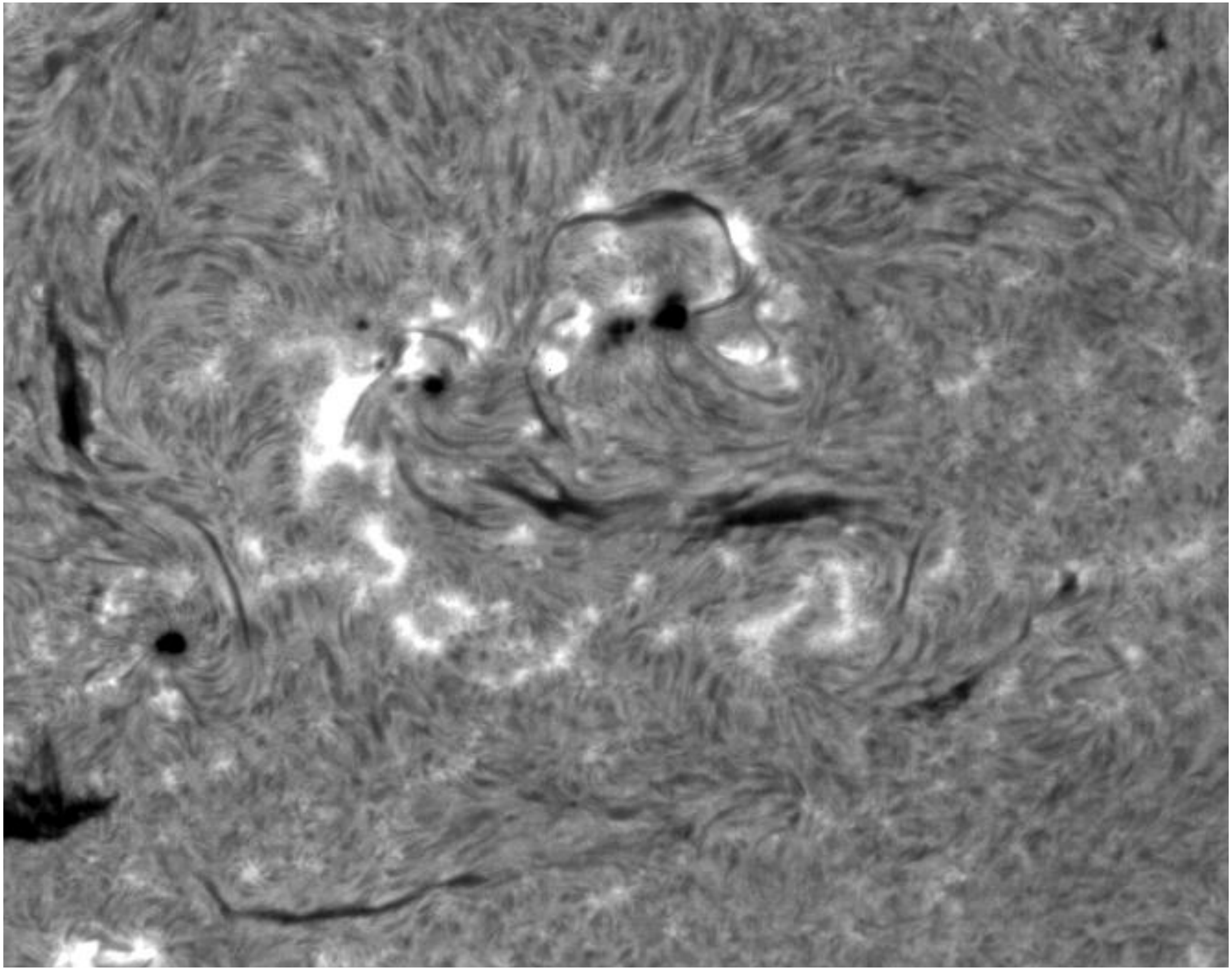
t _ssc
ICME : increase of V
t1: shock
t2 : start of the ICME
t3 : end of the ICME

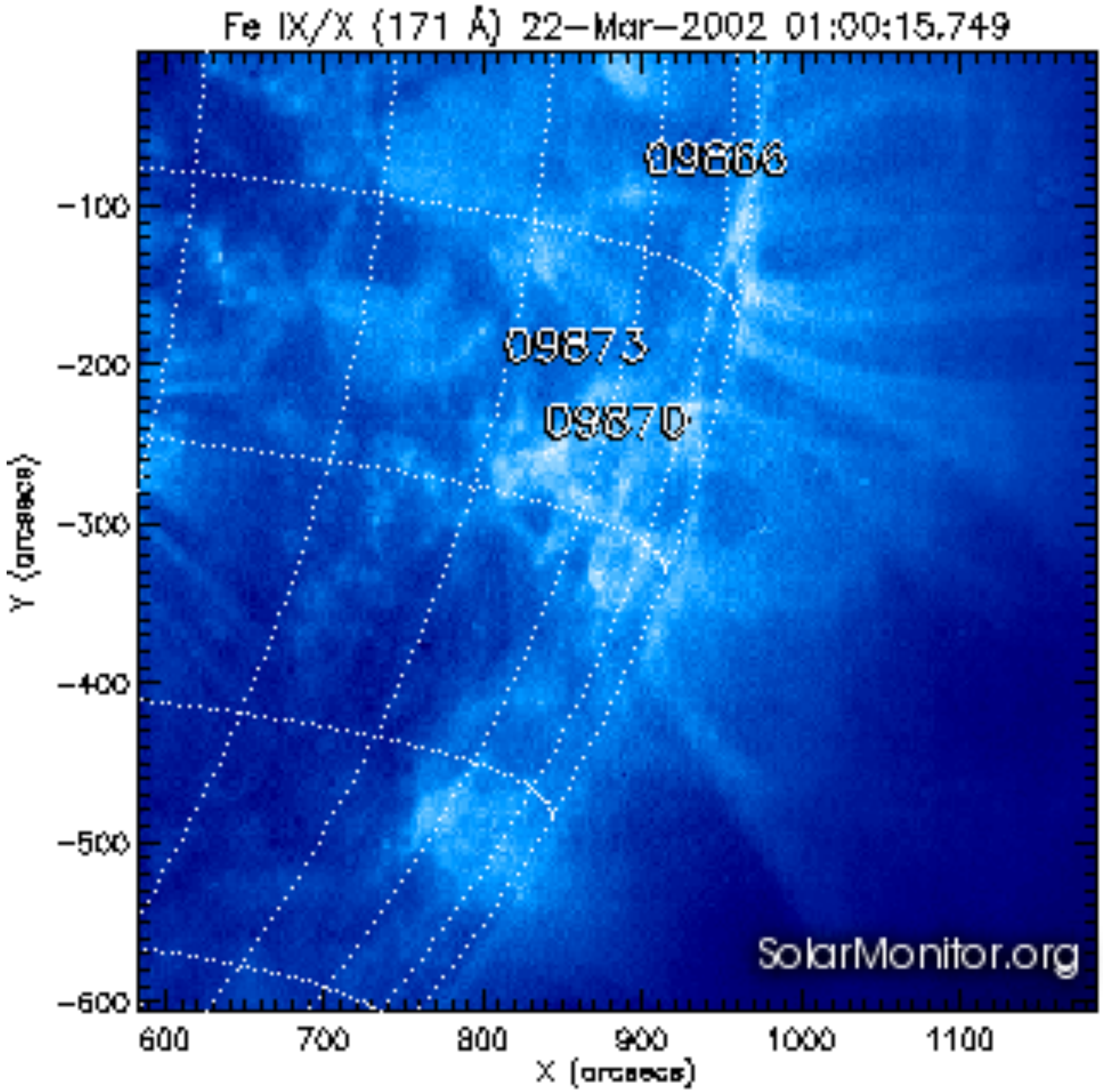


Statistics for 2002

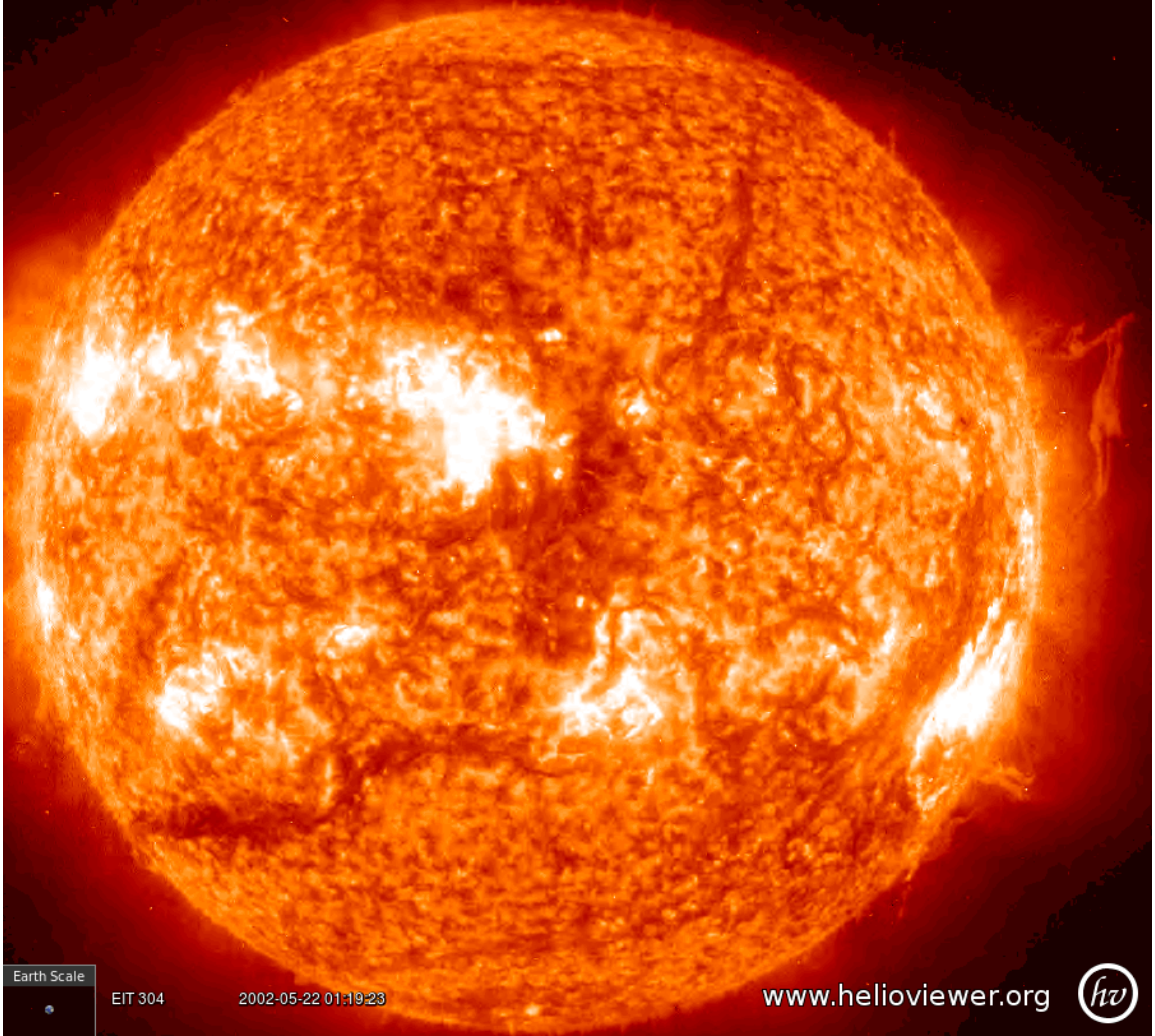
For the 44 CMEs listed in Table 16 and associated with an SSC (as leading or participating) in Table 2,

- 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.





Fe IX/X (171 Å) 22-Mar-2002 01:00:15.749
09866
09873
09870
SolarMonitor.org
-100
-200
-300
-400
-500
-600
Y (arcsecs)
600
700
800
900
1000
1100
X (arcsecs)


Earth Scale
EIT 304
2002-05-22 01:19:23
www.helioviewer.org

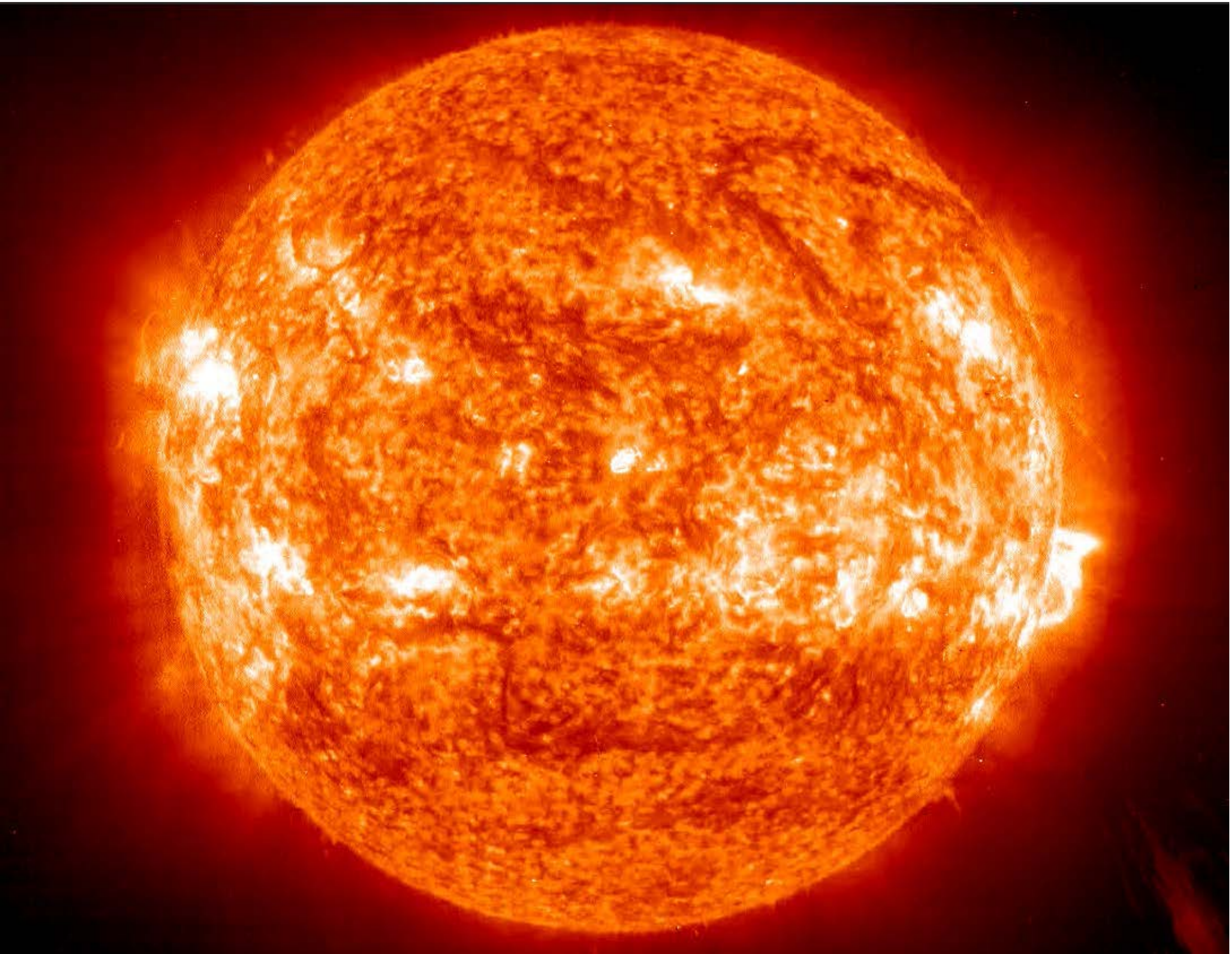
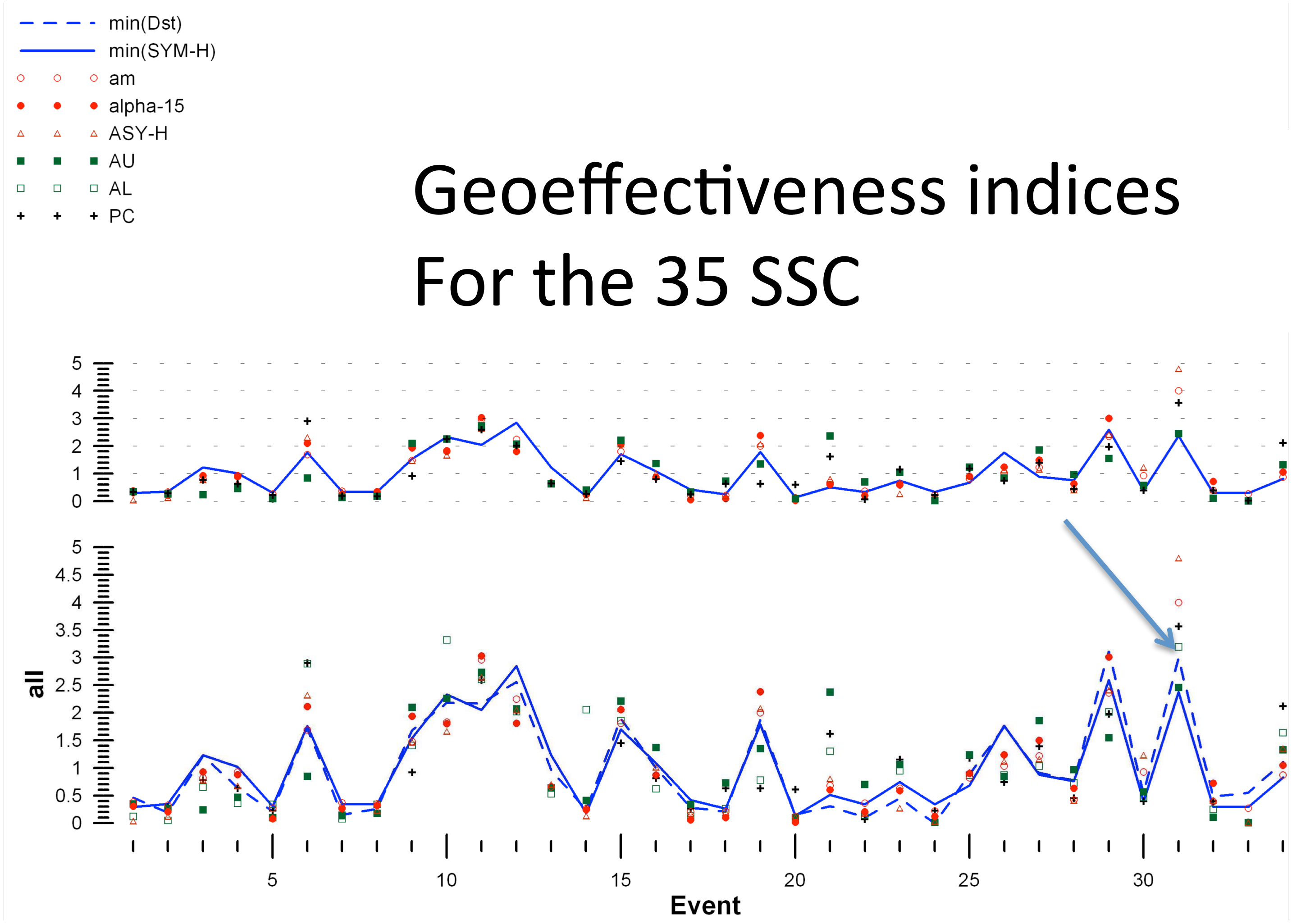


Table 2. Major Interplanetary Structures Causing Moderate Storms along the Different Phases of Solar Cycle 23

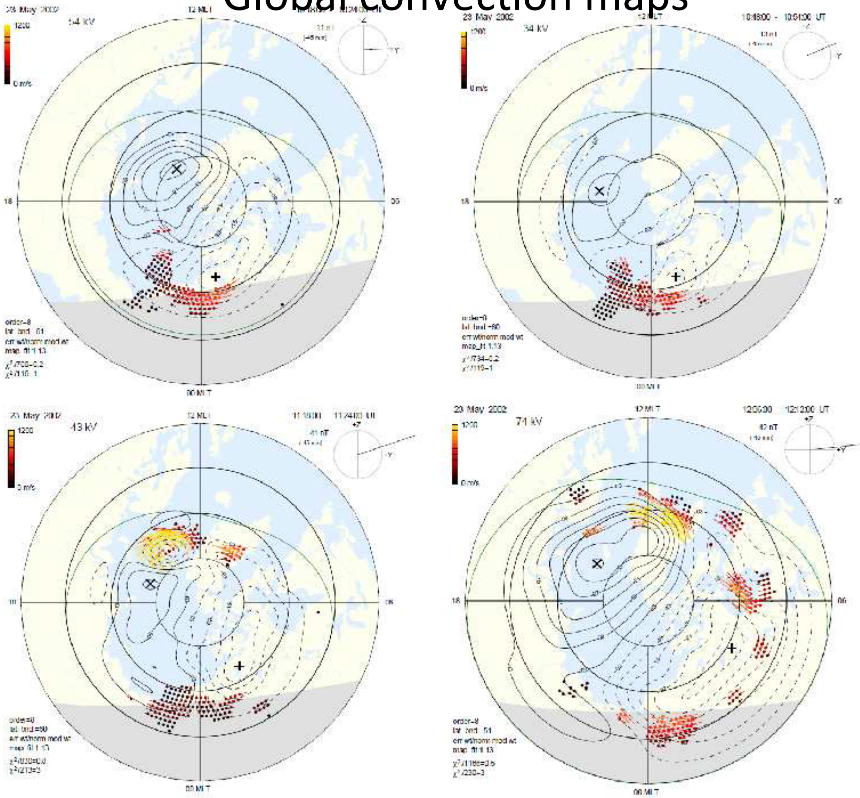
Solar Cycle Phase	Number of Storms	Major IP Structures and Percentage of Storms they Caused
Rising phase (1997–1999)	53	CIR/HSS (30.2 %) ICME (24.5 %) SHOCK-ICME (17.0 %) SHOCK/SHEATH (9.4 %)
Maximum (2000–2002)	62	CIR/HSS (33.9 %) ICME (22.6 %) SHOCK-ICME (14.5 %) SHOCK/SHEATH (16.1 %)
Declining (2003–2005)	75	CIR/HSS (60.0 %) ICME (20.0 %) SHOCK-ICME (5.3 %) SHOCK/SHEATH (9.3 %)
Minimum (1996, 2006–2008)	23	CIR/HSS (82.6 %) ICME (8.7 %)

Geoeffectiveness indices For the 35 SSC



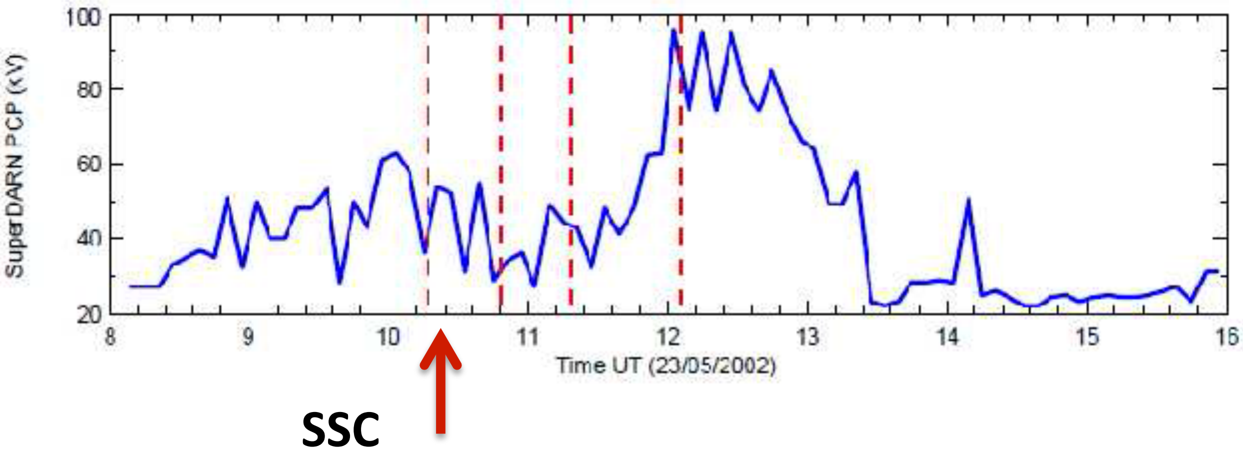
For the 35 SSC we see that the Dst can be used as a proxy of the geoeffectiveness

Global convection maps

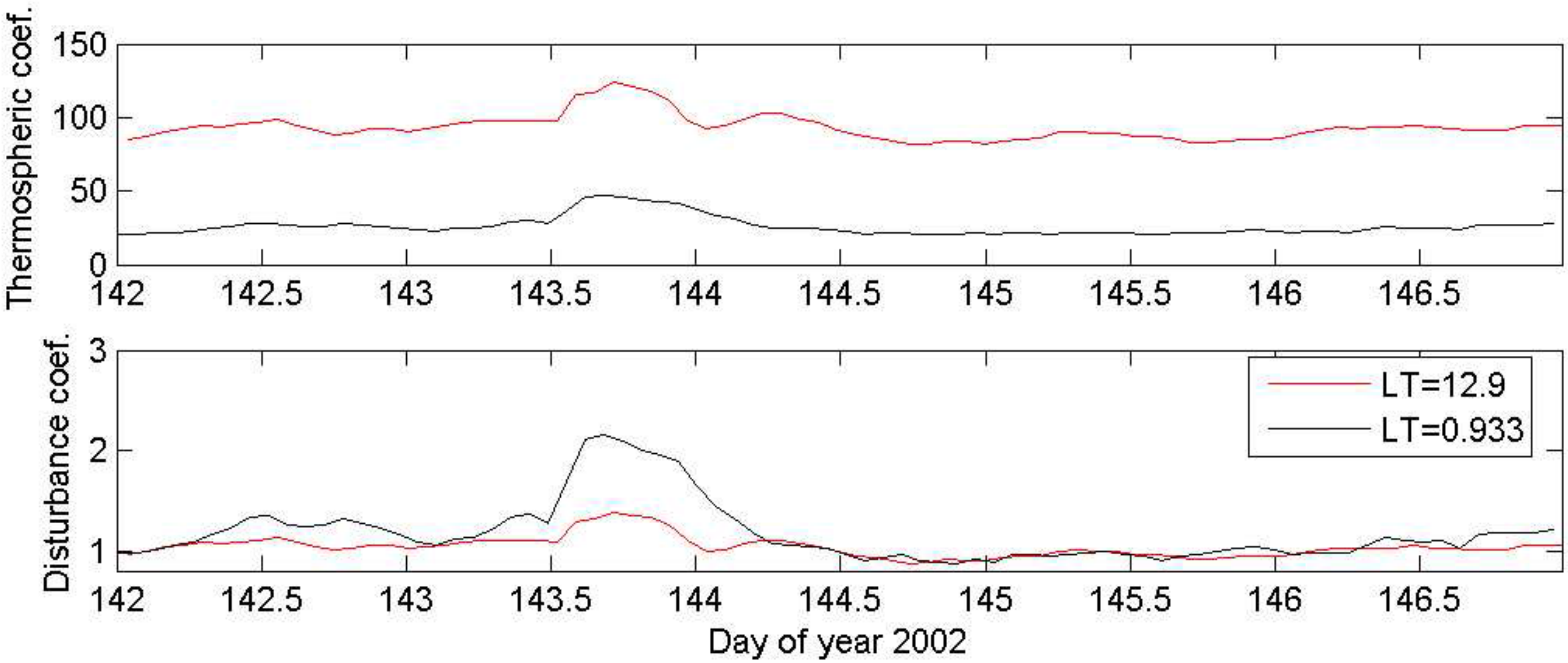


Ionospheric radars SuperDARN : Polar Cap potential through the pole

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

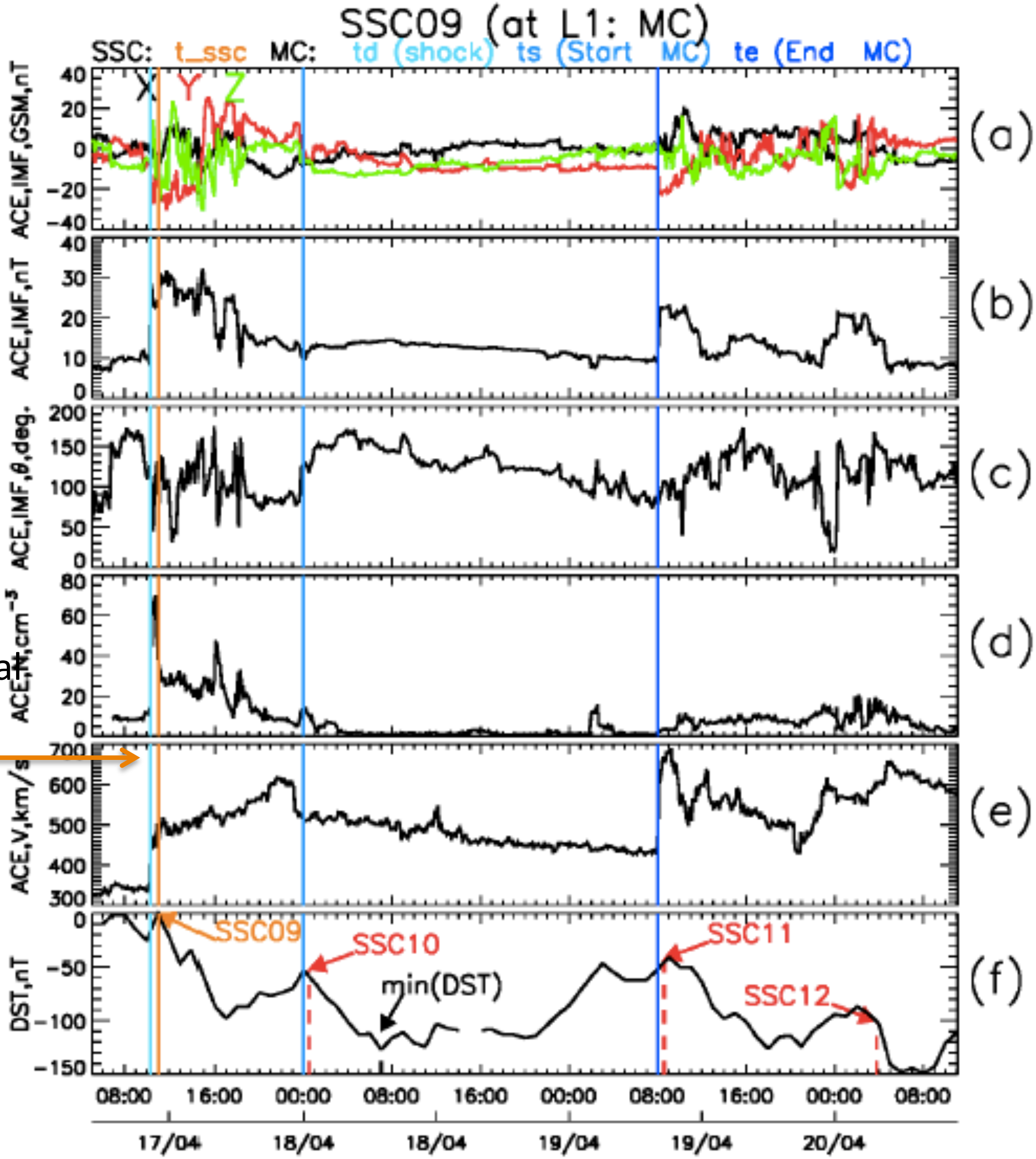
Coef. = 2 => augmentation de 100% of the density.

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 1. Groups of CMEs associated to SSCs. CMEs and SSCs are ordered in chronological order.

35 SSC, 27 Halo CMEs, 30 non halo CMES

Group No.	CME No.	SSC No.
Group01	CMEh00 CMEn01	SSC01
Group02	CMEn02	SSC03
Group03	CMEh03 CMEh04 CMEp05 CMEh06 CMEp07 CMEp08 CMEh09 CMEp10 CMEh11 CMEh12	SSC04 SSC05 SSC06
Group04	CMEn13	SSC08
Group05	CMEn14 CMEh15 CMEn16 CMEn17 CMEh18	SSC09 SSC10 SSC11 SSC12
Group06	CMEh19	SSC13
Group07	CMEn44 CMEh20 CMEh21 CMEn45	SSC14 SSC15
Group08	CMEh22 CMEn46 CMEp48 CMEn56 CMEp23 CMEp24 CMEh25	SSC16 SSC17 SSC18 SSC19
Group09	CMEp47	SSC20
Group10	CMEn49 CMEh26 CMEp27 CMEp28 CMEh29 CMEp30 CMEh31	SSC22 SSC23
Group11	CMEh33	SSC24
Group12	CMEn52 CMEn53	SSC25 SSC26
Group13	CMEh34	SSC27
Group14	CMEh35 CMEp50 CMEn51 CMEh55	SSC28
Group15	CMEh36	SSC29
Group16	CMEn54	SSC30 SSC31
Group17	CMEn57 CMEh39 CMEp40	SSC32 SSC33 SSC34
Group18	CMEh41	SSC35
Not associated	[illegible]	SSC02 SSC07 SSC21



Example

Sheath arrival
SSC09