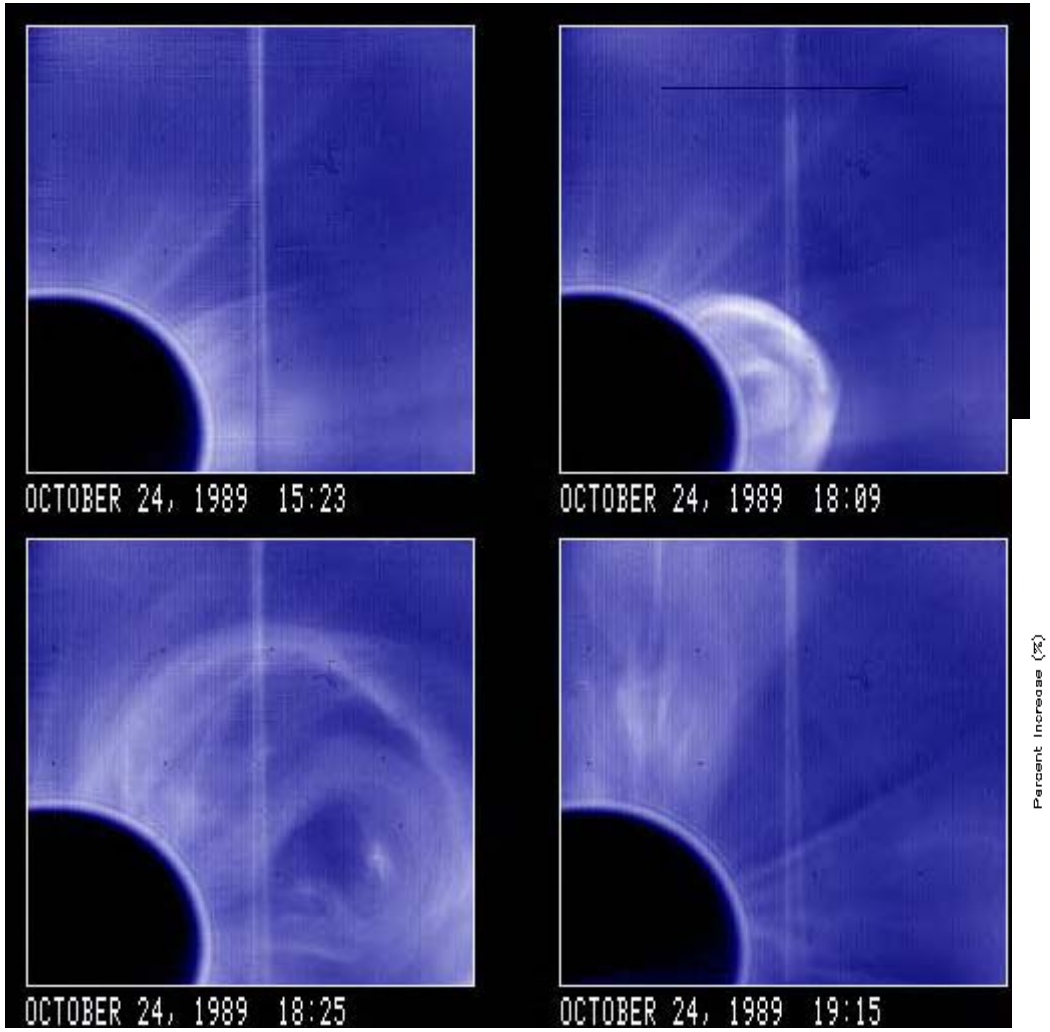
Solar Sources of GLE Events of Cycle 23

Nat Gopalswamy
NASA Goddard Space Flight Center
Greenbelt, Maryland, USA

Plan

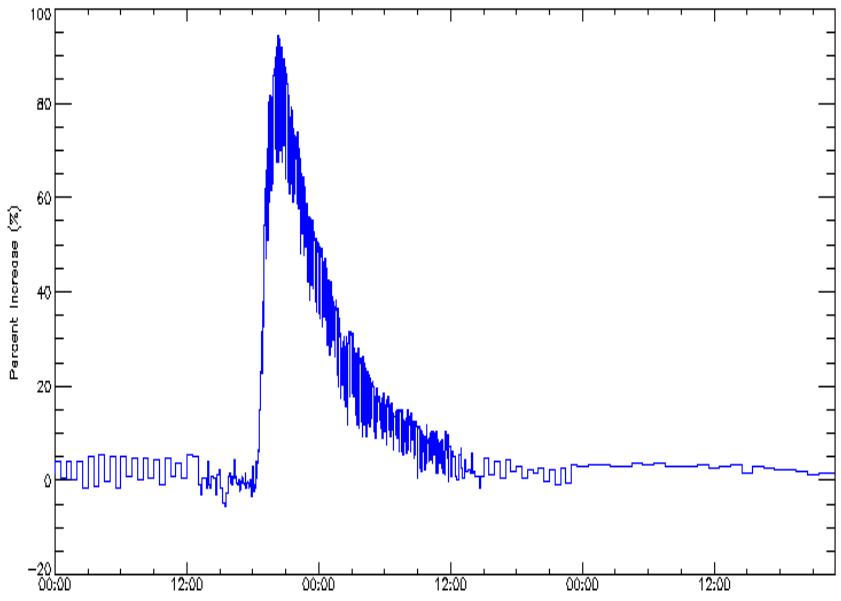
- List of Cycle 23 GLEs
- Flare and CME properties
- Example: 2006 Dec 13 GLE
- GLE release with respect to transient activities
- Peculiar GLE (2001 April 18)
- GLE Release Height and Alfven Speed Profile
- Summary

GLE # 45 1989 Oct 24



V = 1453 km/s
W = 108 degrees

6 CMEs measured in cycle 23
Cliver 2006



GLE Events of Cycle 23

CME height at GLE release

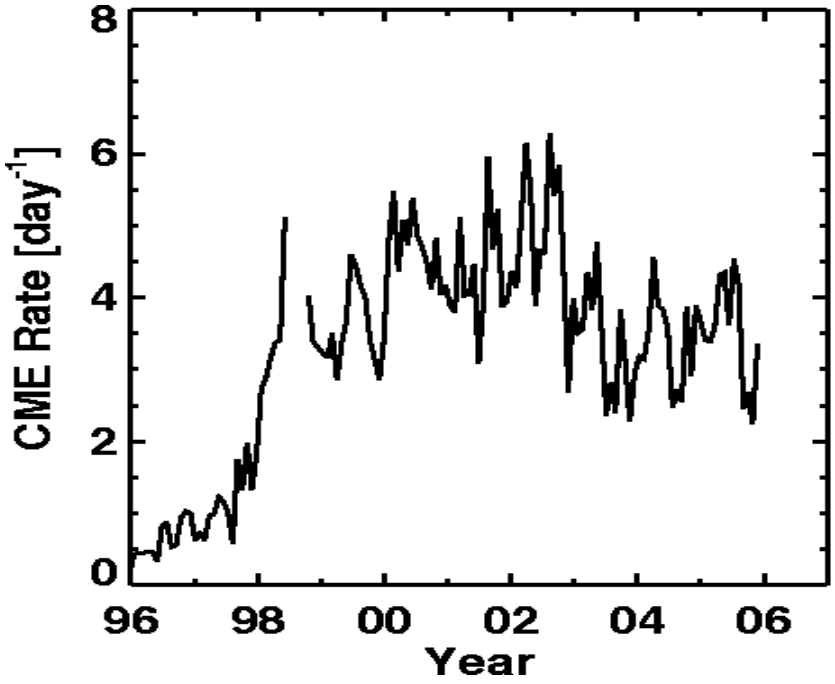
Event #	GLE event Date	GLE Onset (Obs)	GLE Onset (Inf)	Peak time (UT)	GLE Int. (%)	Type II Onset	Type III Onset	Flare onset	Flare Class /Location	CME Onset	CME ht (Rs)	Sky Speed (km/s)	Space Speed (km/s)
1	1997Nov06	12:10	12:07	14:00	11.3	11:53	11:52	11:49	X9.4/S18W63	11:39	5.2	1556	1726
2	1998May02	13:55	13:52	14:05	6.8	13:41	13:35	13:31	X1.1S15W15	13:32	3.3	938	1332
3	1998May06	08:25	08:22	09:30	4.2	08:03	08:01	07:58	X2.7/S11W65	07:55	3.8	1099	1208
4	1998Aug24	22:50	22:47	02:05	3.3	22:02	22:04	21:50	X1.0/N35E09	DG	DG	DG	DG
5	2000Jul14	10:30	10:27	11:00	29.3	10:28	10:18	10:03	X5.7/N22W07	10:25	1.4	1674	1741
6	2001Apr15	14:00	13:57	14:35	56.7	13:47	13:49	13:19	X14/S20W85	13:35	3.3	1199	1203
7	2001Apr18	02:35	02:32	03:10	13.8	02:17	02:15	02:11	?/S23W117	02:11	5.9	2465	2712
8	2001Nov04	17:00	16:57	17:20	3.3	16:10	16:13	16:03	X1.0/N06W18	16:13	8.0	1810	1846
9	2001Dec26	05:30	05:27	06:10	7.2	05:12	05:13	04:32	M7.1/N08W54	05:06	4.2	1446	1779
10	2002Aug24	01:18	01:15	01:35	5.1	01:01	01:01	00:49	X3.1/S02W81	00:59	3.6	1913	1937
11	2003Oct28	11:22	11:19	11:51	12.4	11:02	11:03	11:00	X17/S20E02	11:07	3.9	2459	2754
12	2003Oct29	21:30	21:27	00:42	8.1	20:42	20:41	20:37	X10/S19W09	20:43	8.7	2029	2049
13	2003Nov02	17:30	17:27	17:55	7.0	17:14	17:16	17:18	X8.3/S18W59	17:19	3.0	2598	2981
14	2005Jan17	09:55	09:52	09:59	3.0	09:43	09:41	09:52	X3.8/N14W25	09:43	3.2	2547	2802
15	2005Jan20	06:51	06:48	07:00	277.3	06:44	06:45	06:39	X7.1/N14W61	06:33	4.0	3242	3675
16	2006Dec13	02:45	02:42	03:05	92.3	02:26	02:24	02:17	X3.4/S06W23	02:25	4.2	1774	2164

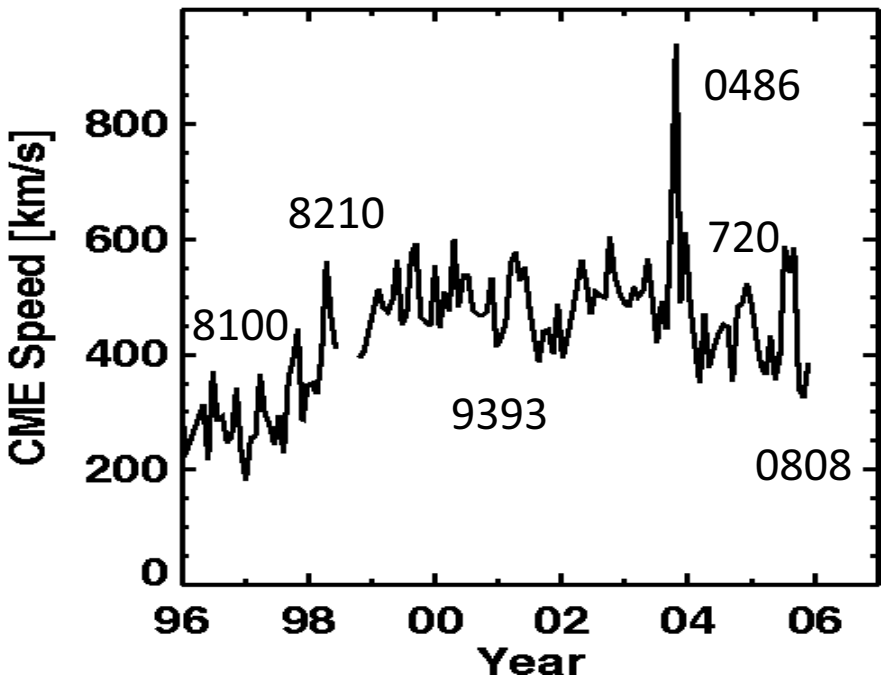
Normalized wrt to the arrival of Electromagnetic signals at Earth

- Typical enhancement is < 10%

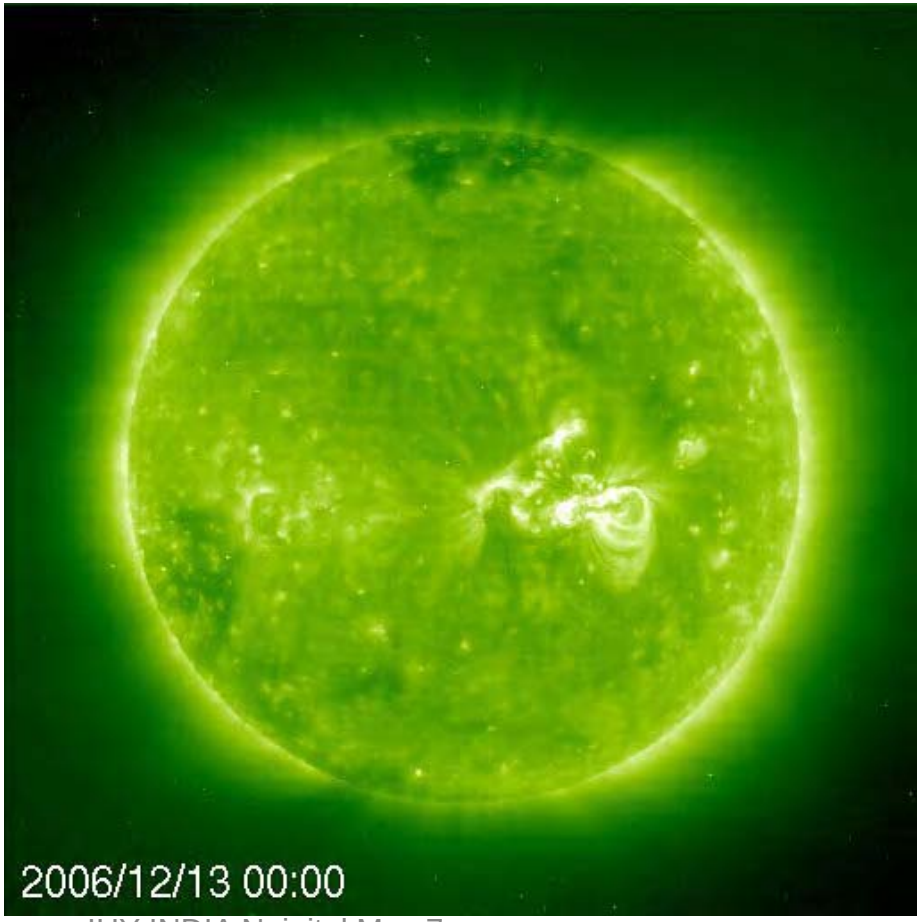
- Solar cycle: [4,5,7] Rise, Max, Decl
- Rare occurrence: 16 in 11 y → 1.4/y

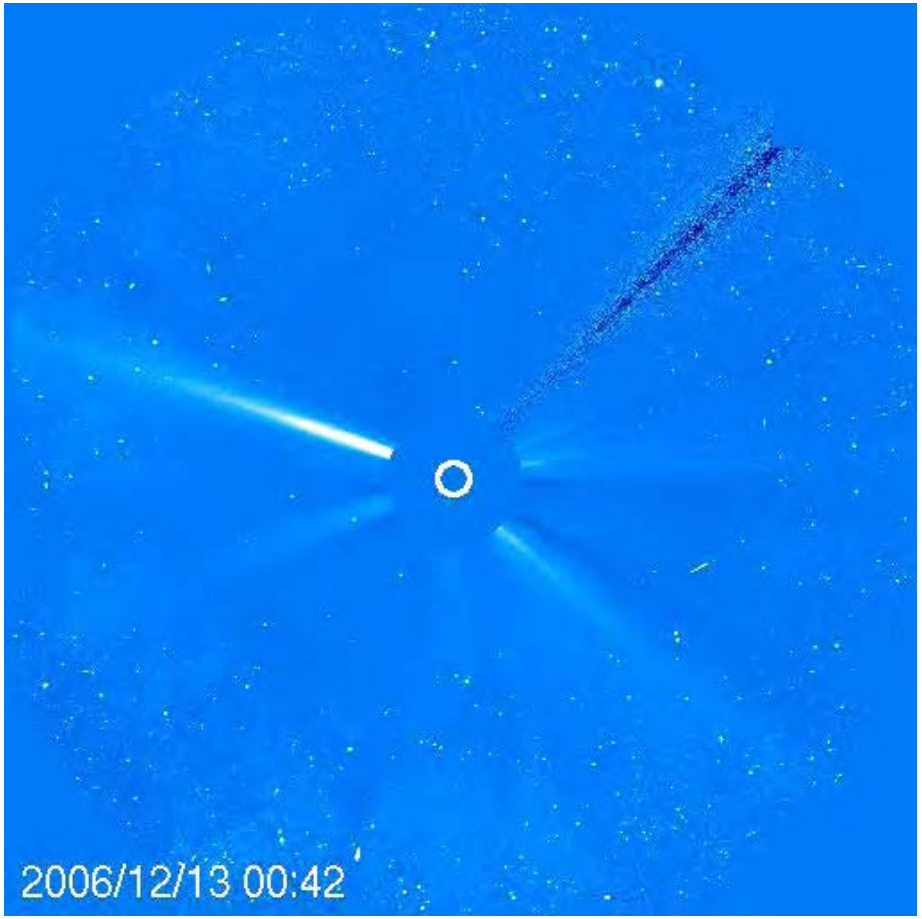
Super AR → High Speed CMEs



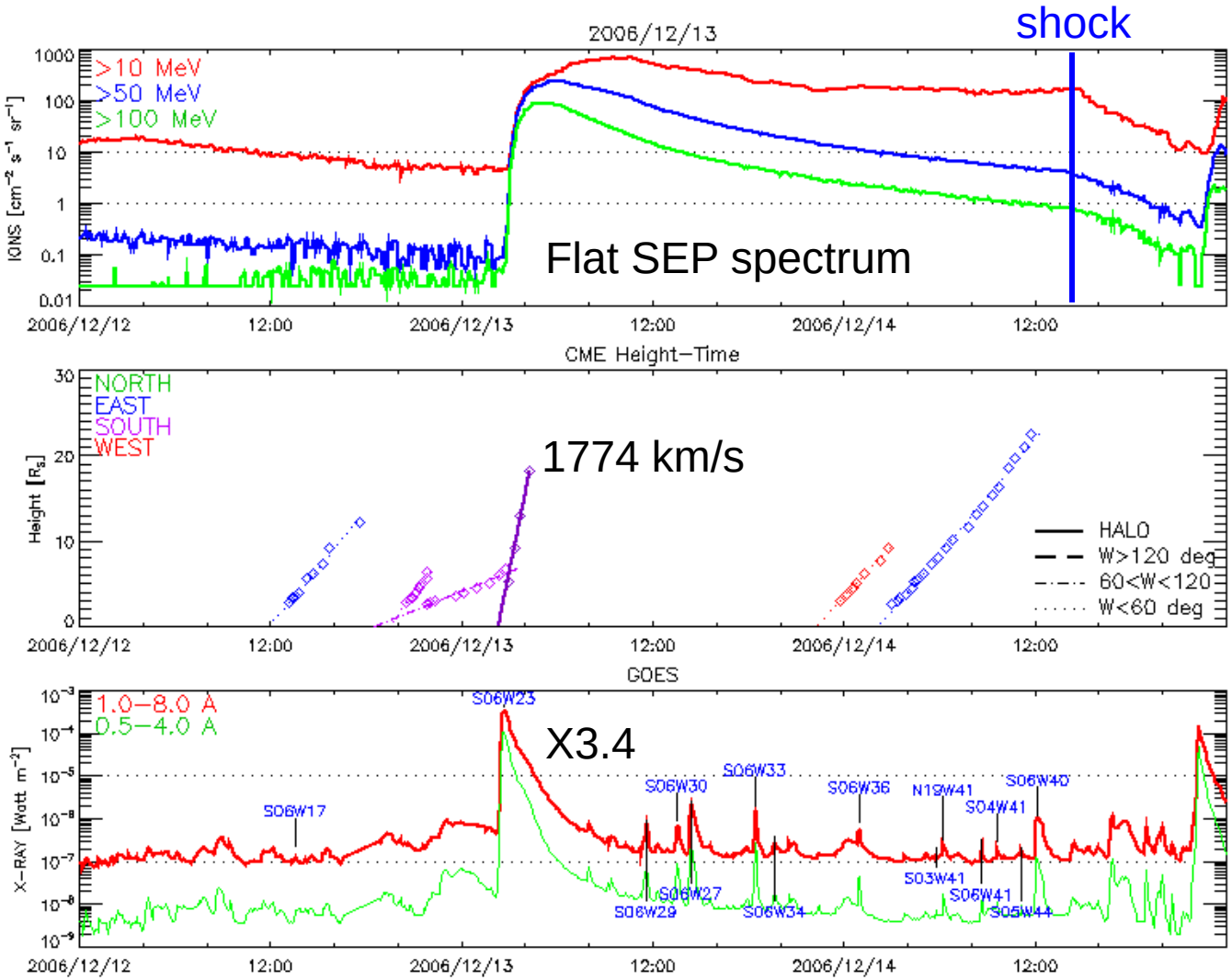


Second Largest GLE





2006 12 13 Event (AR 0930)

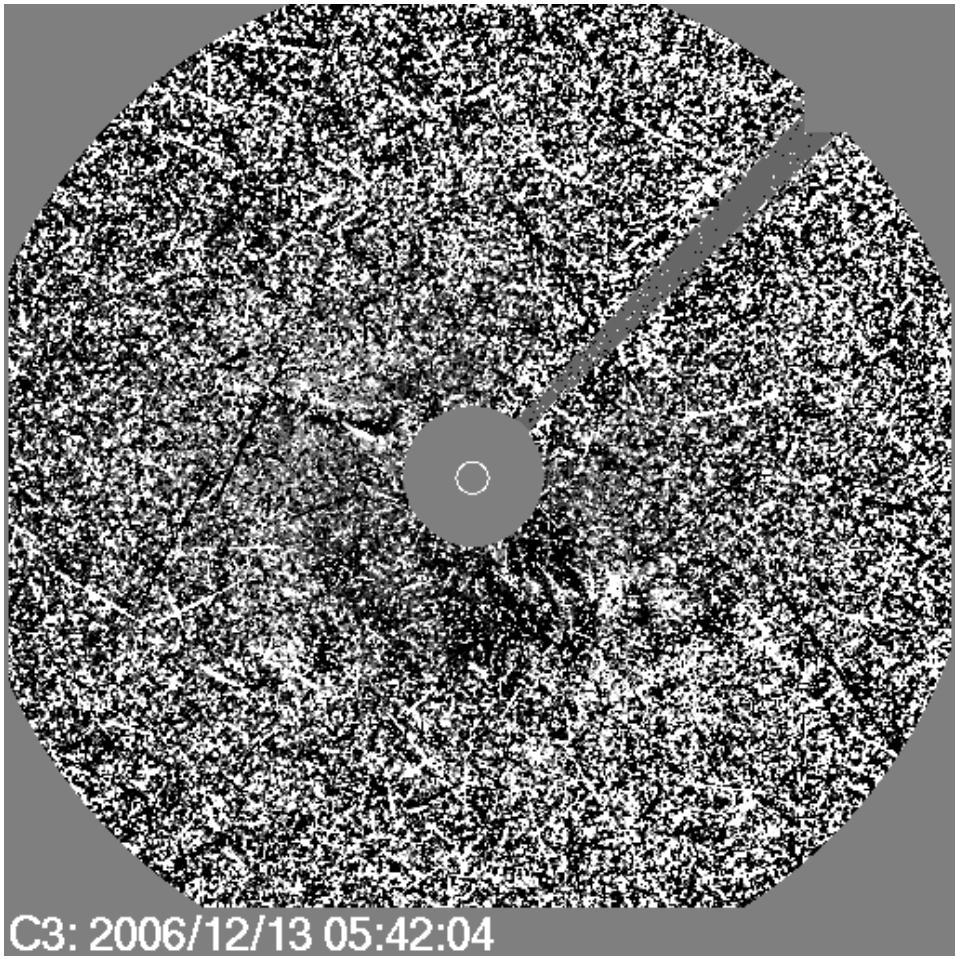


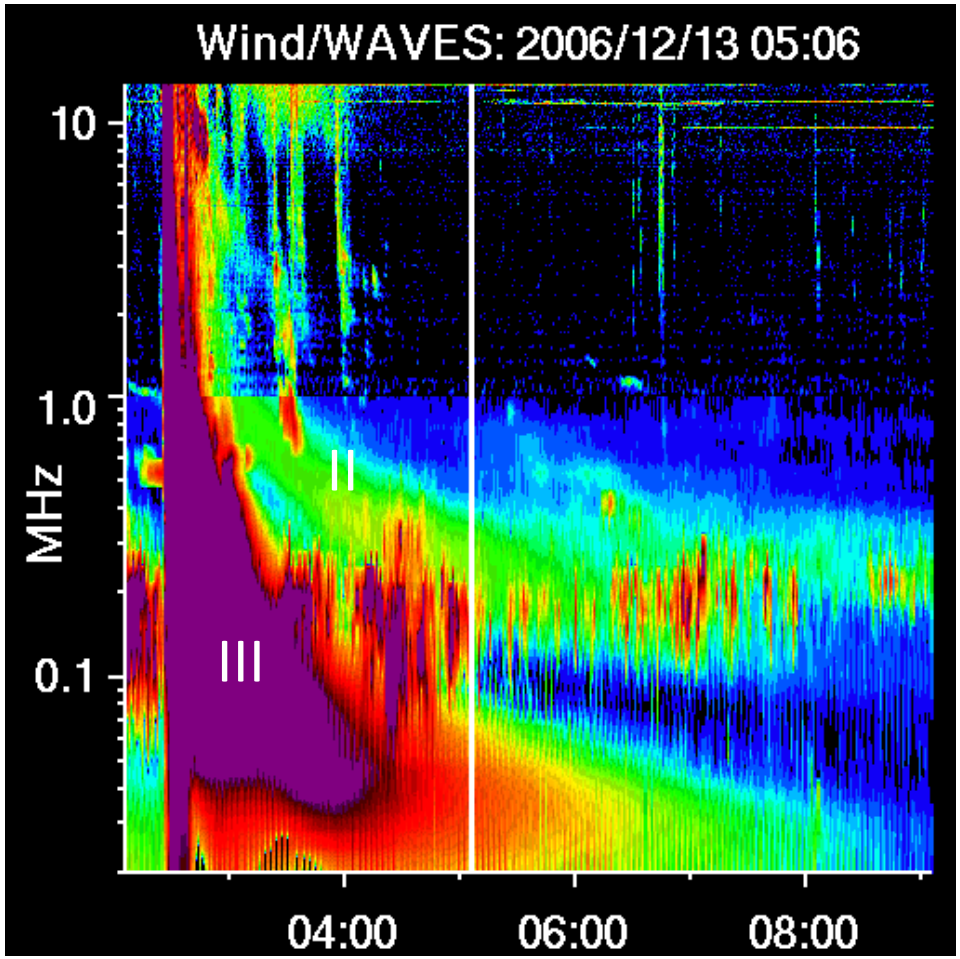
GLE onset: 02:45
At the Sun: 02:42

CME onset: 02:25
Metric II : 02:26
DH Type III: 02:24

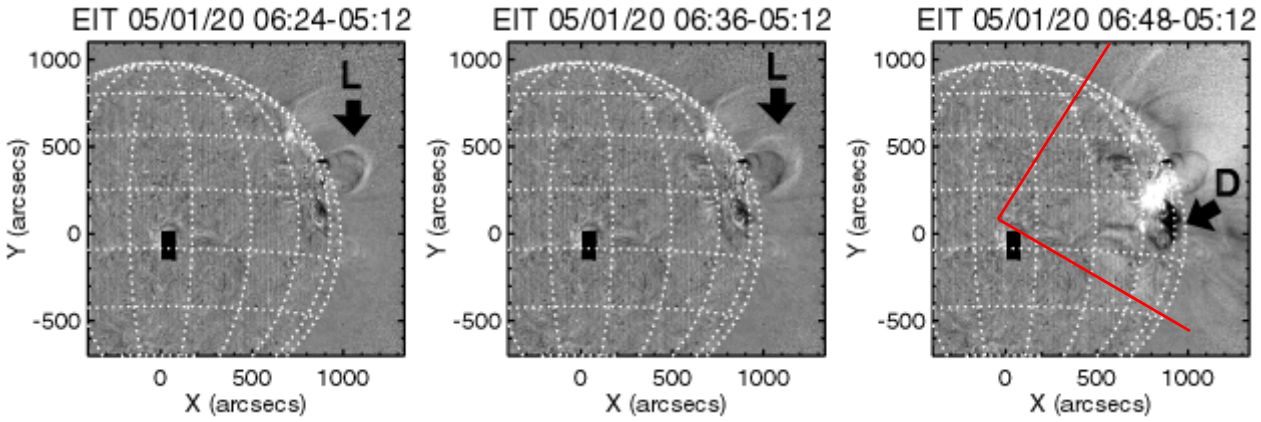
Flare onset: 02:17

DH Type III and Type II

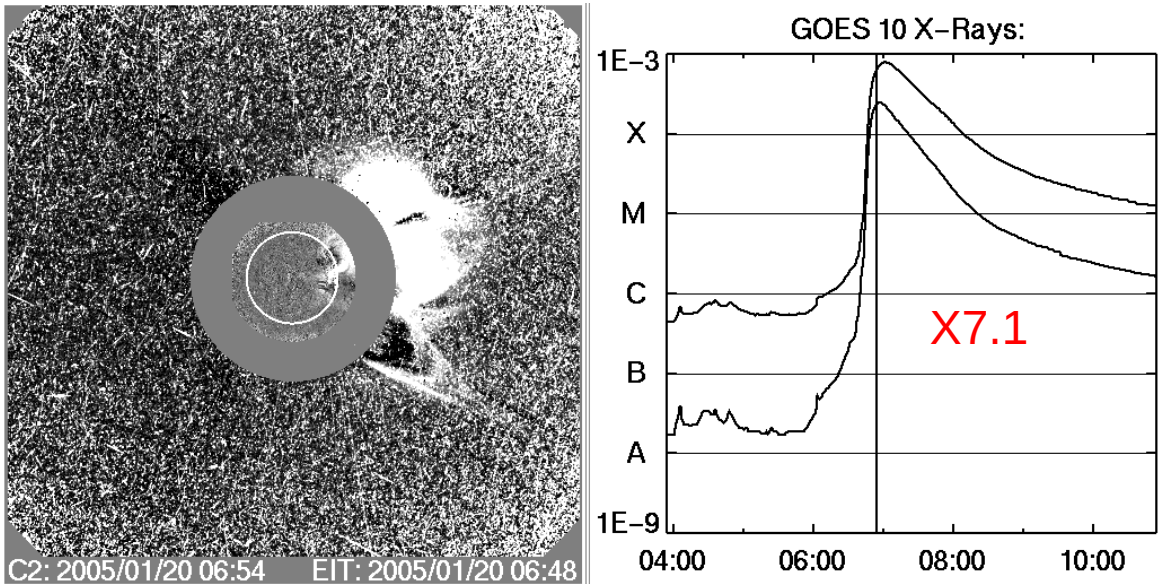




Solar Source of Jan 20 05 CME

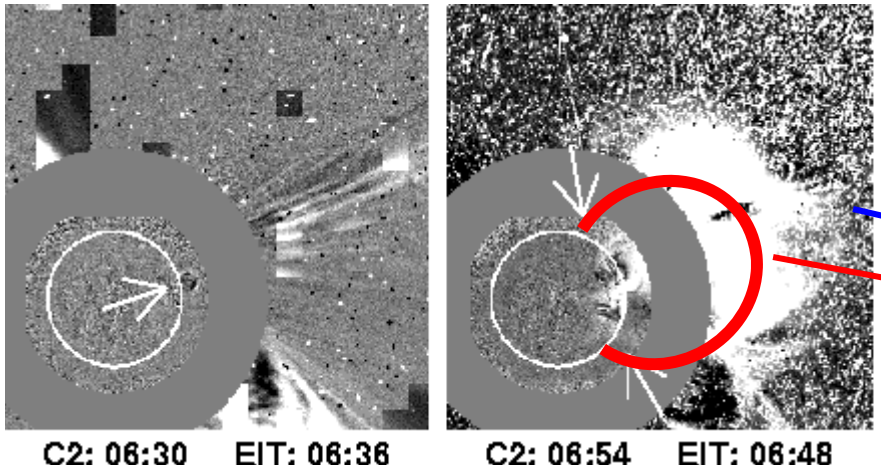


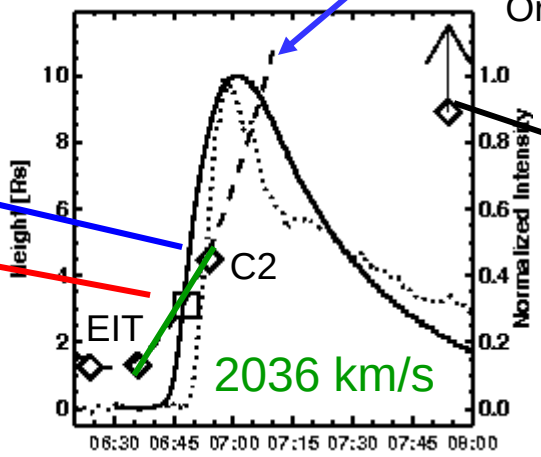
Motion in the 6:36 UT frame, before flare onset
Quadrant-filling at 6:48 UT



LASCO CME first appears at 6:54 UT, but at 4.5 Rs

The Largest cycle-23 Ground Level Enhancement of Solar protons





$h = 6.052 - 0.3361t + 0.0057t^2$
(t min from 06:00 UT)
t =54 → dh/dt = 0.28 Ro/min
Or 3242km/s

C3
Rapid deceleration or the height underestimated due to snowstorm

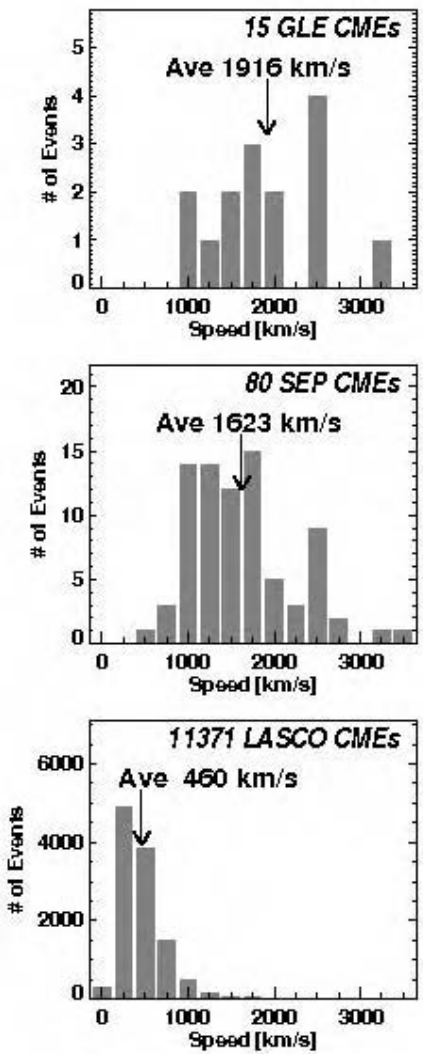
January 20 2005 Event

- O Snow-storm at first appearance → Particles reached in < 16 min
- O CME speed ~ 3200 km/s (sky-plane)
  ~3600 km/s (cone-model)
- O Rapid deceleration
- O Consistent with GLE acceleration by CME-driven shocks

Is the January 20 2005 GLE event a new kind of storm?

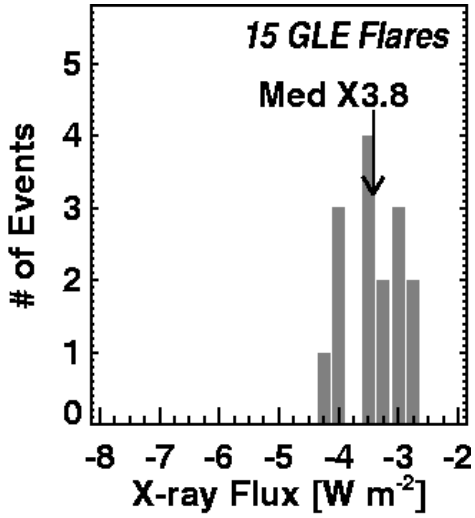
No. It is similar to other GLE events in their CME association

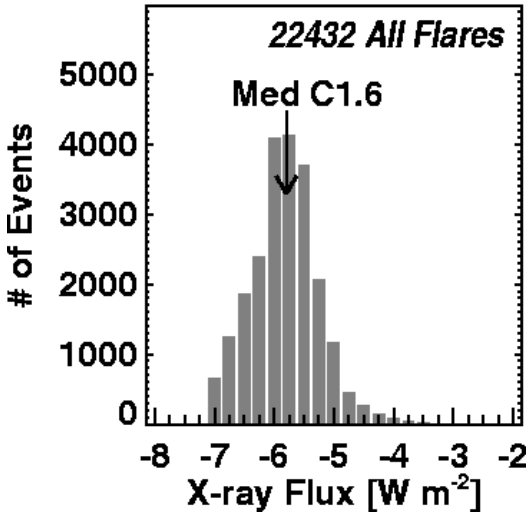
CME Speed

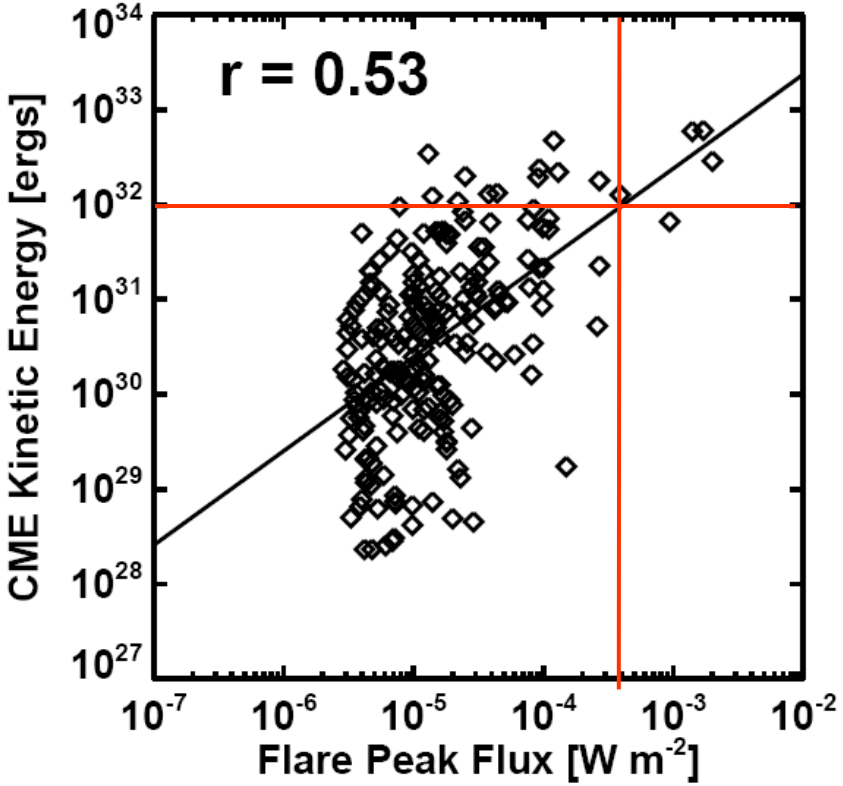


The average speed of GLE CMEs (1916 km/s) is greater than that of the SEP associated CMEs (~1623 km/s). The GLE associated CMEs are >4 times faster than the average CME (460 km/s)

Flares Associated with GLEs

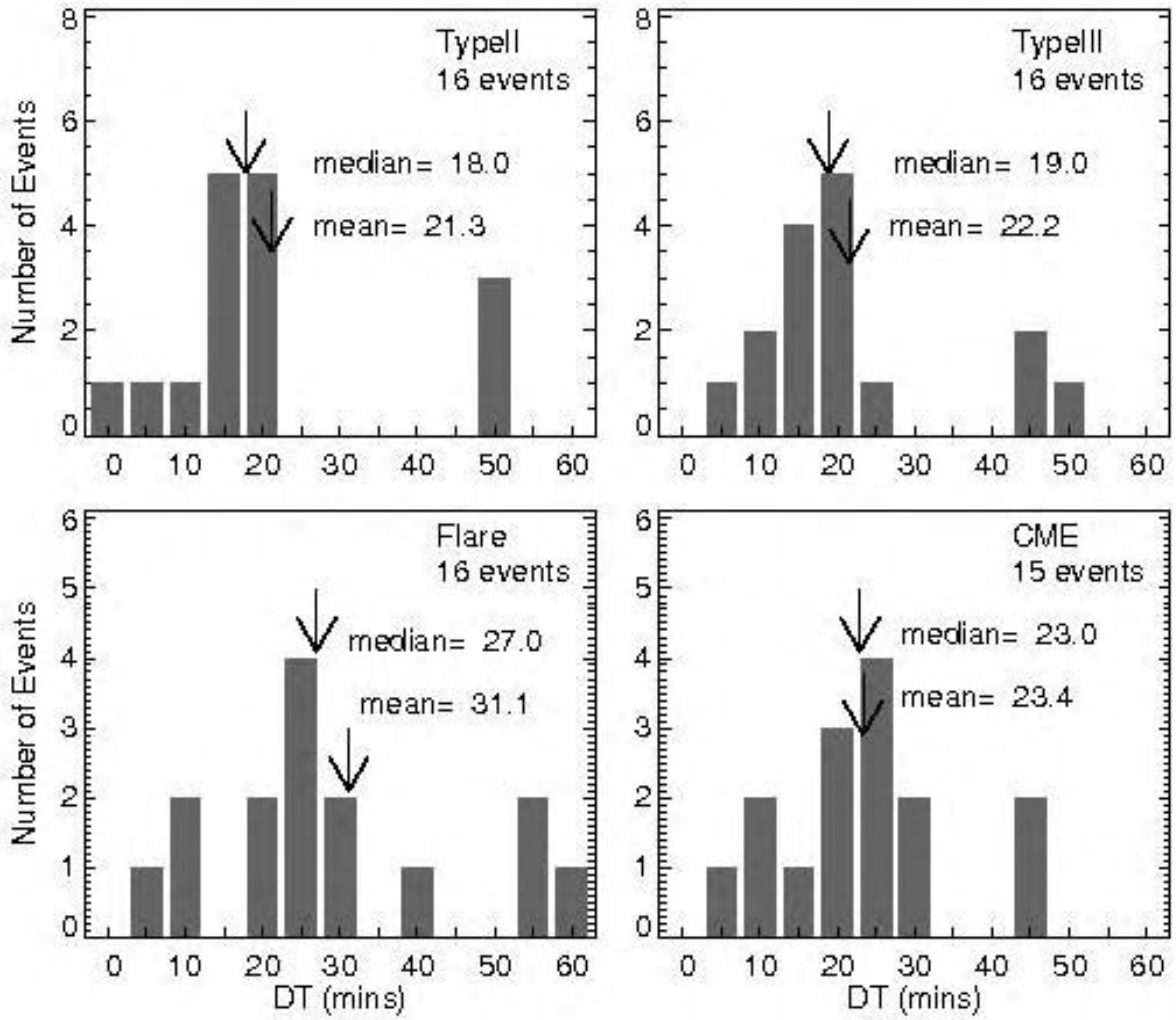






The GLE flare size corresponds to a CME KE ~10^{32} erg
- at the top end of the spectrum

Delay of GLE release with respect to metric type II bursts, DH type III bursts, flares, and CMEs



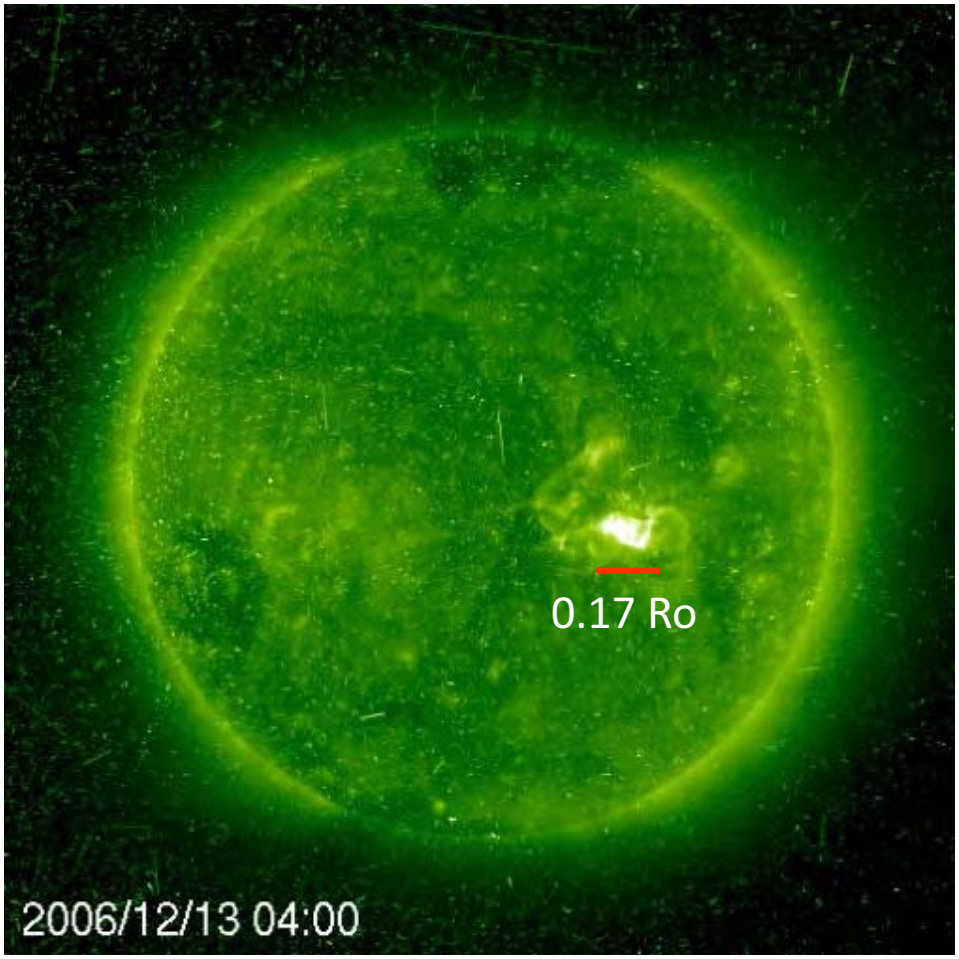
The median delay is the smallest for metric type II bursts (18 min) and the largest for flares (27 min) The delay of DH type III (19 min) is very close to that of m type II

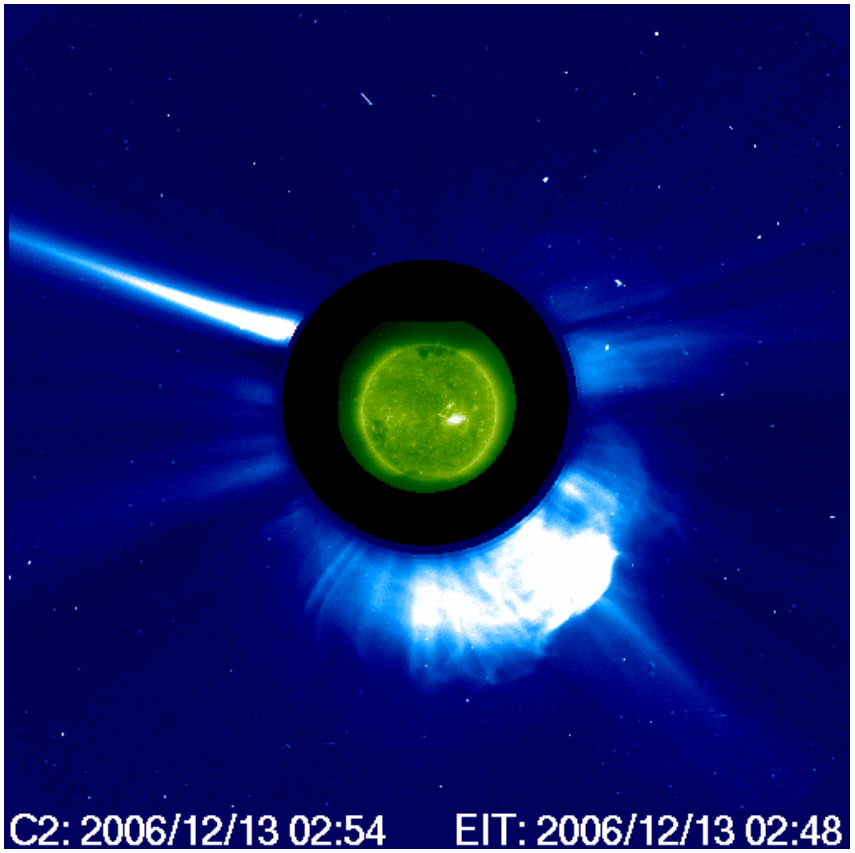
We may not be able distinguish between flare & shock mechanisms from the delay time alone.

Flare vs. CME: Angular Size

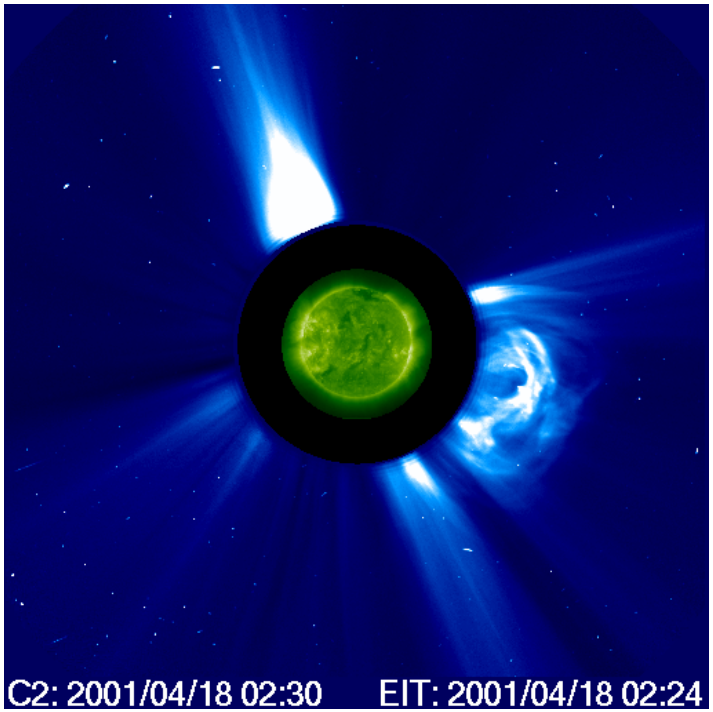
Size of flare arcade: 0.17 Ro or 116000 km

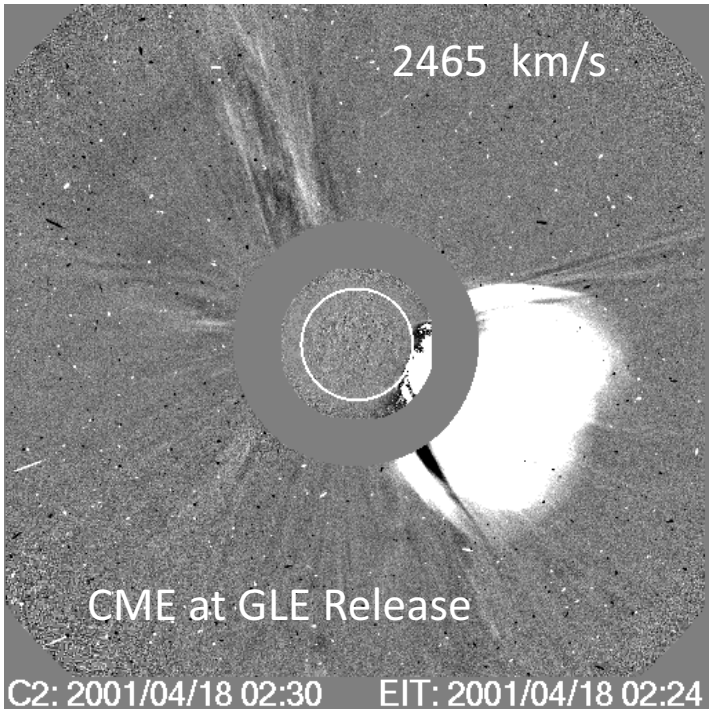
Angular size: 9.7 degrees (heliographic)

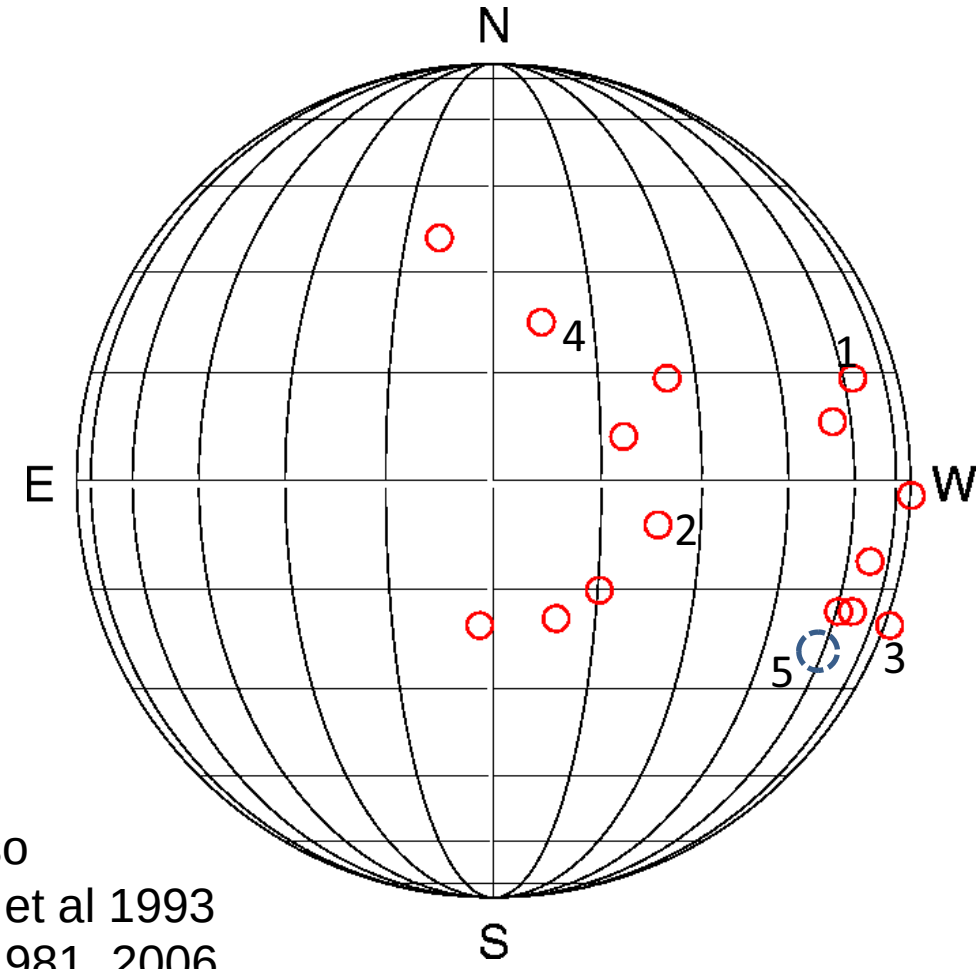




16 GLEs from Cycle 23
One from a backside CME



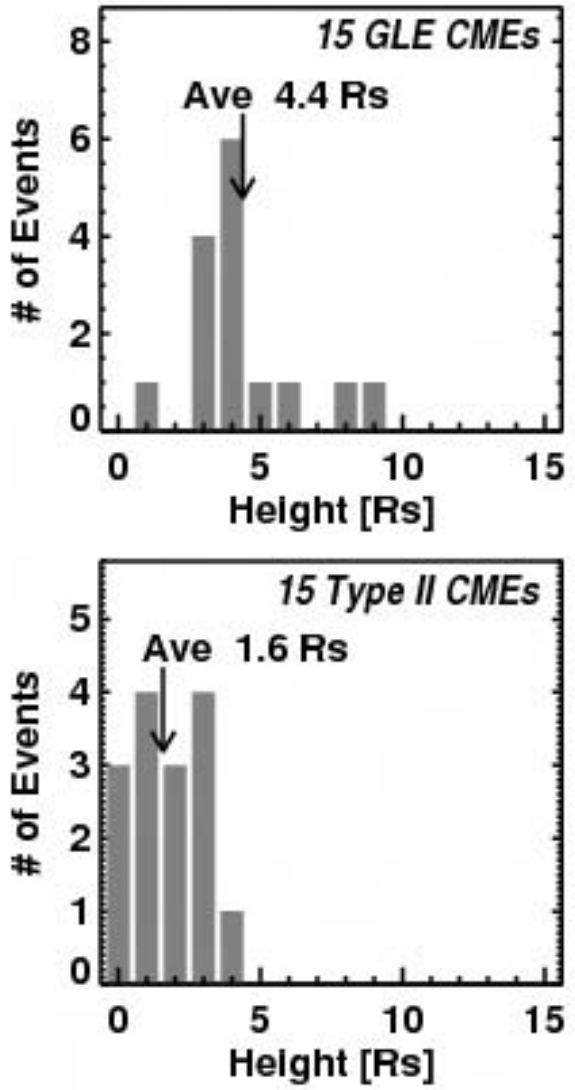




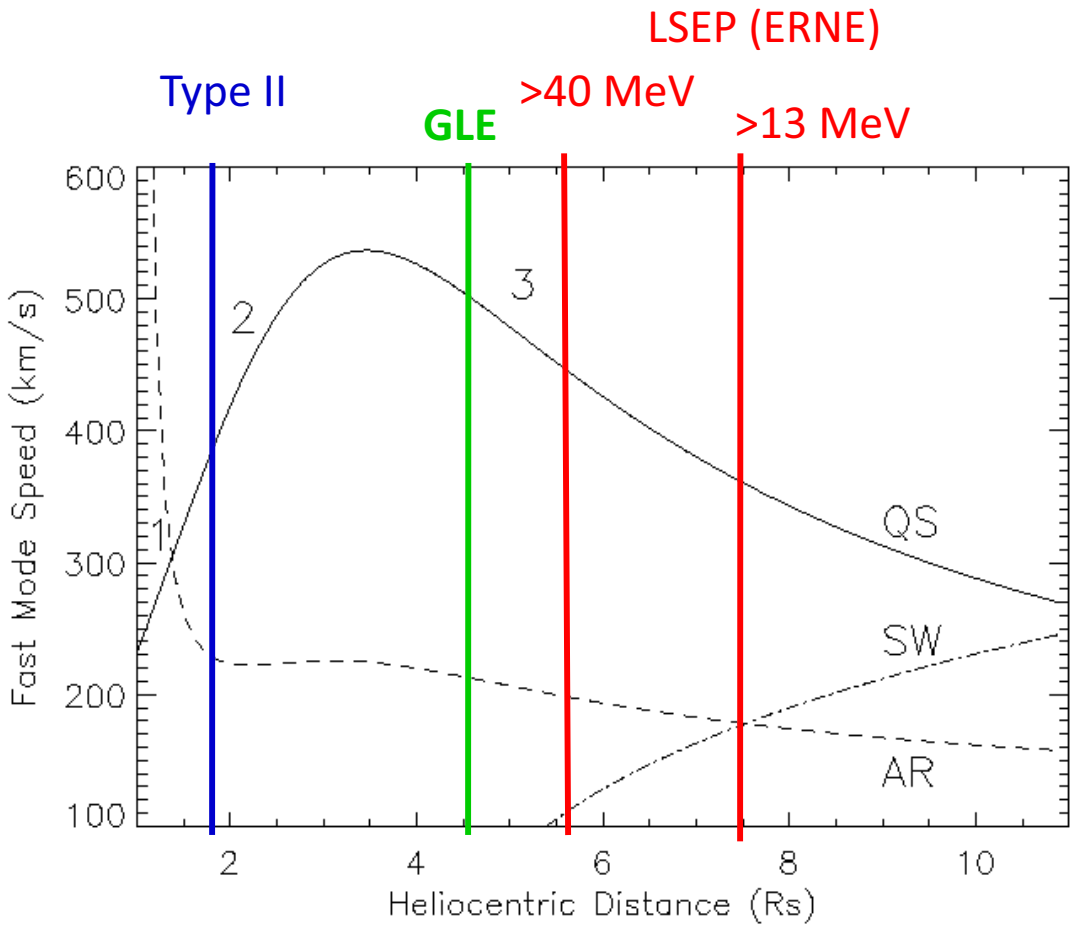
See also
Kudela et al 1993
Cliver 1981, 2006

○ 30 deg behind the limb (S23W120)
5th largest GLE of cycle 23
2001 April 18

CME Height @GLE &SEP Release Compared to CME Height @ Type II Onset



CME height at

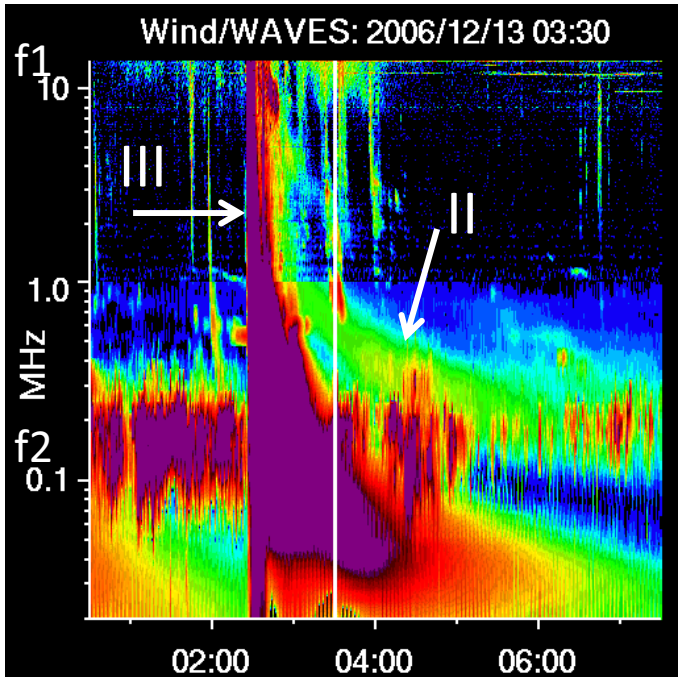


Shocks already present in all GLE events. Particles released beyond 4 Rs

Wind/WAVES Type II Bursts

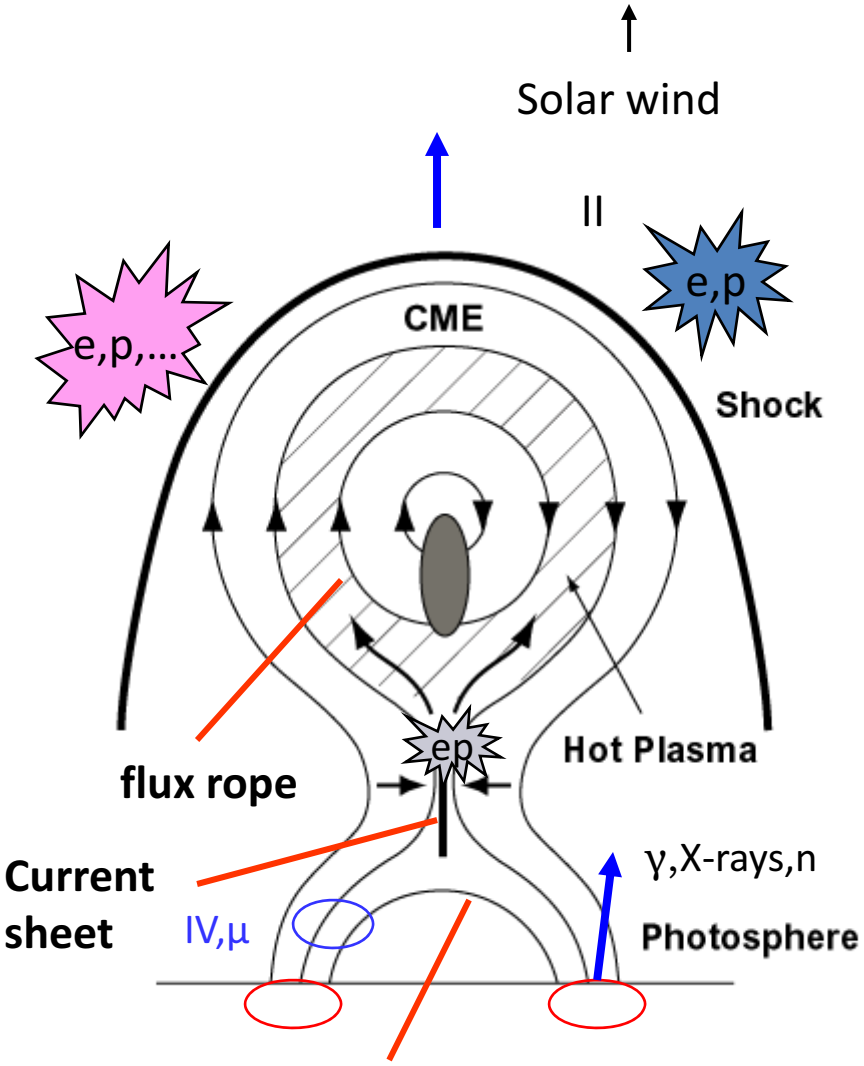
	DH II Start		End		f1	f2
#	Year	UT	Year	UT		
1	1997/11/06	12:20	11/07	08:30	14	0.1
2	1998/05/02	14:25	05/02	14:50	5[a]	3.0
3	1998/05/06	08:25	05/06	08:35	14	5.0
4	1998/08/24	22:05	08/26	06:20	14	0.03
5	2000/07/14	10:30	07/15	14:30	14	0.08
6	2001/04/15	14:05	04/16	13:00	14	0.04
7	2001/04/18	02:55	04/18	14:00	1[b]	0.10
8	2001/11/04	16:30	11/06	11:00	14	0.07
9	2001/12/26	05:20	12/27	05:00	14	0.15
10	2002/08/24	01:45	08/24	03:25	5	0.40
11	2003/10/28	11:10	10/29	24:00	14	0.04
12	2003/10/29	20:55	10/29	24:00	11	0.50
13	2003/11/02	17:30	11/03	01:00	12	0.25
14	2005/01/17	09:25	01/17	16:00	14	0.03
15	2005/01/20	07:15	01/20	16:30	14	0.03
16	2006/12/13	02:45	12/13	10:40	12	0.15

[a]Earlier start possible f1 = 14 MHz at 14:06 UT;
[b]Type II like event starts 14 MHz around 2:30 UT



The presence of type II bursts at DH wavelengths indicates strong shocks -- much stronger than cases where only metric type II bursts are present

Generic Eruption



Adapted from Martens and Kuin 1986

Two sources of particle acceleration : shock & flare

Injection of hot plasma into the CME structure, resulting in higher charge states in magnetic clouds

The prominence material is cool occasionally observed at 1 AU as low charge state interval.

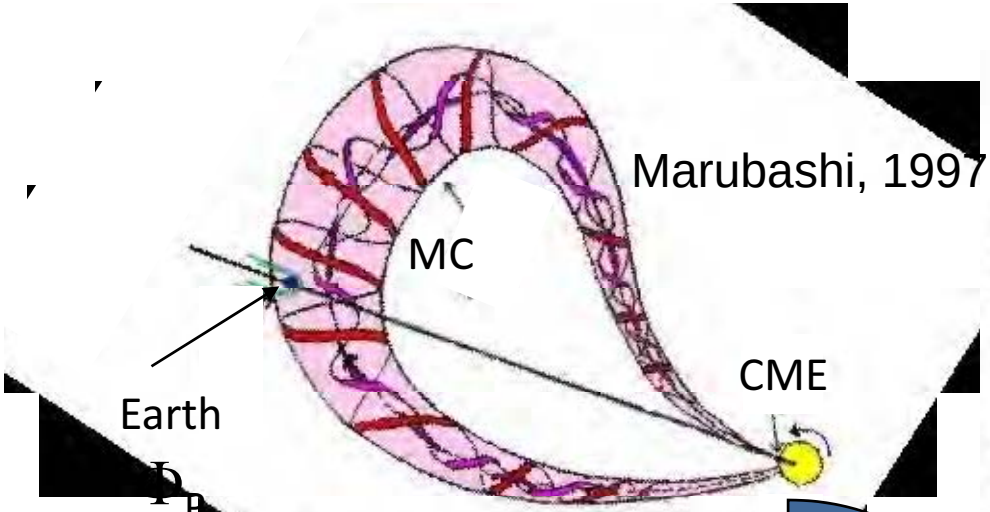
Injection of nonthermal electrons → moving type IV radio bursts (since 1957)

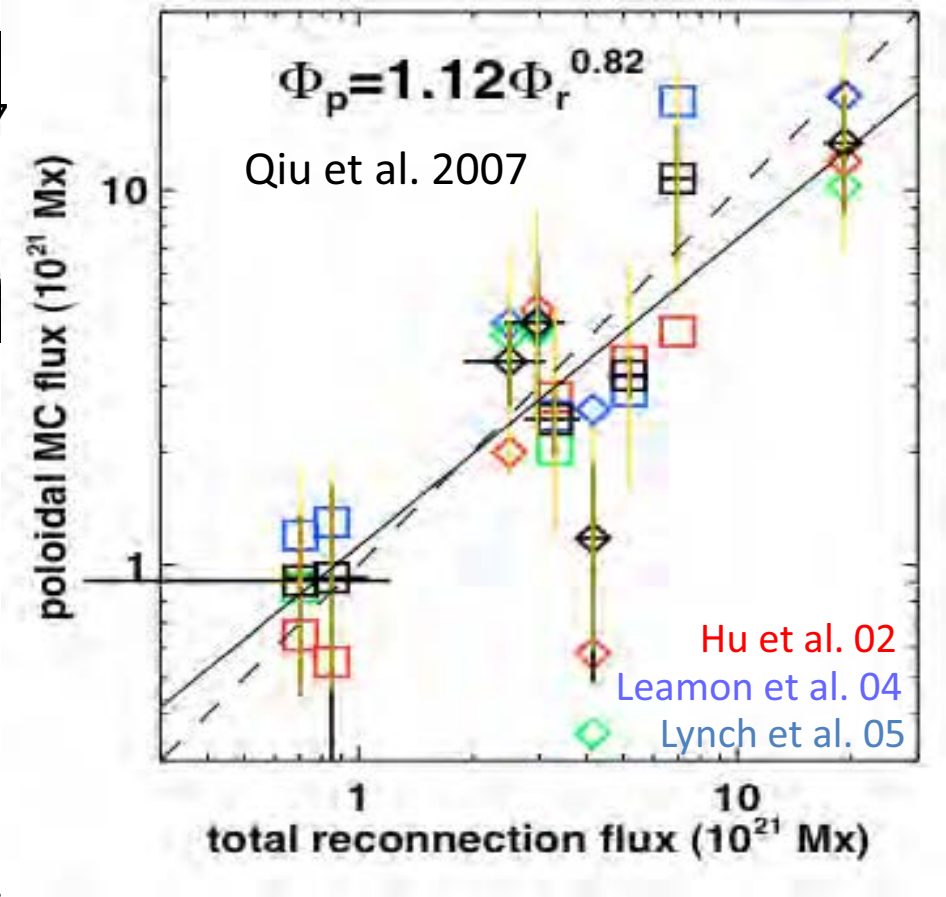
Hard X-ray moving sources in the corona from RHESSI (Krucker 2008)

How do flare particles escape into the IP medium?

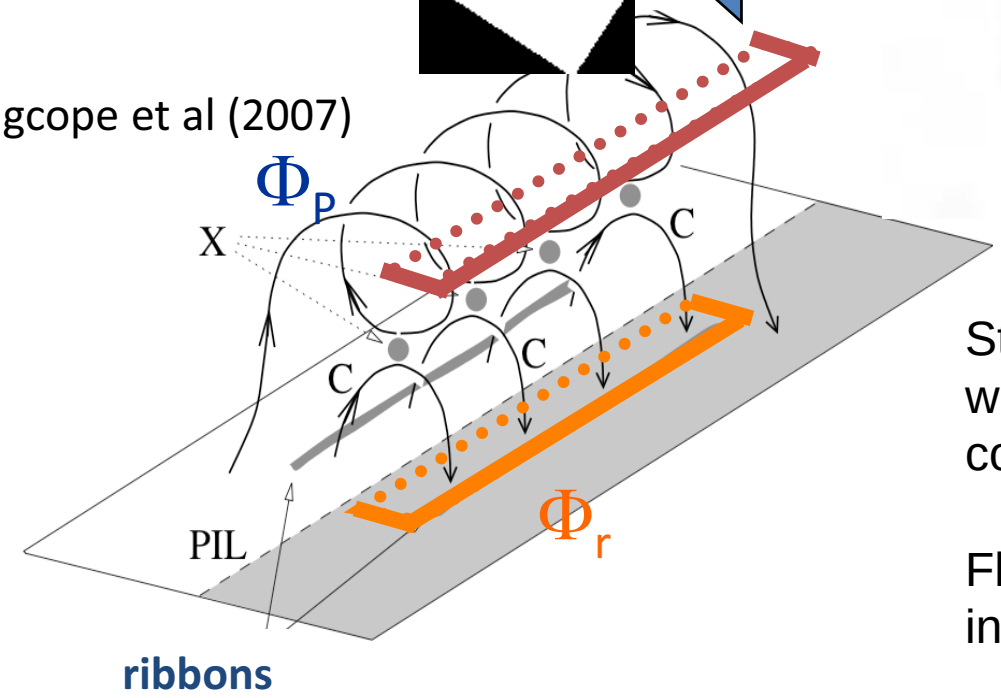
Type III bursts indicate open field lines

No type III when no CME!





Longcope et al (2007)



Standard CSHKP model seems to work when IP and coronal data are compared

Flare particles are likely to be trapped in the flux rope

Example of X-Class flare without CME and Type III: 2005 Jan 15

- The flare location can be seen in SOHO/EIT image (direct and difference)
- GOES light curve shows the X1.2 flare starting, peaking, and ending at 00:22, 00:43, and 01:02 UT, respectively.
- Wind/WAVES dynamic spectrum radio-burst activity
- The flare was associated with an intense microwave burst starting peaking and ending at 00:30, 00:40, and 01:11 UT at 15.4 GHz with 3000 SFU. The frequency of peak emission ~17 GHz (4000 SFU).
- RHESSI images show a compact hard X-ray source (not shown)
- TRACE images at 1600 A show multiple thin loops straddling the neutral line, making only a small angle with the east-west neutral line

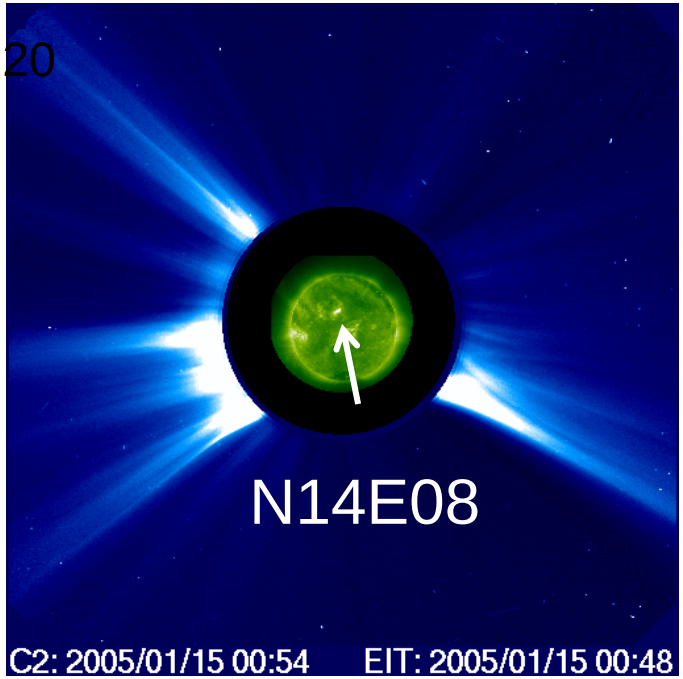
X1.2 Flare from AR 0720
(flare duration: 40 m)

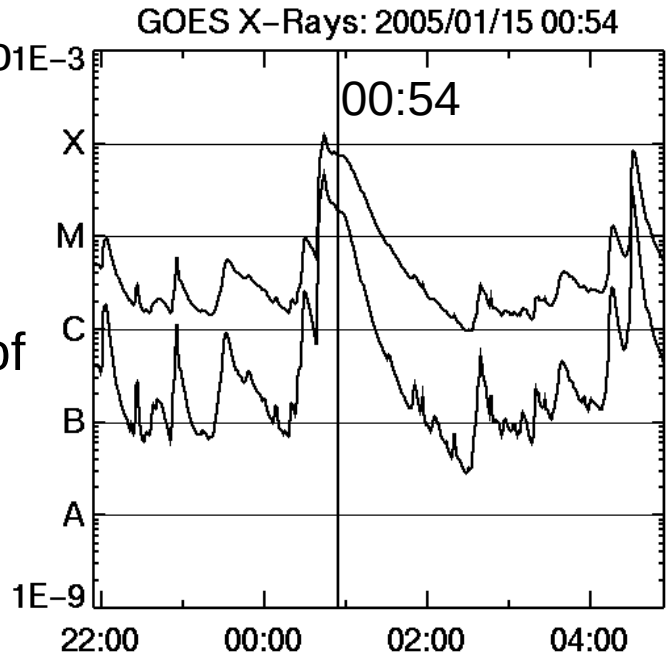
LASCO movies show
no mass motion

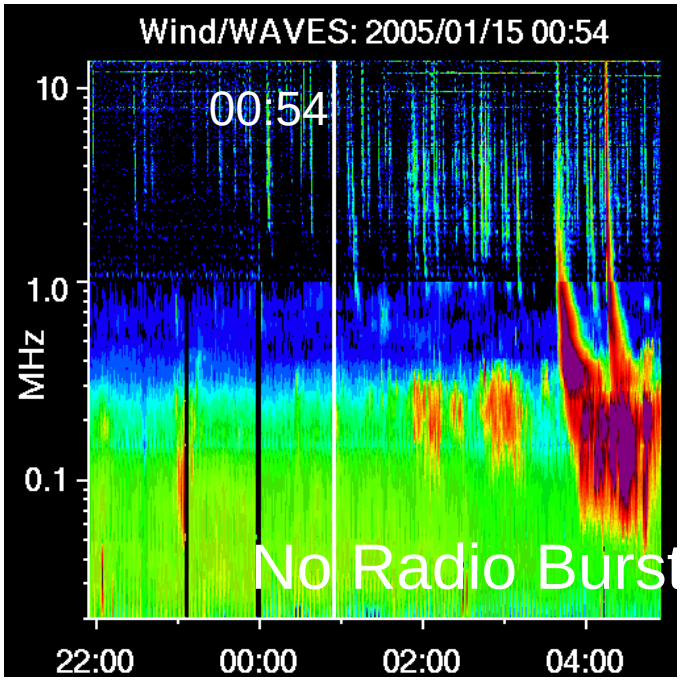
H-alpha flare (1 F)
showed no eruption

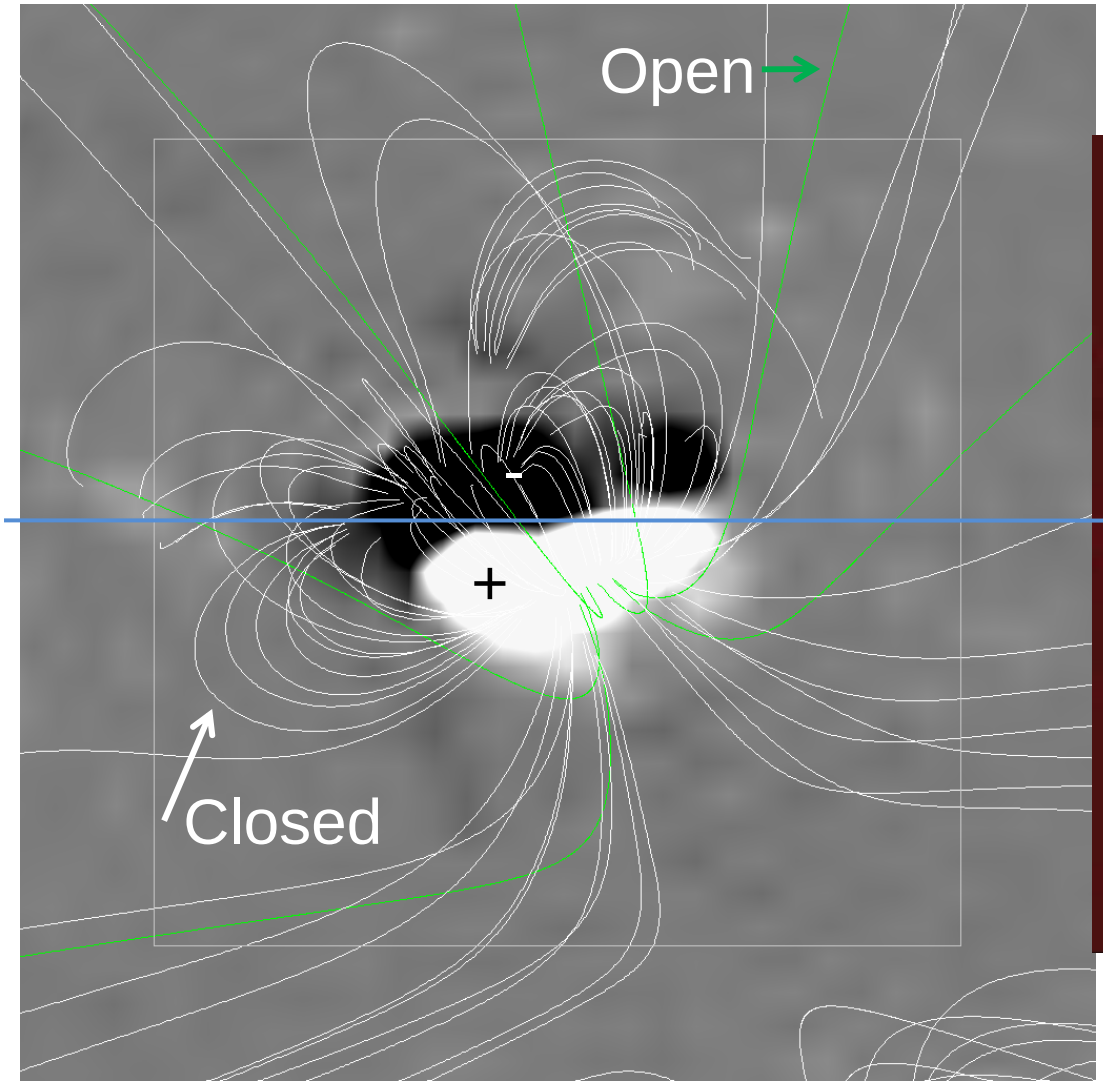
Intense microwave
burst 4474 SFU
peaking at 17 GHz
(from Nobeyama Radio
Polarimeter data).

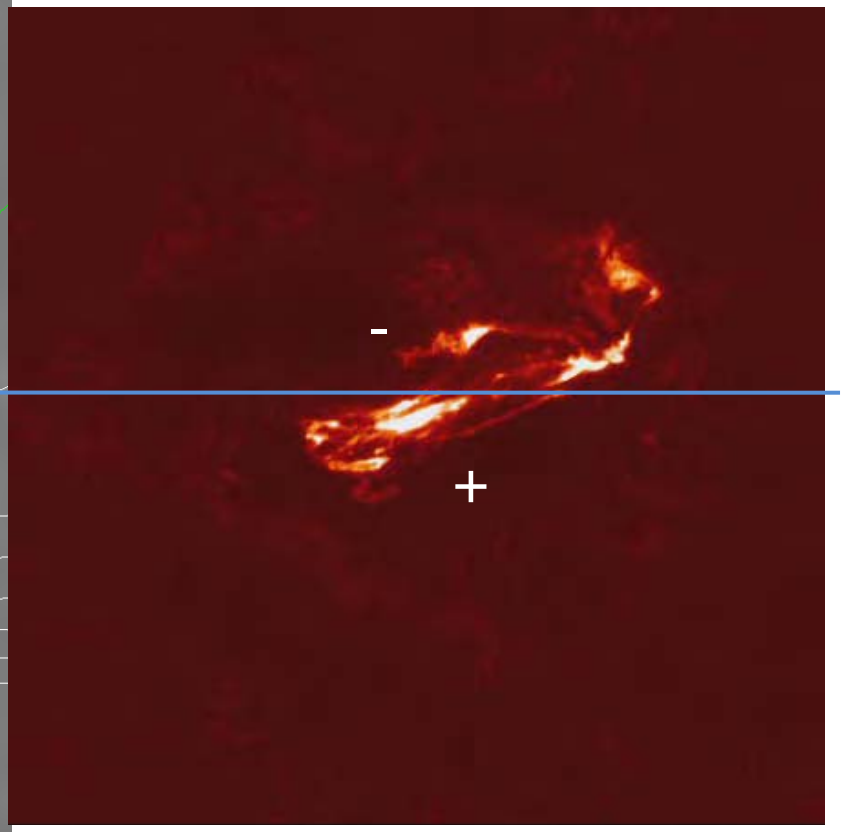
Hard X-ray burst from
RHESSI
No type radio burst of
any type associated
with the flare.
Nearest type III
was ~3 hours later.











TRACE 1600 Å Flare Image at 00:54

Potential field source surface extrapolation in the source region (AR 0720). Closed and open field lines shown. Note open field lines from the positive polarity patch. No type III → accelerated electrons had no access to open field lines, confined to closed field lines.

TRACE flare loops straddle the neutral line. Movie shows lots of motion within the loops, but no eruption. The flare loops are constrained by closed field lines.

Table 1 List of X-Class Flares without Associated CMEs

#	Flare Start	End	Dur	Imp	Location	AR #	H-α	III	μ fpk/flux
1	2000/06/06 13:30	13:39	16	X1.1	N18E12	9026[d]	N	N	2.7/560
2	2000/09/30 23:13	23:21	8	X1.2[c]	N07W90	9169	N	N	15.4/2800
3	2001/04/02 10:04	10:14	16	X1.4	N17W60	9393	1B[e]	Y	15.4/1200
4	2001/06/23 04:02	04:08	9	X1.2[c]	N10E23	9511	1B	N	5/100
5[a]	2001/11/25 09:45	09:51	9	X1.1[c]	S16W69	9704[d]	N	N	15.4/130
6	2002/10/31 16:47	16:52	8	X1.2[c]	N29W90	0162	N	N	8.8/3300
7[b]	2004/02/26 01:50	02:03	20	X1.1	N14W15	0564	2N[e]	N	15.4/830
8	2004/07/15 18:15	18:24	13	X1.6	S11E45	0649	N	N	8.8/530
9	2004/07/16 01:43	02:06	29	X1.3	S11E41	0649	N	N	15.4/1900
10	2004/07/16 10:32	10:41	14	X1.1	S10E36	0649	1F[e]	Y	15.4/1200
11	2004/07/17 07:51	07:57	8	X1.0	S11E24	0649	3B[e]	N	5/820
12	2005/01/15 00:22	00:43	40	X1.2	N14E08	0720	1F	N	15.4/3000
13[a]	2005/09/15 08:30	08:38	16	X1.1	S12W14	0808	2N	N	15.4/4100

[a]There were frequent blobs of material along the streamer near the position angle of the flare throughout the day.
[b]A small wisp of material was seen close to the north pole (PA ~350) at flare peak. This is probably unrelated to the flare.
[c] These flares were isolated; no other X-class flares from these regions. Rest of the regions had other X-class flares with CMEs. [d]These two regions had no open filed lines. [e]Listed as eruptive H-alpha flare.

Summary

- From timing relationships (flare, CME, Type II, Type III) it is difficult to say which mechanism is important
- Source location favors shock acceleration
- Standard eruption model also favors shocks because flare particles have hard time escaping into the interplanetary space
- However, every GLE event is accompanied by Type III bursts (open field lines)
- GLEs, like large SEP events, are consistent with shock acceleration :
- GLE associated CMEs are of highest energy (mostly halo CMEs and the average speed is ~2000 km/s)
- GLE events are associated with type II bursts at over a wide wavelength range (suggesting that the shock is strong throughout the interplanetary space)
- One GLE event originated from 30 degrees behind the west limb so the flare component may not propagate to Earth, while the shock component can.