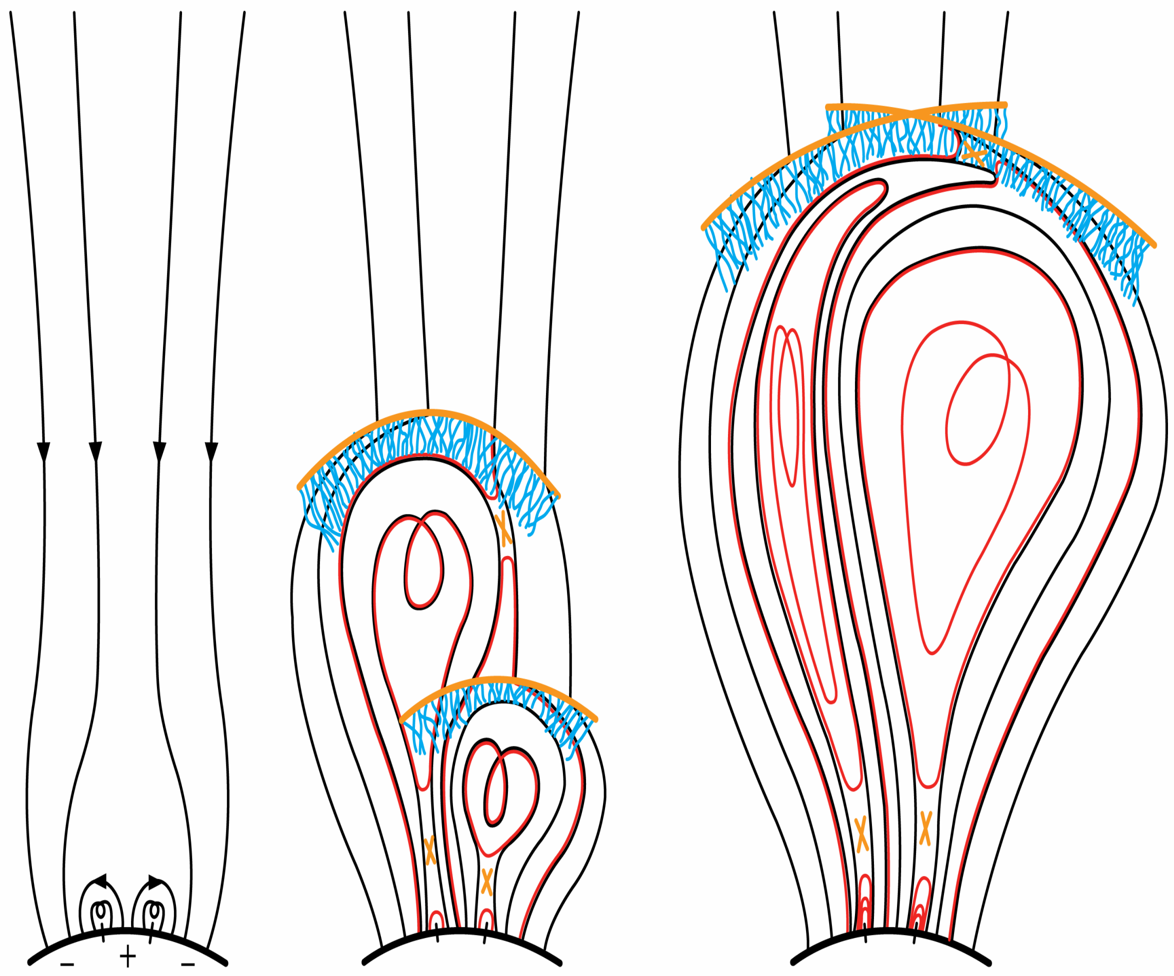
What causes an extreme event - a "twin-CME" scenario?



Space Climate 5

06/17/2013
Oulu, Finland

G. Li(1), L. Zhao(1), L. Ding(2), Y. Jiang(2)

1. UAHuntsville
2. NJIST

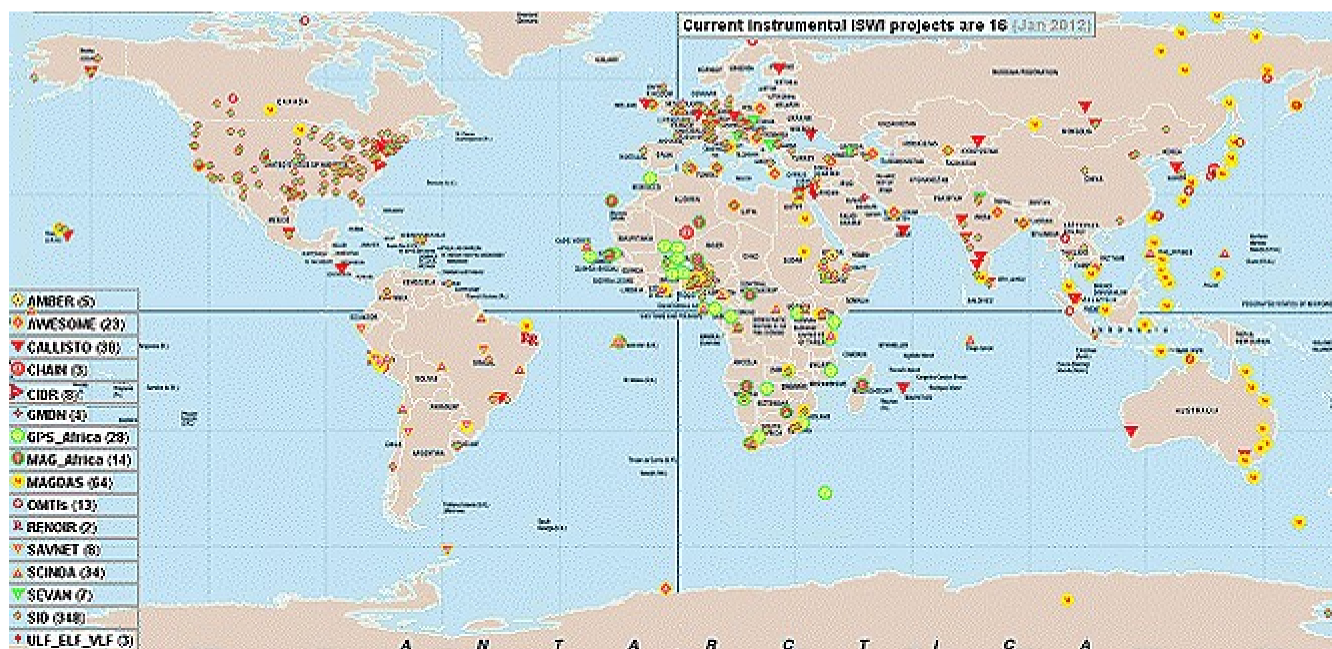
Space Weather: an international concern

In **2009**, the International Space Weather Initiative (ISWI) is formed to promote the *observation, understanding, and prediction* of *space weather* phenomena, and to *communicate the results to the public*.

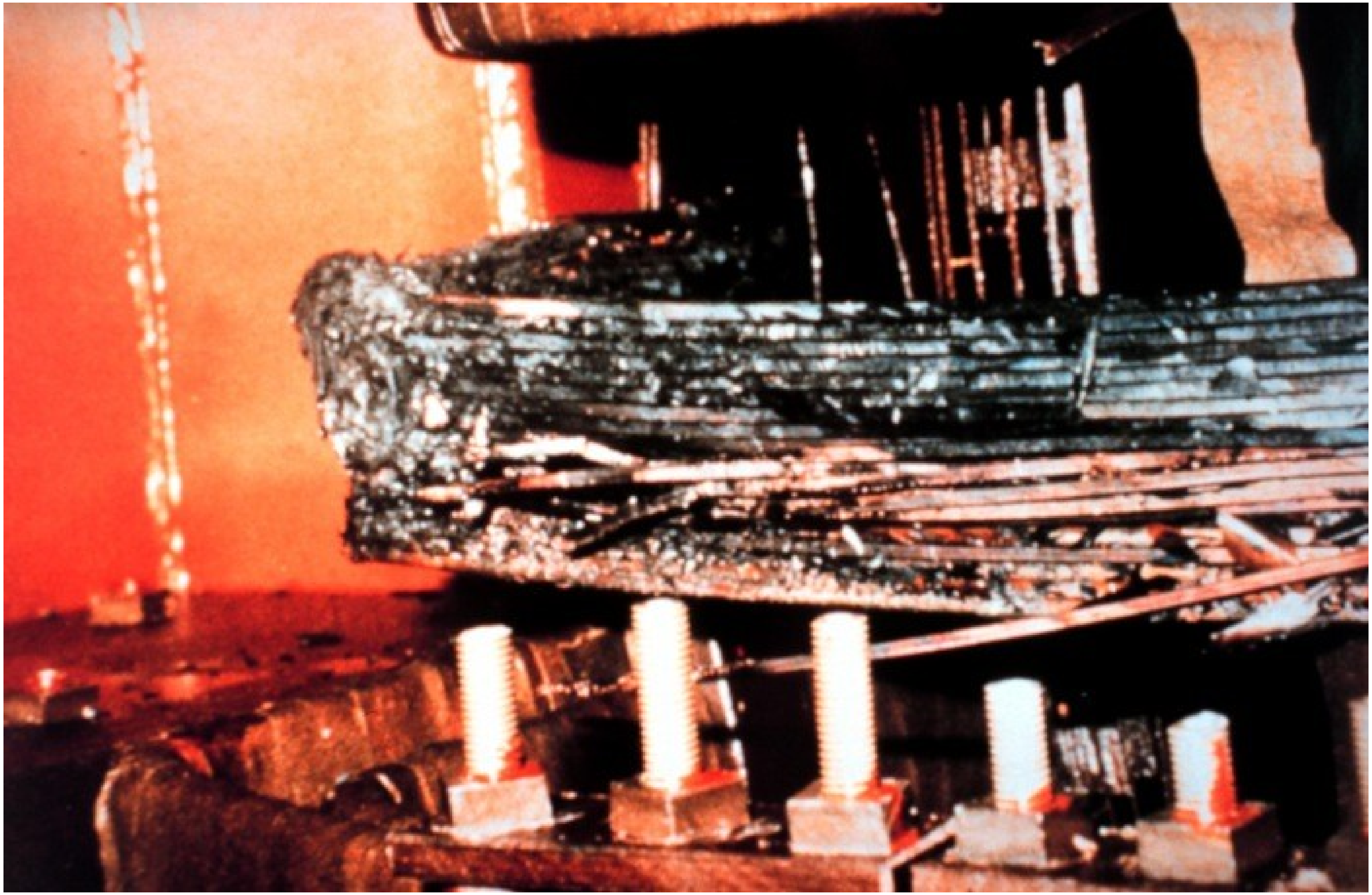
By 2012,

- more than 70 countries
- over hundreds stations world wide

Space Weather is taking the stage!



Impacting our everyday life



Melted transformer in Quebec power grid, following a solar flare in March 1989

Image: HydroQuebec

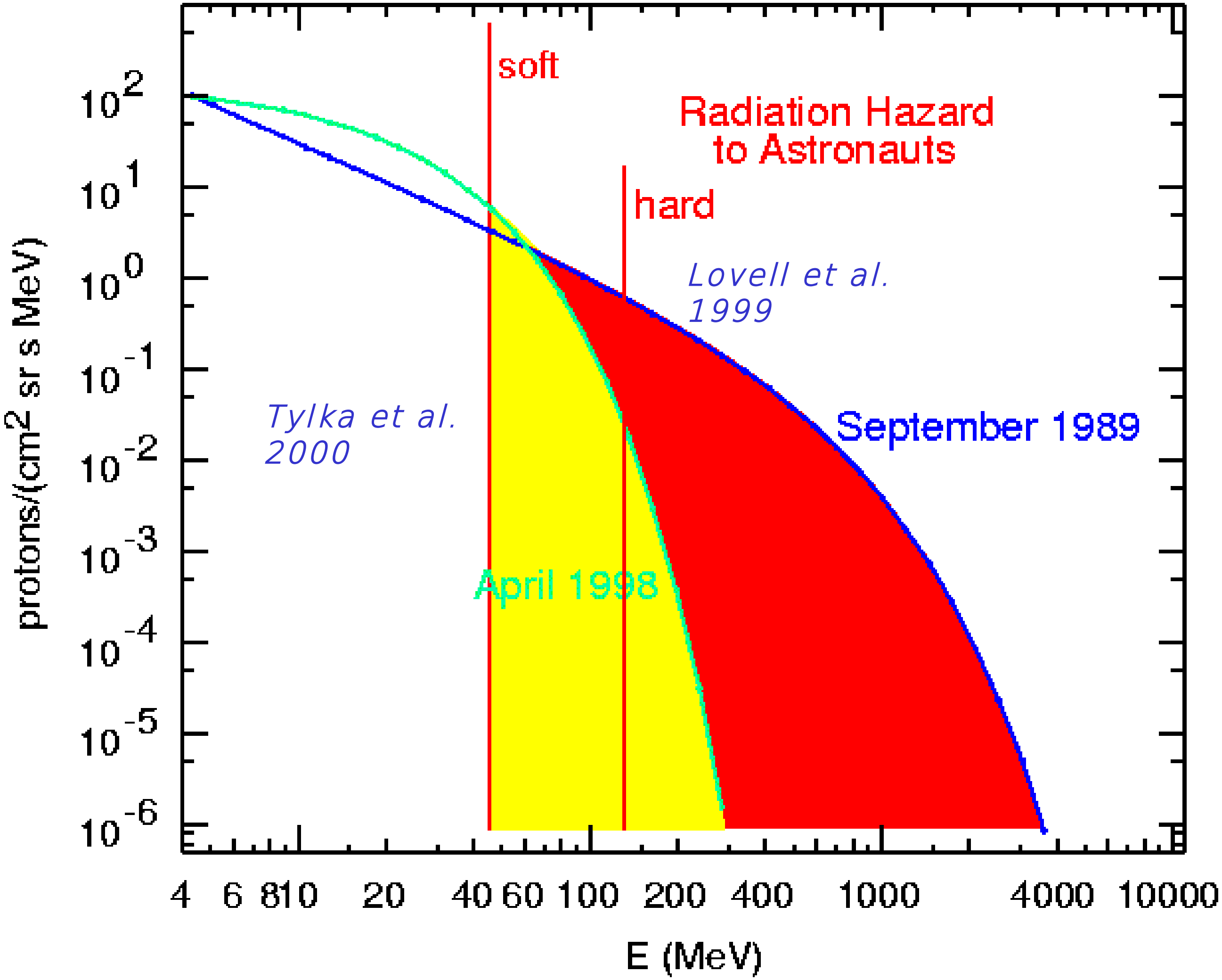
Solar Energetic Particles: No. 1 Space Hazard

Table 1. The Causes of Hazards

Parameter	Effects	Sources
Protons 0.1-1 MeV	surface damage to materials	primarily radiation belt particles
Protons 1-10 MeV	displacement damage in solar cells	radiation belts and shock acceleration in space
Protons >10 MeV	ionization and displacement damage and sensor background	radiation belts, solar energetic particle and galactic cosmic rays
Protons >30 MeV	damage to biological systems	same as above
Protons >50 MeV	single-event effects	same as above
Ions >10 MeV $nucleon^{-1}$	single-event effects	solar energetic particle and galactic cosmic rays
GeV particles (ground level events)	single-event effects and hazards to humans in polar flights and deep space	same as above

Feynmann, J. & Gabriel, S.B., On space weather consequences and predictions, Journal of Geophysical Research, Volume 105, pp. 10543 (2000)

Event variablity



Spectral shape is crucial to the radiation dose.

Proton spectra for 2 similar events:

- *speed:~1800 km/s CMEs*
- *location: on the west limb.*

Behind 10 g/cm², these spectra produce:

0.05 rem/hour*

4 rem/hour*

Average Person** || **Radiation-Worker Limit** || **Astronaut Limit
0.4 rem/year** || **5 rem/year,** || **50 rem/year

Radiation Calculation for astronauts on the way to the moon.

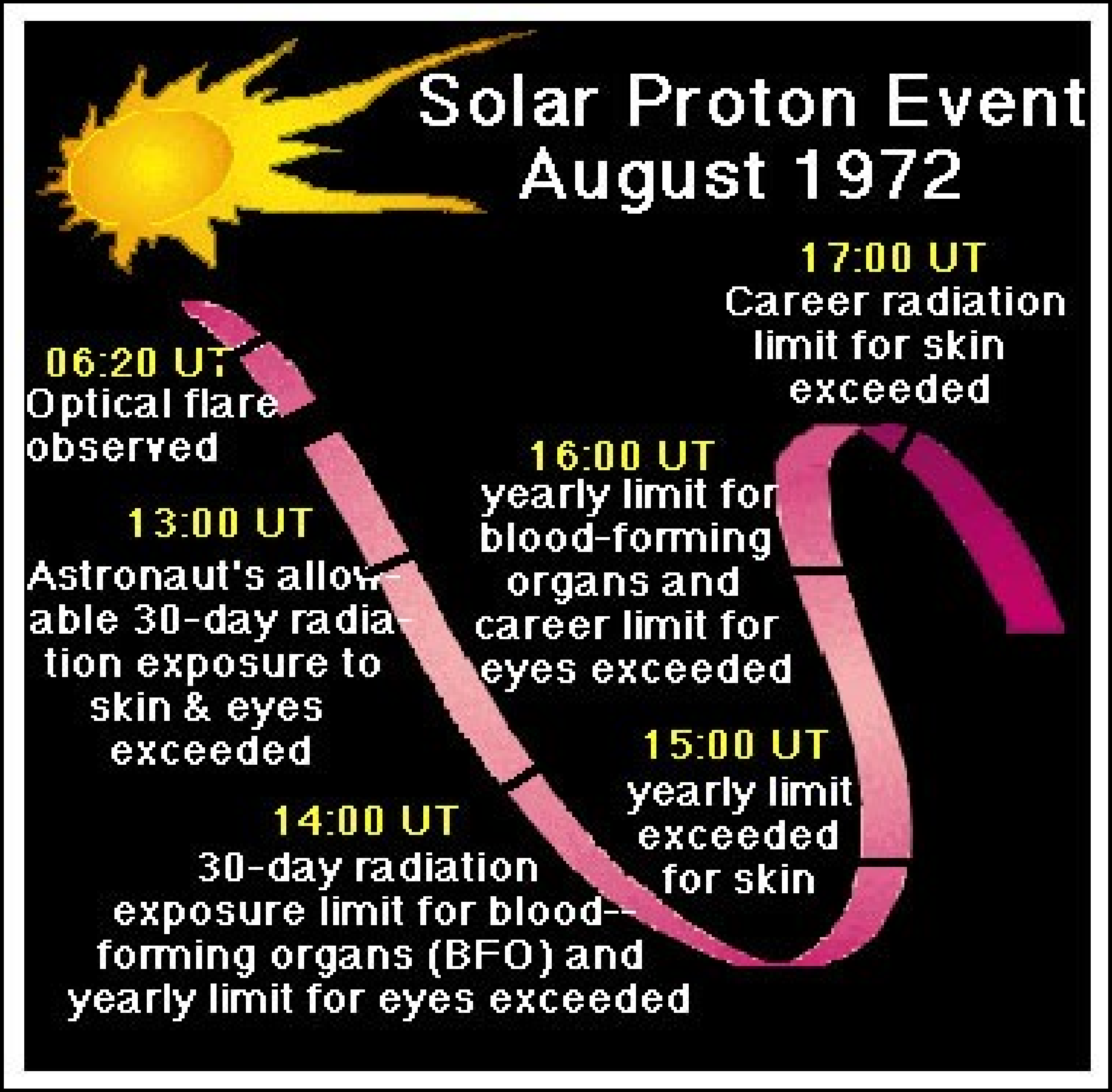


Image: Windows to the Universe, UCAR

Shock acceleration

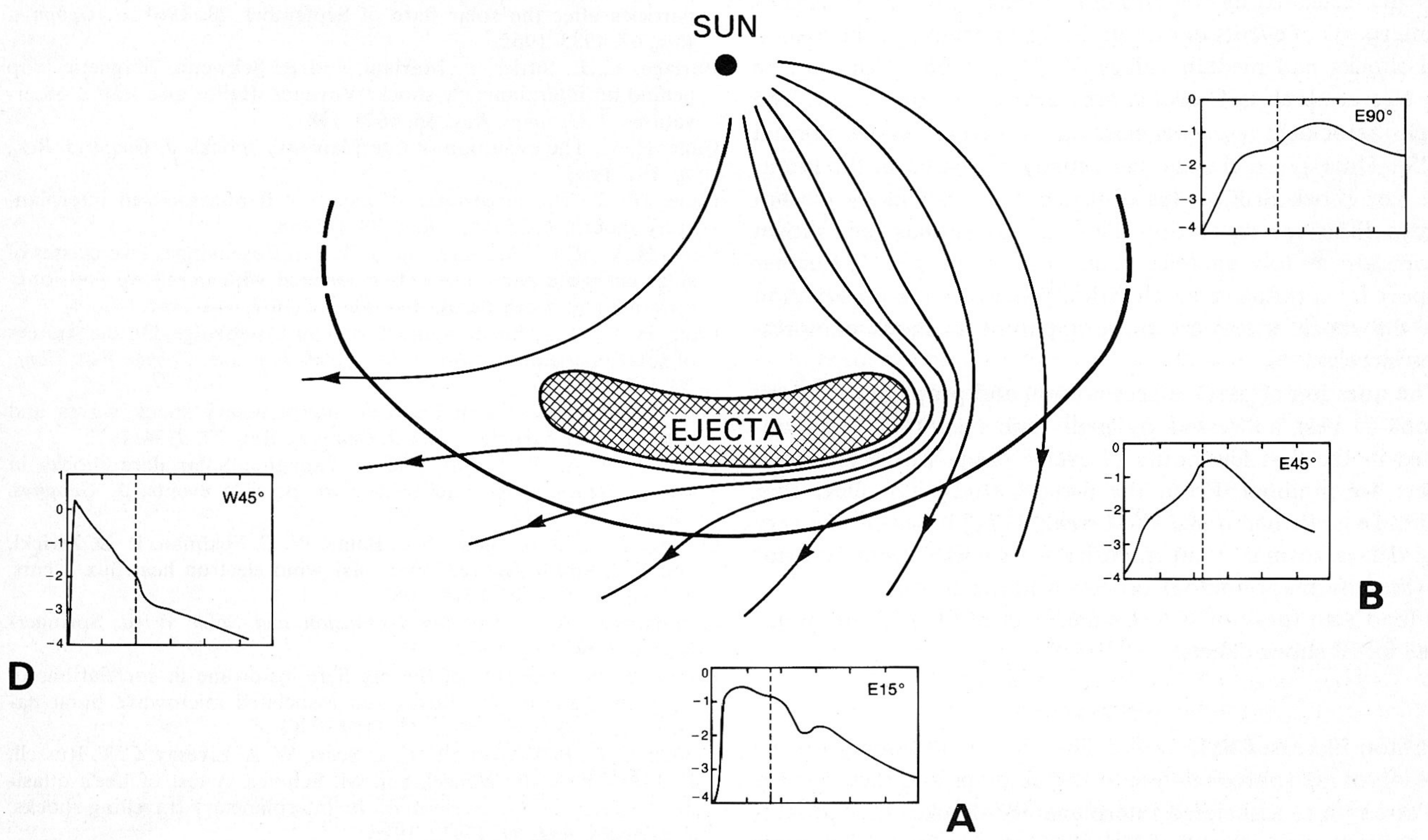
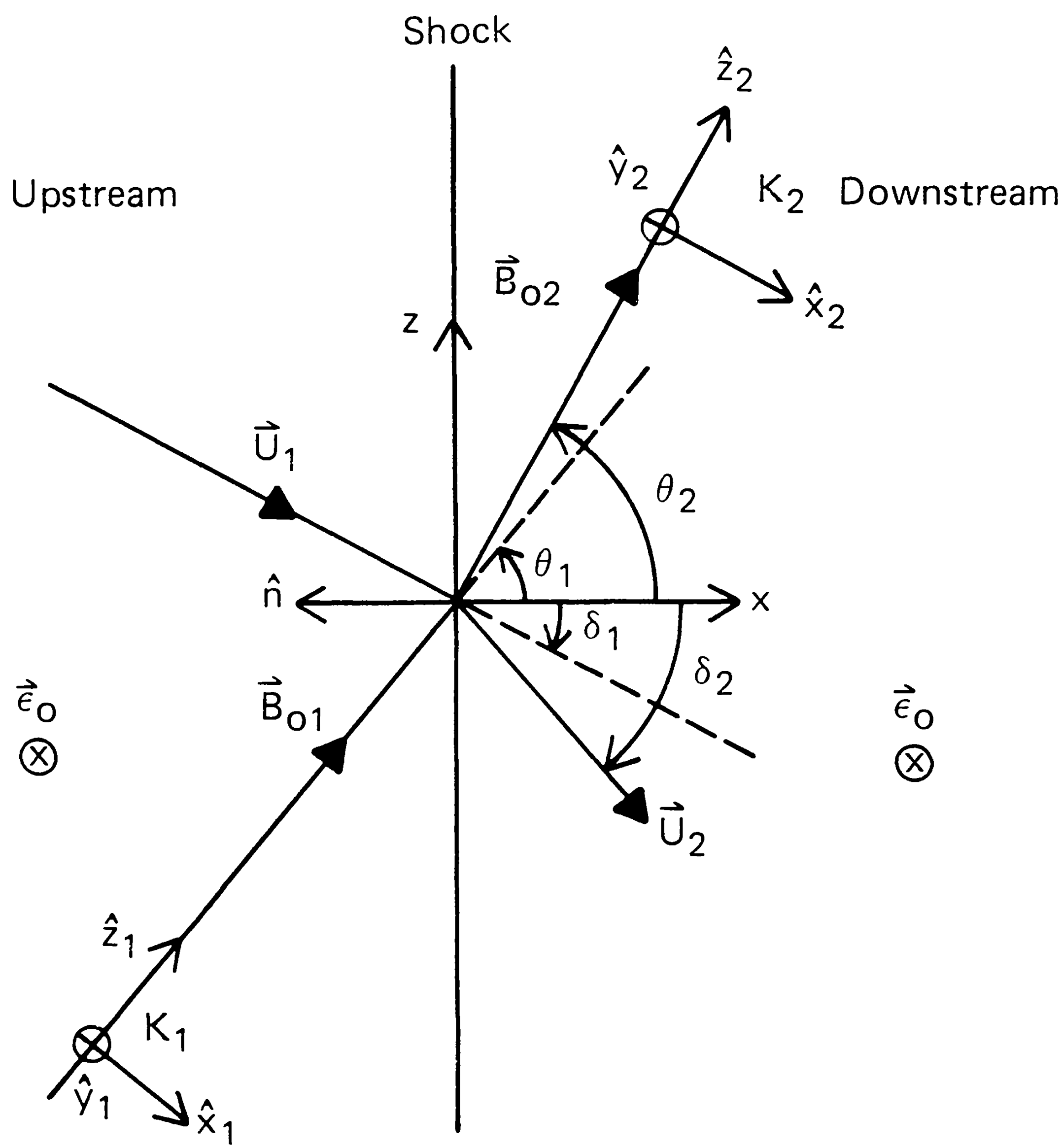


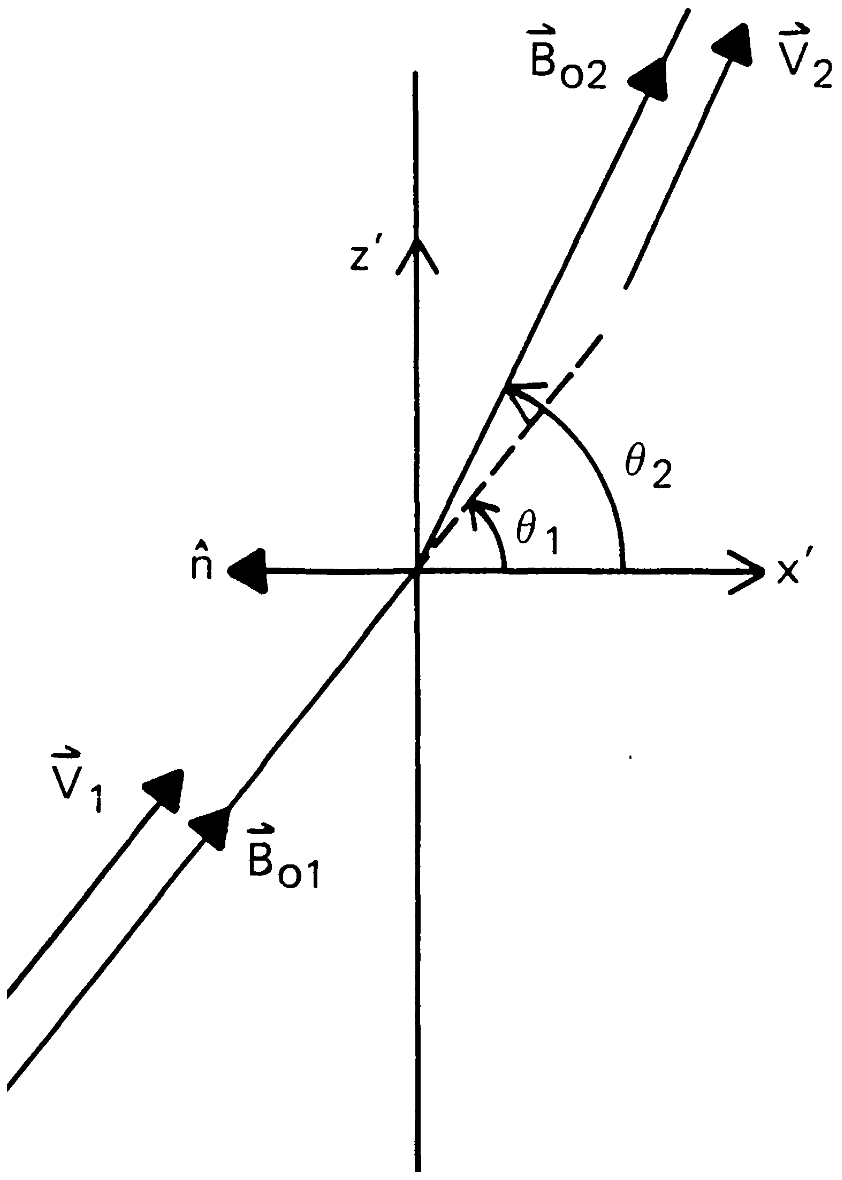
Fig. 15. The figure shows representative profiles of actual events at 20 MeV for different spacecraft trajectories through a shock. Note that for a very energetic shock the western flank would be more extensive than the picture presented here. See the text for a more detailed description of this figure.

Cane, Reames & von Rosenvinge, JGR, 93, 9555, 1988

Mathematical description of a shock



Shock frame



de Hoffman frame

Rankine Hugoniot (MHD)Equations

Relating upstream parameters and downstream parameters

conservation laws

$$[\mathbf{B}\cdot\hat{\mathbf{n}}]_d^{up}=0$$

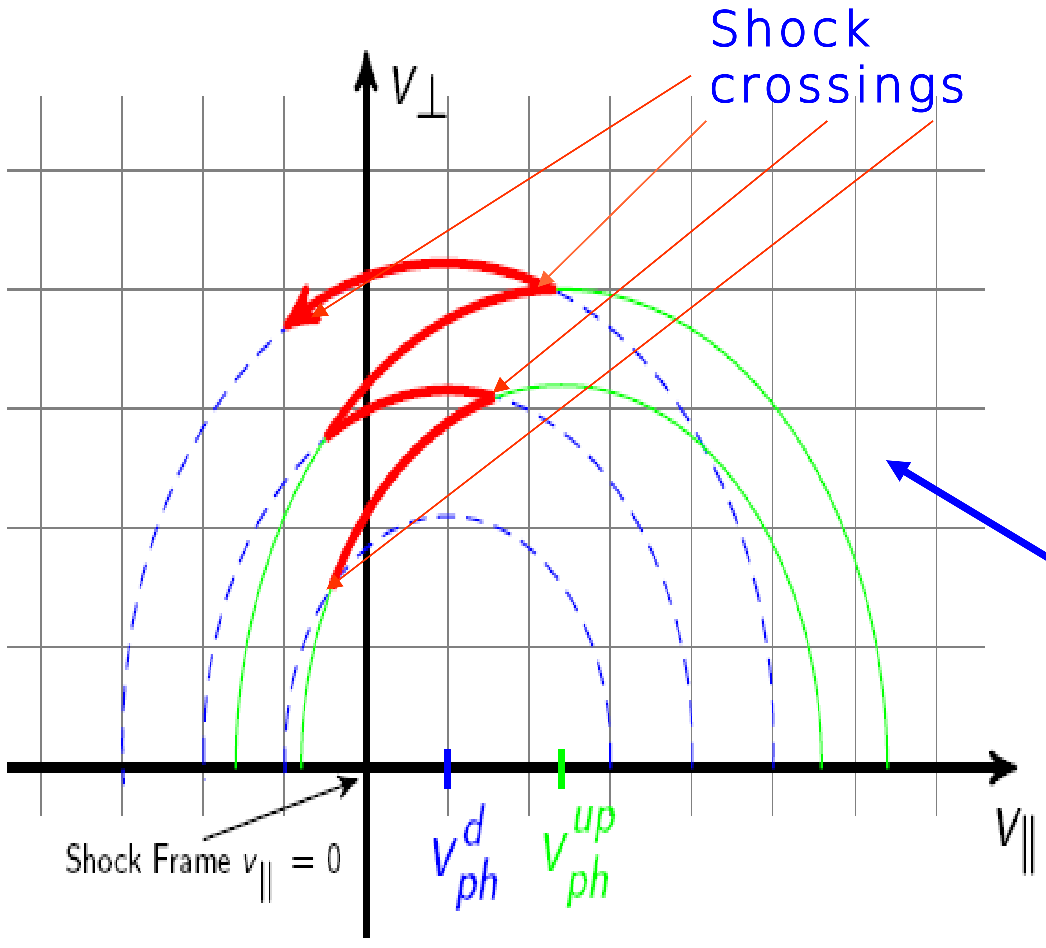
$$[\hat{\mathbf{n}}\times(\mathbf{u}\times\mathbf{B})]_d^{up}=0$$

$$[\rho\mathbf{u}\cdot\hat{\mathbf{n}}]_d^{up}=0$$

$$\left[\mathbf{u}\cdot\hat{\mathbf{n}}\left\{\frac{\gamma}{\gamma-1}P+\frac{1}{2}\rho u^2+\frac{B^2}{4\pi}\right\}-\frac{(\mathbf{B}\cdot\hat{\mathbf{n}})(\mathbf{Bu})}{4\pi}\right]_d^{up}=0$$

$$\left[\rho\mathbf{u}(\mathbf{u}\cdot\hat{\mathbf{n}})+(P+B^2/8\pi)\hat{\mathbf{n}}-(\mathbf{B}\cdot\hat{\mathbf{n}})\mathbf{B}/4\pi\right]_d^{up}=0$$

Diffusive shock acceleration 101--
the picturesque approach

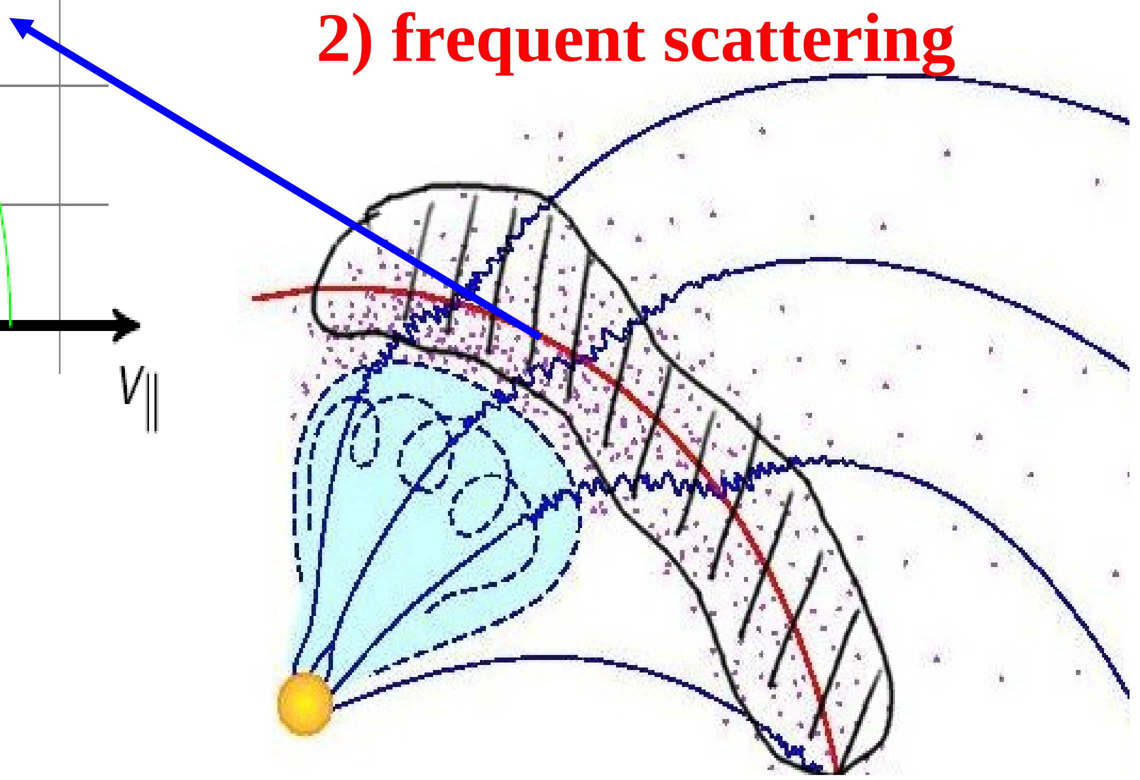


Sugiyama & Terasawa, 1999

Clearly, an efficient acceleration Requires:

1) an large enough initial speed

2) frequent scattering



Diffusive Shock acceleration 102-- the standard theory

Parker's transport equation

$$\frac{\partial f}{\partial t} = -V_{w,i}\frac{\partial f}{\partial x_i} + \frac{\partial}{\partial x_i}\kappa_{ij}\frac{\partial f}{\partial x_j} - V_{D,i}\frac{\partial f}{\partial x_i} + \frac{1}{3}\frac{\partial V_{w,i}}{\partial x_i}\frac{\partial f}{\partial \ln p} + Q$$

advection *diffusion* *drift* *energy change*

In conservation form:

$$\frac{\partial f}{\partial t} + \nabla \cdot S + \frac{1}{p^2}\frac{\partial}{\partial p}(p^2 J) = 0$$

$$\mathbf{S} = -\frac{p}{3}\mathbf{u}\frac{\partial f}{\partial p} - \kappa \nabla f$$

$$J = \frac{p}{3} u \cdot \nabla f$$

Effect of turbulence on particle

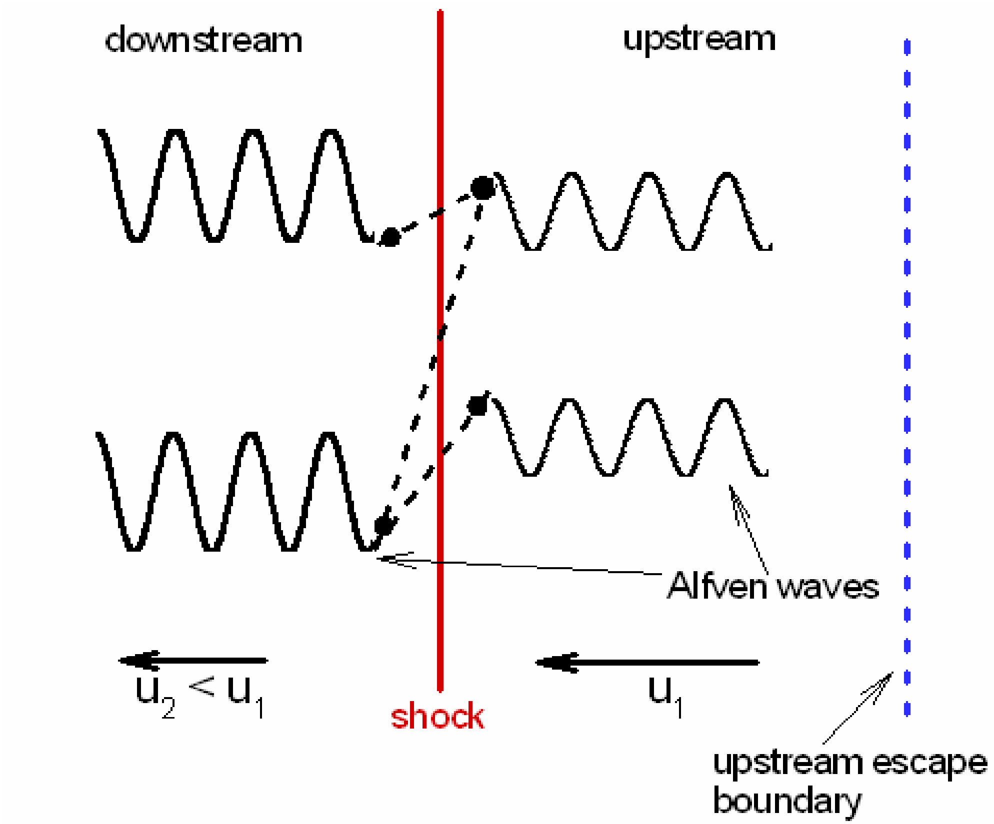
Steady state solution:

$$f(p) \sim p^{-3s/s-1}$$

How to increase the scattering rate, or, get a smaller a kappa?

Note, smaller **κ** lead to higher energy

Wave amplification at a parallel shock



$$\frac{\partial A}{\partial t} + u\frac{\partial A}{\partial r} = \Gamma A - \gamma A,$$

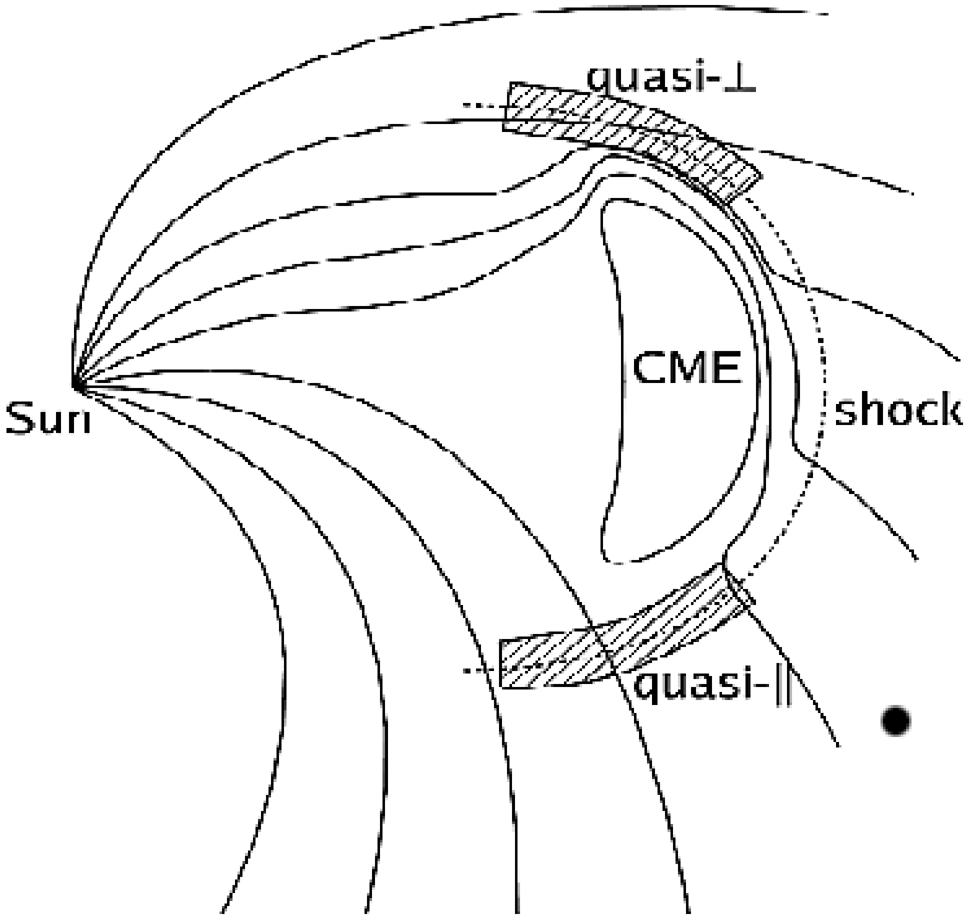
$$\frac{\partial f}{\partial t} + u\frac{\partial f}{\partial r} - \frac{p}{3}\frac{\partial u}{\partial r}\frac{\partial f}{\partial p} = \frac{\partial}{\partial r}\left(\kappa\frac{\partial f}{\partial r}\right),$$

$$\kappa(p) = \frac{\kappa_0}{A(k)}\frac{B_0}{B}\frac{(p/p_0)^2}{\sqrt{(m_p c/p_0)^2 + (p/p_0)^2}},$$

$$I_+(|k| < \gamma m|\Omega|/p_o) = \frac{q|\Omega|NV_A p_o^{q-3}cos\psi}{4(q-4)(q-2)V'^2}\frac{1}{k^2}\left|\frac{\gamma m\Omega}{k}\right|^{4-q} + I_+^o(k)$$

Doppler condition: $k \approx \gamma m\Omega|\mu|/\mu p.\quad \Omega = (Q/A)eB/\gamma m_p$

Complication from geometry



The total diffusion coefficient is given by,

$$\kappa = \kappa_{||} \cos^2(\theta) + \kappa_{\perp} \sin^2(\theta)$$

At a quasi-perp. shock, Alfven wave intensity goes to zero, so contribution of $\kappa_{||} \cos(\theta)$ can be ignored. The major contribution comes from $\kappa_{\perp}$.

Need a good theory of $\kappa_{\perp}$

$\kappa_\perp$ – the Non-Linear-Guiding-Center (NLGC) theory

Hard sphere model: $\kappa_\perp = \kappa_{||} / [1 + (\lambda_{||} / rl)^2]$ Jokippi 1987

Non-Linear-Guiding-center Theory:

$$\kappa_\perp = \frac{a^2 v^2}{3B^2} \int_0^\infty \frac{S_\perp(\mathbf{k}) d^3\mathbf{k}}{v/\lambda_{||} + k_\perp^2 \kappa_\perp + k_{||}^2 \kappa_{||}}.$$

Non-linear in kappa_perp

Matthaeus et al 2003

Beyond steady state solution – Acceleration time scale

Shock dynamic time scale: the time scale during which the shock parameters do not vary significantly.

$$t_{dyn} = \min\{\frac{\mathrm{R(t)}}{\mathrm{dR(t)/dt}}, \frac{\mathrm{B(t)}}{\mathrm{dB(t)/dt}}, \frac{\mathrm{n(t)}}{\mathrm{dn(t)/dt}}\},$$

Shock acceleration time scale: the time scale during which the particle's momentum p → p + dp

$$\Delta t = \frac{3s}{s-1}\frac{\kappa(p)}{u_{sh}^2}\frac{\Delta p}{p}$$

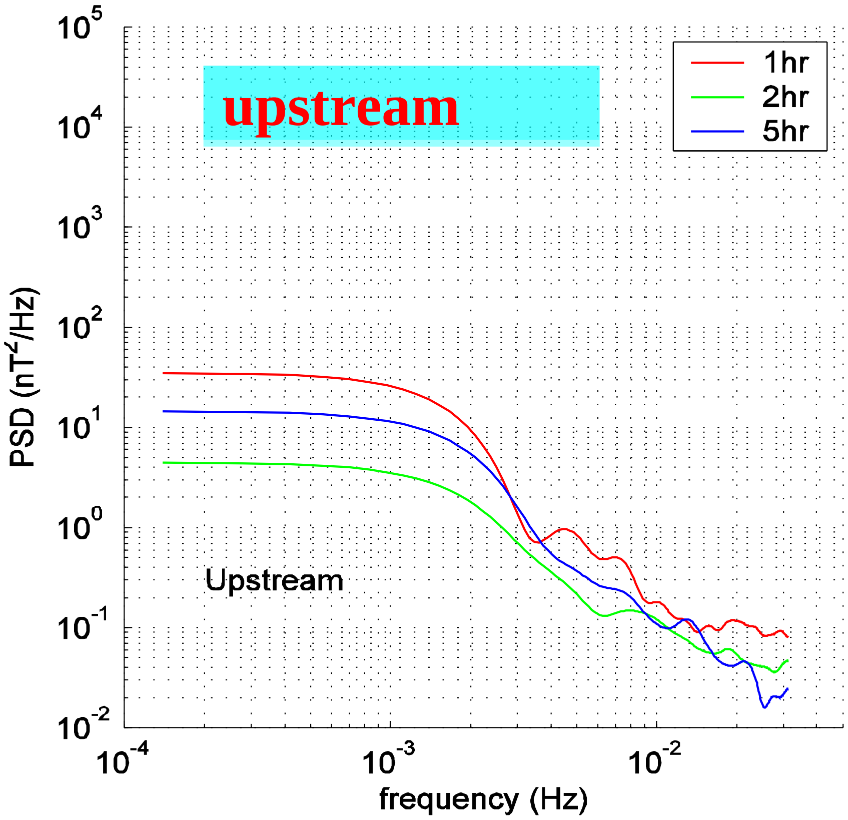
the highest energy is decided by equating these two time scales:

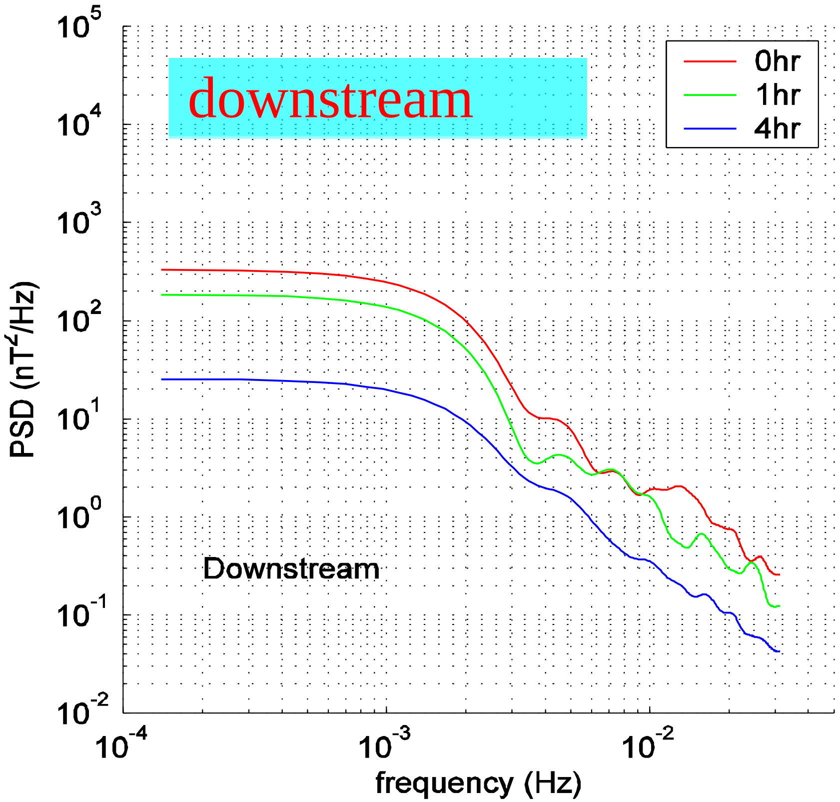
$$t_{dyn} = \int_{p_1}^{p_{max}} \beta \frac{\kappa}{u_{sh}^2}\frac{1}{p} dp.$$

Axford (1981), Drury (1983)

Decrease of κ from observation at a quasi-parallel shock

10/28/2003 event





- Streaming particles can enhance the interplanetary turbulence (upstream).
- The turbulence will further increase when cross the shock front.

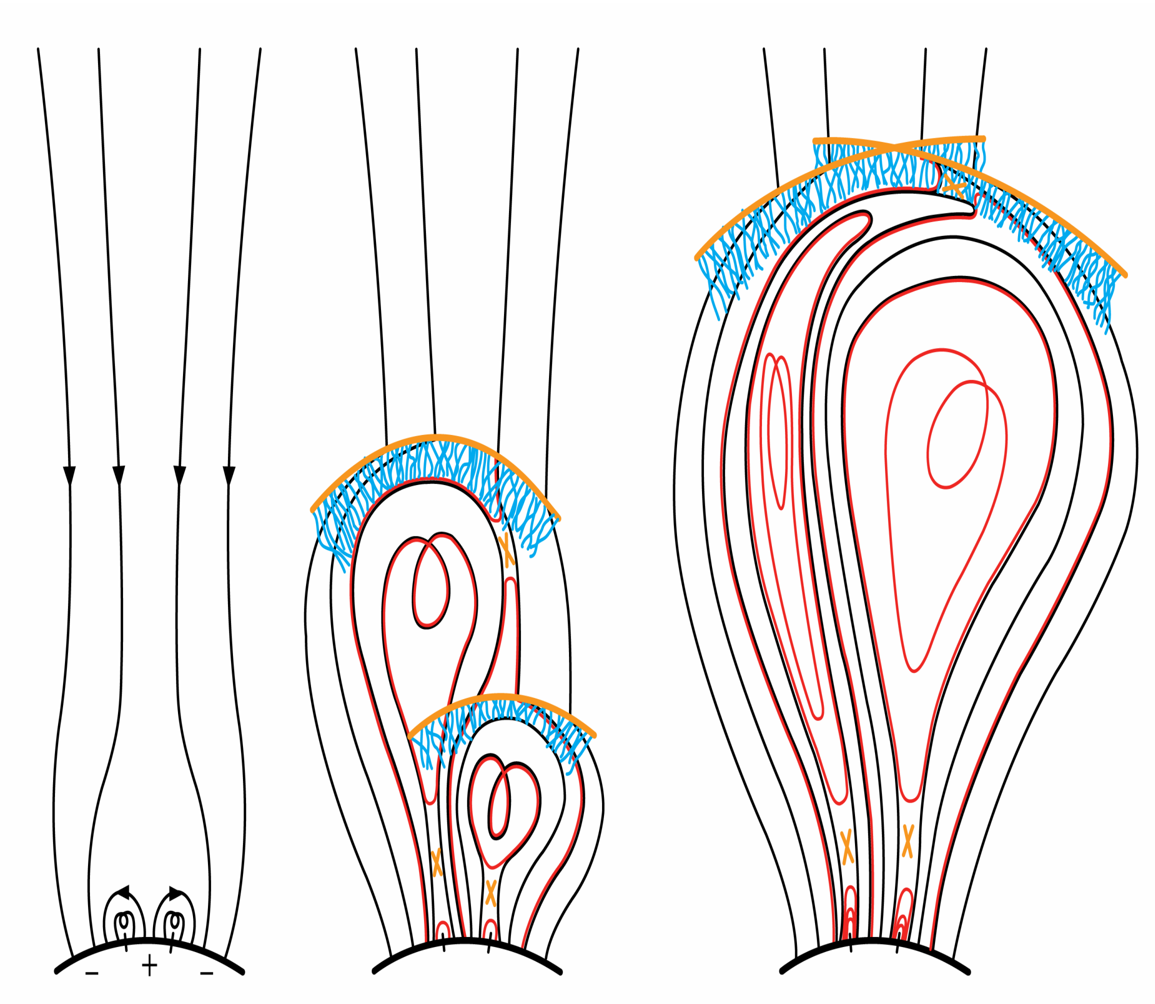
Puzzling facts

Despite the elegant theory of the diffusive shock acceleration mechanism, only a small portion of Fast shocks can lead to large SEP events!

In "normal" conditions, the seed population and the turbulence level are not sufficient to lead to very high energies.

Are there some fortuitous conditions for large or, extreme SEP events?

A twin-CME scenario for large SEP event?



Li et al. 2011, 2012

Twin-CME scenario for GLE:

All 16 GLEs in solar cycle 23 have twin CMEs from the same AR with 9 hours.

Note: Simply going through two shocks does NOT increase the maximum energy and particle intensity by much

Role of the preceding CME:

1) strong turbulence

2) seed population

A decrease of κ by 10 --> an increase of 32 for the maximum kinetic energy.

Besides Energy --- Composition

TABLE I

PROPERTIES OF THE GLE EVENTS IN SOLAR CYCLE 23

date	Flare Longitude	delay (hrs)[a]	Ne/O	Mg/O	Si/O	Fe/O	(Mg+Si+Fe)/O	γ [b]
2001.4.18	120	–	0.17	0.293	0.188	0.16	0.643	2.43
2006.12.13	23	–	0.205	0.210	0.20	0.778	1.188	2.71
1997.11.6	63	16.2	0.26	0.202	0.169	0.650	1.021	2.44
1998.5.2	15	8.6	0.33	0.298	0.203	0.636	1.136	2.7
1998.5.6	65	8.4	0.32	0.249	0.157	0.502	0.909	2.89
2000.7.14	7	14.4	0.16	0.219	0.149	0.09	0.461	3.78
2001.4.15	85	20.2	0.18	0.231	0.196	0.42	0.849	2.09
2002.8.24	81	12	0.15	0.208	0.138	0.19	0.534	2.9
2003.10.28	-8	0.6	0.11	0.201	0.164	0.04	0.406	4.36
2003.10.29	2	10.6	0.24	0.241	0.172	0.14	0.548	3.15
2003.11.2	56	18.4	0.13	0.193	0.119	0.04	0.351	3.44
2005.1.17	25	0.6	0.18	0.185	0.114	0.04	0.340	3.14
2005.1.20	61	22.5	0.23	0.231	0.1620	0.17	0.568	2.14
slow SW	–	–	0.10 ± 0.03	0.15 ± 0.03	0.15 ± 0.03	0.11 ± 0.03	–	–

[a] these delays are from [1], [6] and SOHO/LASCO CME catalog.

[b] adapted from [5], γ values are for protons ≥ 40 MeV.

On average, there are enrichments in Ne/O, Fe/O, $^{22}Ne/^{20}Ne$, and elevated mean charge states of Fe from normal SEP events.

How about “normal” large SEP events?

Large event: 10 pfu at > 10 MeV GOES channel

a) Do large SEP events have preceding CMEs

b) Are there fast single CMEs that lead to large SEP events?

c) Do twin CMEs always lead to large SEP events?

Event classification

Four groups of CMEs:

Group I: fast CME with a preceding CME => large SEP.

Group II: fast CME w/o a preceding CME => large SEP.

Group III: fast CME with a preceding CME => no large SEP.

Group IV: fast CME w/o preceding CME => no large SEP.

Consider only CMEs faster than 900 km/s and have source region in the western hemisphere

Event classification

Four groups of CMEs:

Group I: fast CME with a preceding CME => large SEP.

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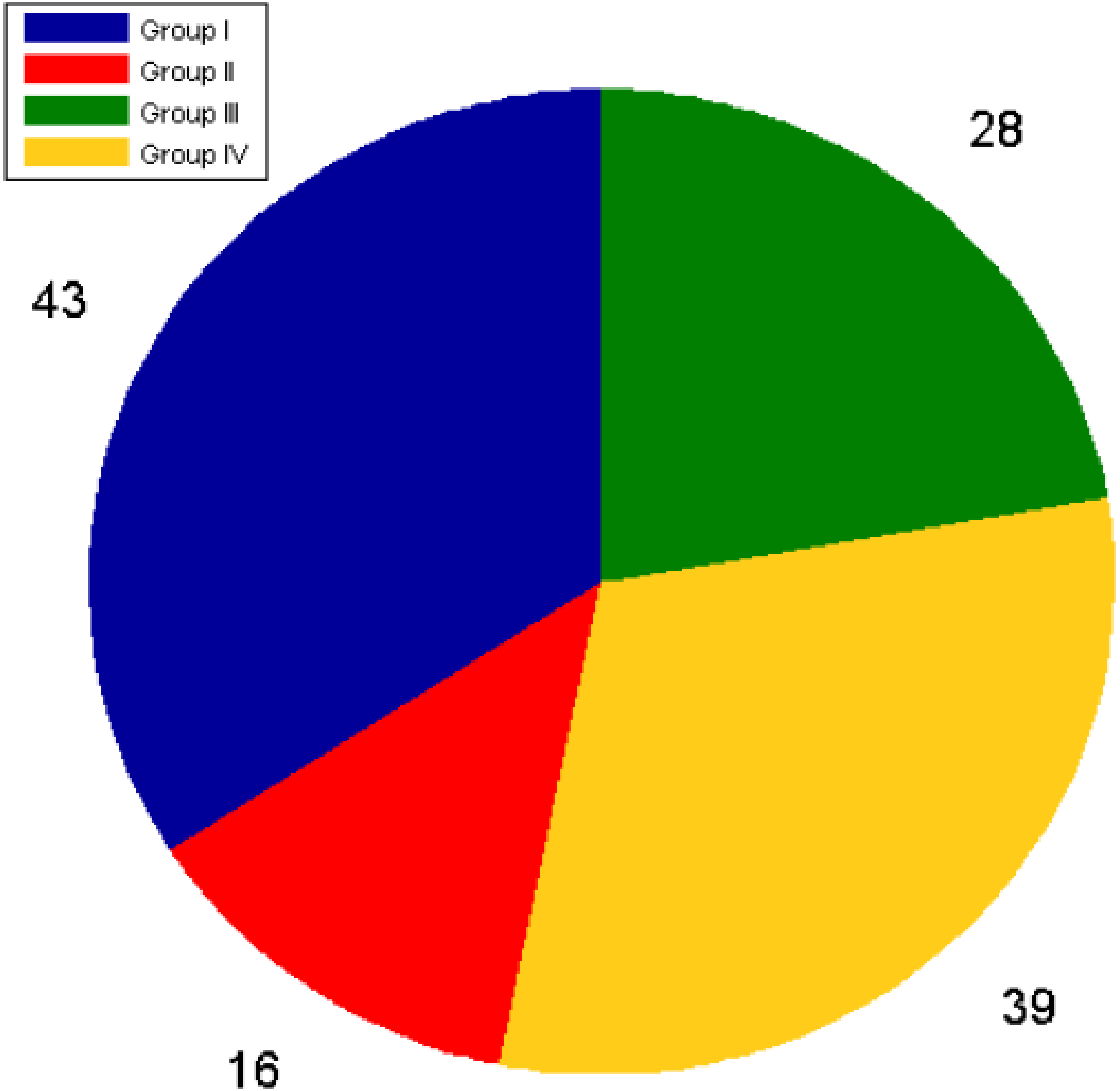
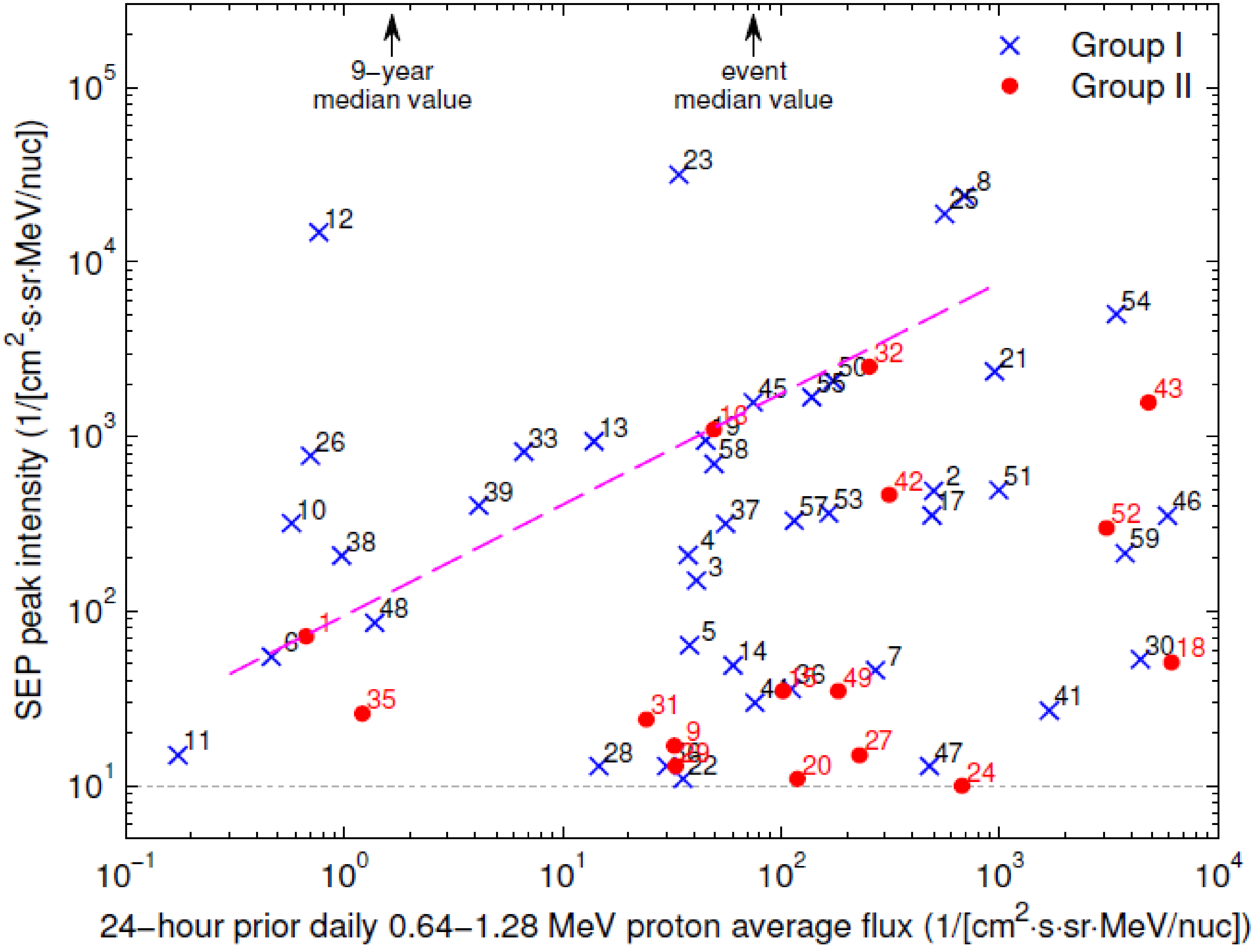
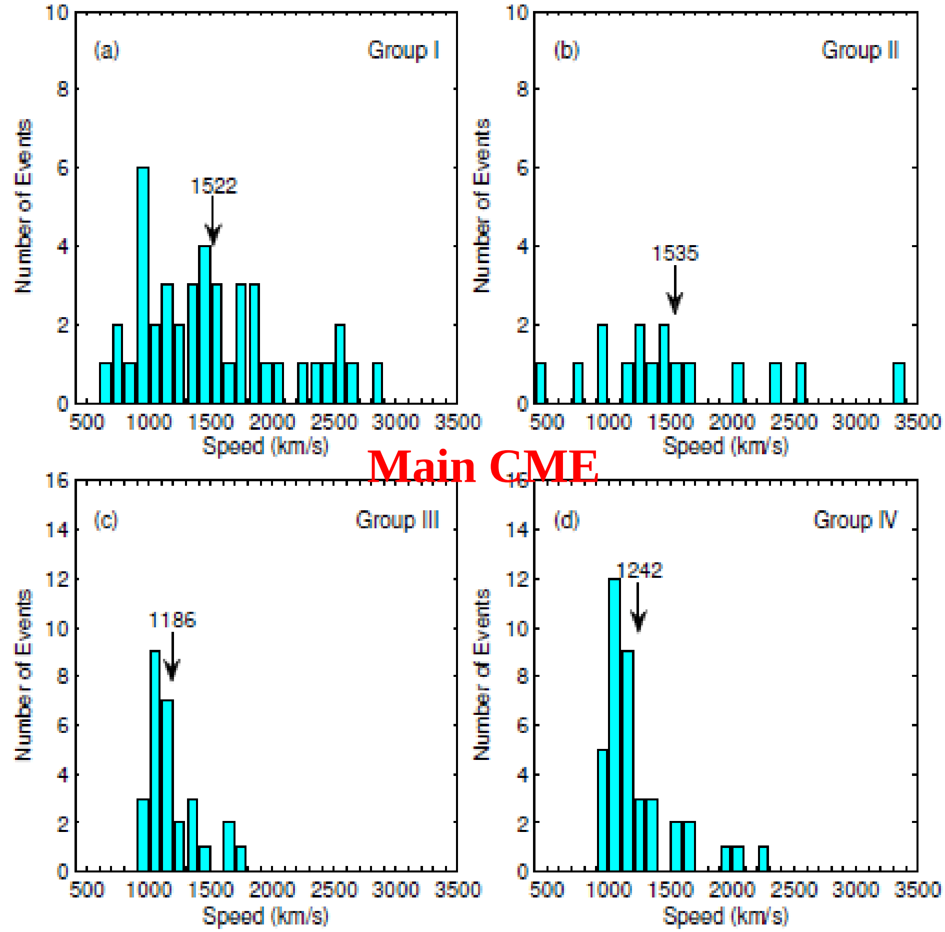
Group IV: fast CME w/o preceding CME => no large SEP.

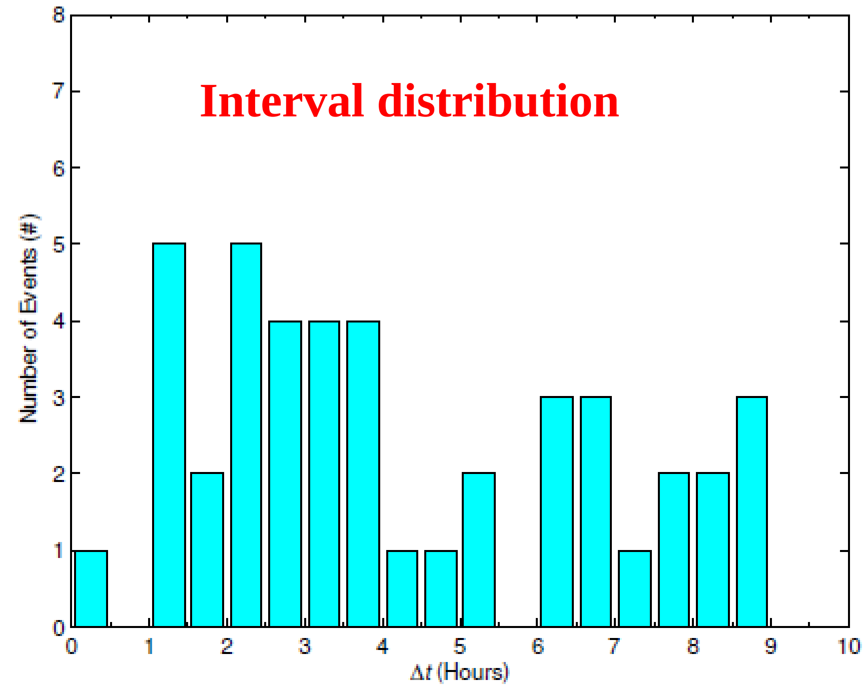
Consider only CMEs faster than 900 km/s and have source region in the western hemisphere

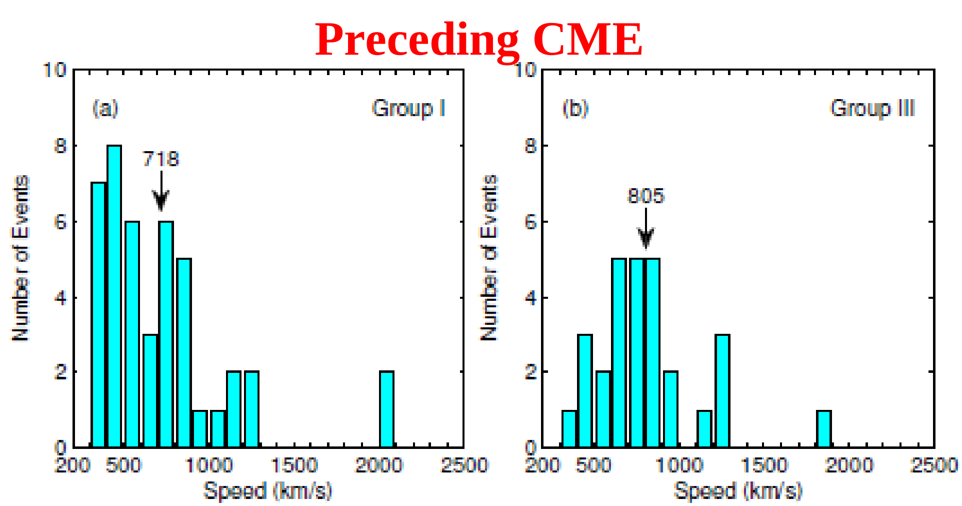

Group I
Group II
Group III
Group IV
28
43
39
16

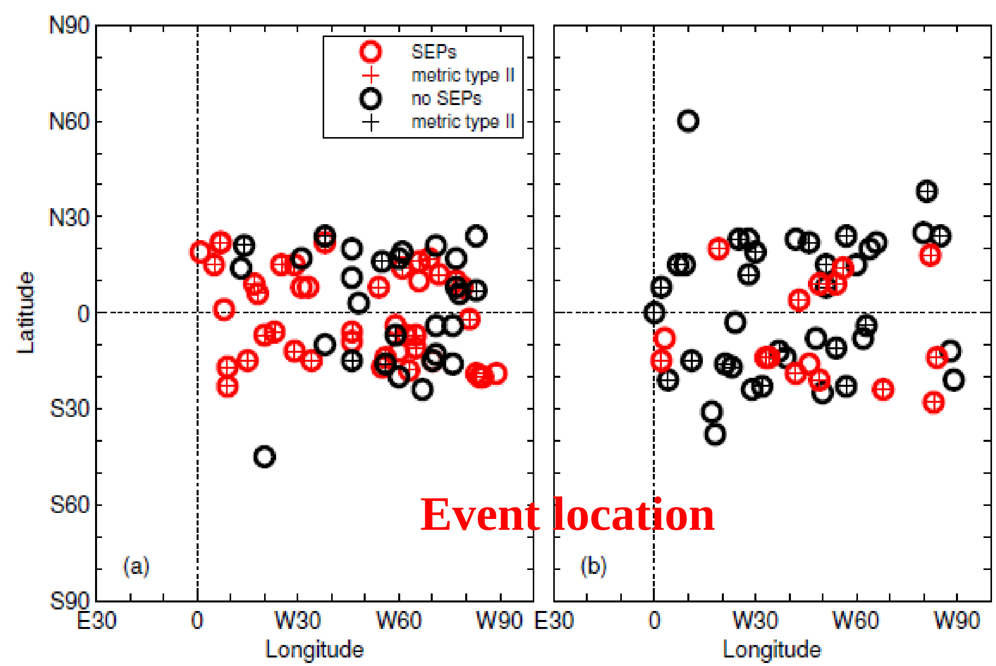
Importance of seed population




Main CME
(a) Group I
1522
(b) Group II
1535
(c) Group III
1186
(d) Group IV
1242
Number of Events
Speed (km/s)


Interval distribution
Number of Events (#)
Δt (Hours)

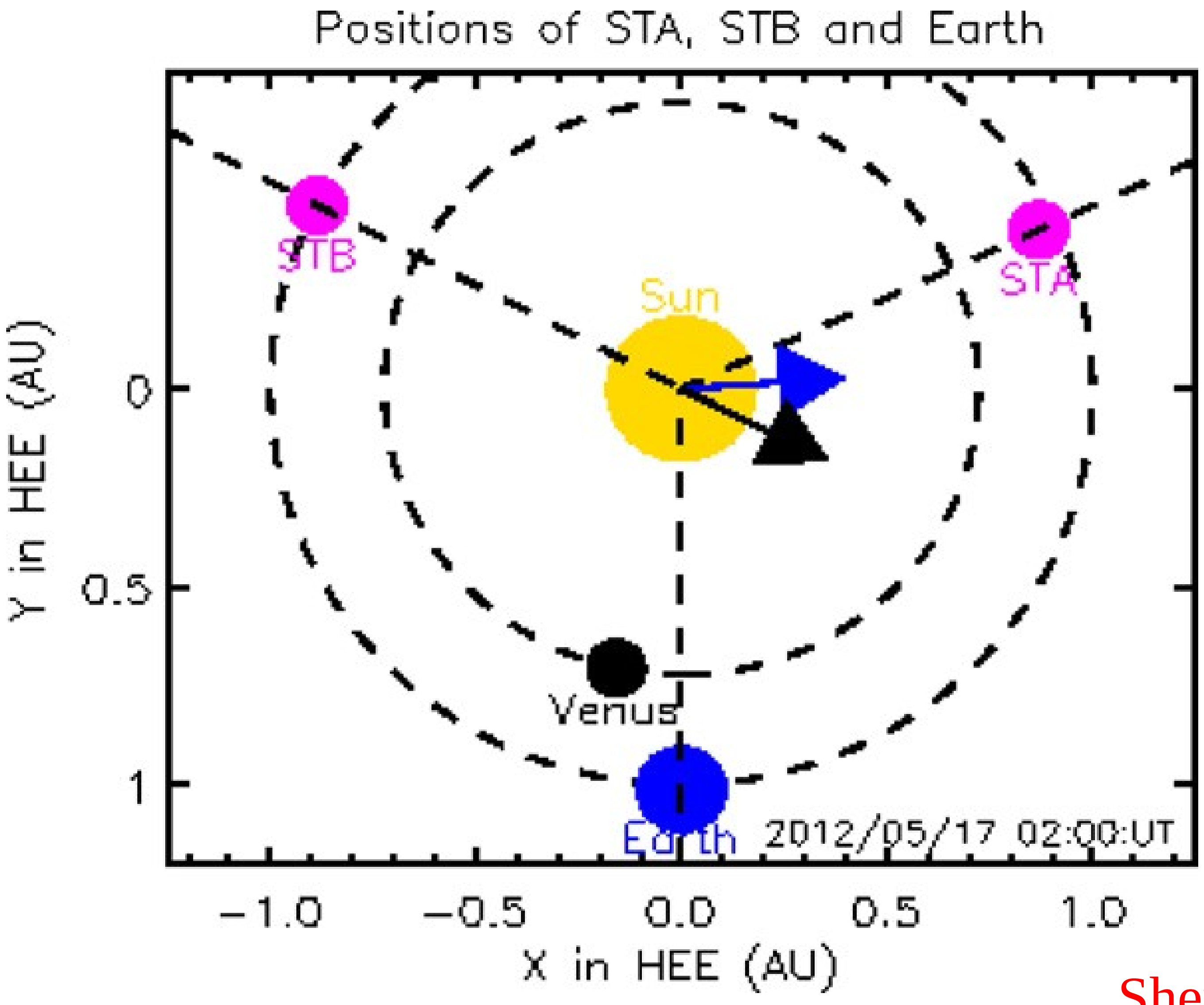

Preceding CME
(a) Group I
718
(b) Group III
805
Number of Events
Speed (km/s)


Event location
SEPs
metric type II
no SEPs
metric type II
(a)
(b)
Latitude
Longitude

A special subset of twin-CMEs

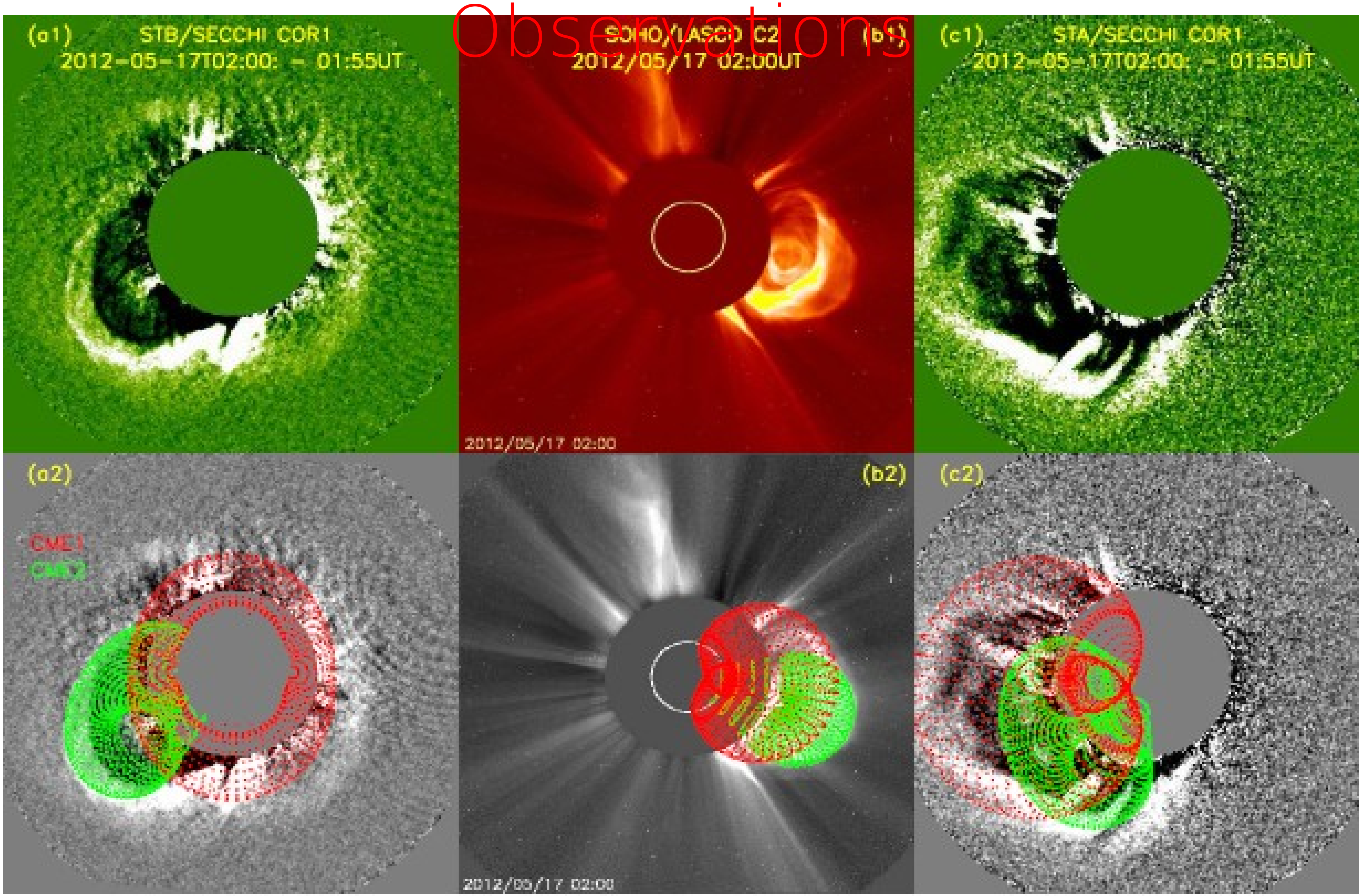
homologous sympathetic eruptions leading to converging shocks

the May 17 2012 GLE event

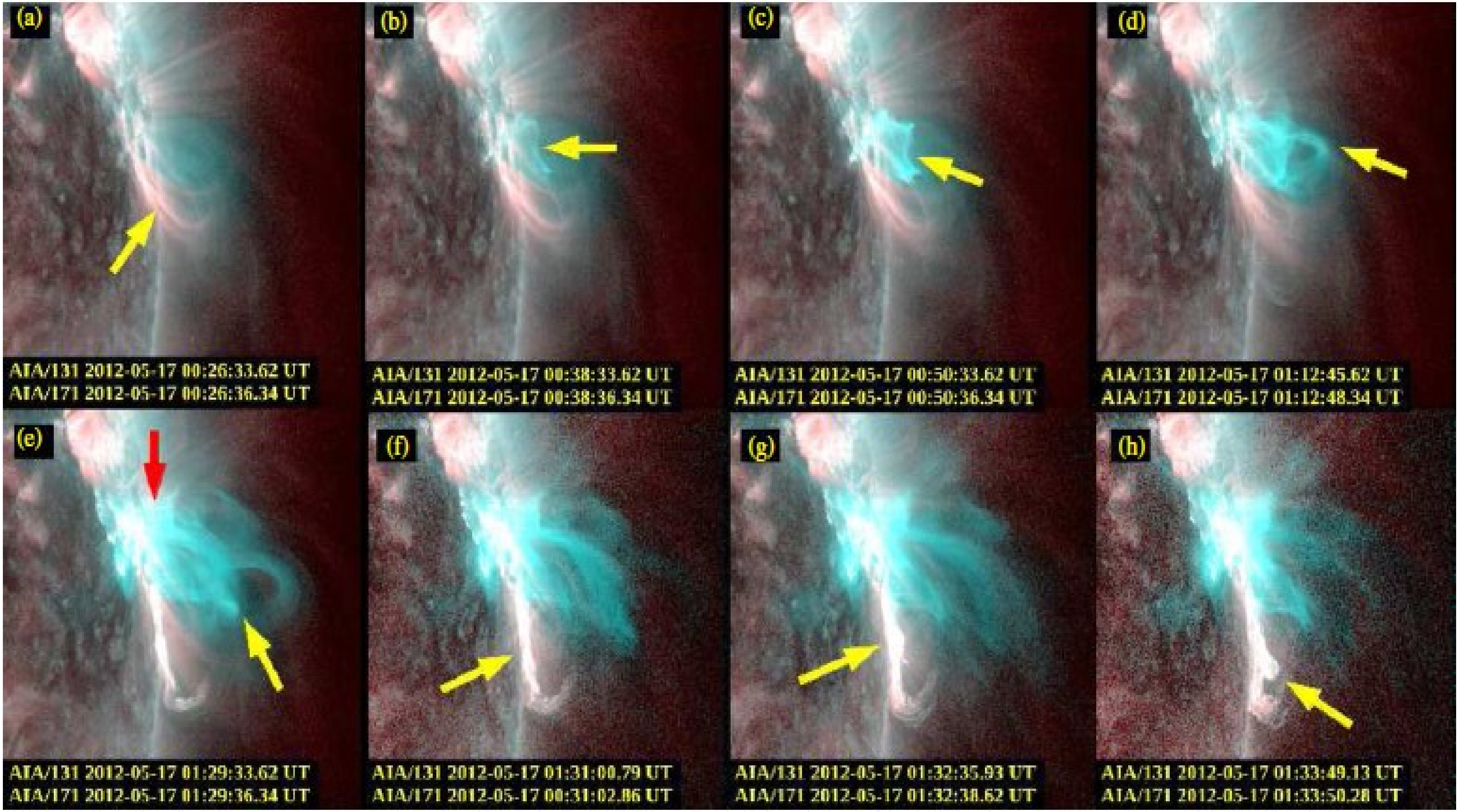


Shen et al. (2013)

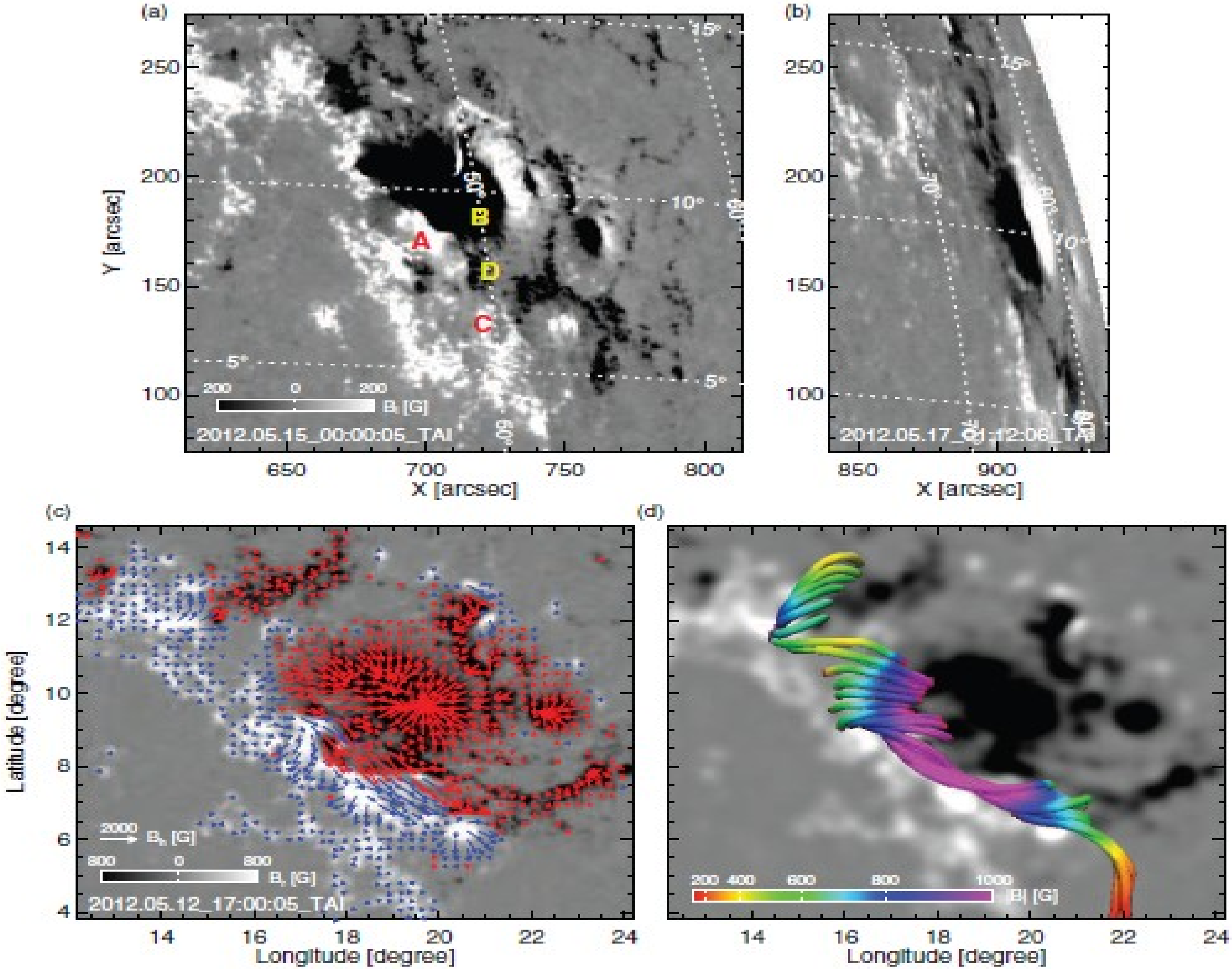
STEREO and SOHO Observations



SDO/AIA observations



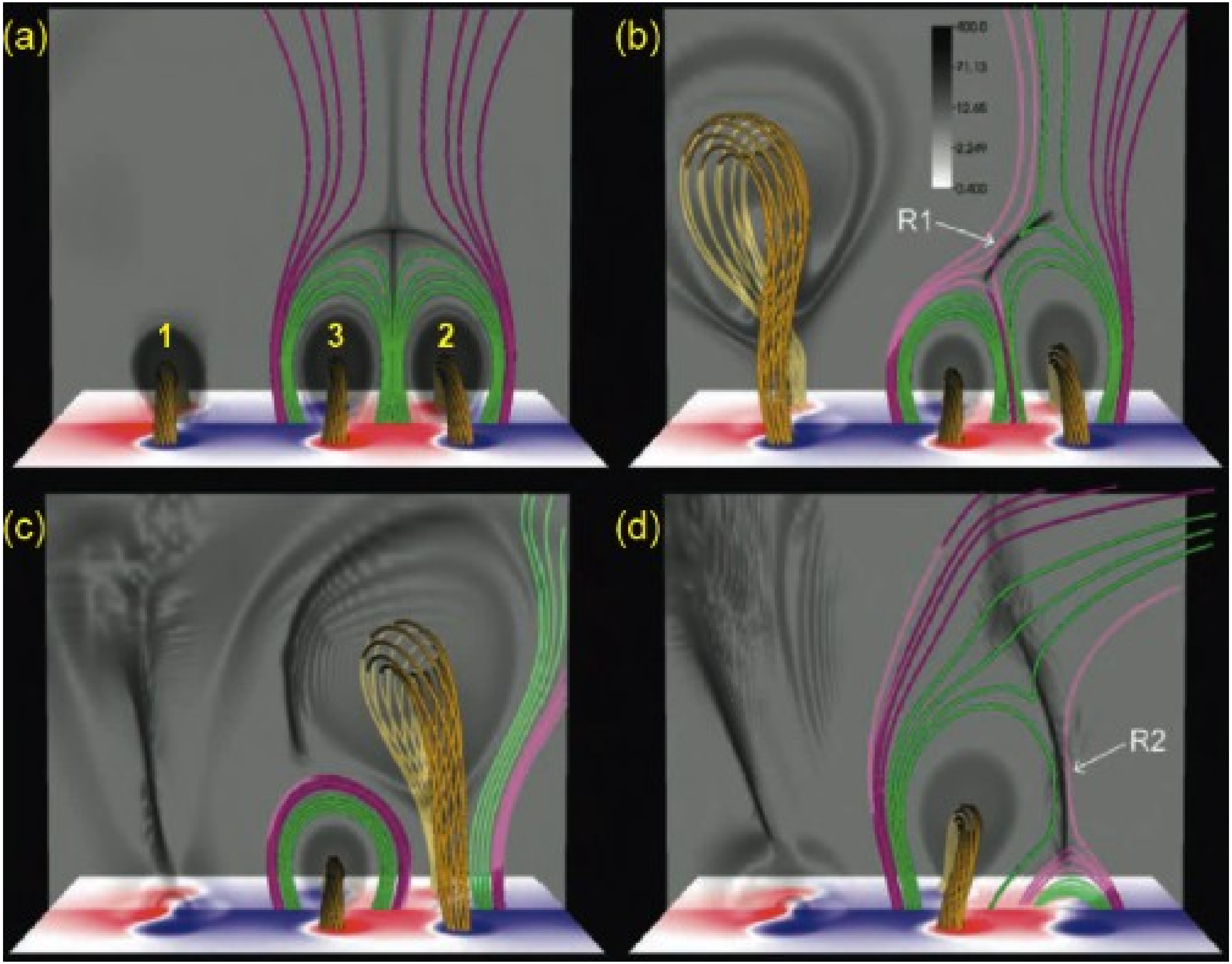
Pre-event magnetic field reconstruction



Emerging clues

1. a complicated non-bipolar background coronal field;
2. a curved NIL that seems to have two segments;
3. two sets of flux loops in non-parallel configuration residing
above the two segments of NILs;
4. a pre-existing flux rope at the first segment prior to the eruption.

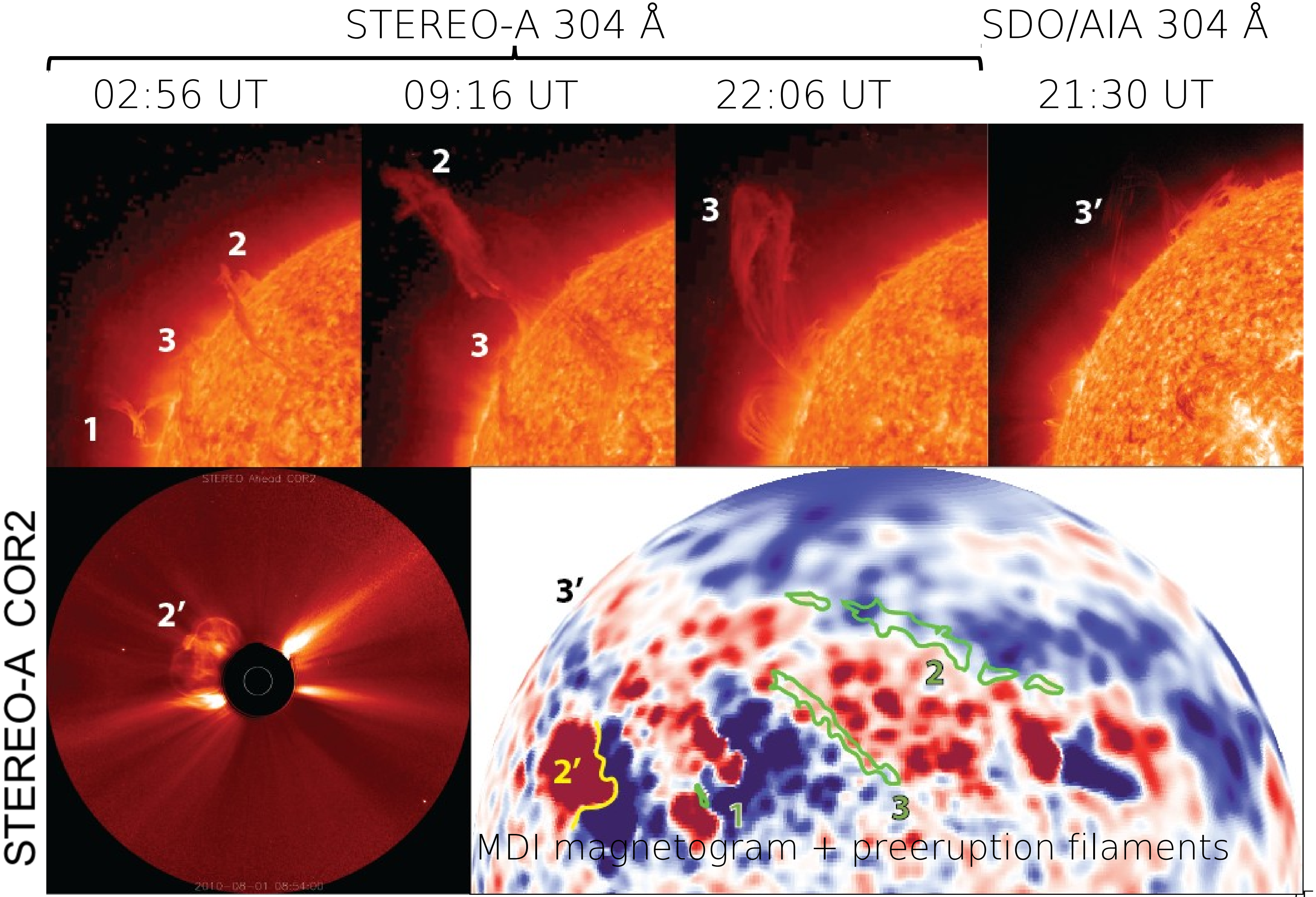
Twin CMEs in sympathetic eruption



Torok et al. (2011)

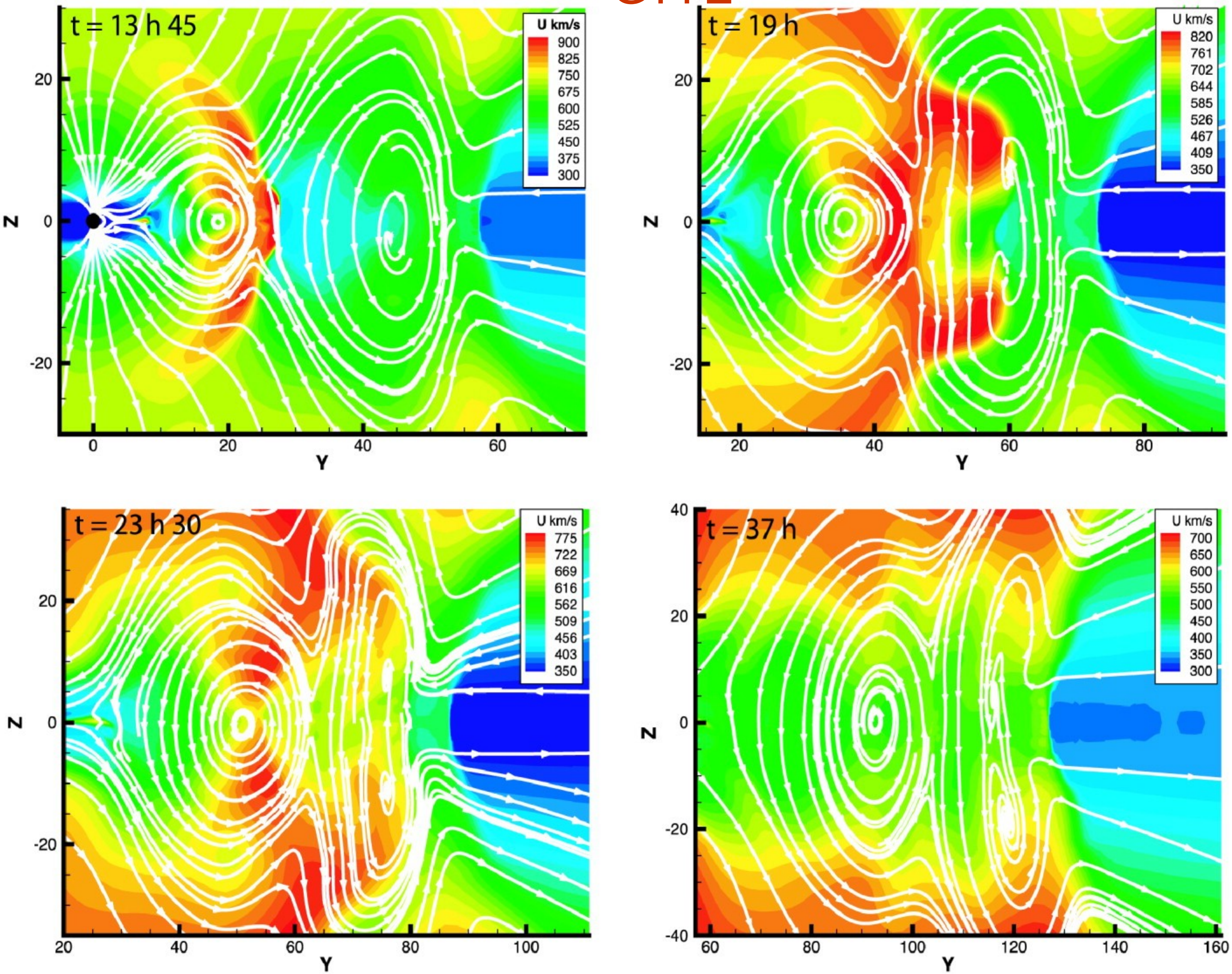
Twin CMEs are common

Sympathetic CMEs on 2010 August 1-2



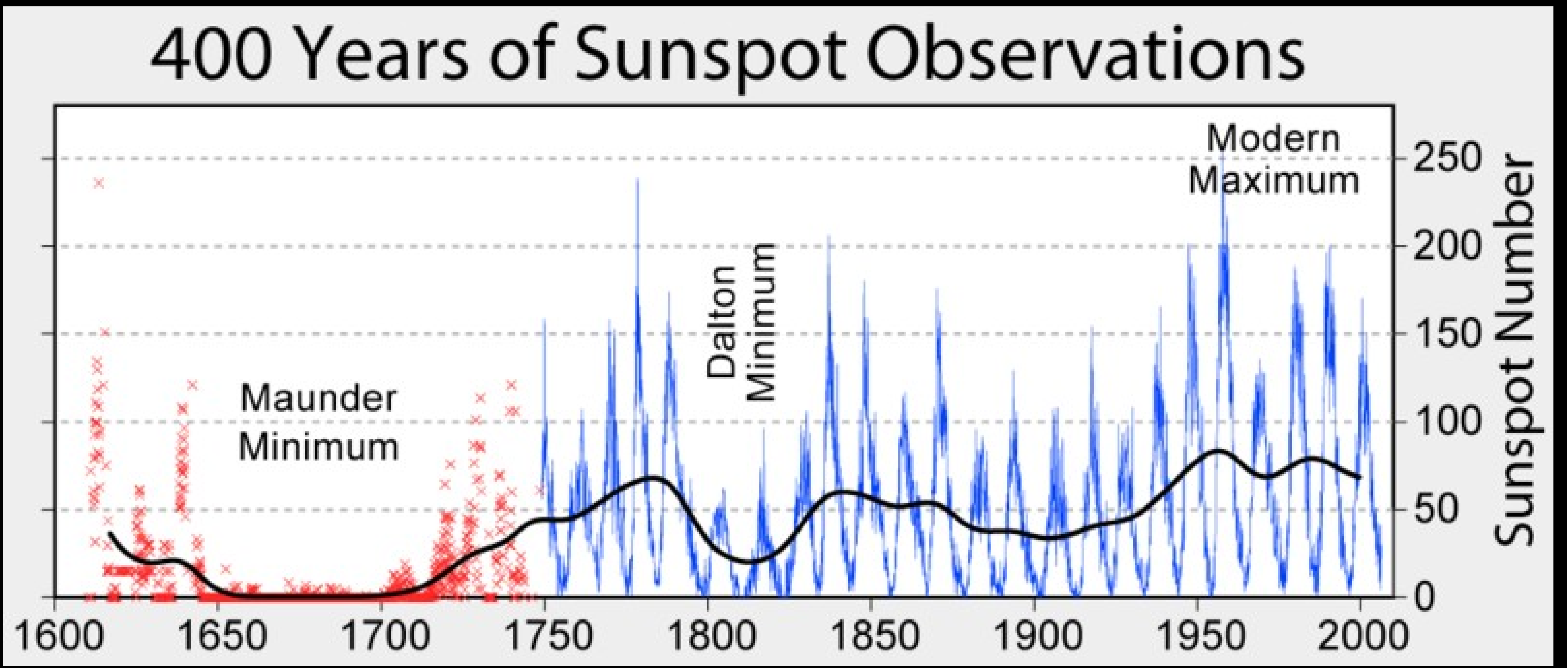
Schrijver & Title (2011).

MHD simulation of 2 interacting-CME



Lugaz et al. (2005)

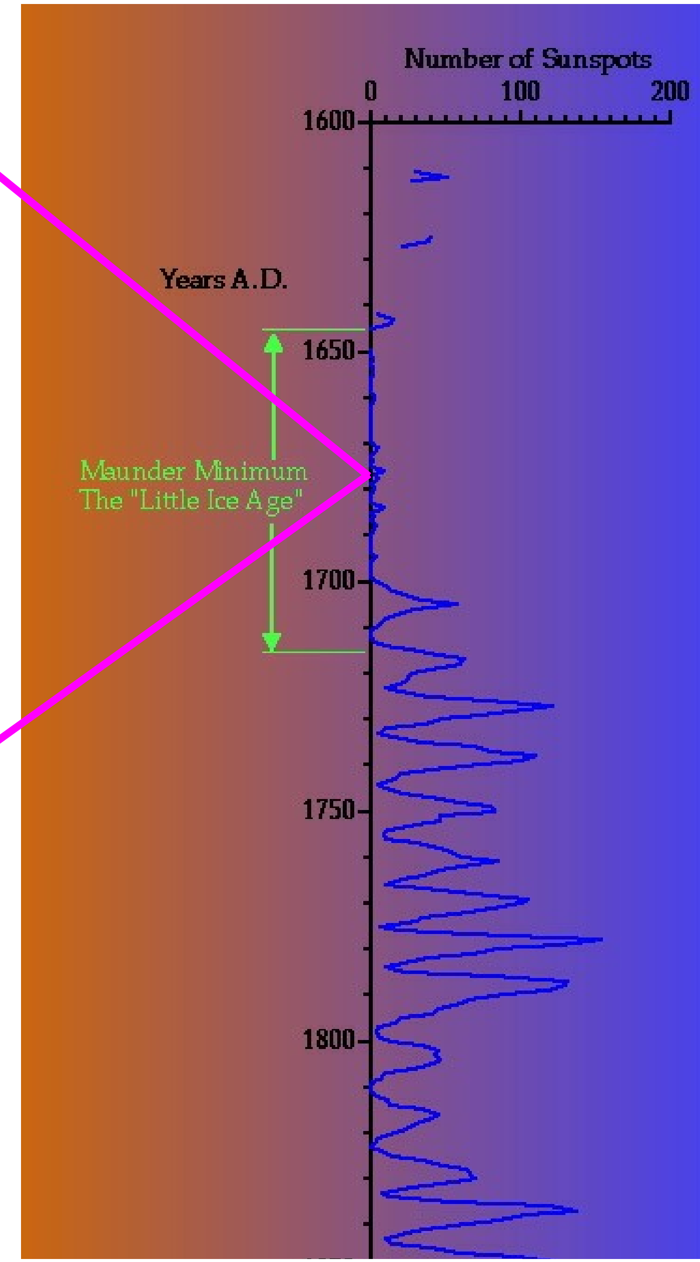
Solar Cycle
Sunspot Number (Wikipedia)



Influence of solar activity on the Earth's climate

Frozen Thames River, 1677

Little Ice Age

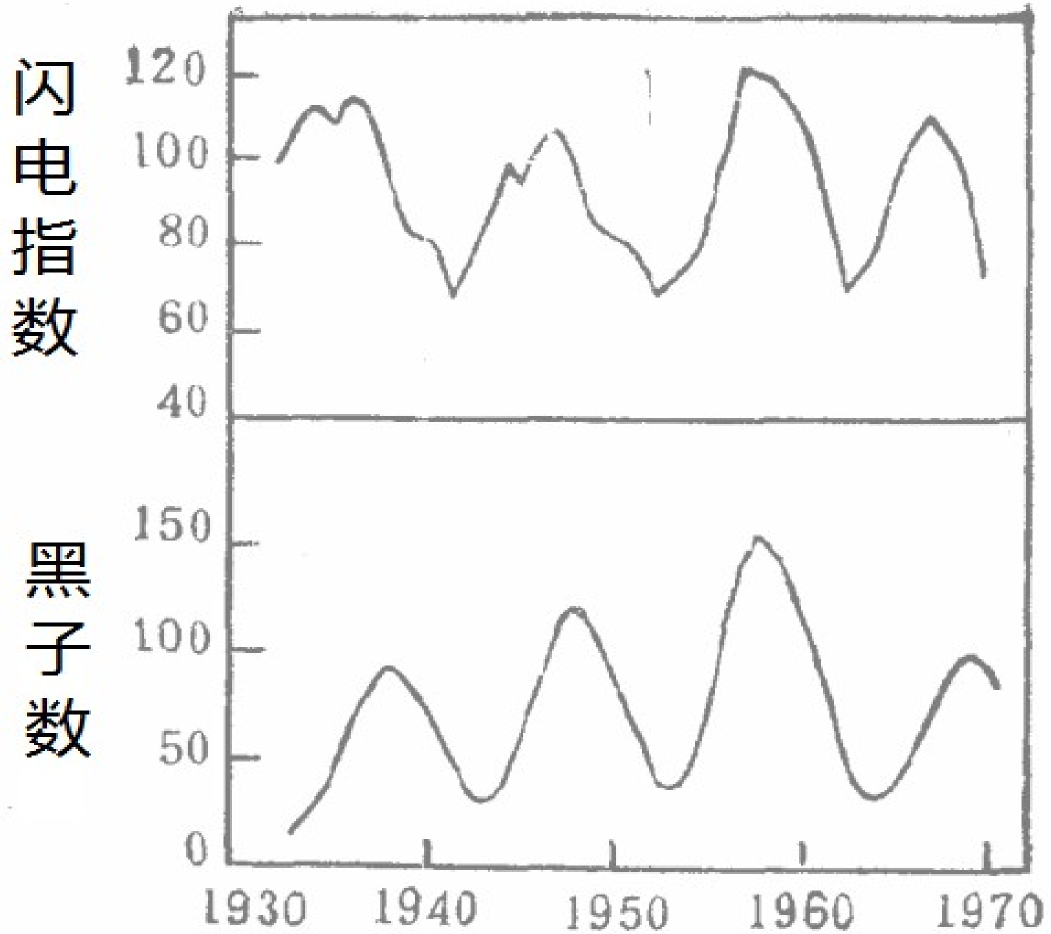


Tomorrow's Space Climate

is

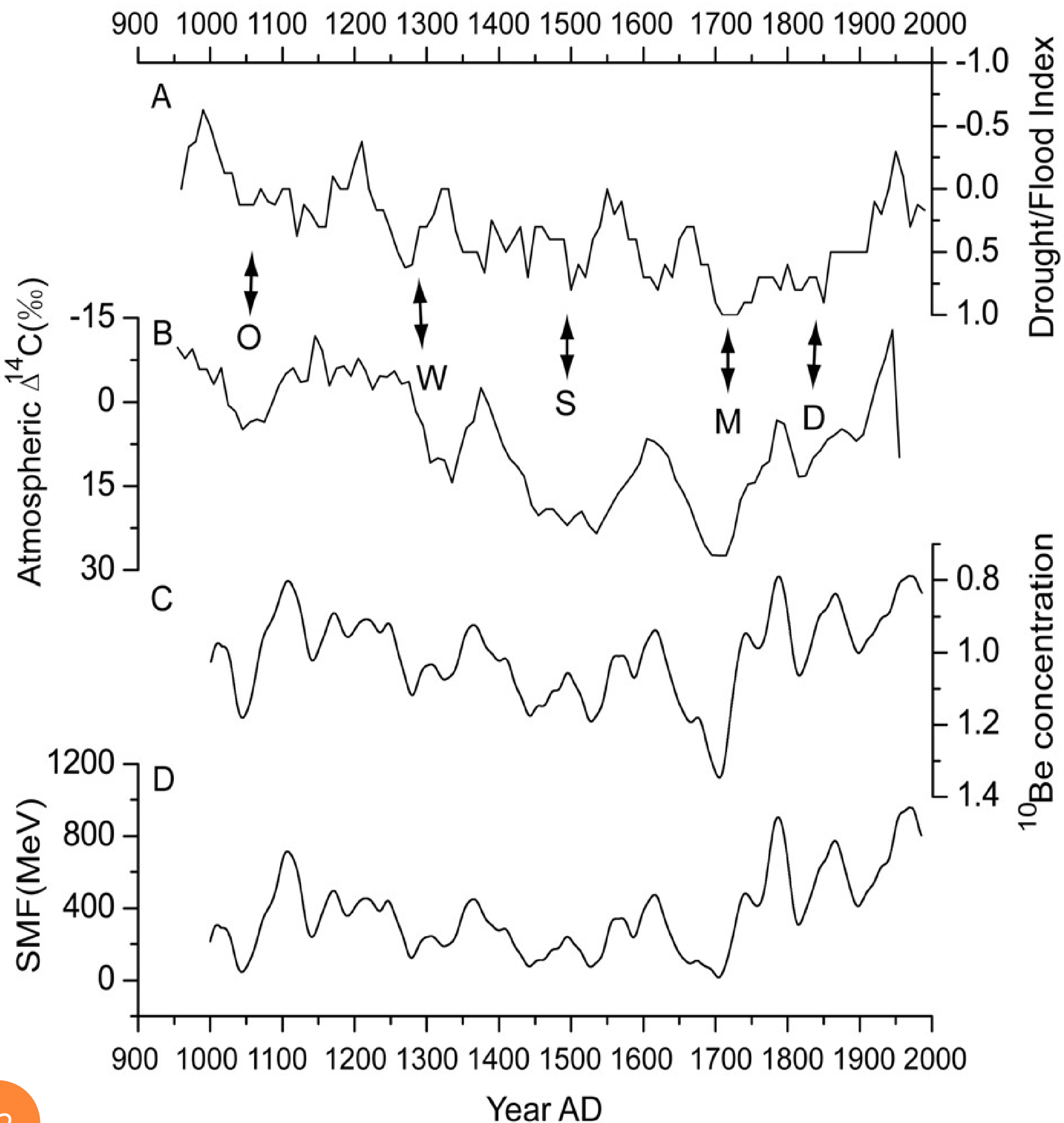
Today's Space Weather

研究现状 --- 太阳活动对地球的影响



年平均黑子数（下部）与闪电指数年平均值（上部）的5年滑动平均数

斯特林费罗（1974）取英国40个代表站的雷暴天数的平均平方值定义为闪电指数。



- Comparison of variations between precipitation of Longxi and solar activity since AD 960. The atmospheric 14C (after removal of linear trend) comes from Stuiver et al. (1998) (B), the averaged 10Be concentration (normalized) (C) and the reconstructed solar modulation function(SMF) (D) come from Muscheler et al. (2007). The letters O, W, S, M, D in (B) represent five minima of solar activity known as Oort (AD 1010–1050), Wolf (AD1280–1340), Spoerer (AD 1420–1530), Maunder (AD 1645–1715) and Dalton (AD 1795–1820) during the last millennium.

Climate of the Past, 2008.