Solar Origins of the October November 2003 Extreme Events

C2: 2003/10/23 08:54   EIT: 2003/10/23 08:48

C2: 2003/10/28 11:30   EIT: 2003/10/28 11:24

C2: 2003/11/02 17:54   EIT: 2003/11/02 17:48

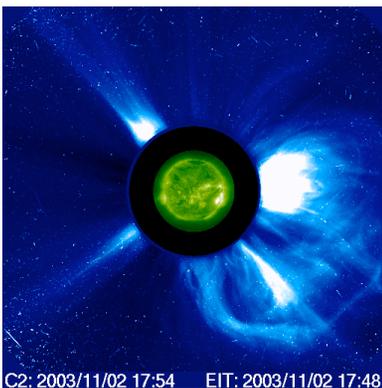C2: 2003/11/18 08:50   EIT: 2003/11/18 08:48

ALL CMEs 7567
Average 489 km s^{-1}
Fraction
Apparent Speed [km s^{-1}]

ALL CMEs 8008
Average 47 deg
Non Halo 7109
Fraction
Apparent Width [deg]
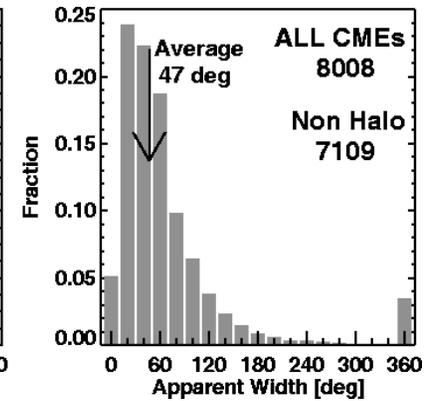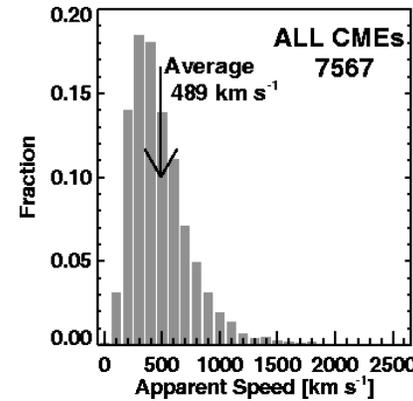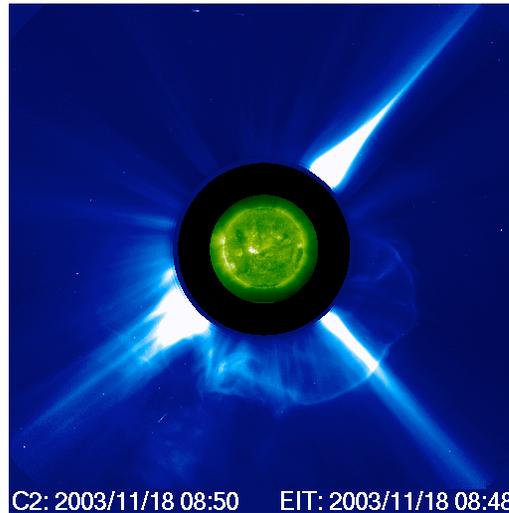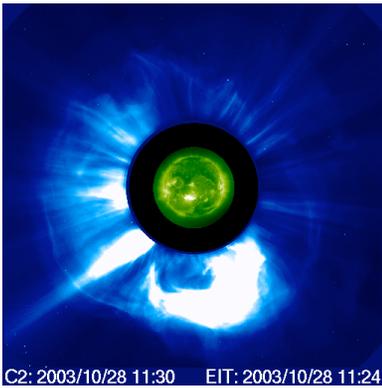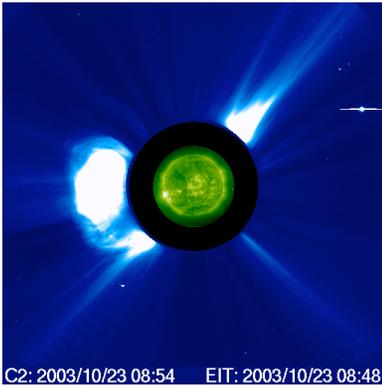
N. Gopalswamy

NASA/GSFC

SHINE 2004 WG3 Thursday, June 1 Big Sky, Montana

SOHO
Solar and Heliospheric Observatory
Observatoire Solaire et Héliosphérique
esa european space agency agence spatiale européenne   NASA
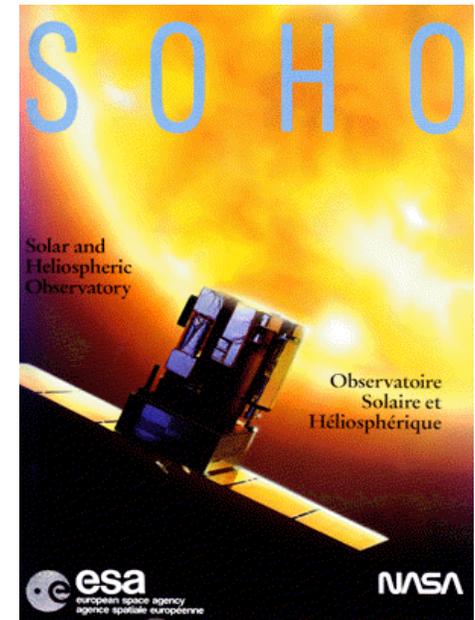
In this Talk…

- Properties of the Solar Source
- Properties of the October – November CMEs in comparison with the general population of SOHO/LASCO CMEs
- 1-AU arrival times of CME-driven shocks
- Limits to CME speed and Maximum energy extractable from solar active regions

Extreme Solar Eruptions of October-November 2003

- Extreme flare size (>X28)
- Extreme CME speed (2700 km/s)
- Extreme concentration of energetic CMEs
- Extreme concentration of IP radio bursts
- Extreme AR area: 0.26% of solar surface
- Extreme SEP event: 33,000 pfu
- Extreme ICME magnetic field ~ 60 nT
- Extreme geoimpact: - 465 nT
- Extreme solar wind speed (~2000 km/s)
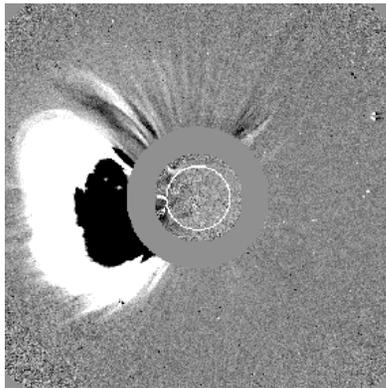
Eruption Centers
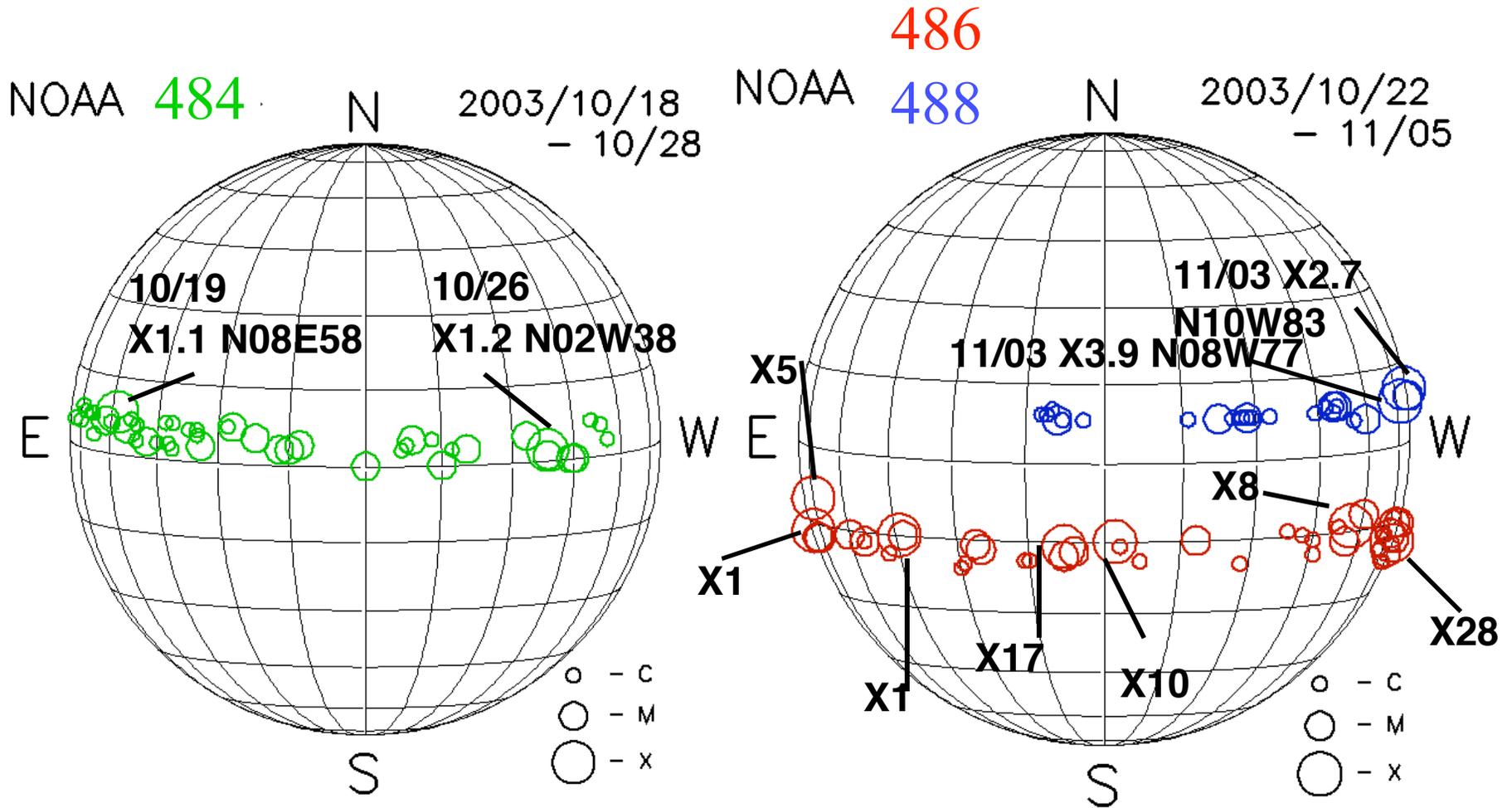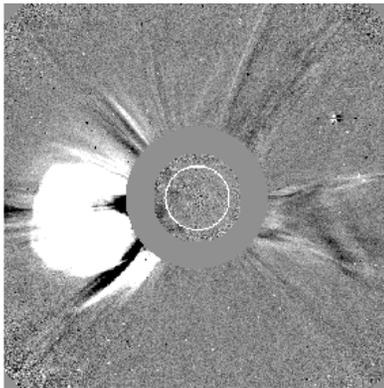
Recurrent Eruptions: Flares

- 143 flares from the three regions (X,M, & C only)
- Recurrence time of 3 h for dozens of flares.
- This means the regions released their free energy in fragments
- Average recurrence time is smallest for AR 484 (4.5 hours)
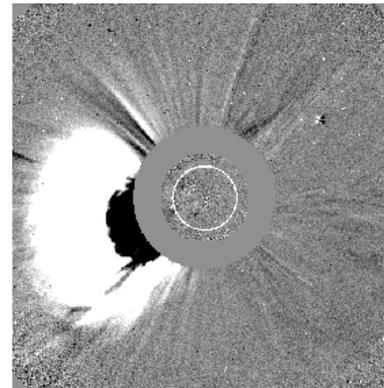- Largest number of total, M and X flares from AR 486
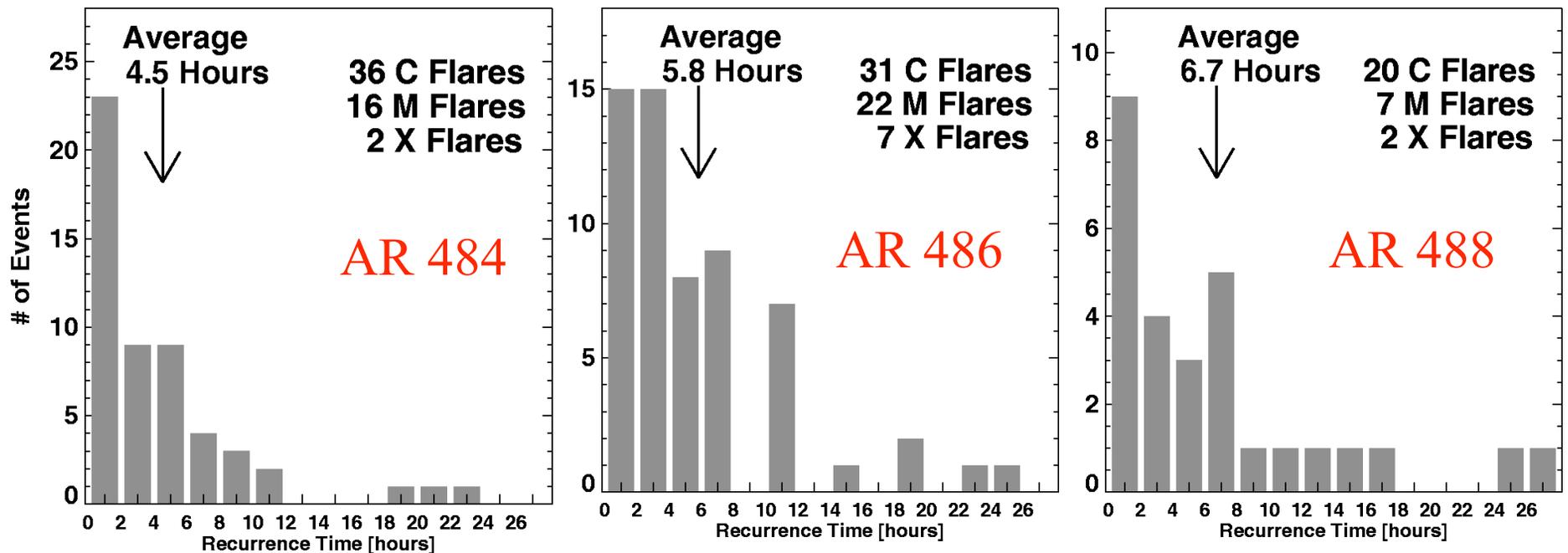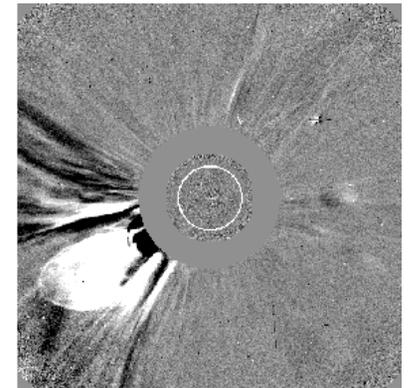
At least
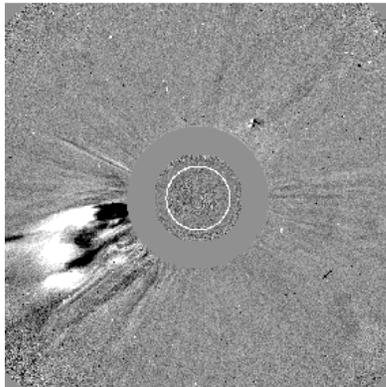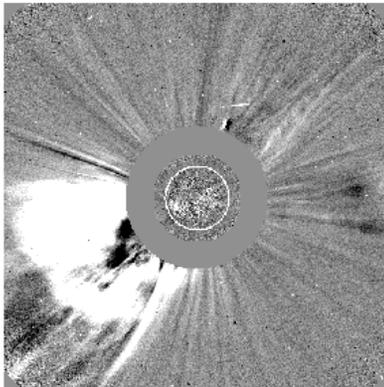74 CMEs
From
3 ARs,
0484
0486
0488

2003/10/23 09:06   2003/10/23 20:30   2003/10/24 03:30   2003/10/24 05:54

2003/10/24 21:30   2003/10/25 05:30   2003/10/26 06:54   2003/10/28 11:30
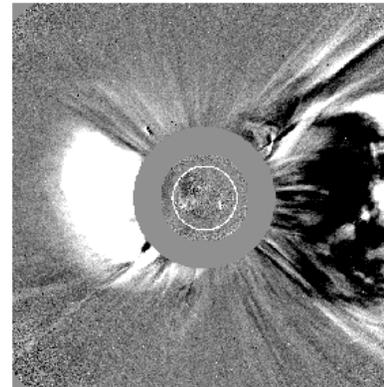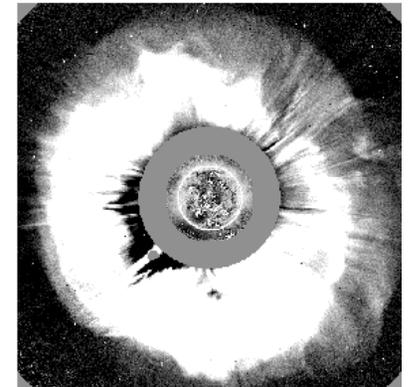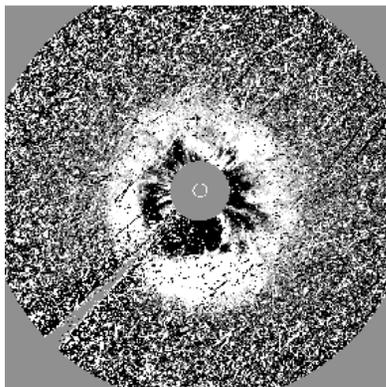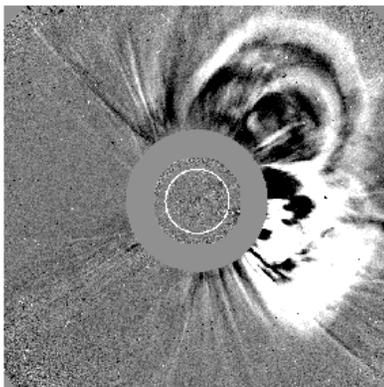
2003/10/29 22:18   2003/11/01 23:30   2003/11/02 17:54   2003/11/04 20:06
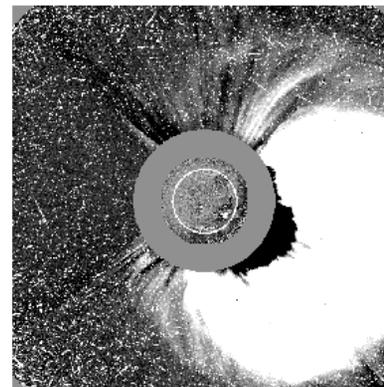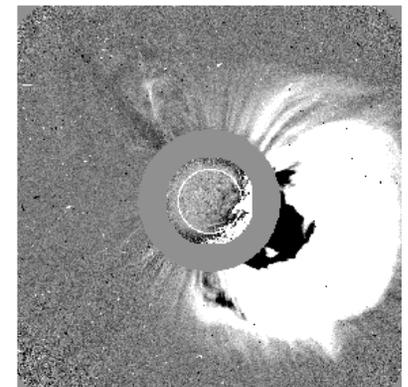
Oct-Nov 2003 CMEs with respect to CMEs of cycle 23
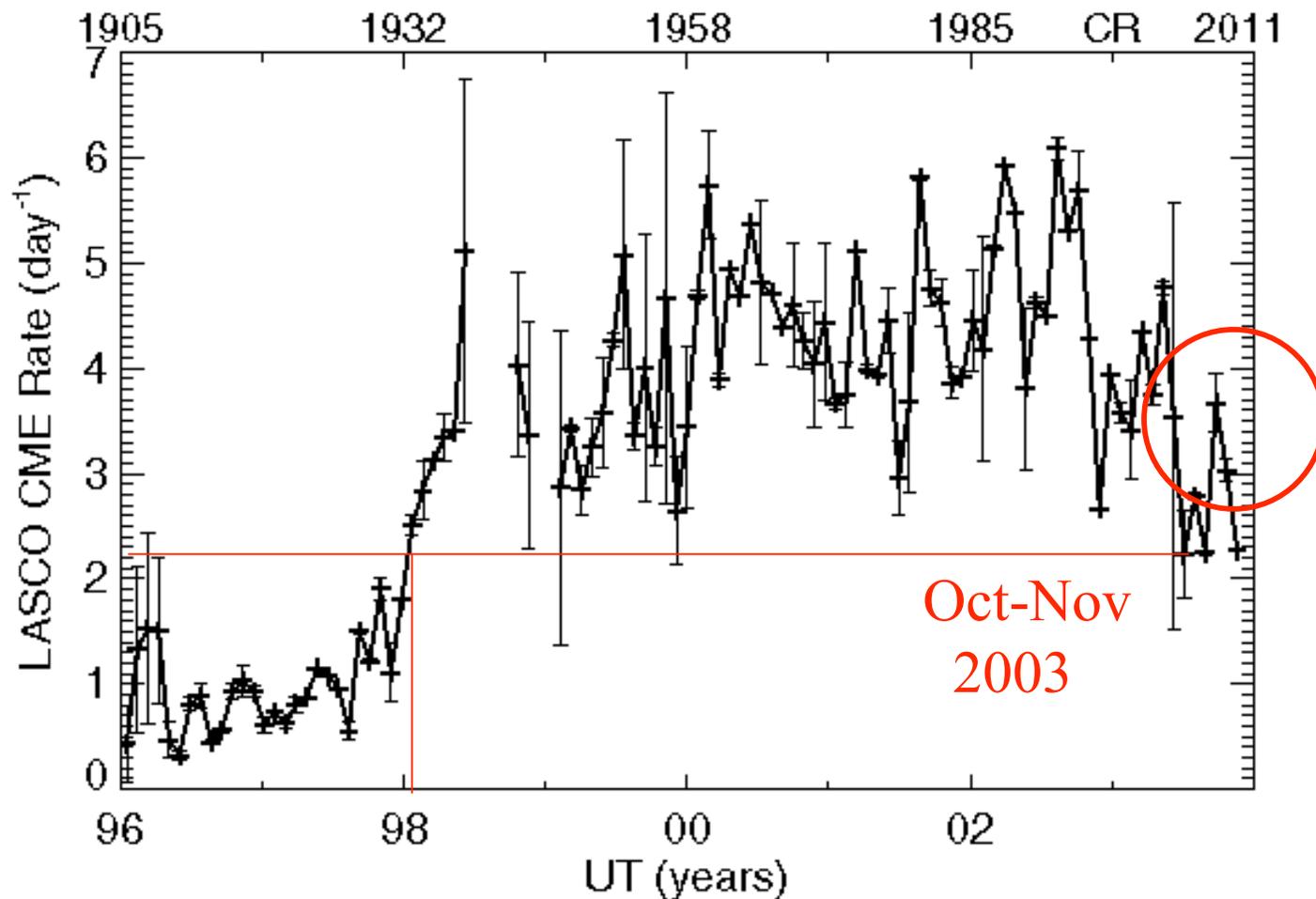
Oct-Nov 03 Vs Cycle 23 CMEs
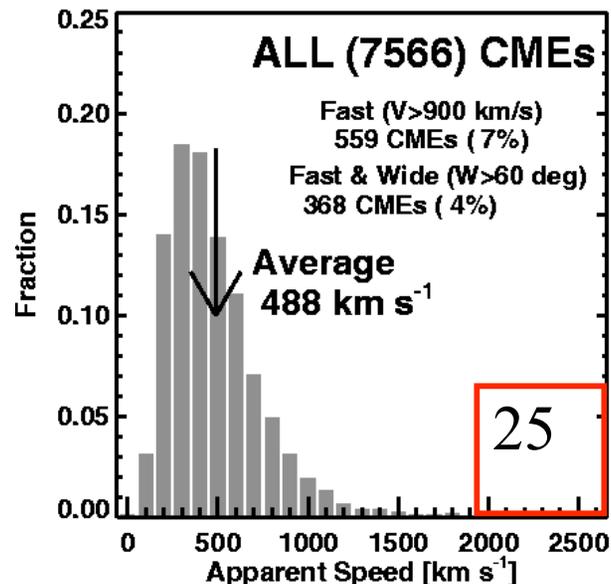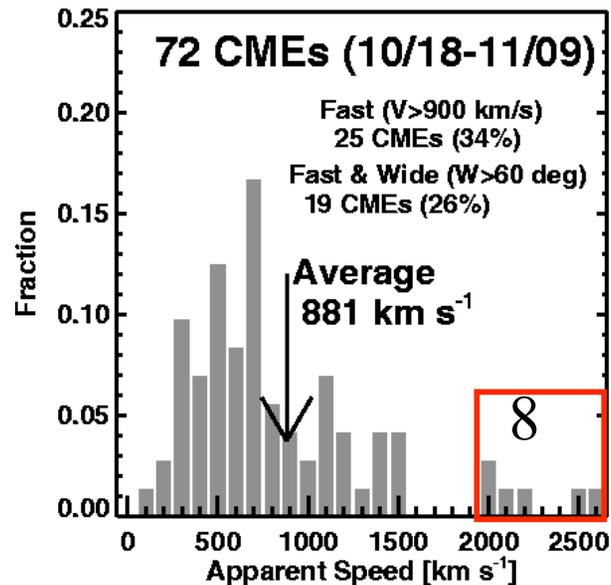
- Oct-Nov CMEs: faster & wider on the average

- The fastest CME (2657 km/s) occurred on Nov 04

- Large fraction of halo CMEs (13% Vs. 3%)

- Large fraction of ultrafast (>2000 km/s) CMEs (11% Vs. 0.3%)

Extreme Concentration Of energetic CMEs

Type II Radio Bursts: Shocks near the Sun
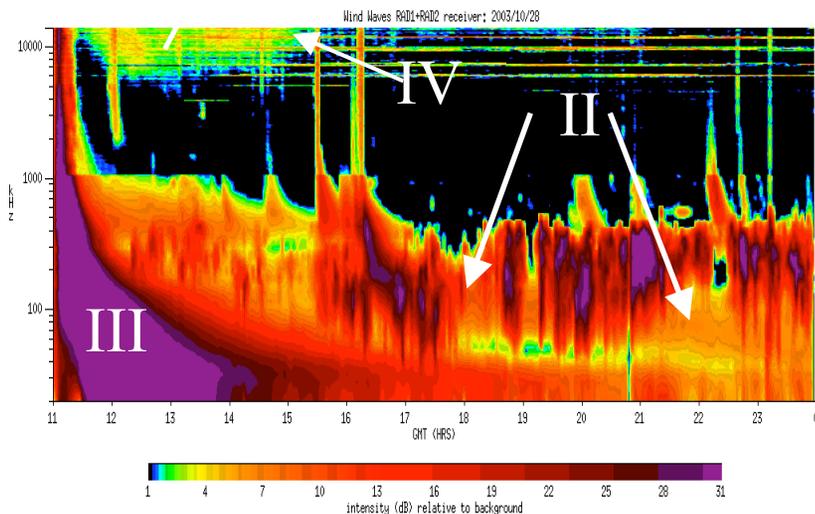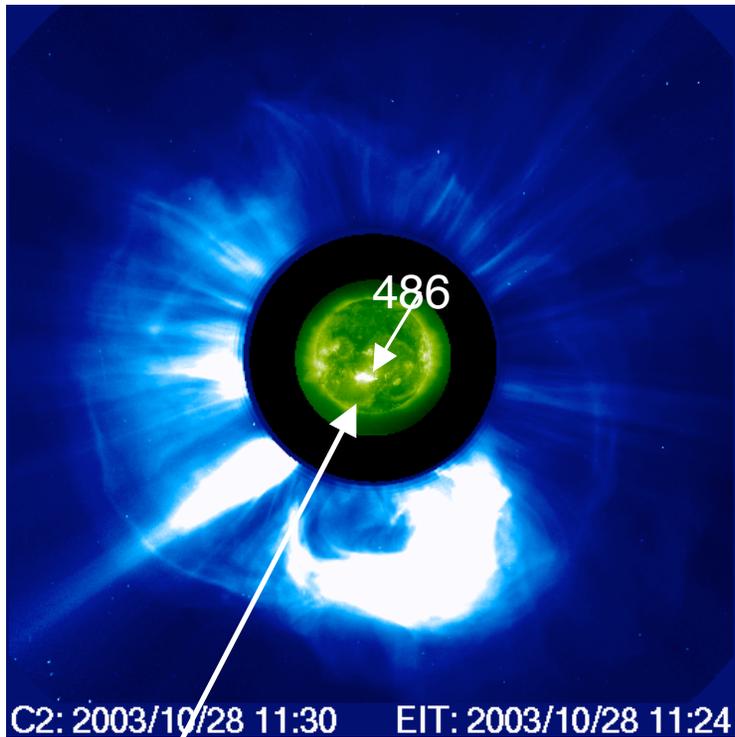
C2: 2003/10/28 11:30   EIT: 2003/10/28 11:24

	UT	Metri	DH-km	In situ
10/21	04:10	βIV	β	
10/26	07:00	βIV	β	
10/26	17:45	βIV	β	β
10/28	11:10	βIV	β β	β
10/29	21:15	βIV	β β	β
11/01	22:55	β	β	
11/02	09:23		β β	
11/02	17:30	βIV	β β	β
11/03	01:15	βIV	β	
11/03	10:00	βIV	β β	
11/04	20:00	βIV	β β	β
11/05	01:40	x	β	

12 DH type II bursts. 6 DH-km (~70 in cycle 23)
11 WAVES IV bursts. (Only 12 other in cycle 23!)

Eight Shocks Reached Earth During the Oct-Nov Period

SoHO/CELIAS/MTOF   Proton Monitor
Solar Wind Speed (km/s)
10/24 14:47

SoHO/CELIAS/MTOF   Proton Monitor
Solar Wind Speed (km/s)
10/26 07:49

SoHO/CELIAS/MTOF   Proton Monitor
Solar Wind Speed (km/s)
10/26 18:35

http://umtof.umd.edu/pm/

SoHO/CELIAS/MTOF   Proton Monitor
Solar Wind Speed (km/s)
11/04 05:53

SoHO/CELIAS/MTOF   Proton Monitor
Solar Wind Speed (km/s)
11/06 18:56 47h

ACE/SWICS T.Zurbuchen
2 hour averages
10/30 16:20
10/28 01:30
10/29 06:00

In situ Shocks & Associated CMEs

L1 Shock	CME (PA, speed, width)	Solar Region (Flare, AR, Loc)
10/24 14:47 UT	10/22 20:06 PA93 1085 km/s W=134	10/22 19:50 M9.9 AR0486 S22E90 ?
10/26 07:49 UT	10/23 08:54 PA088 1406 km/s W=115	10/23 08:19 X5.4 AR0486 S21E88
10/26 18:35 UT	10/23 20:06 PA101 1136 km/s W=089	10/23 19:50 X1.1 AR0486 S17E84
10/28 01:30 UT	10/26 17:54 PA 266 1537 km/s W=150	10/26 17:21 X1.2 AR 0484 S02W38
10/29 06:00 UT	10/28 11:30 PA092 2459 km/s W=360	10/28 09:51 X17.2 AR0486 S16E08
10/30 16:20 UT	10/29 20:54 PA092 2029 km/s W=360	10/29 20:37 X10.0 AR0486 S15W02
11/04 05:53 UT	11/02 17:30 PA262 2598 km/s W =360	11/02 17:03 X8.3 AR0486 S14W56
11/06 18:56 UT	11/04 19:54 PA257 2657 km/s W=360	11/04 19:29 X28 AR0486 S19W83
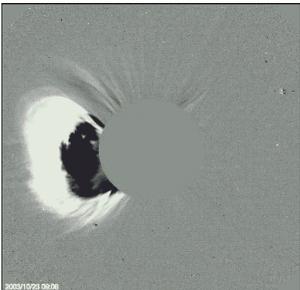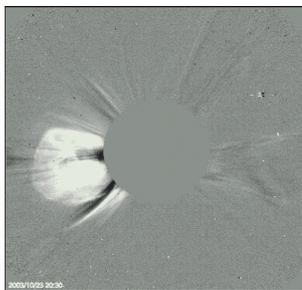
10/23 08:54   10/23 20:06   10/28 1054   10/29 20:37   11/02 17:30   11/04 19:54
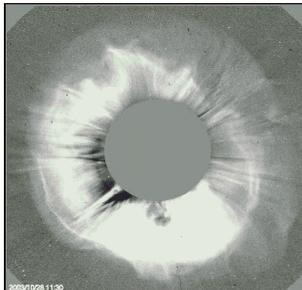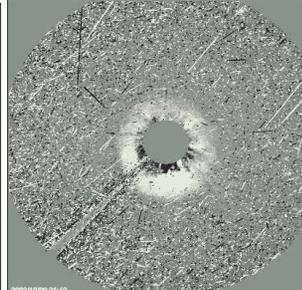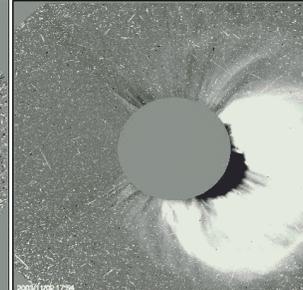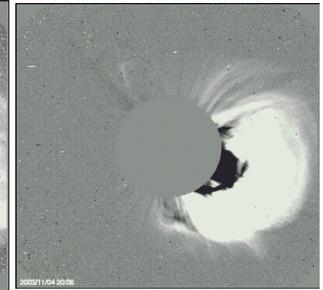
October-November 2003: Solar Energetic Particle Events (> 1000 pfu)

Ip = 10 pfu (> 10 MeV) is considered hazardous.
Three Ip >1000 pfu events occurred during Oct-Nov 03
(1 pfu = 1 proton/cm^2/s/sr)
Only 33 such events since 1976

	Year	# of SEP Events
	1996	-
Each 1	1997	-
denotes a	1998	1 1 Diff ARs
>1000 pfu	1999	-
event	2000	1 1 Diff ARs
	2001	1 1 1 1 1 Diff ARs
	2002	1 4/21
	2003	1 1 1 AR0486

All the three > 1000 pfu events (1) are from AR 486!
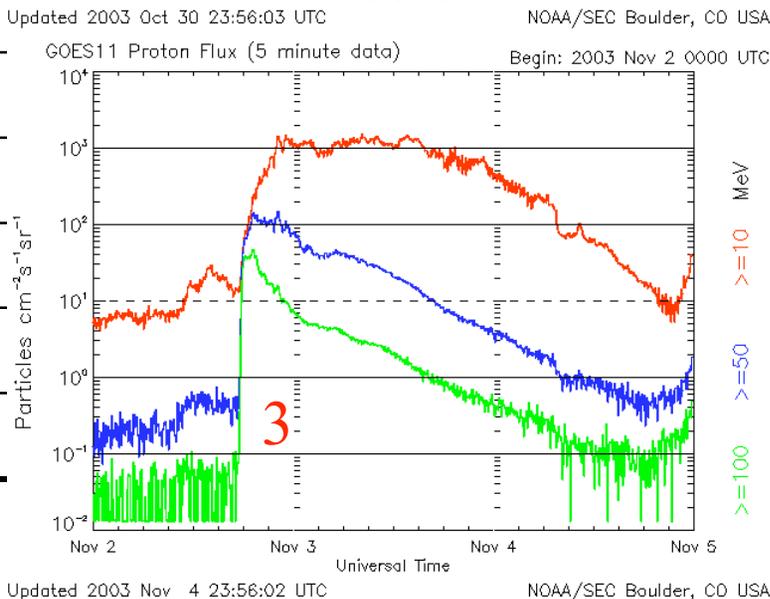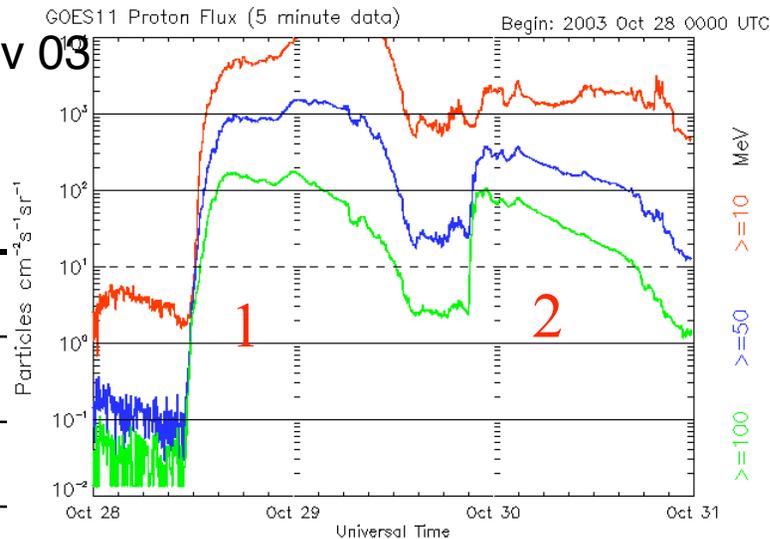
CMEs and SEPs

At least 5 large SEP
Events
- Mostly from 486
- One from 0484
-10/28 CME
produced the largest
> 10 MeV
flux (33,600 pfu)
>10^4 pfu Events: Cycle 23
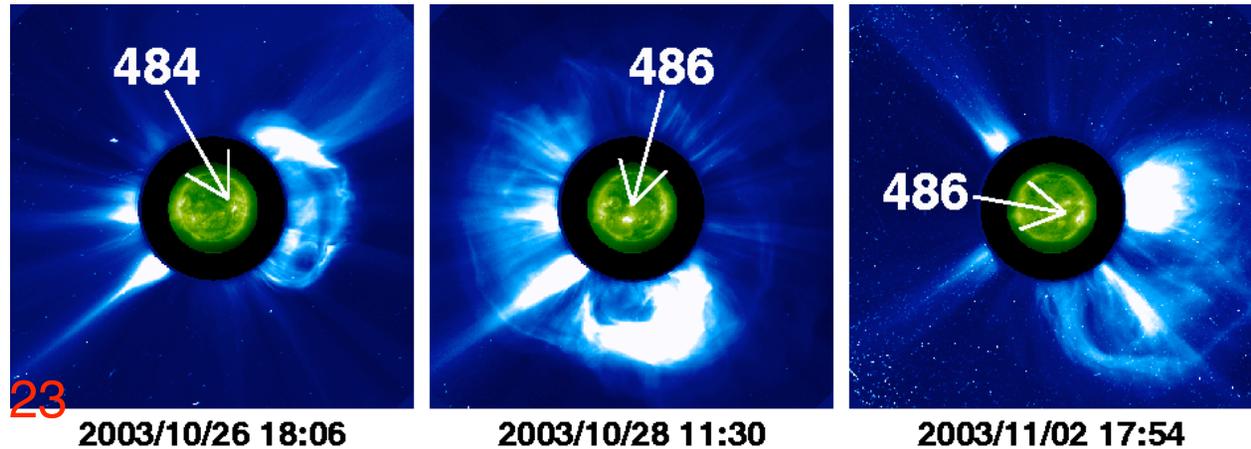
10/28/03	33,600
11/04/01	31,700
07/14/00	24,000
11/22/01	18,900
11/08/00	14,800
09/24/01	12,900

Bigger (since 1976):

10/19/1989	– 40,000
03/21/1991	– 43,000

484   486   486

2003/10/26 18:06   2003/10/28 11:30   2003/11/02 17:54

442 pfu   33600 pfu   3850 pfu   1210 pfu   145 pfu
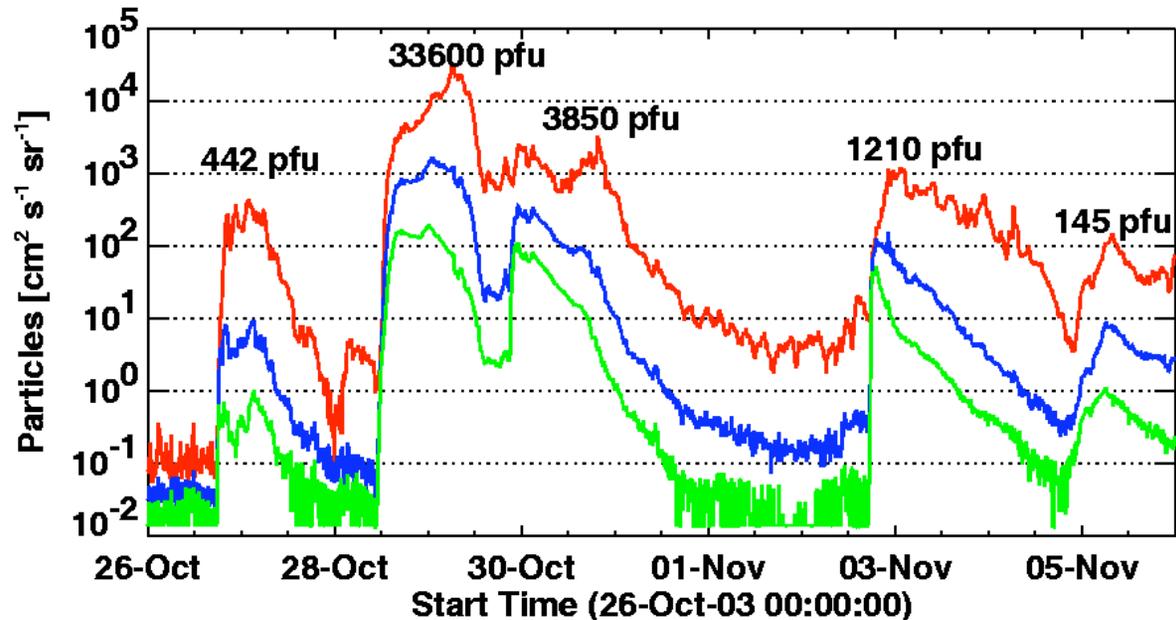
CME Speed vs 10 MeV Proton Intensity

- October Nov 2003 events extend the data points slightly to the right
- These plus the 1989 and 1991 events suggest an upper limit to the CME speed (~3000 km/s)

ALL

23 P: R=0.43, S=1.11
20 NP: R=0.58, S=0.66
14 Code *: R=0.68, S=1.45

Proton Flux [pfu]

CME Speed [km/s]

FRONTSIDE ONLY

21 P: R=0.70, S=0.92
11 NP: R=0.46, S=1.03
13 Code *: R=0.74, S=1.34

Proton Flux [pfu]

CME Speed [km/s]
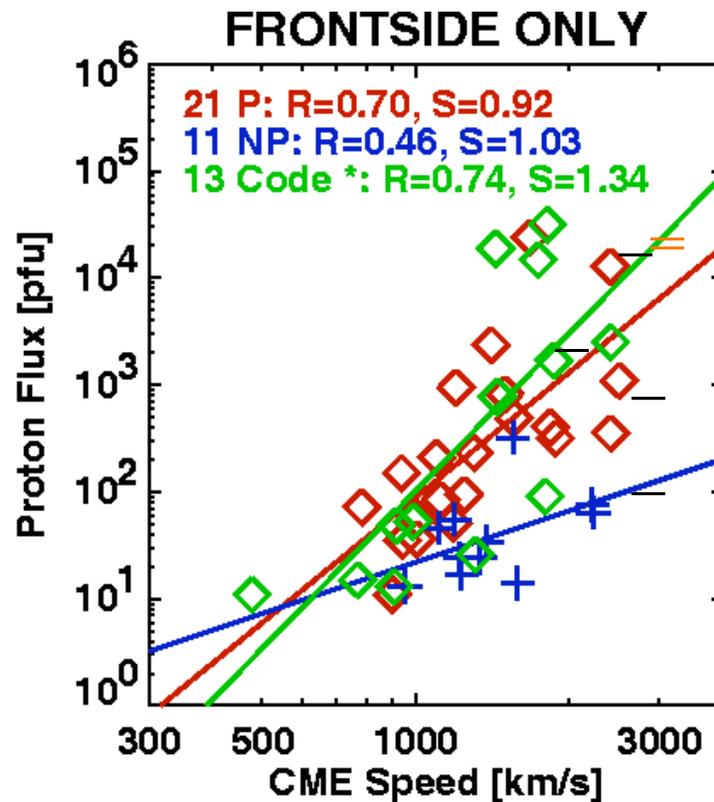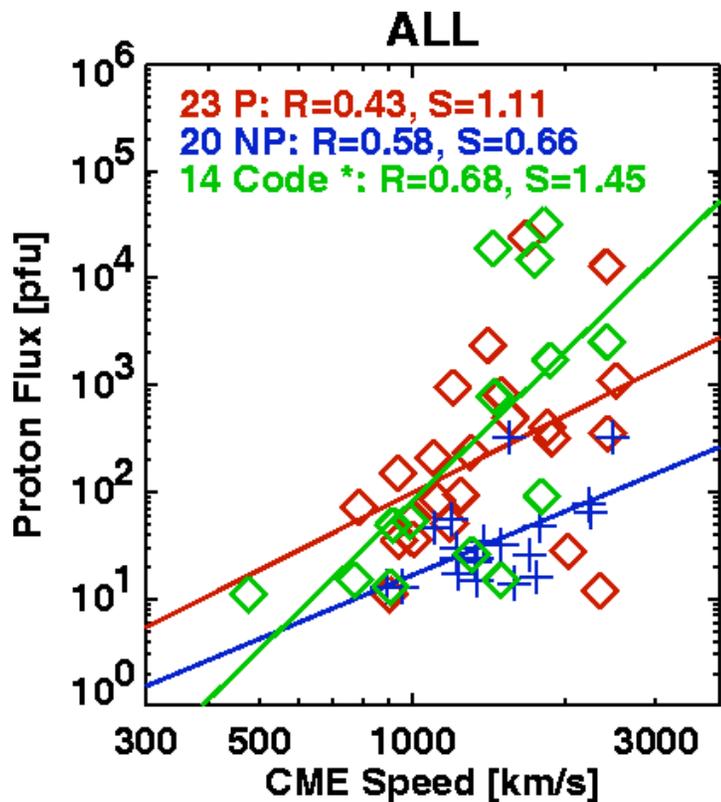
_ Oct-Nov03
_ 89, 91

Diamond symbols
Red: SEP events
With pre-CMEs
Blue: SEP events
W/o pre-CMEs
Green: Other
Interactions
(streamer interactio
Below occulting disl

Shocks from 10/28-29 `03 CMEs Arrived at Earth in < 20 h

Eruption Onset	TT (hrs)	Vcme (km/s)
04/15/38	21.2	2020
02/28/42	20.5	2080
02/07/46	17.8	2350
07/16/59	19.5	2170
08/04/72	14.6	2790
10/28/03	19.0	2459
10/29/03	19.7	2029
07/14/00	27.4	1670
10/26/03	31.5	1537
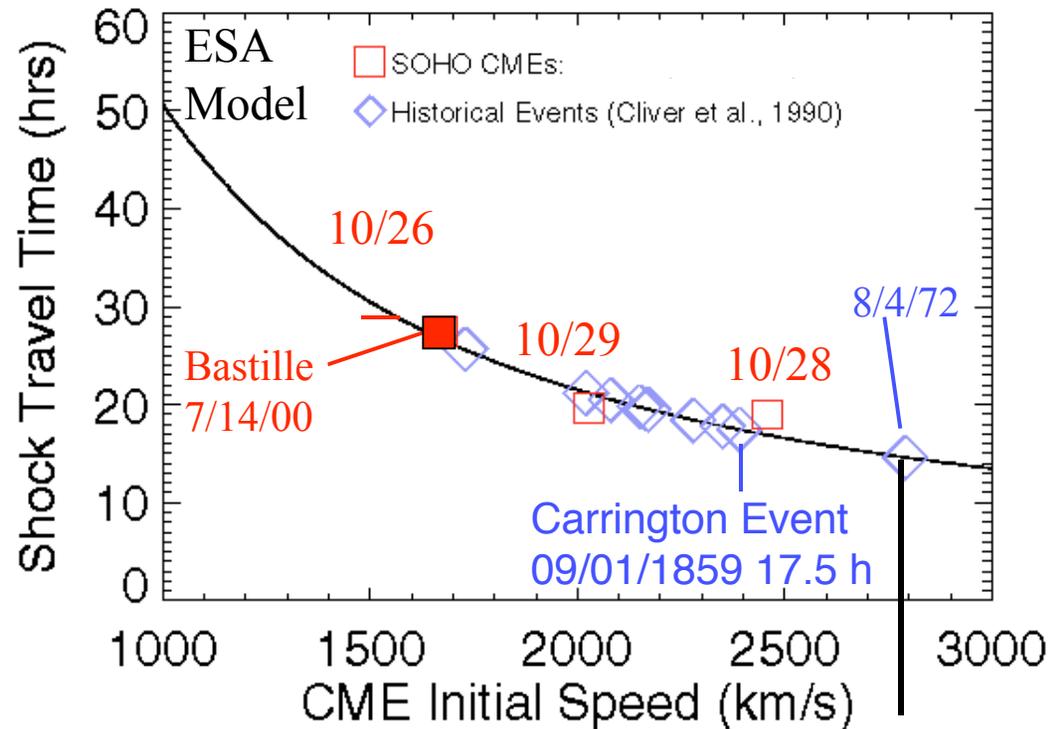
CME onset to shock arrival at L1

ESA Model

SOHO CMEs:
Historical Events (Cliver et al., 1990)

10/26
Bastille 7/14/00
10/29
10/28
8/4/72
Carrington Event 09/01/1859 17.5 h

2790km/s

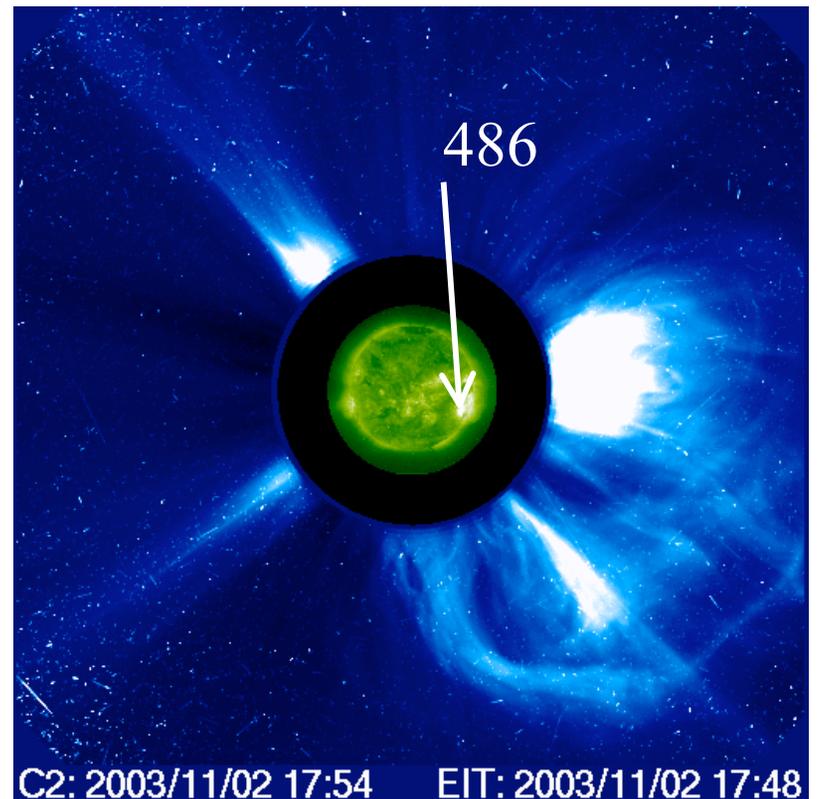# Fastest CME of Cycle 23

- 2003/11/04 CME: V = 2700 km/s
- Limb CME so speed is close to actual value
- Mass ~ 2×10^{16} g
- Kinetic Energy ~ 7×10^{32} erg
- The shock arrived after ~ 47 h because of grazing incidence.
- Similar to the inferred speed for the Aug 72 event

486

C2: 2003/11/02 17:54   EIT: 2003/11/02 17:48

Active Region Area as a Fraction of the Solar Hemisphere

#	NOAA	AREA	DATE
01	0486	2610	2003/10/30
02	9393	2240	2001/03/29
03	9169	2140	2000/09/20
04	0069	1960	2002/08/19
05	0484	1750	2003/10/23
06	0488	1750	2003/10/31
07	0105	1520	2002/09/11
08	8323	1460	1998/09/04
09	9690	1420	2001/11/11
10	8651	1370	1999/08/03

About 0.6% of the disk was covered by ARs
→ Implications to irradiance
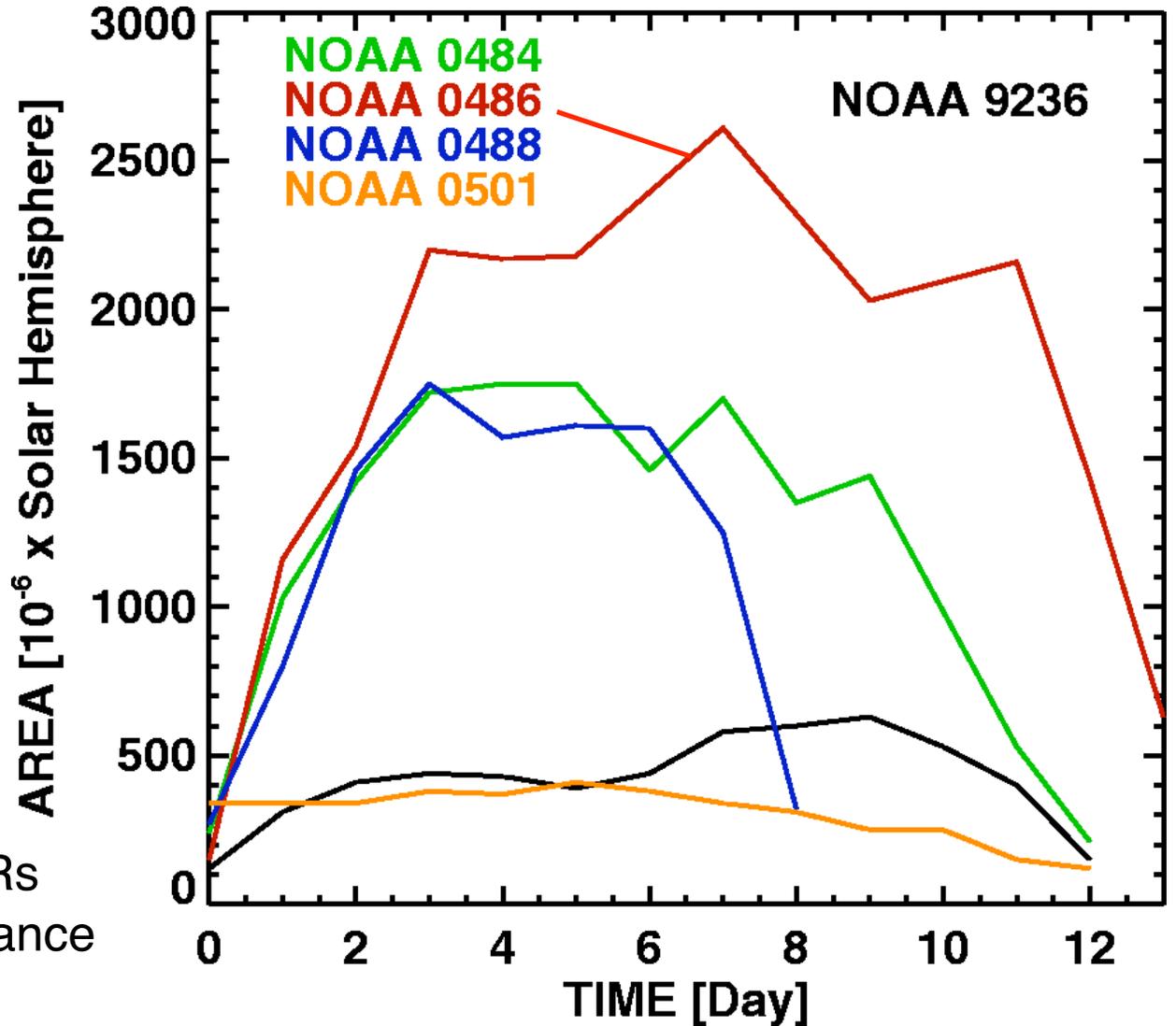
Total, Potential & Free Energies

- Potential $\frac{1}{8\pi} \int B_p^2 \, dV$ (from LOS B)

- Total $\frac{1}{8\pi} \int B_T^2 \, dV$ (from Vector B)

- Free Energy ~ Total – Potential

  ~ Potential Energy

See, however, Metcalf (2004), McTiernan (2004)
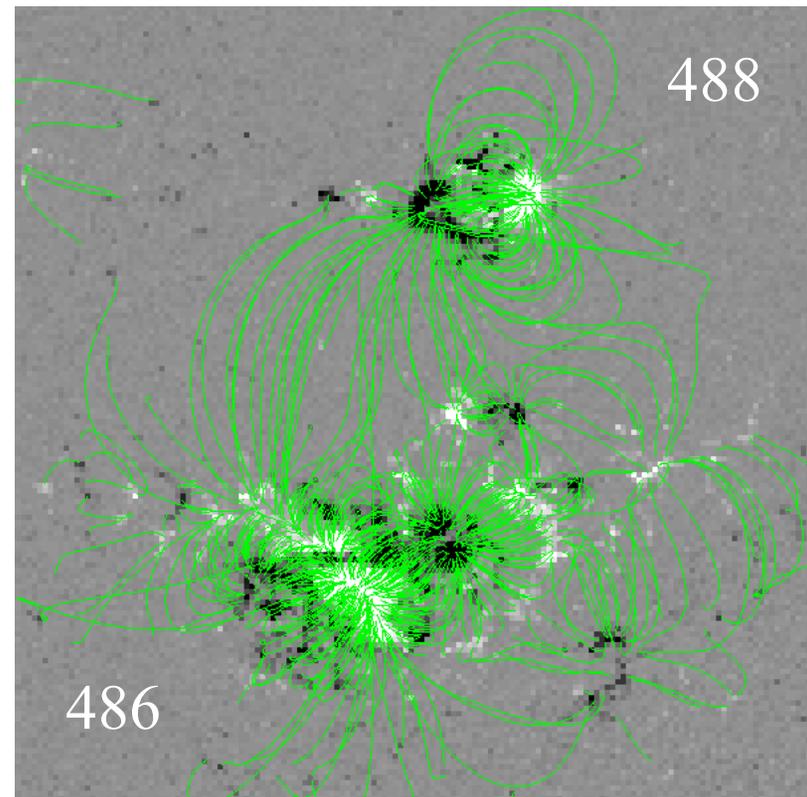
AR Potential Energy & CME Kinetic Energy

- AR 486: Volume ~ 10^{31} cm^3
  (300 x 300 x 300 arcsec^3)

- Potential Energy ~ 2×10^{33} erg

- Total Magnetic Energy ~ 2 x PE ~ 4×10^{33} erg

- Free energy ~ 2×10^{33} erg

- CME Kinetic Energy ~ 7×10^{32} erg

- ~1/3 of free energy goes into CME KE

For AR 7216 U_t ~3.2×10^{33} erg (Metcalf et al. 1995)
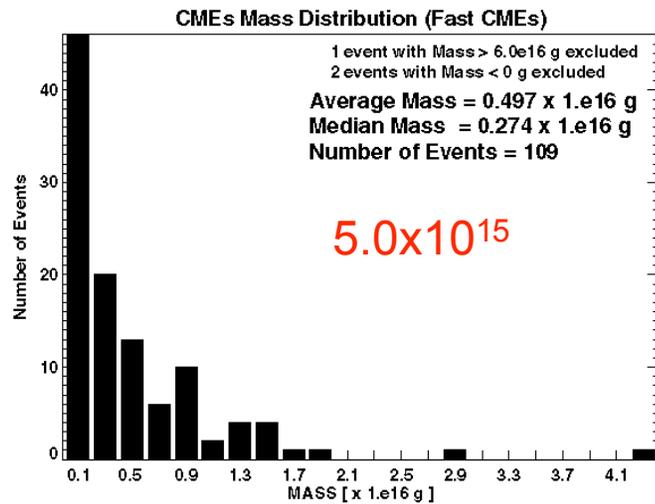All other forms of energy an order of magnitude lower for large CMEs (Emslie et al.2004 JGR)

Kinetic Energy of a 10^{17} g, 3000 km/s CME:
4.5×10^{33} erg → limit of CME energy & Travel time

Potential Field Extrapolation From MDI Magnetogram

488

486

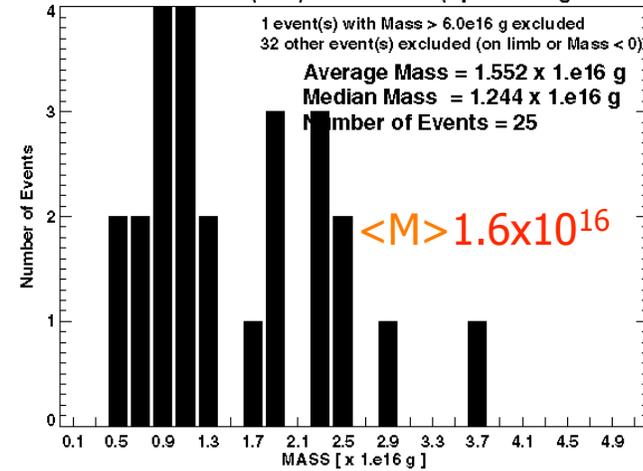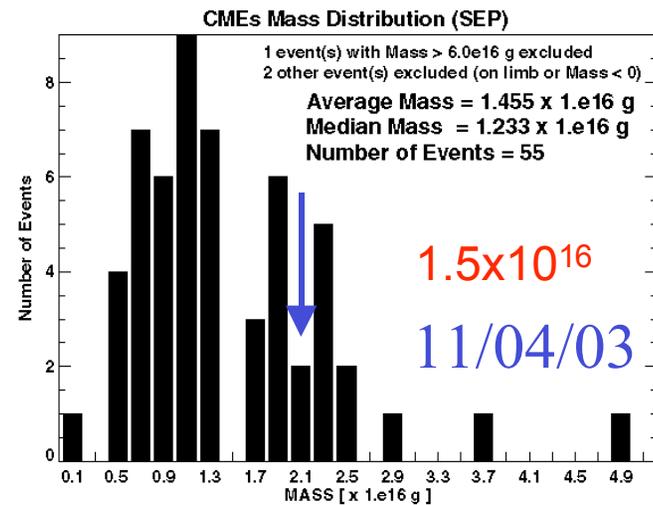Courtesy: Yang Liu

CME Masses

CMEs Mass Distribution (Fast CMEs)

1 event with Mass > 6.0e16 g excluded
2 events with Mass < 0 g excluded
**Average Mass = 0.497 x 1.e16 g
Median Mass = 0.274 x 1.e16 g
Number of Events = 109**

5.0×10^{15}

CMEs Mass Distribution (SEP) Limb events (Up to 30 degrees off-limb)

1 event(s) with Mass > 6.0e16 g excluded
32 other event(s) excluded (on limb or Mass < 0)
**Average Mass = 1.552 x 1.e16 g
Median Mass = 1.244 x 1.e16 g
Number of Events = 25**

$<M>1.6 \times 10^{16}$

CMEs Mass Distribution (SEP)

1 event(s) with Mass > 6.0e16 g excluded
2 other event(s) excluded (on limb or Mass < 0)
**Average Mass = 1.455 x 1.e16 g
Median Mass = 1.233 x 1.e16 g
Number of Events = 55**

1.5×10^{16}

11/04/03

$<M> \sim 1.5 \times 10^{15}$ g for all CMEs
(Vourlidas 2004)

Worst-Case Scenario

- There were only 25 of the 8000 CMEs had speed > 2000 km/s; only 4 with speed > 2500km/s

- Inferred speeds of historical events is < 2800 km/s

- CMEs probably have a speed limit of ~ 3000 km/s

- This limit arises from the maximum energy extractable from an active region (<10^{34} erg)

- The Sun-Earth Travel time of shocks has a limit of ~ half a day

$$t = a.b^v + c$$
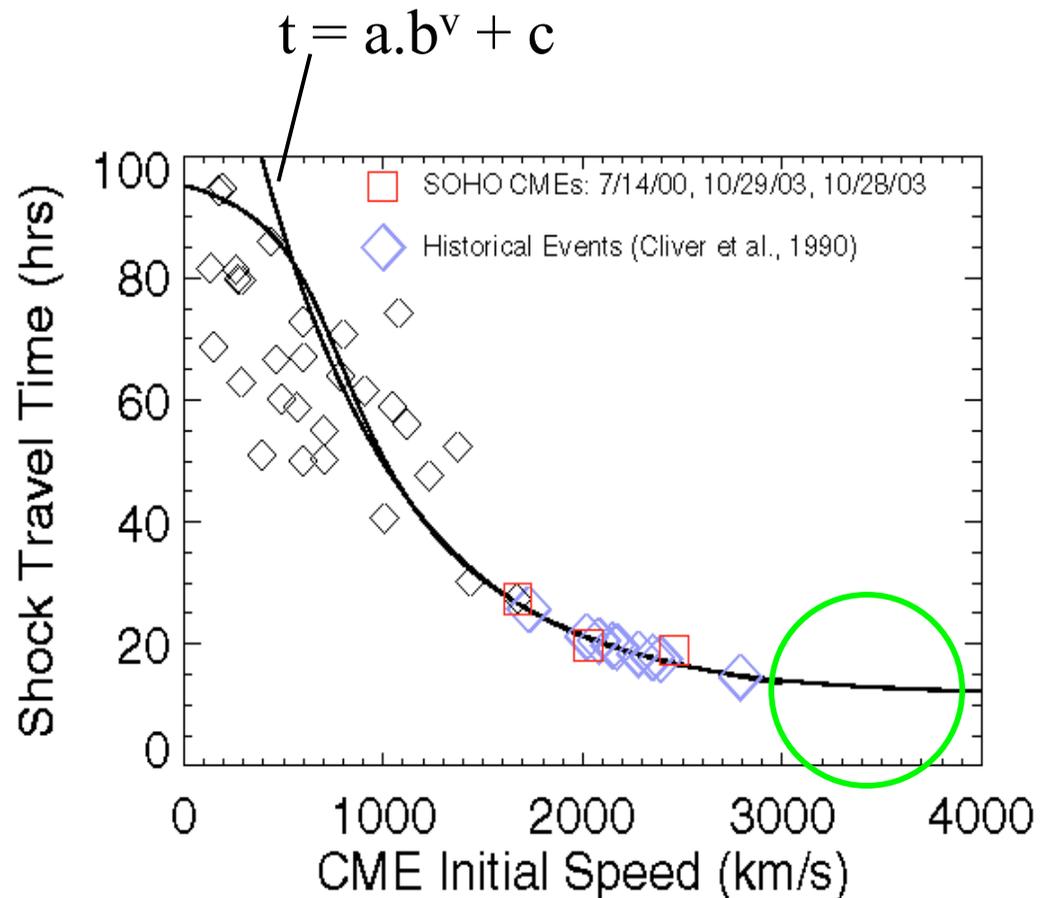
CMEs Don't Kill Dinosaurs

There is a limit to the maximum energy extractable from solar active regions

- Historical Shock Transit Times
- SOHO's Extensive Observations (M, V)
- Empirical Shock Arrival Model Curve
- Measured Size of Active Regions
- Measured Photospheric Magnetic Field (B)
- CME Kinetic Energy
- Estimated Magnetic Potential Energy

October-November 2003 Geomagnetic Storms

Storms of Cycle 23 with Dst < -200 nT

00 2003/11/20 24:00 -465

01 2003/10/30 23:00 -401

02 2001/03/31 09:00 -358

03 2000/07/16 01:00 -301

04 2000/04/07 01:00 -288

05 2001/11/06 06:00 -277

06 2001/04/12 00:00 -256
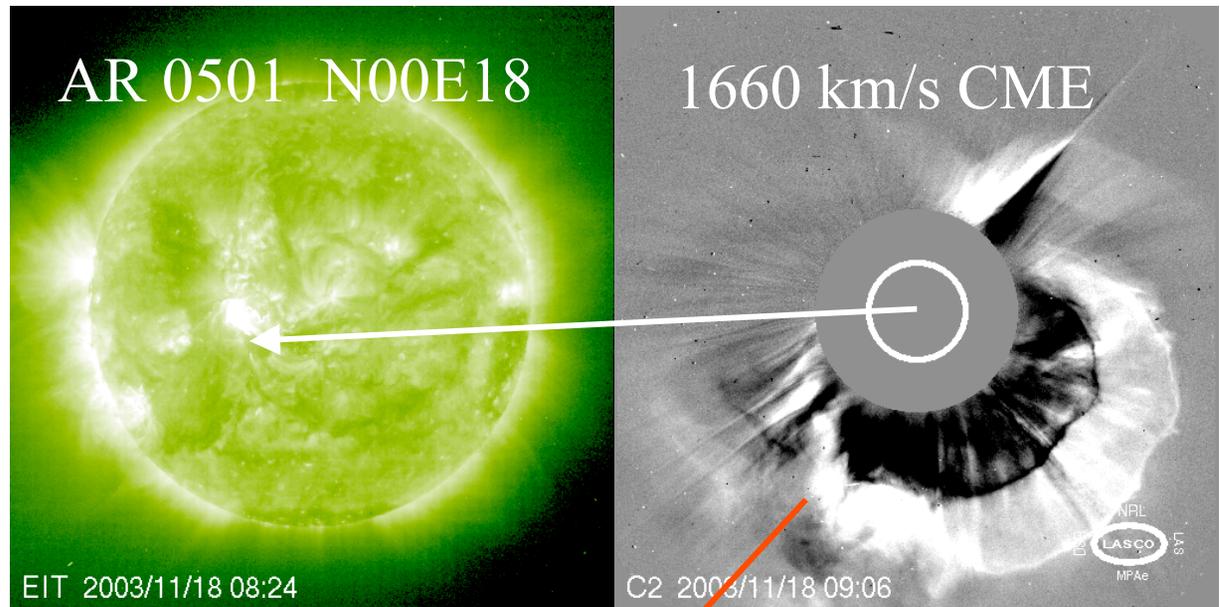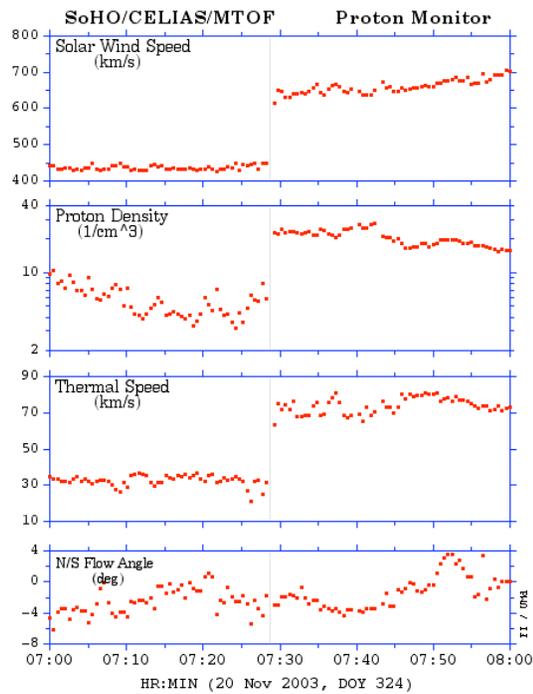
07 1999/10/22 07:00 -237

08 2000/08/12 10:00 -235
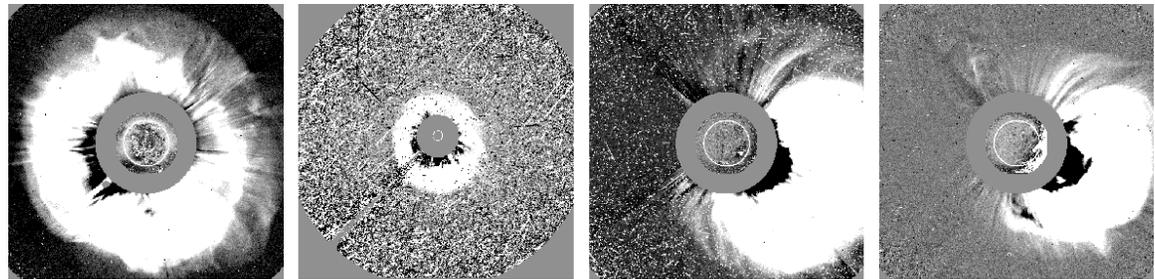
2003/10/28 11:30   2003/10/29 21:42   2003/11/02 17:54   2003/11/04 20:06

-363 nT

-401 nT

-84 nT

Only SC
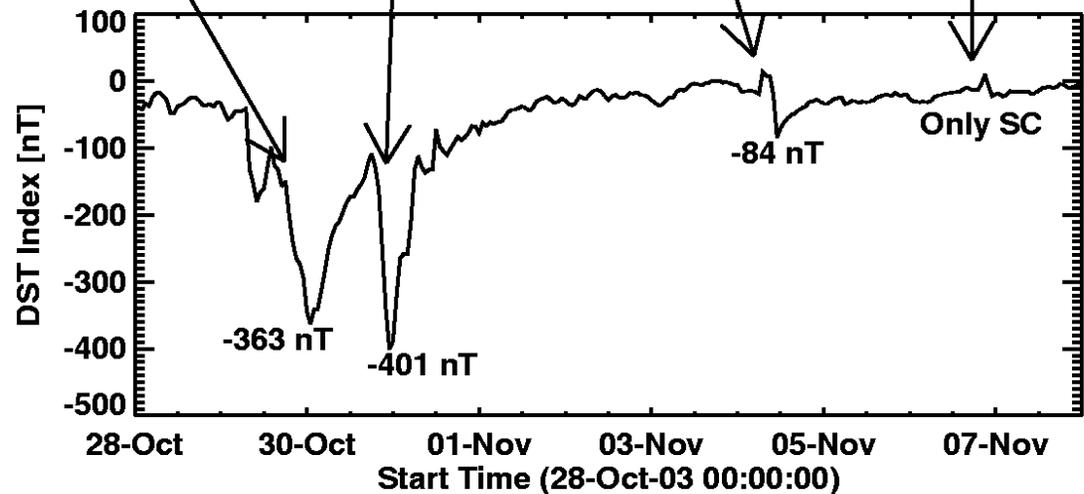
October-November 2003 Geomagnetic Storms:
Return of the Dragon

Unusually Large Travel time for a fast CME. Why?

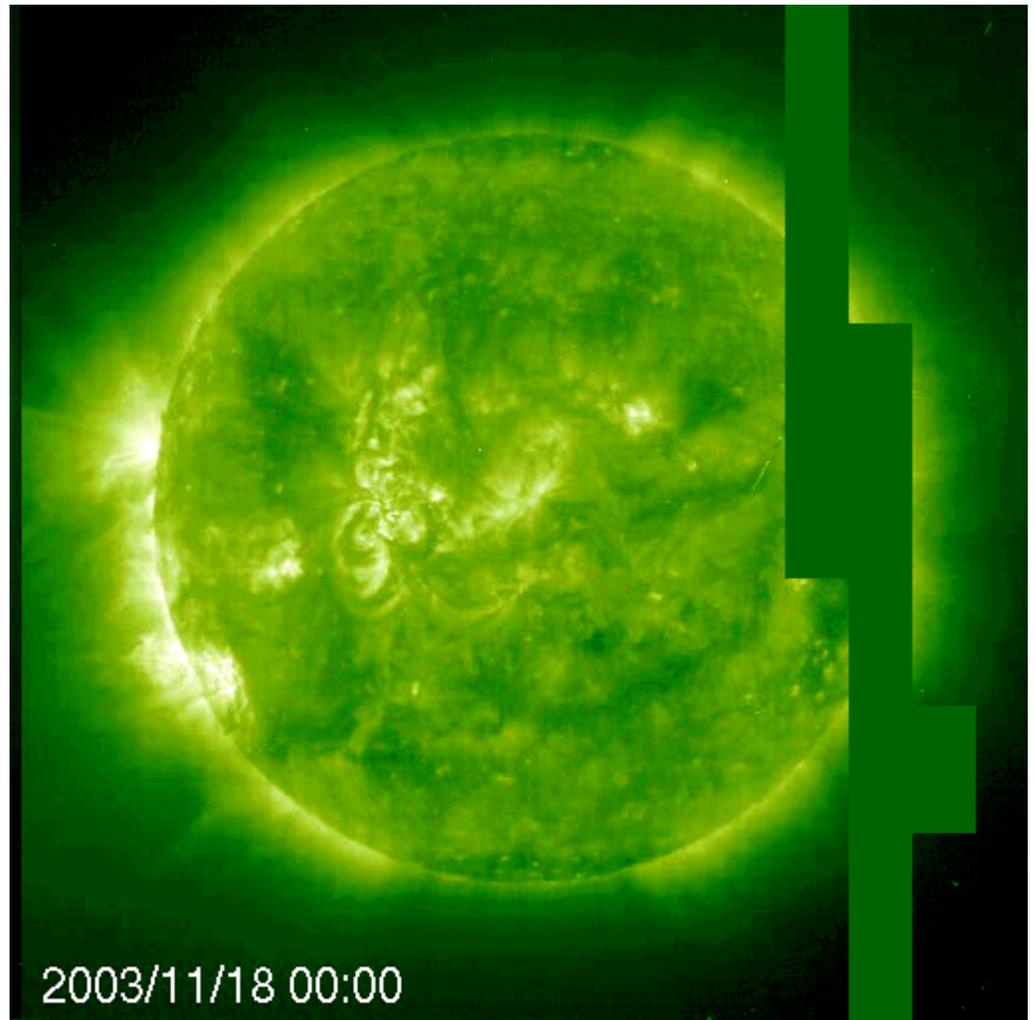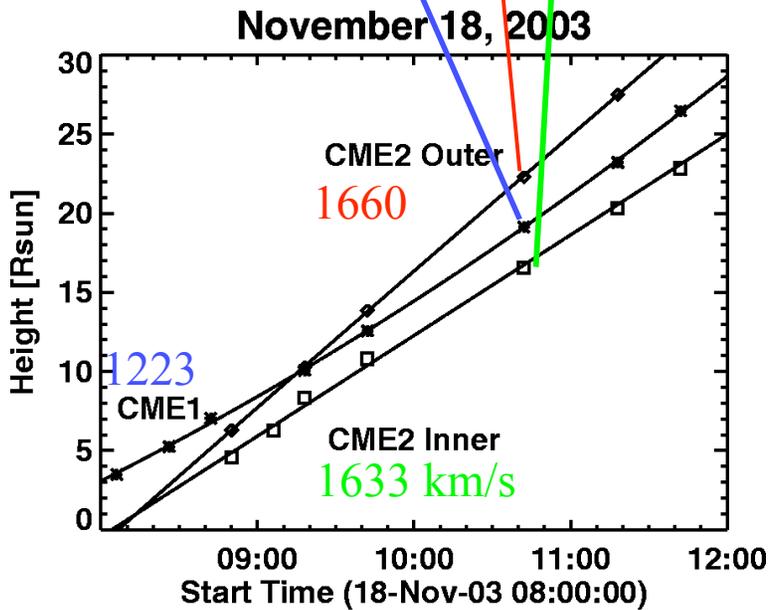CME onset: 11/18 08:15
L1 shock: 11/20 07:30
Travel time ~ 47 h
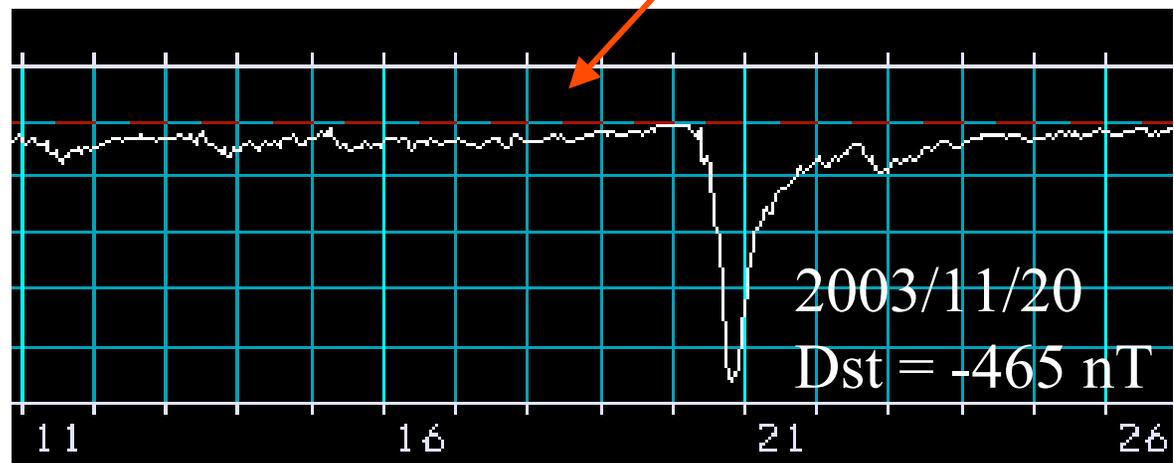
Why did the 2003/11/18 CME-shock arrived so late?
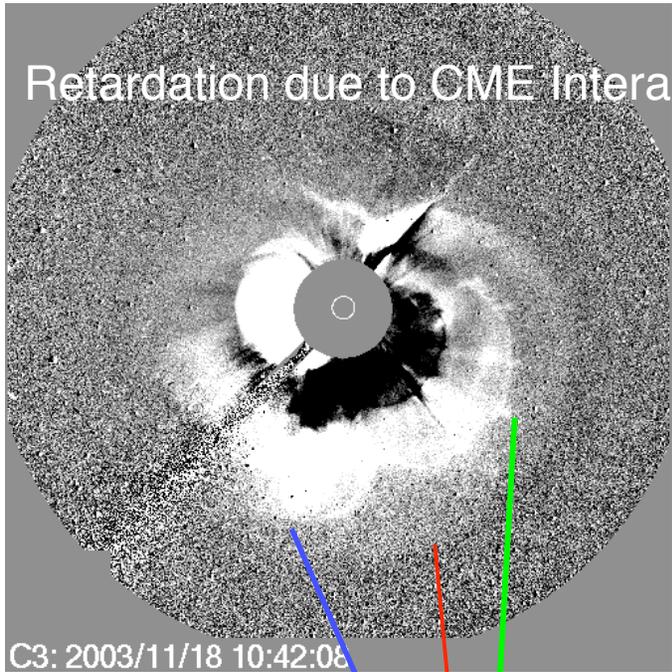
V= 1660 km/s
T = 47 h

2003/11/18 CME
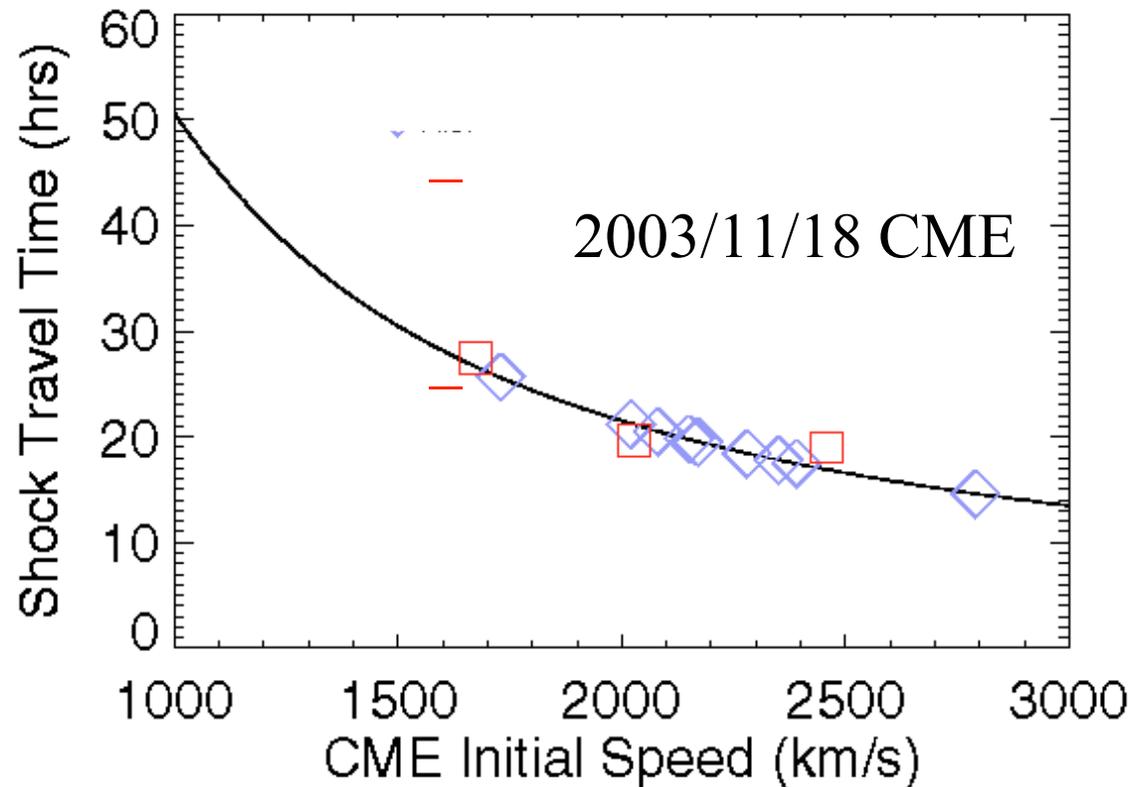
Extreme Deceleration of 11/18/03 CME

CORONAL HOLE DEFLECTS CME?

Retardation due to CME Intera

C3: 2003/11/18 10:42:08

November 18, 2003

CME2 Outer
1660

1223
CME1

CME2 Inner
1633 km/s

Height [Rsun]

Start Time (18-Nov-03 08:00:00)

2003/11/18 00:00

Extreme Impact on Geospace

78 Geomagnetic Storms During 1996–2003
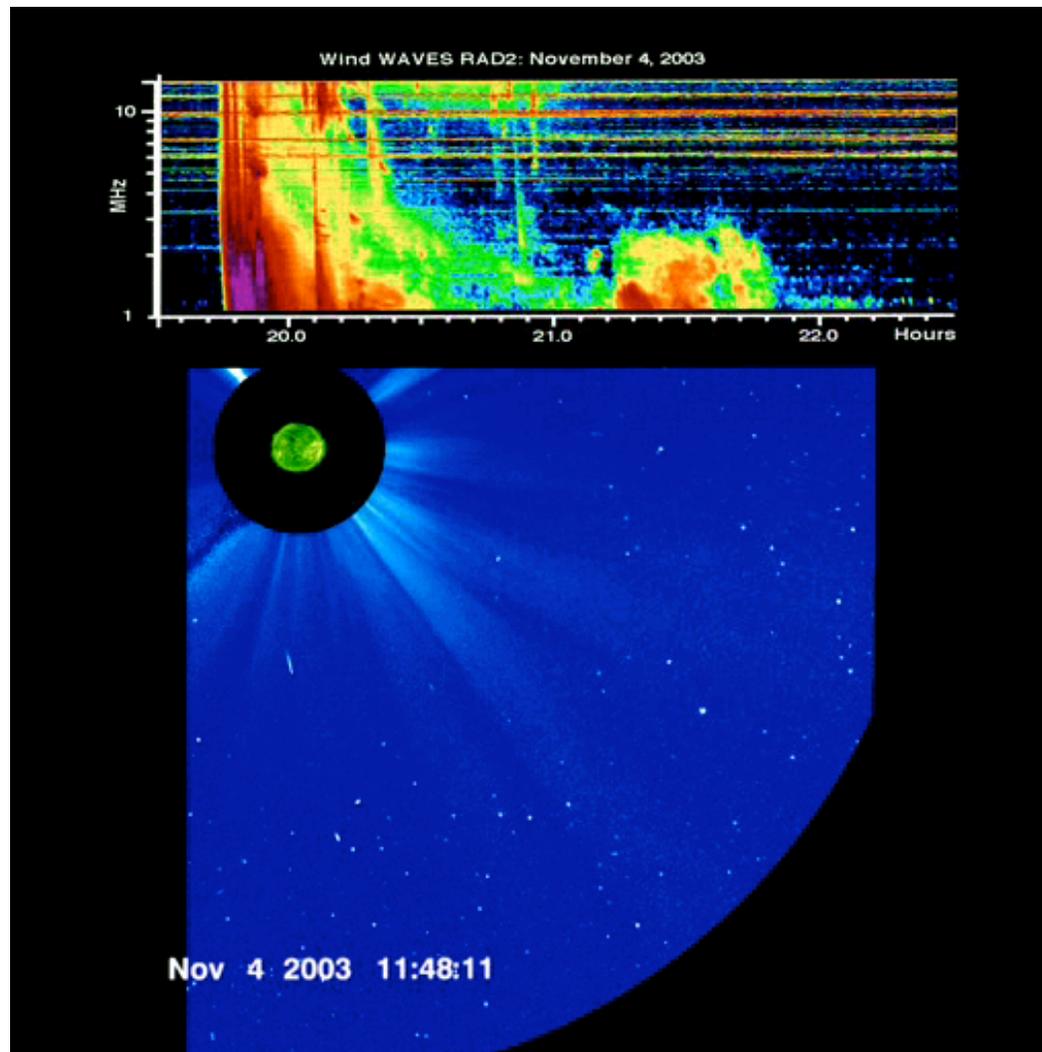
Cycle 23 Storms Dst < -100 nT

Bastille   10/30   10/31   11/20
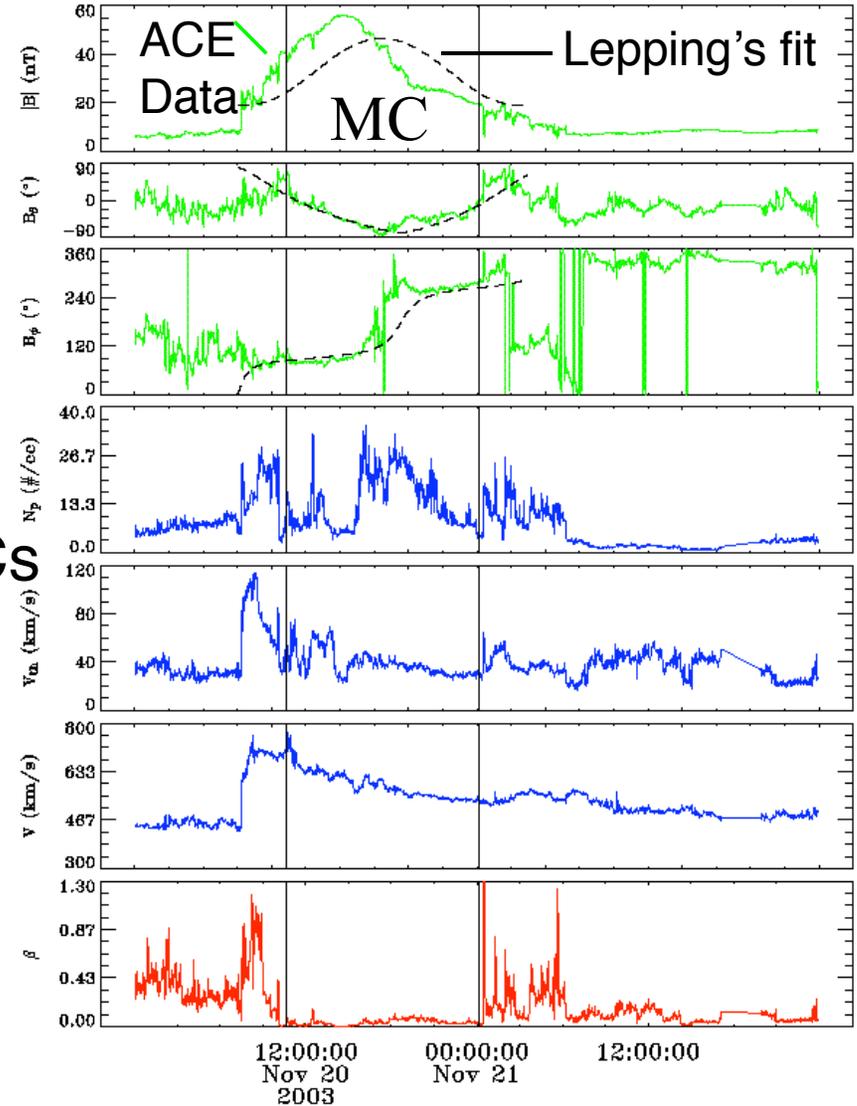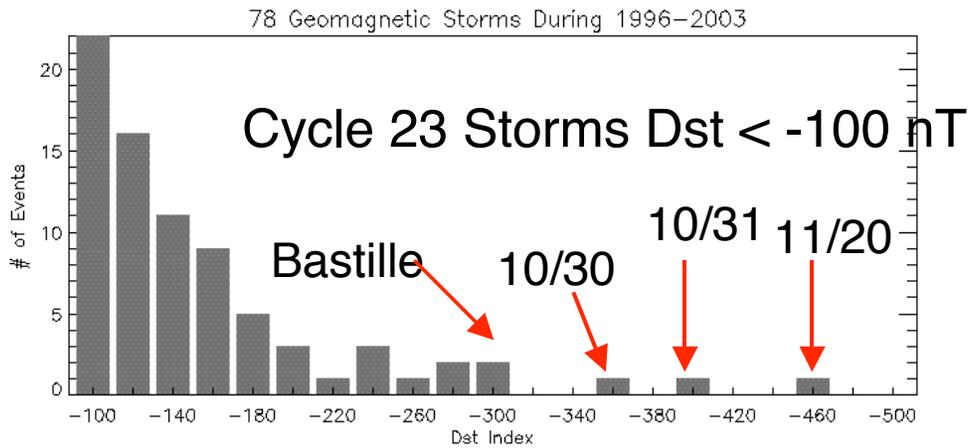
Axial Fields of Cycle 23 MCs

WIND   N = 82

Bo   mean = 17.8 nT

⟨B⟩ mean = 10.1 nT

Bo σ/mean = 0.39

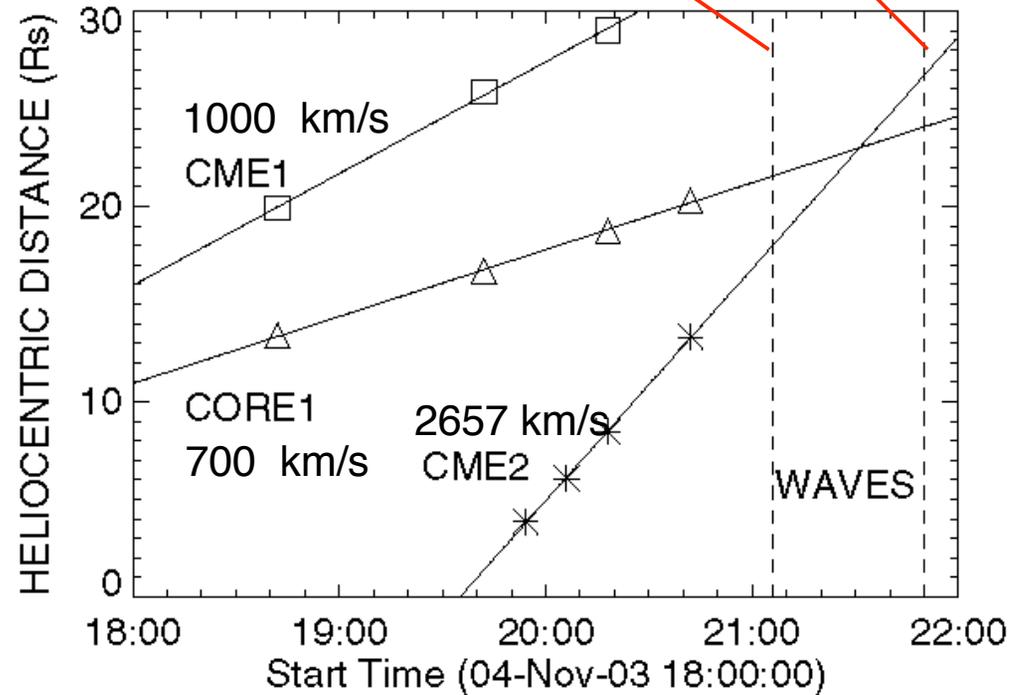⟨B⟩ σ/mean = 0.40

11/20

1998   2000
10/19   07/15 09/18
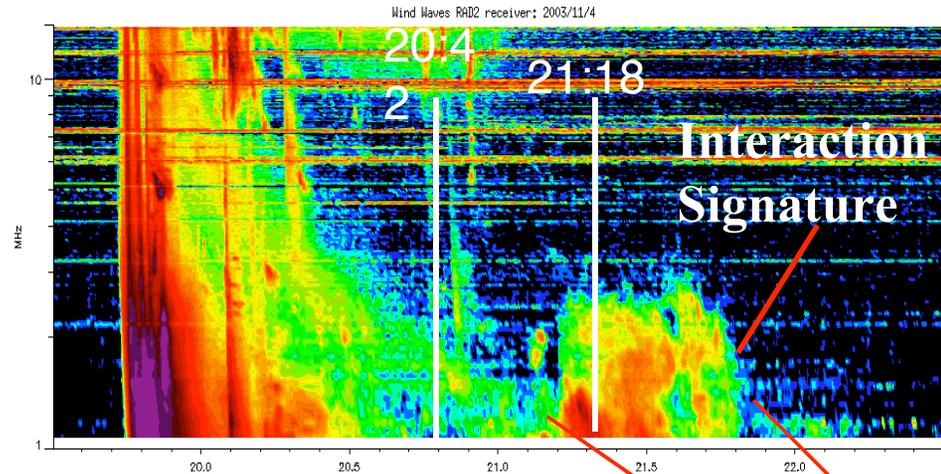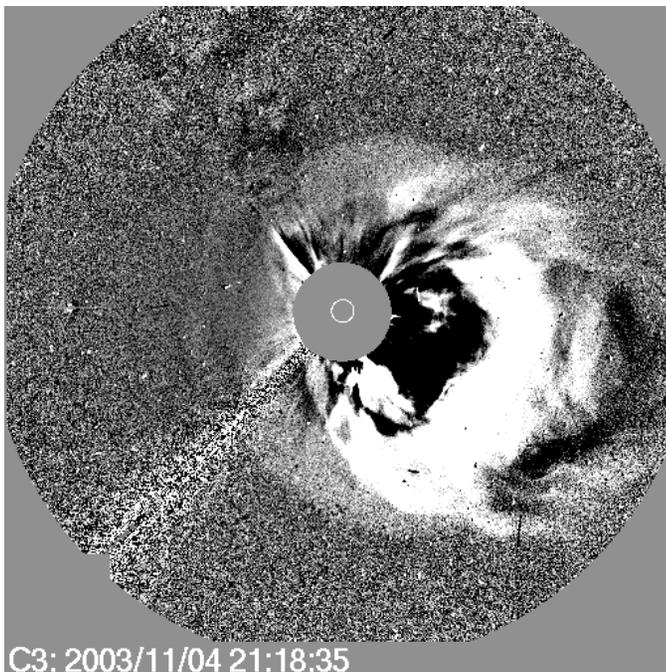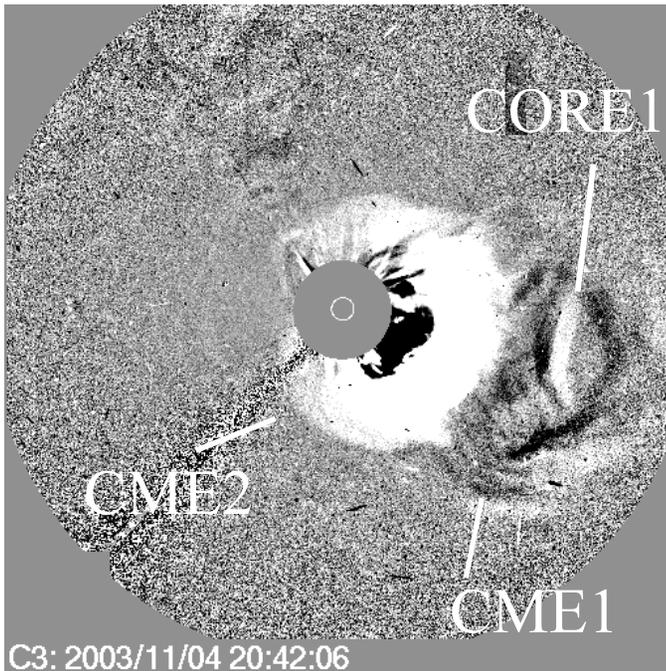
ACE Data   MC   Lepping's fit
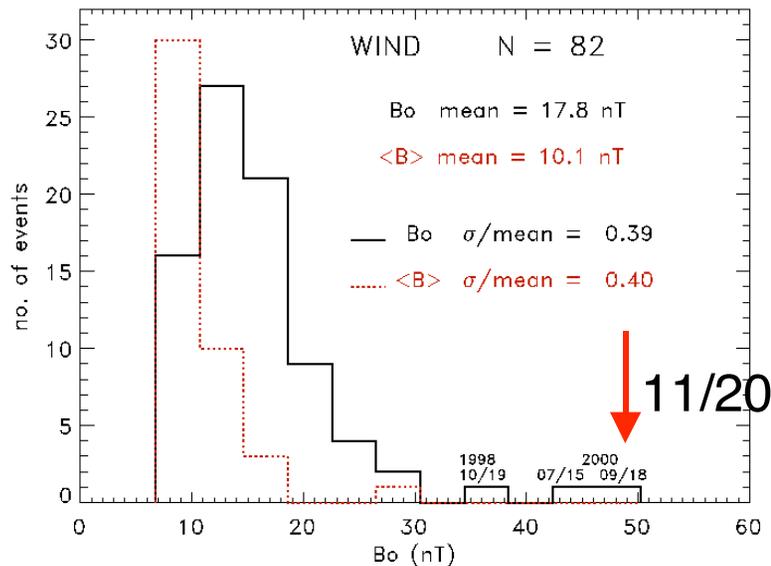
Courtesy: N. Ness, R. Lepp
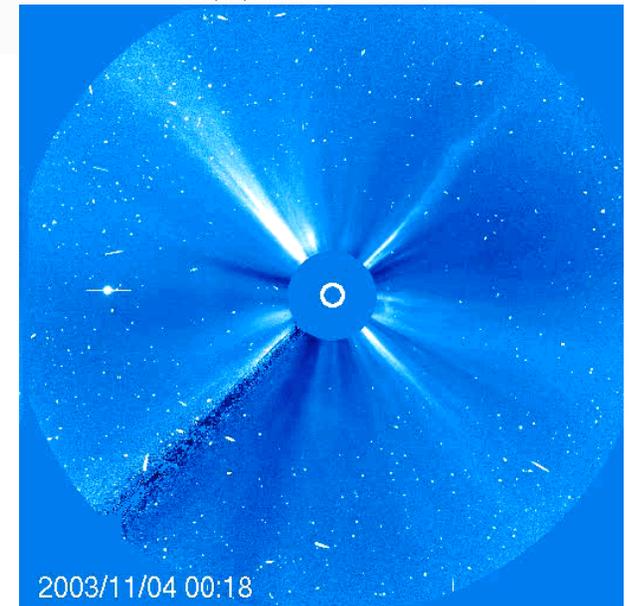
The Fastest CME of the cycle
Wind & SOHO
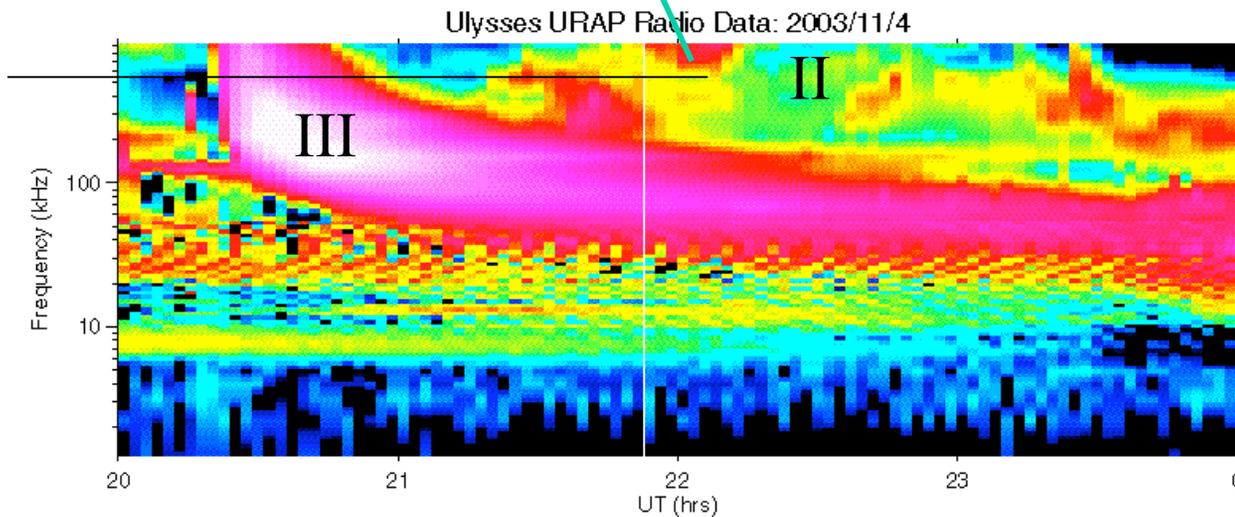
CME Interaction

Where is the Interaction Region?

- Nothing happening above the opposite limb
- The CME is at 18 Rs from the Sun just before interaction.
- The ambient density is expected to be 10^4 per cc.
- When the shock enters the dense structure, the upstream plasma frequency jumps → frequency of emission jumps
- At the same time, the intensity is enhanced: Change in Alfven speed
  dVa/Va = dB/B – _ dN/N
can strengthen the shock

C3: 2003/11/04 20:42:06

C3: 2003/11/04 21:18:35
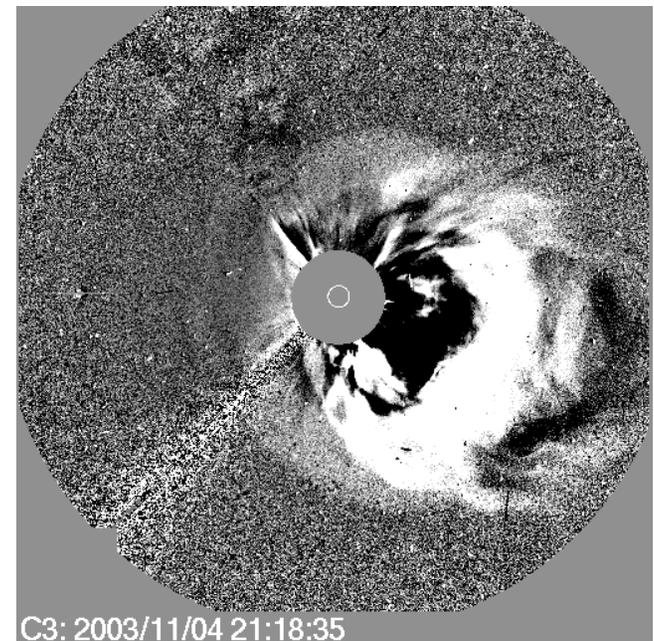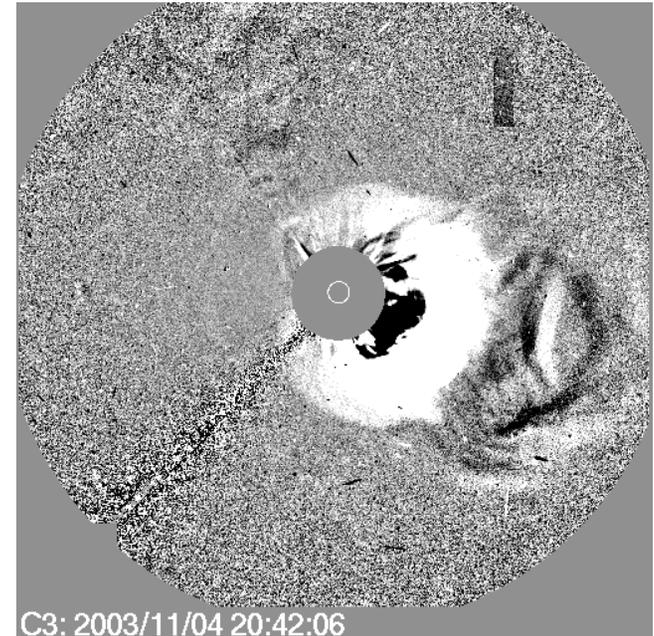
Interaction detected by Wind, Ulysses & Cassini

Cassini at 8.7 AU: Radiation has to travel for additional 64 min

Wind: 21:10; Uly: 21:50; Cass: 22:18

Wind Waves RAD1+RAD2 receiver: 2003/11/4

Cassini RPWS   4 November 2003

Ulysses URAP Radio Data: 2003/11/4

2003/11/04 00:18
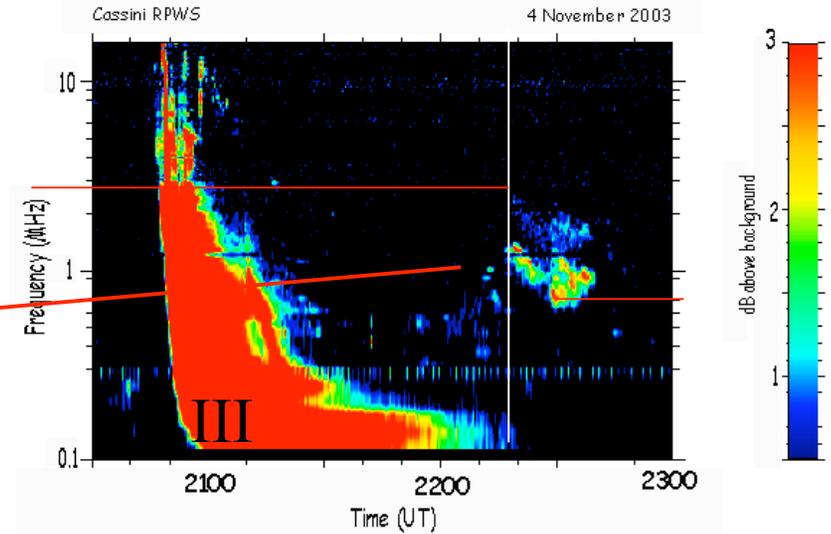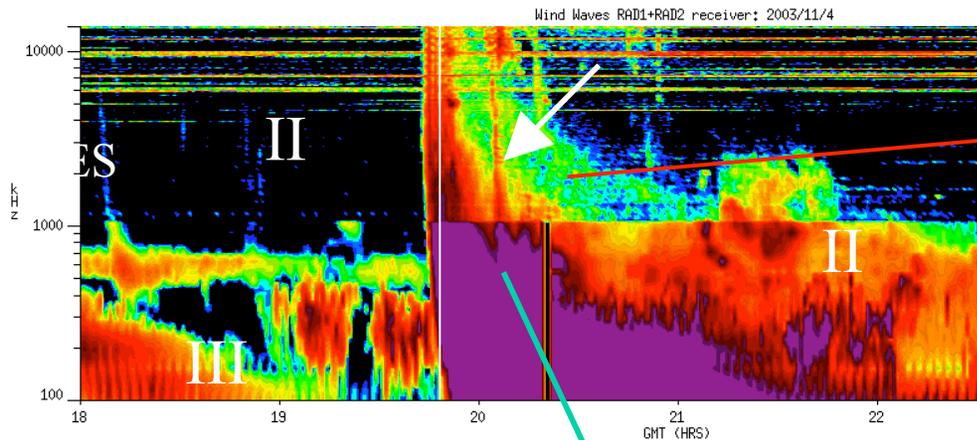
Summary

- Record-setting speed (2657 km/s) on 2003/11/04 associated with the largest X-ray flare (X28); (previous: 2604 km/s on 5/12/2000)
- 2003 had 9 ultrafast (>2000 km/s) CMEs: 8 during Oct-Nov 2003 period. During cycle 23 (8 yrs) there were only 25 ultrafast CMEs. Only 4 CMEs had V > 2500 km/s
- Inferred speed of historical events is < 2800 km/s
- The Oct-Nov CMEs were faster and wider on the average $\rightarrow$ SEPeffective and Geoeffective
- 12 shocks near the Sun; 8 shocks detected *in situ*
- Both the Earth-directed CMEs produced intense geomagnetic storms (-363 & -401 nT). AR 501 (484) produced a CME on 11/18 that resulted in the largest storm of the cycle (-465 nT)
- About 1/3 of the magnetic free energy seems to go into the CME kinetic energy; Maximum free energy ~ a few 10^{33} erg
- There seems to be an upper limit to the CME speed ~ 3000 km/s, implying at least a half a day travel time for CME-driven shocks

Maximum Energy Extractable

- Free Energy = 5×10^{33} erg
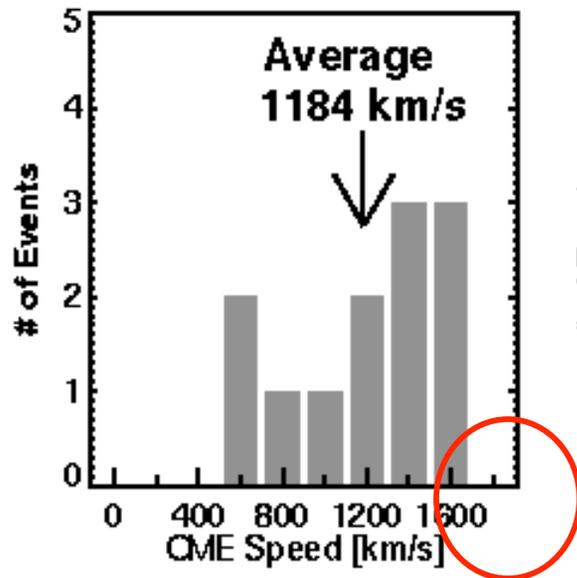- If all the energy goes into CMEs,

$$\_ MV^2 = 5 \times 10^{33} \text{ erg}$$

=> V = 3160 km/s for M = 10^{17} g

Properties of Type IV Bursts
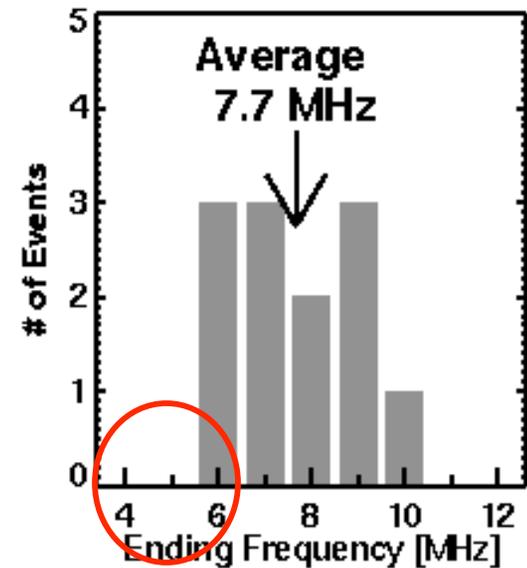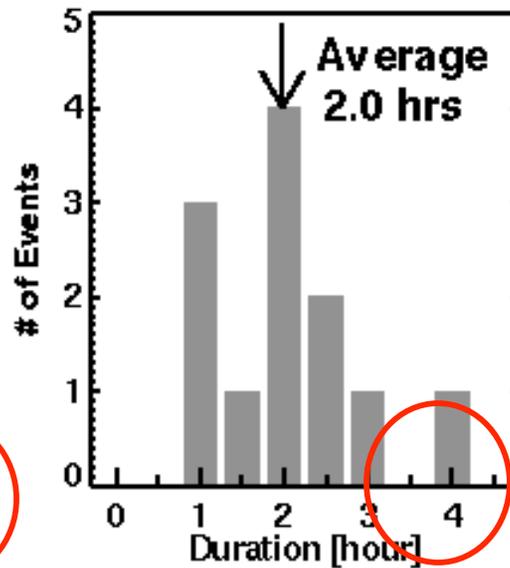## 12 Events from 1997-2002
11 Events from 10/21-11/04 2003

1668 km/s

Lowest ending f
→ Tallest loops