Coronal Mass Ejections – the drivers of space weather

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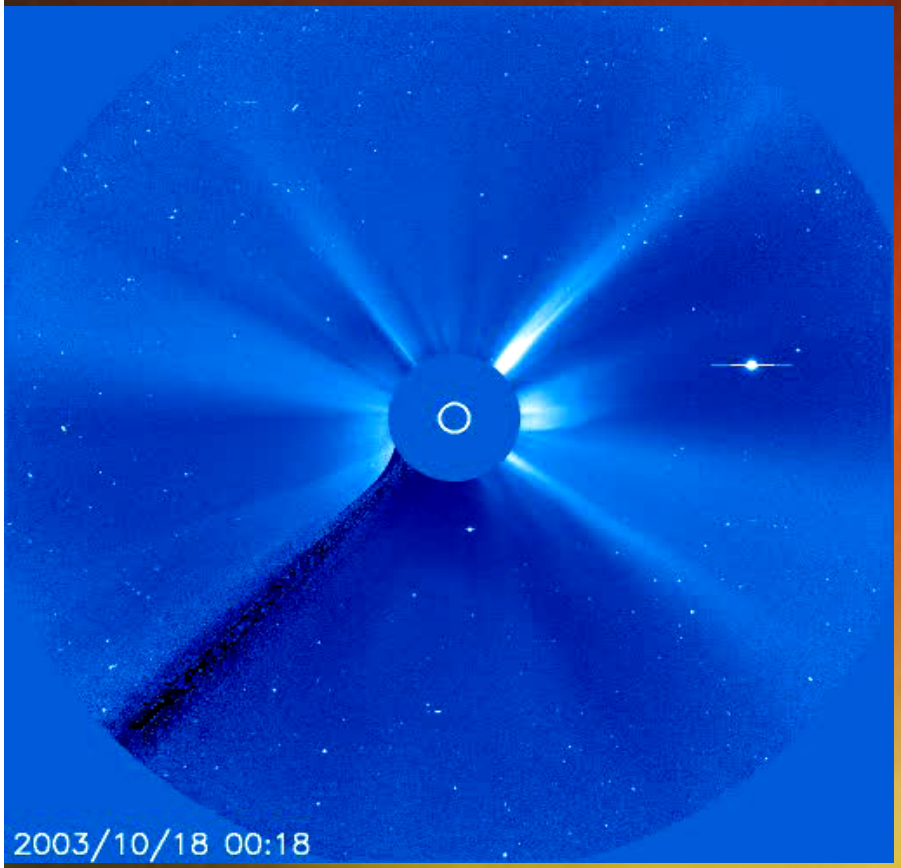

Coronal mass ejections (CMEs) are huge plasma clouds of enormous dimensions ejected by the Sun at speeds of several hundreds of km/s. They drive shock waves that literally shake major parts of the heliosphere, including the planets' magnetospheres.

TIEMS Oslo Coference Oct. 2012:
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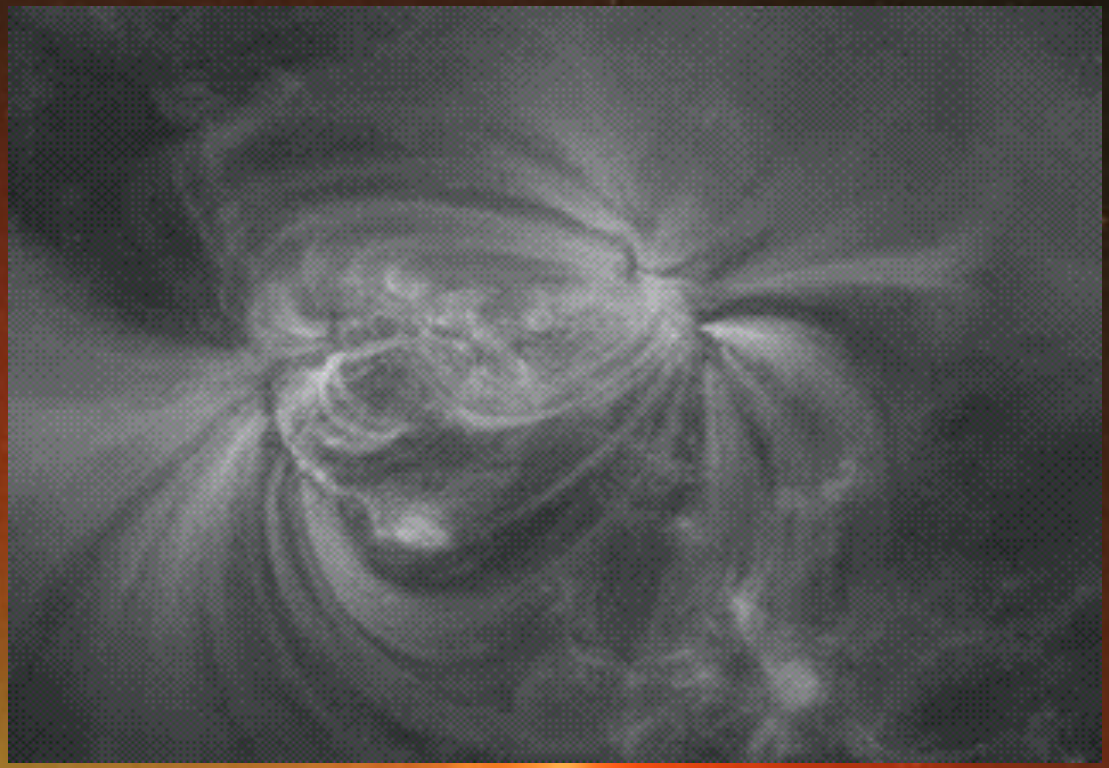
1859: The begin of space weather research



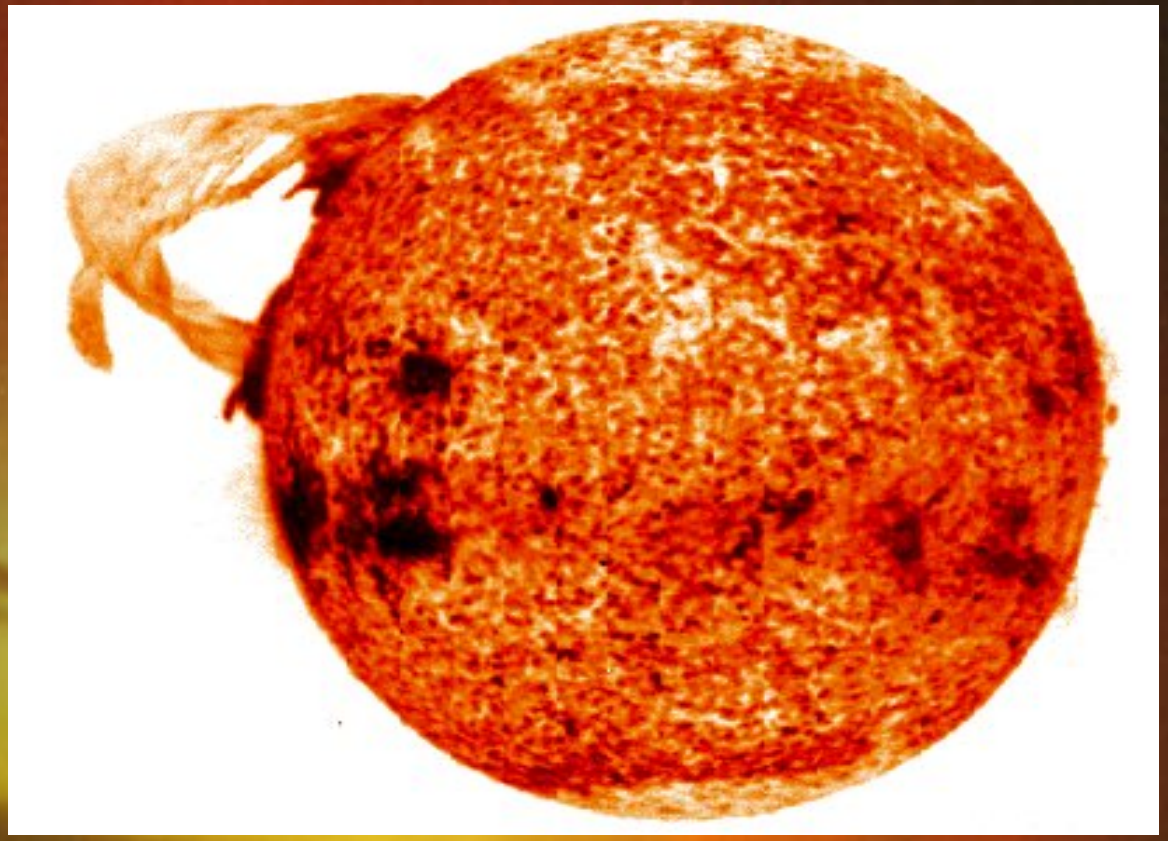
A solar flare, as observed by **TRACE**

Carrington was the first man who happened in 1859 to observe a flare and also to notice the connection with the strong geomagnetic storm 17 hours later.

Note what the "father of space weather" noted at the end of his report:
"...one swallow does not make a summer!"

However, it took more than 100 years, until the real culprits for space weather effects were revealed:
Coronal mass ejections (CMEs).

Skylab in 1973 initiated CME research



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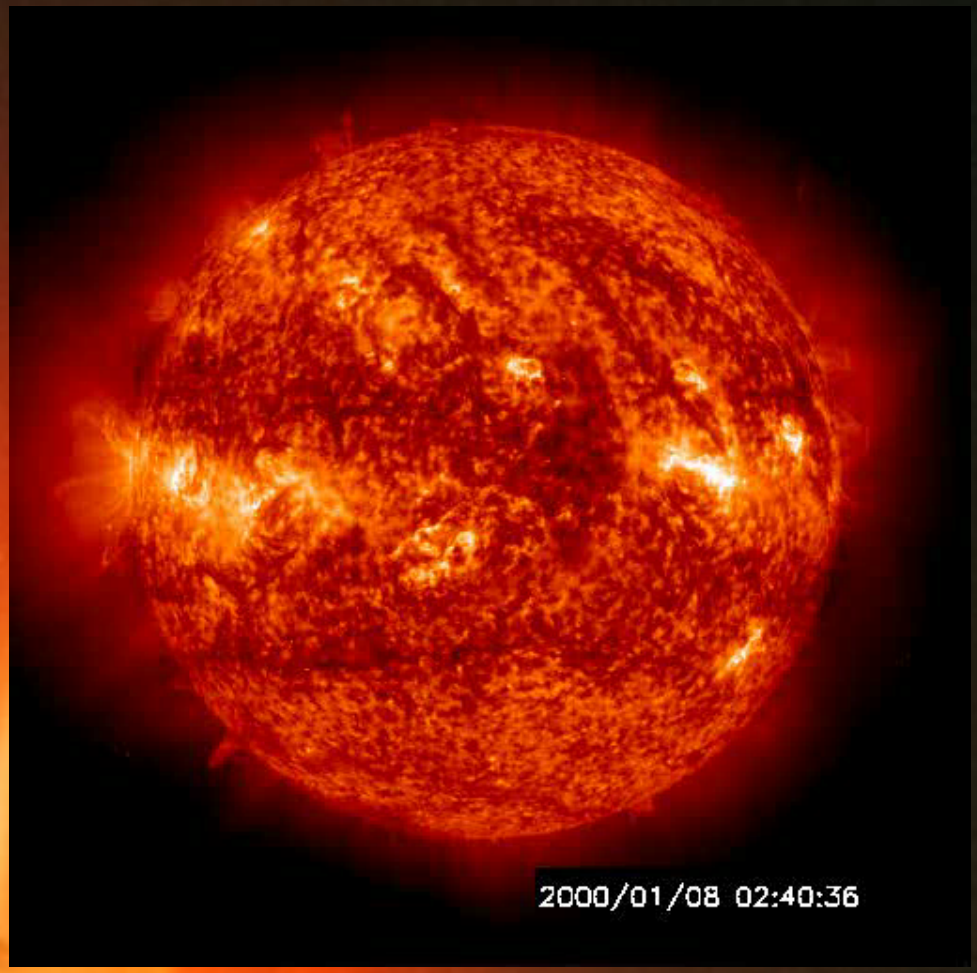
Eruptive prominences and disappearing filaments

A disappearing filament, seen in H-alpha by HASTA



Prominences/filaments: best visible in the He^+ line (30.4 nm), by EIT on SOHO

They are the same: just eruptive prominences!

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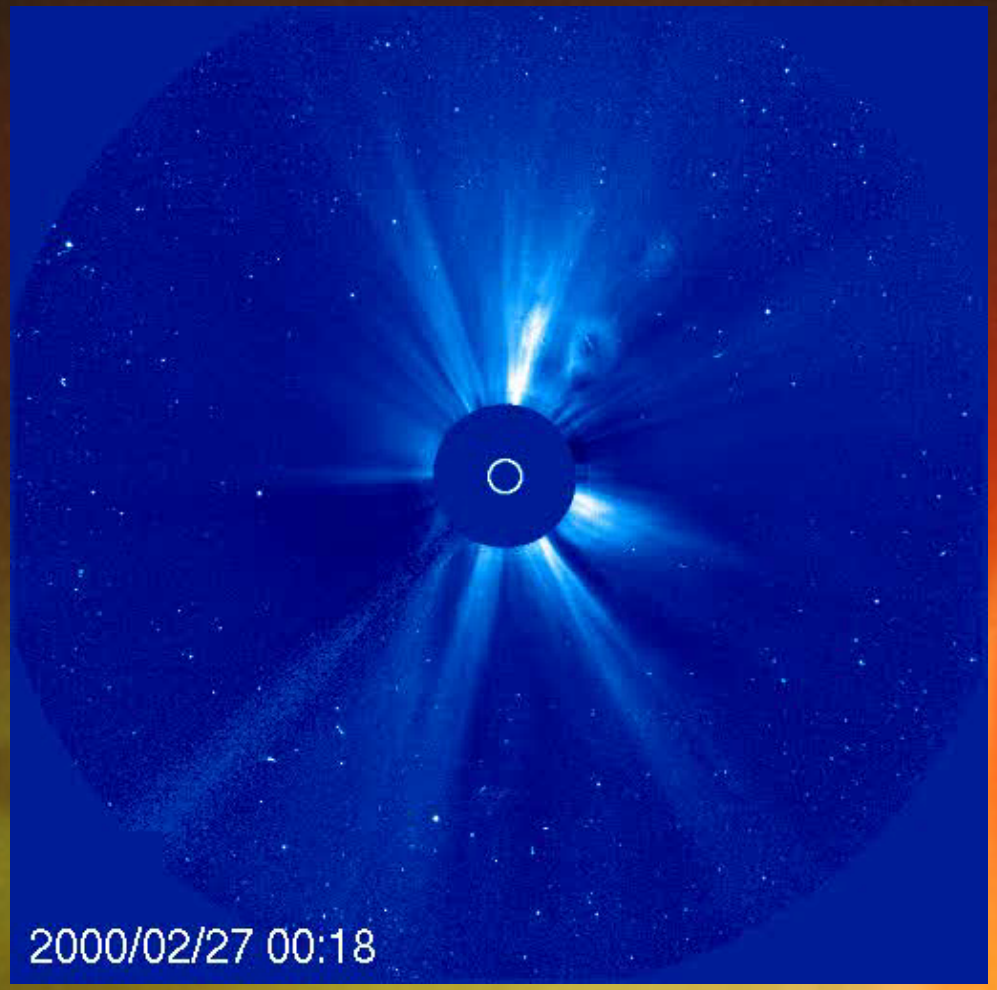
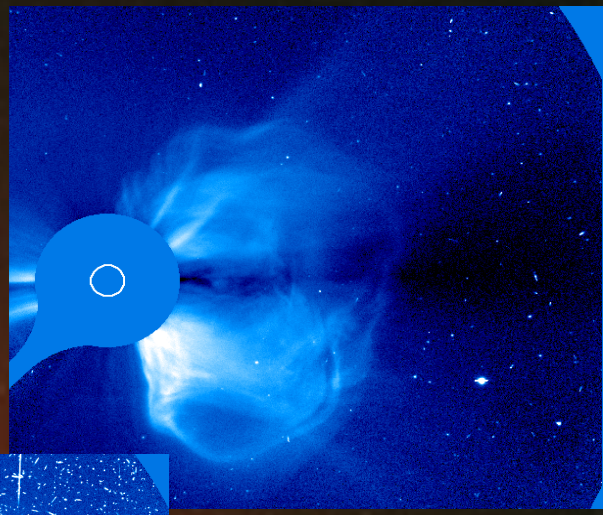
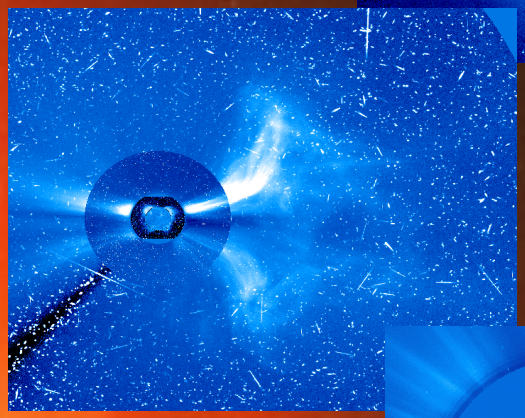
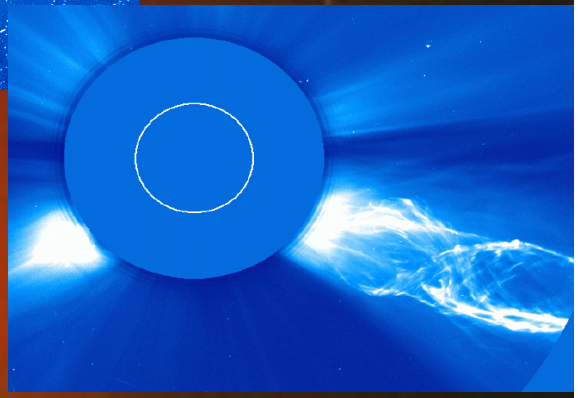
CMEs are spectacular!









Most big CMEs show this characteristic 3-part structure:

- bright outer loop,
- dark void
- bright inner kernel

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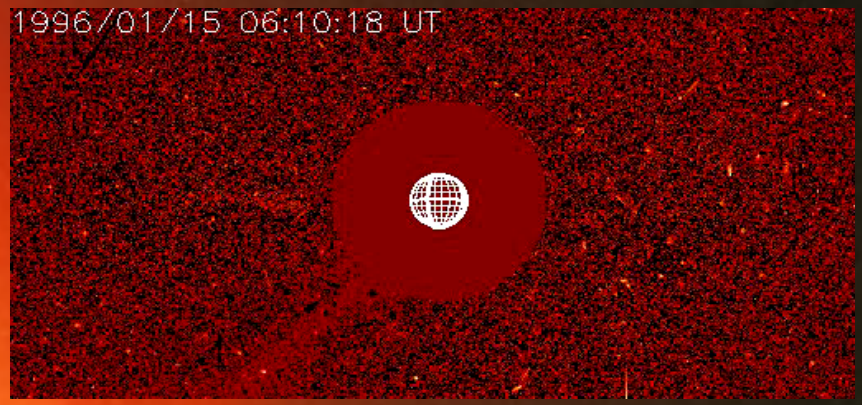
The definition of a CME

"We define a **coronal mass ejection (CME)** to be an observable change in coronal structure that occurs on a time scale of a few minutes and several hours and involves the appearance (and outward motion, RS) of a new, discrete, bright, white-light feature in the coronagraph field of view." (Hundhausen et al., 1984, similar to the definition of "mass ejection events" by Munro et al., 1979).

CME: coronal -------- mass ejection,
not: coronal mass -------- ejection!

In particular, a CME is NOT an
Ejección de Masa Coronal (EMC),
Ejectie de Maså Coronalå,
Eiezione di Massa Coronale
Éjection de Masse Coronale



The community has chosen to keep the name "CME", although the more precise term **"solar mass ejection"** appears to be more appropriate.

An **ICME** is the interplanetary counterpart of a CME

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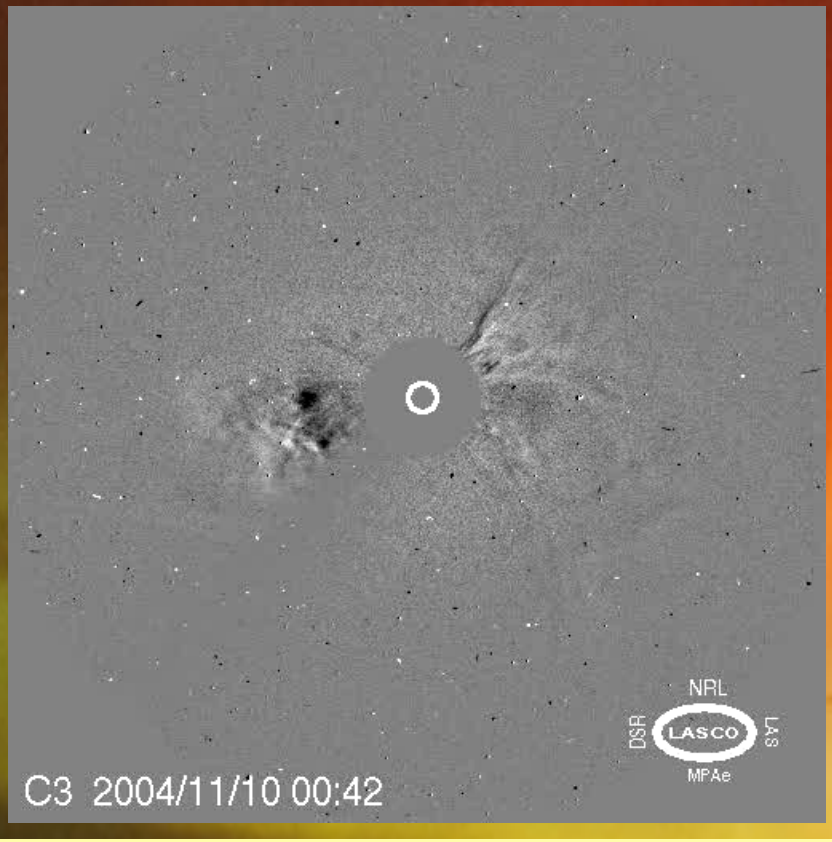
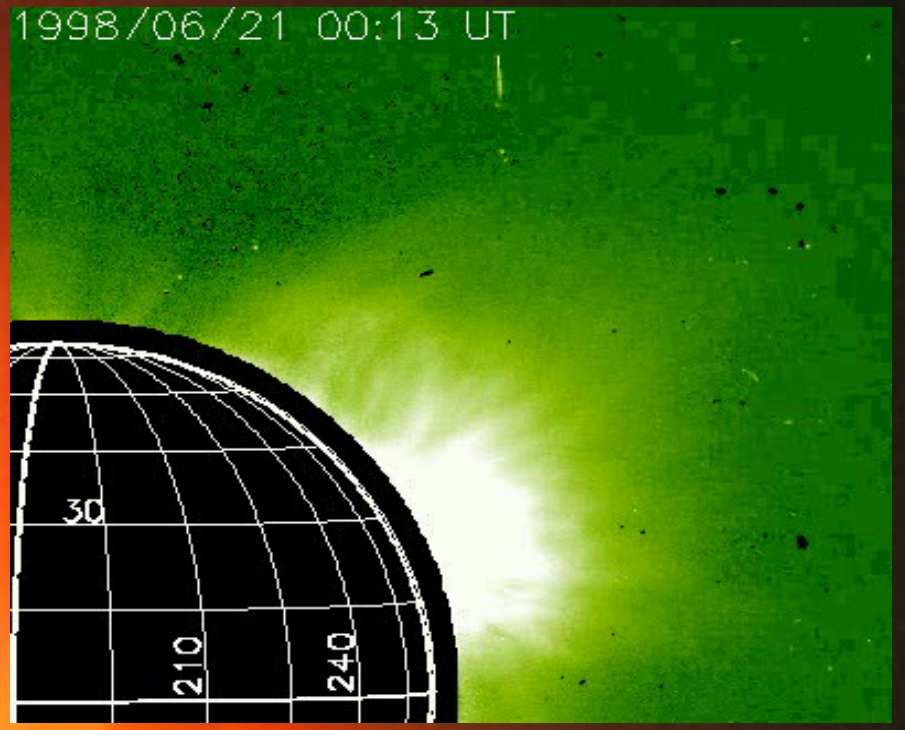
Different types of CMEs ?

The bandwidth of CME properties (speed, acceleration profiles, sizes, event associations, etc) is enormous. It is hard to conceive that they are all due to the same release and acceleration mechanisms.



This extremely fast limb CME of Nov. 10, 2004, went to 30 Rs in 2 hours!



This "balloon" took some 30 hours to finally take off! It was the offspring of an eruptive prominence.

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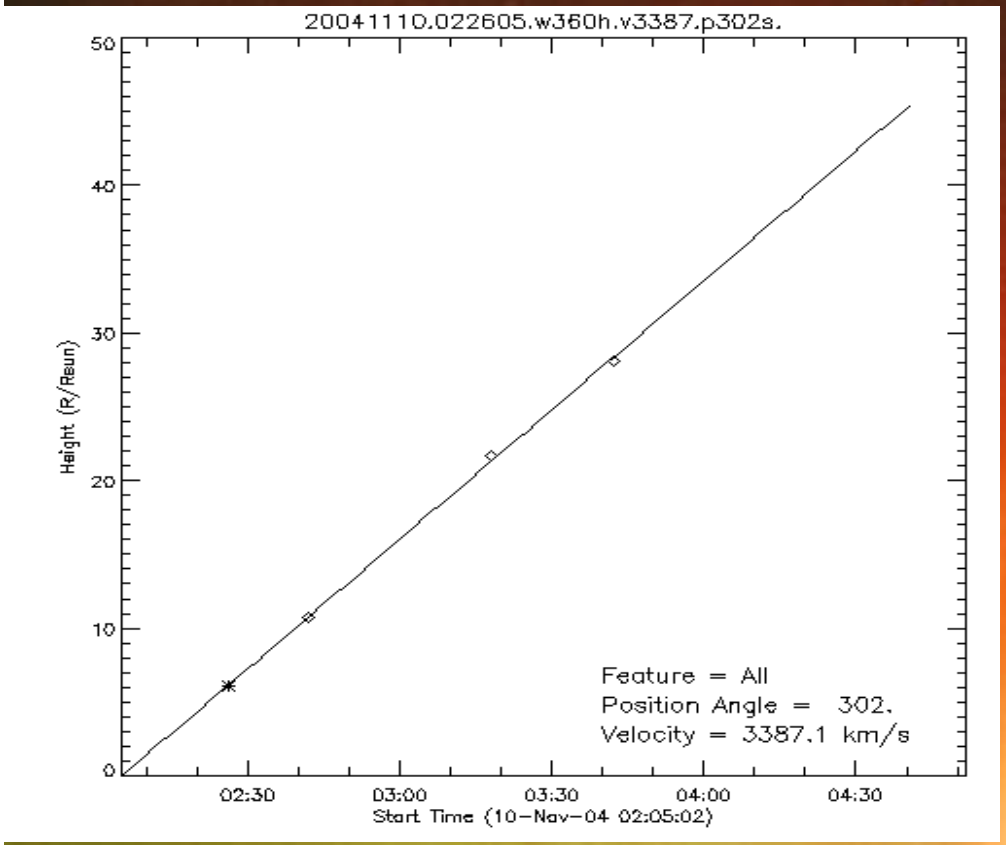
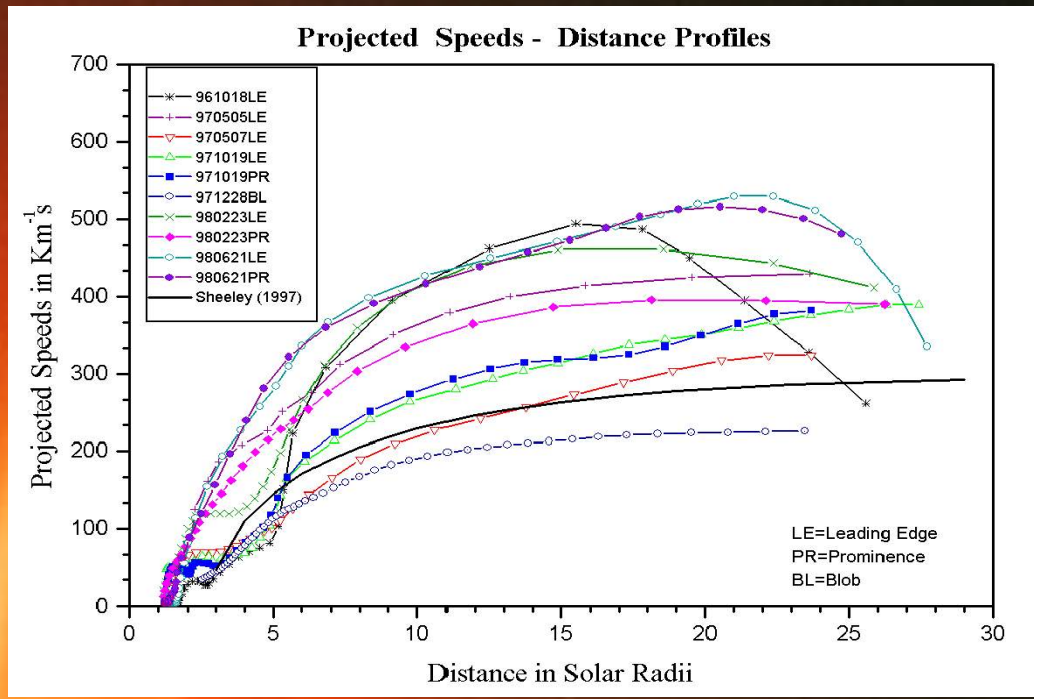
Different types of CMEs ?

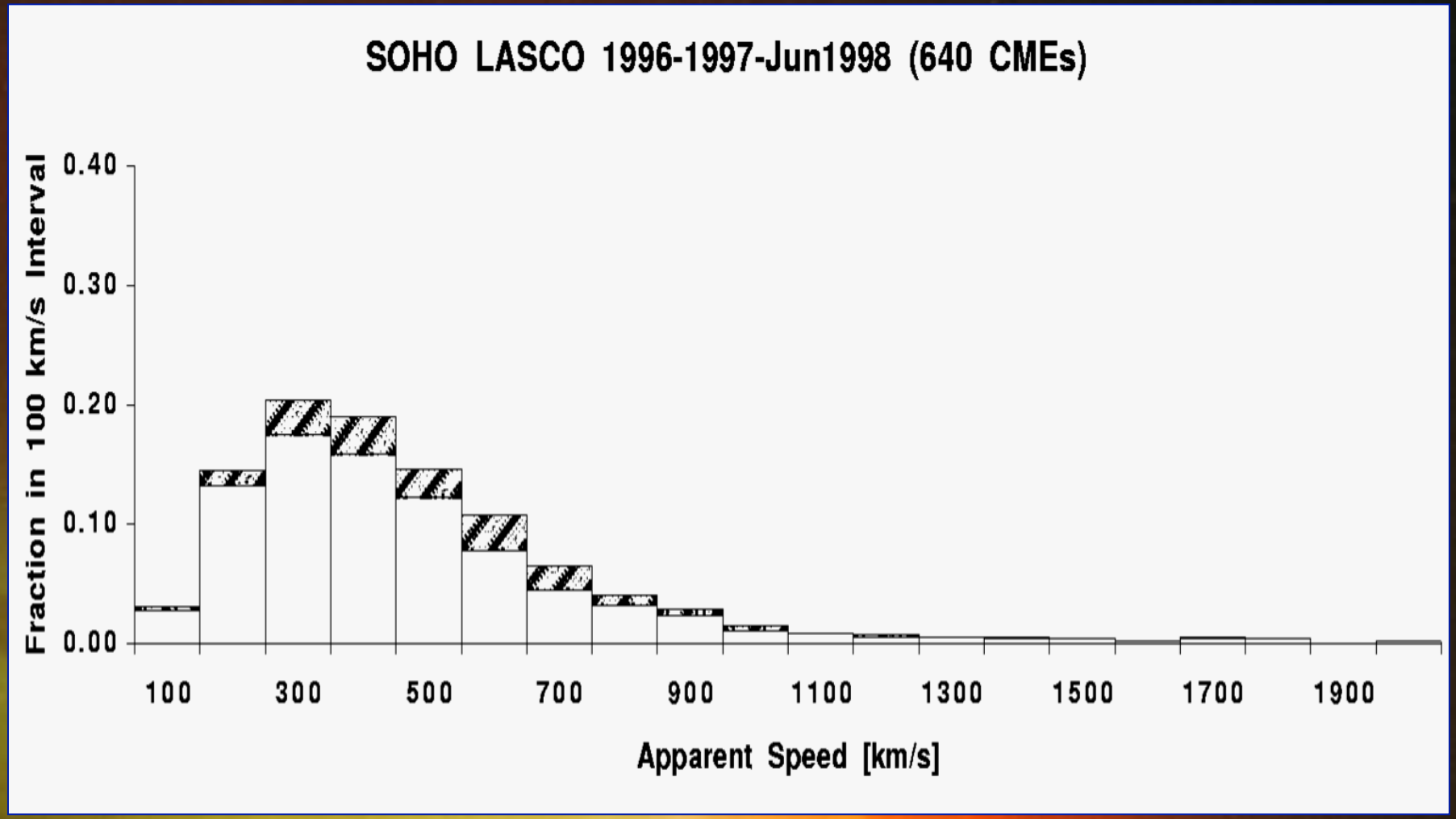




This extremely fast limb CME of Nov. 10, 2004, went to 30 Rs in 2 hours!

These balloons took some 30 hours to finally take off! They are offsprings of eruptive prominences.

Different types of CMEs ?



Histogram of apparent front speeds of 640 CMEs,
observed by **LASCO** on **SOHO**

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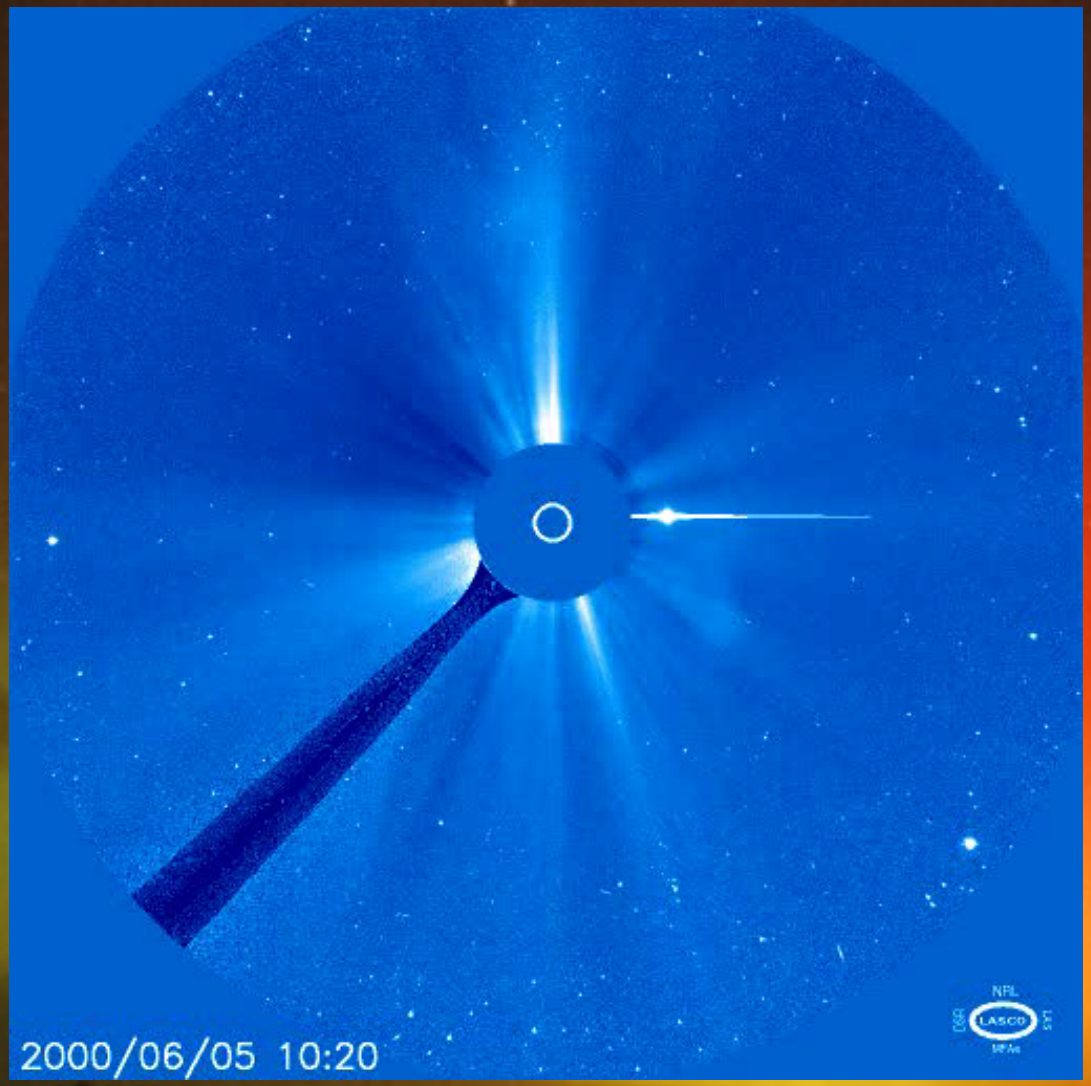
Limb CMEs and „halo“ CMEs



A series of dramatic CMEs observed by LASCO C3 on SOHO

Halo CMEs, if pointed towards (not away from!) the Earth, may cause disturbances of the Earth‘s geomagnetism: Geomagnetic Storms,
Space Weather.

Towards or away from Earth?
That can only be decided using simultaneous disk observations

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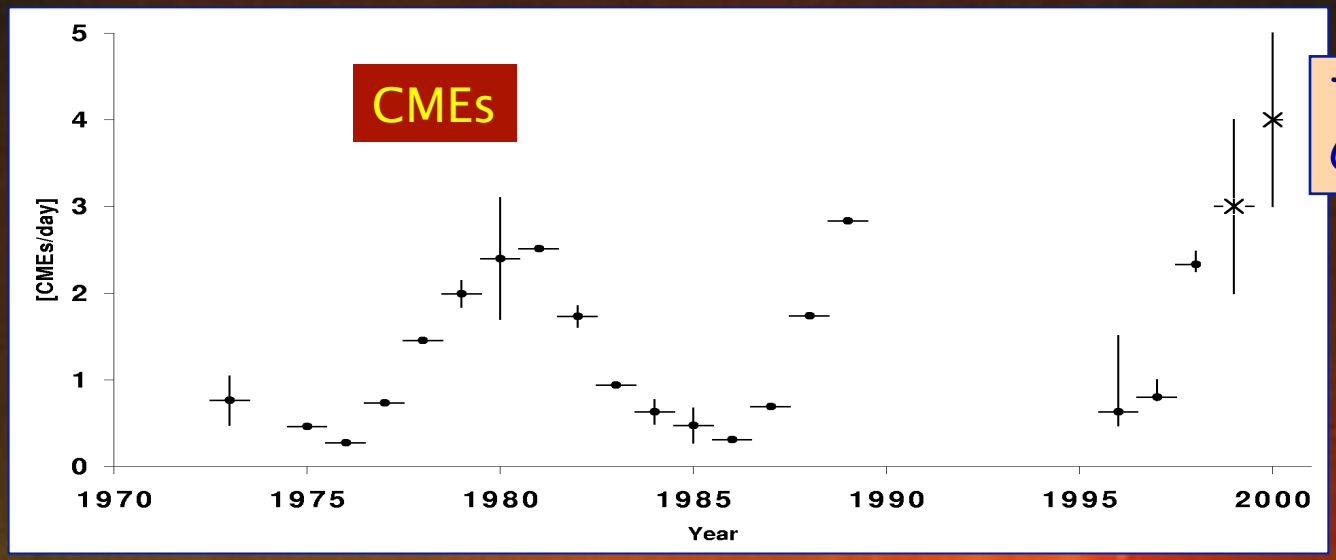
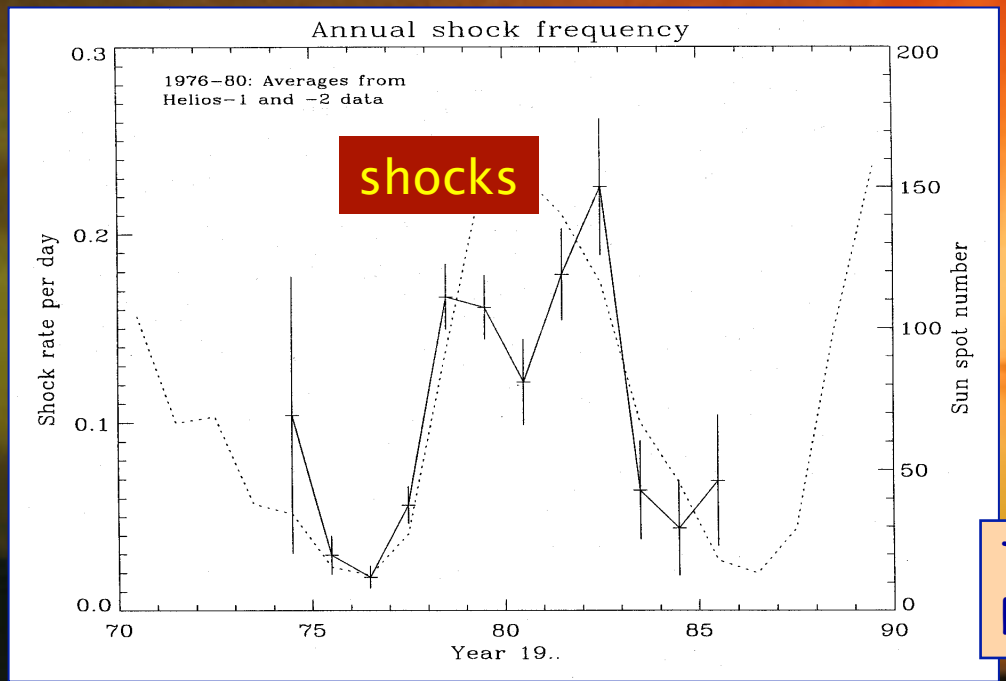
CMEs and shock rates during 2 solar cycles



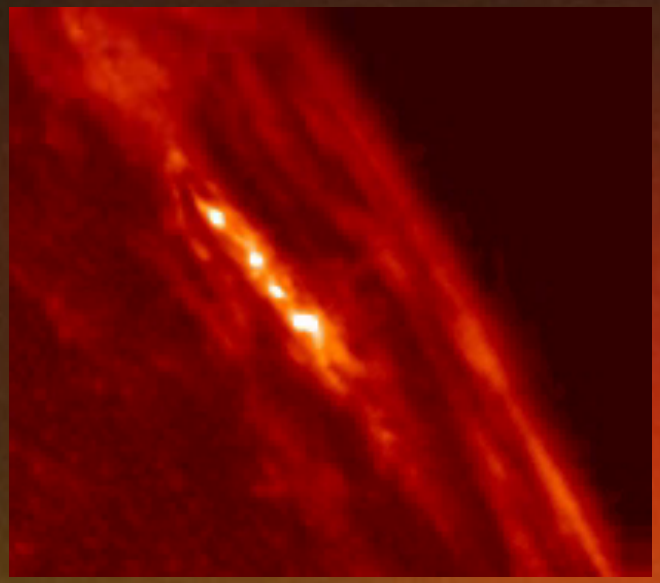
The daily rate of all CMEs

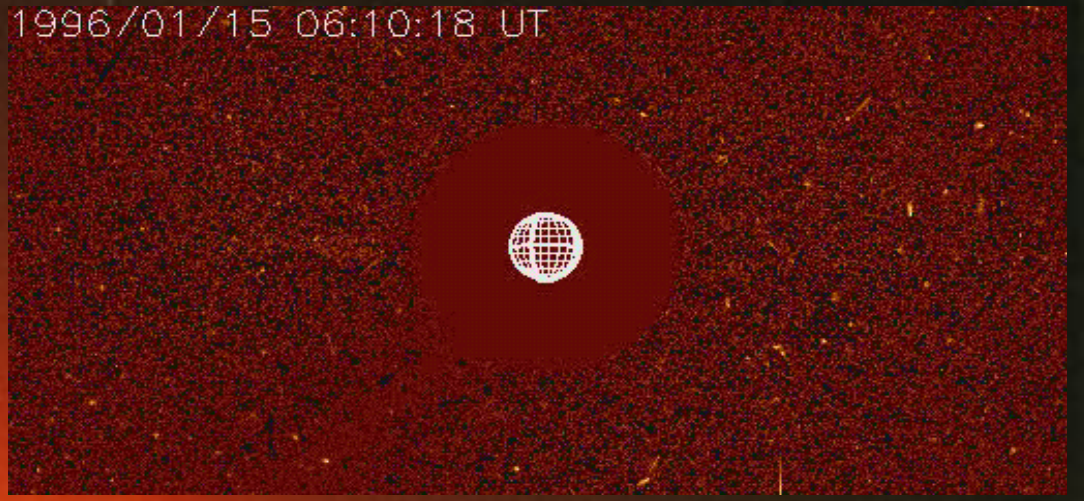
- There is a clear maximum of CME and shock occurrence at maximum acticivty.
- Between minimum and maximum, the rates of both: shocks and CMEs vary by a factor of 10.
- The ratio between CME and shock rates is 10.



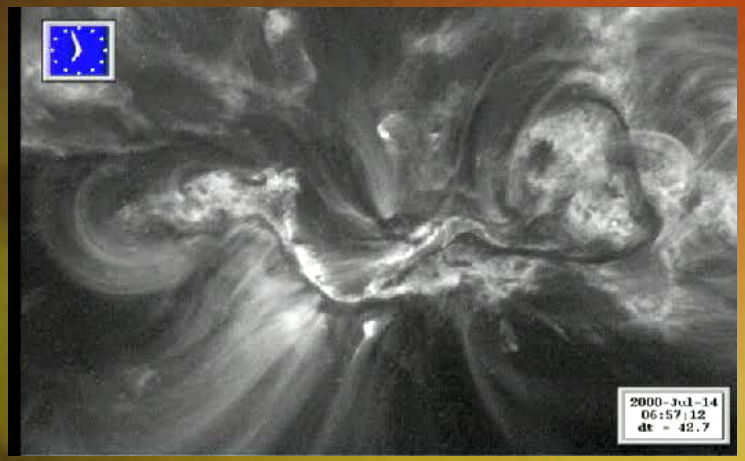
The daily rate of shocks seen by an *in-situ* observer

The relationship between flares and CMEs





The CME of Jan 15, 1996, as seen by LASCO-**C3** on **SOHO**



The „Bastille“ flare, on July 14, 2000

- Flares are localized short-duration explosions in the solar atmosphere, seen in visible light, EUV, X- and Gamma-rays.
- CMEs are large-scale expulsions of huge plasma clouds that may drive shock waves.
- Flares and CMEs often occur in close temporal context.

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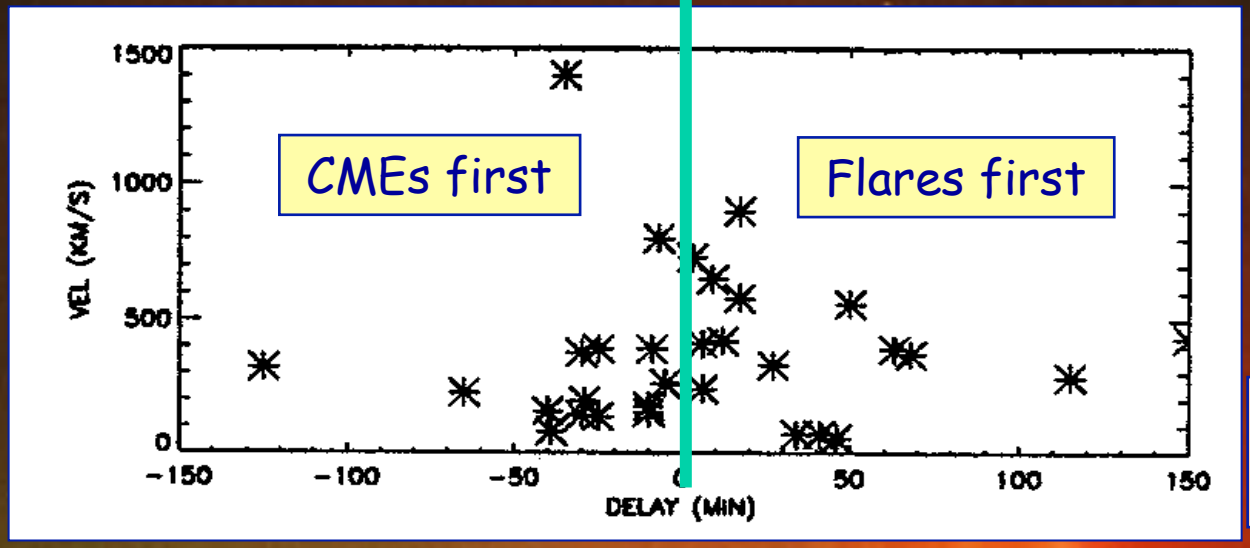
CME-flare relation, a hen-and-egg situation?



Time separation between flares and correlated CMEs

The simple but important conclusions from these studies:

Flares occurring after their associated CMEs cannot be their cause, quite logically.

Flares and CMEs are probably symptoms of a more basic "magnetic disease" of the sun.

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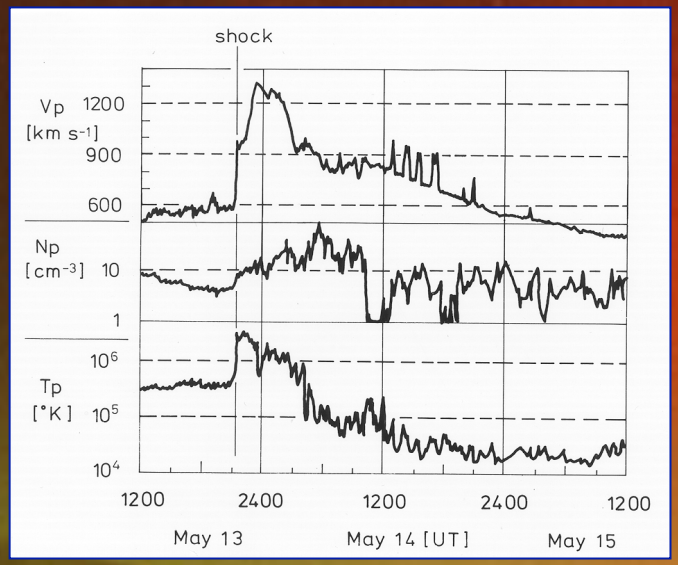
The flares vs CMEs controversy,

problematic for space weather predictions

Since Skylab/Helios times we learned to look for CMEs/shocks/ejecta rather than for flares as has been common for the past 130 years.



Results from correlations between CMEs and interplanetary shocks:

- an observer within the angular span of a fast >400 km/s) CME has a 100% chance to be hit by a fast shock wave,
- every shock (except at CIRs) can be traced back to a fast CME.

These shocks and the driver gases following them have a near 100% chance of becoming geo-effective, if ejected towards Earth.

Note: no such statement applies to flares!

Indeed: there are flares without CMEs (and geo-effects) and there are CMEs (and geo-effects) without flares.

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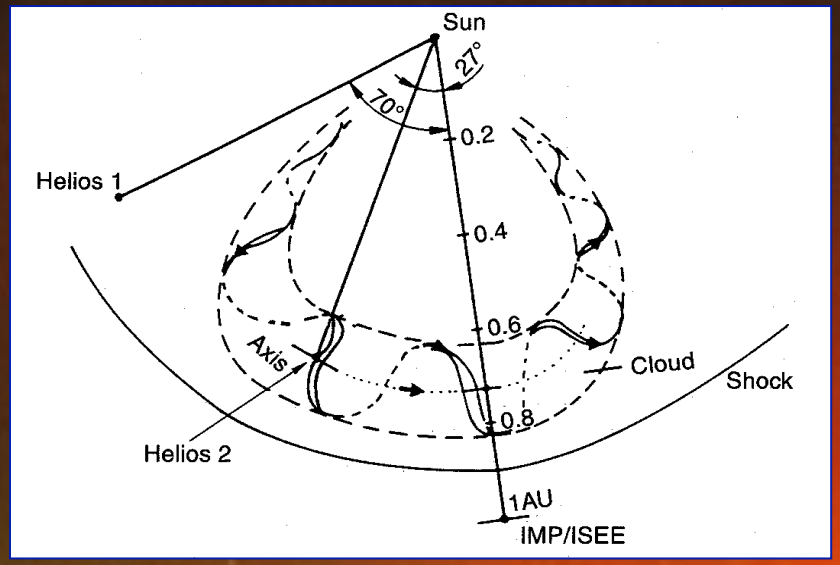
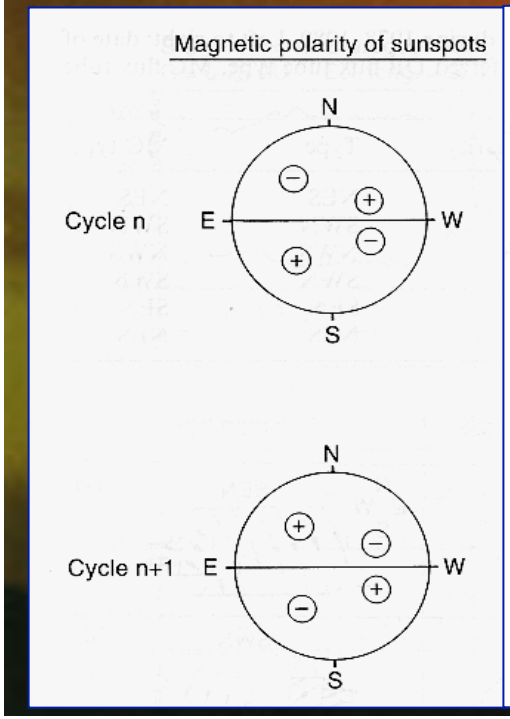
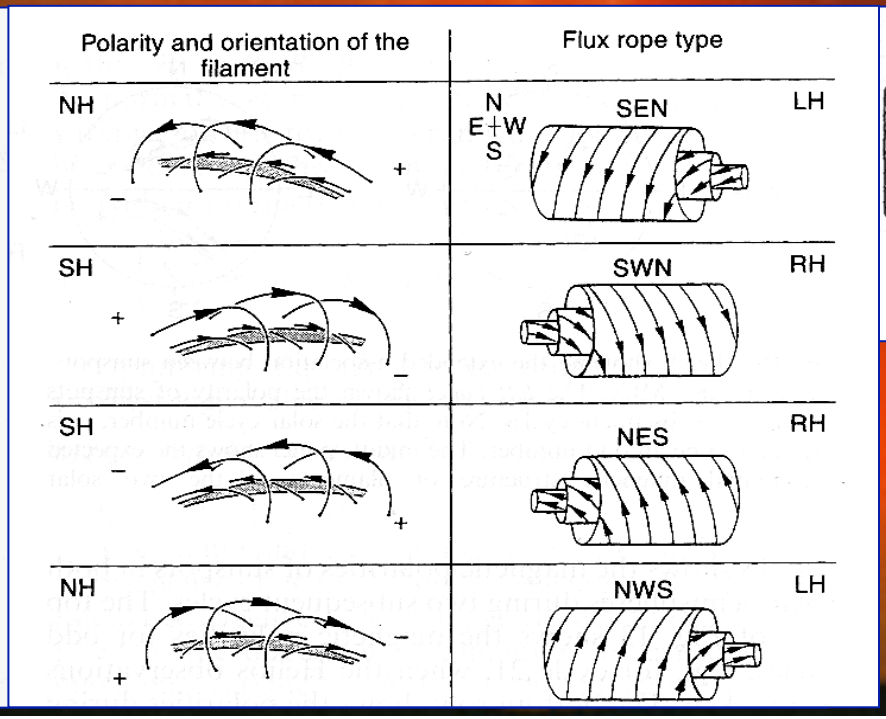
Ejected plasma clouds in space

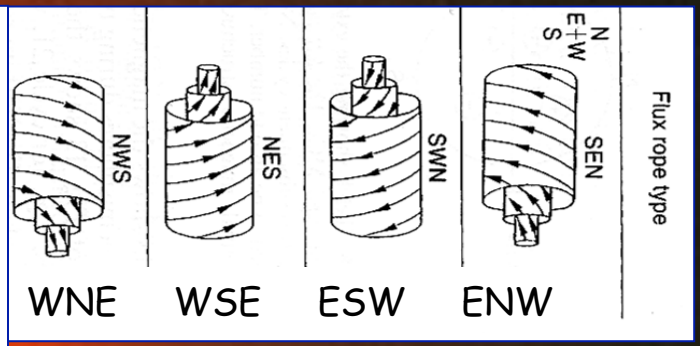


Magnetic clouds imply large-scale rotations of the magnetic field vector

Also possible at times

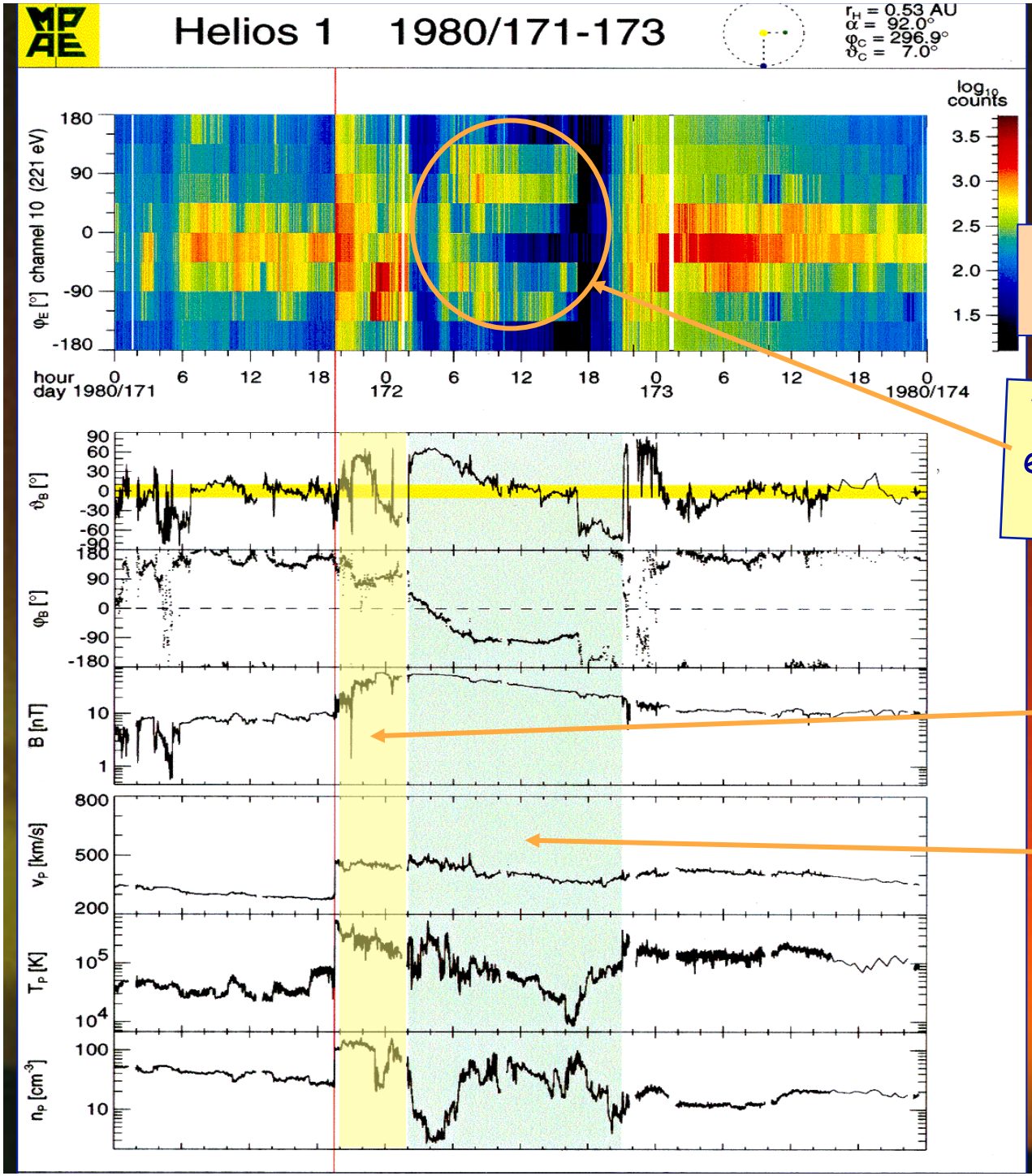






Note: No S in WNE and ENW clouds!

Ejected plasma clouds in space



A typical "magnetic cloud", following a fast shock wave

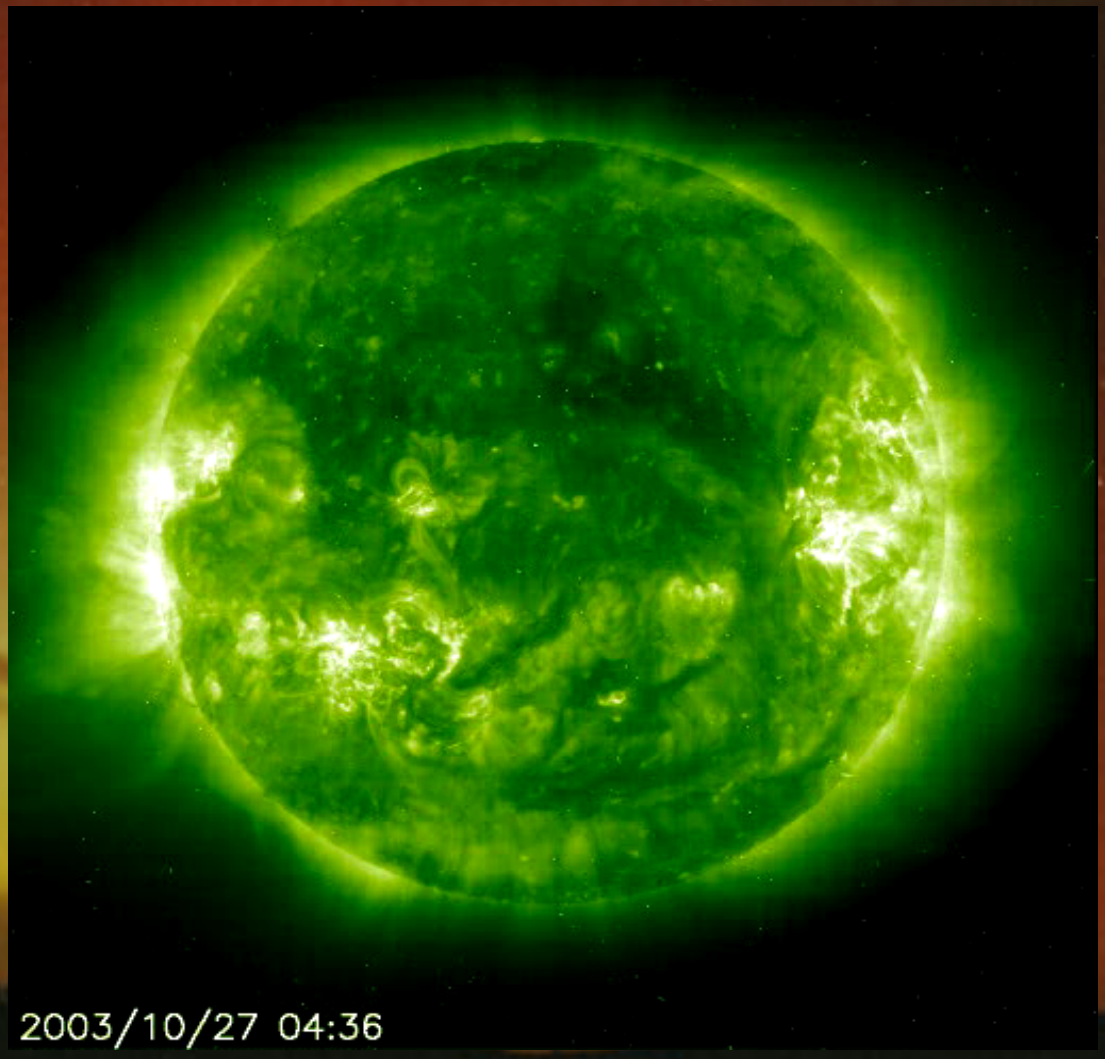
This cloud contains "bidirectional electrons", evidence for magnetic cut-off

Typical CME products in the interplanetary medium:

- just shocked "sheath" plasma (compressed and heated),
- and sometimes "driver gas", incl. magnetic clouds,
- no more signs of 3-part structure, in general!

Major open questions to this day

We cannot predict CMEs before they occur:
Neither time, nor location, nor strength.



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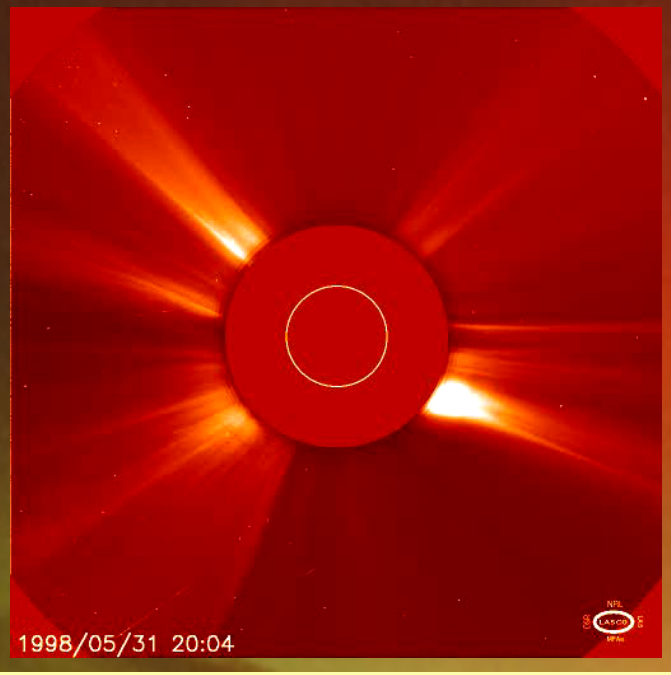
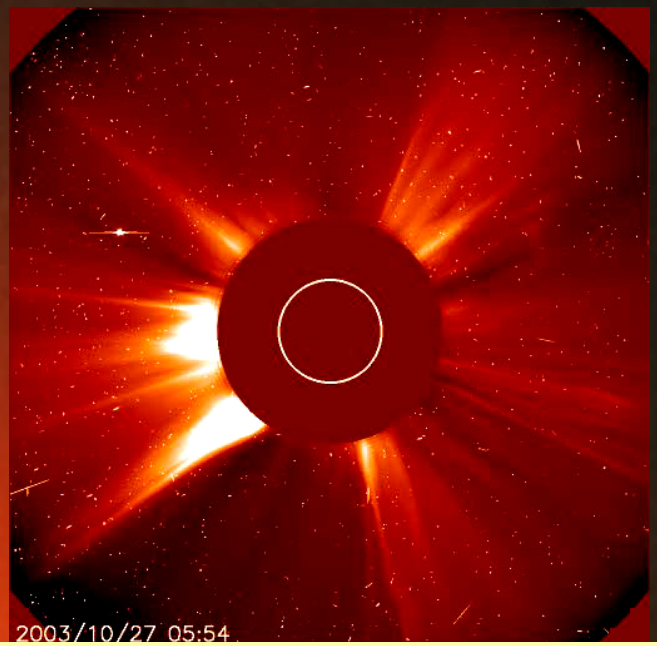
The onset of coronal mass ejections

What is the actual trigger of a CME?



Two small comets were evaporating near the Sun. A few hours later a huge ejection occurred. Coincidence?



On October 28, 2003, in conjunction with a X13 flare, there occurred a gigantic CME. 8 hours earlier a little comet had evaporated!

Coincidence?

By the way: In the first 15 years mission time, SOHO has seen more than 2000 little comets and some 15,000 CMEs...

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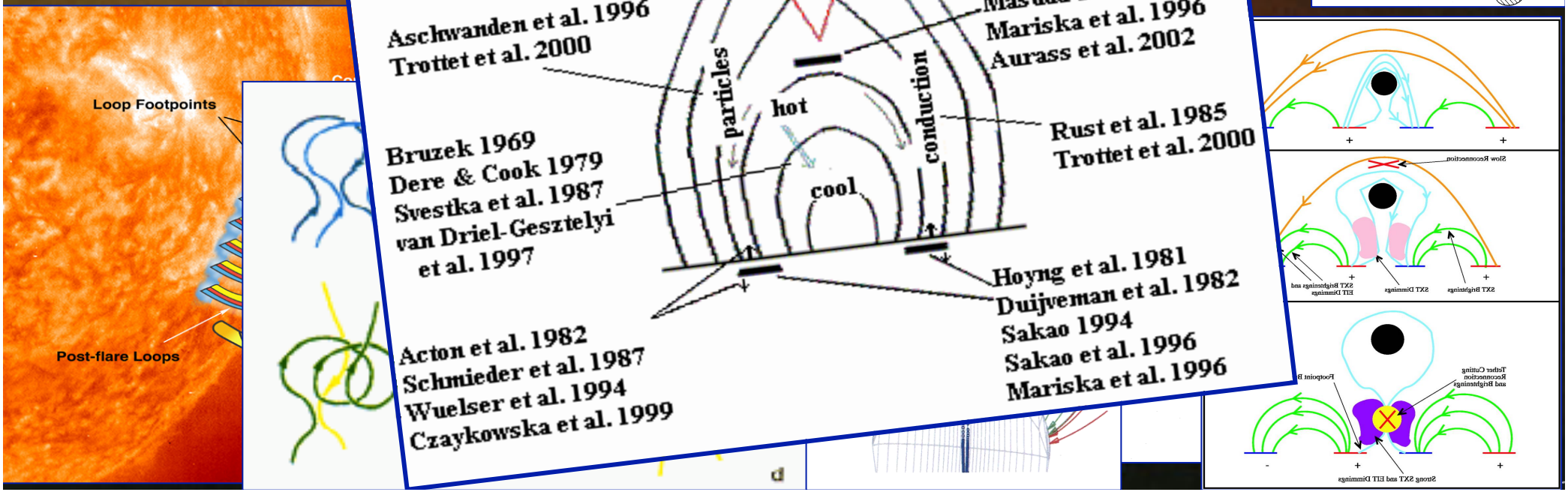
The role of reconnection for CMEs

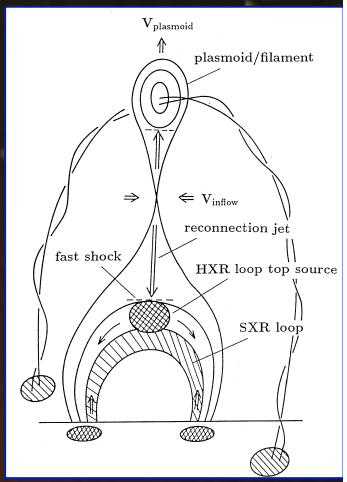
What is the observational evid… ction to occur?

Candidates: X… energetic particles.

Where d…

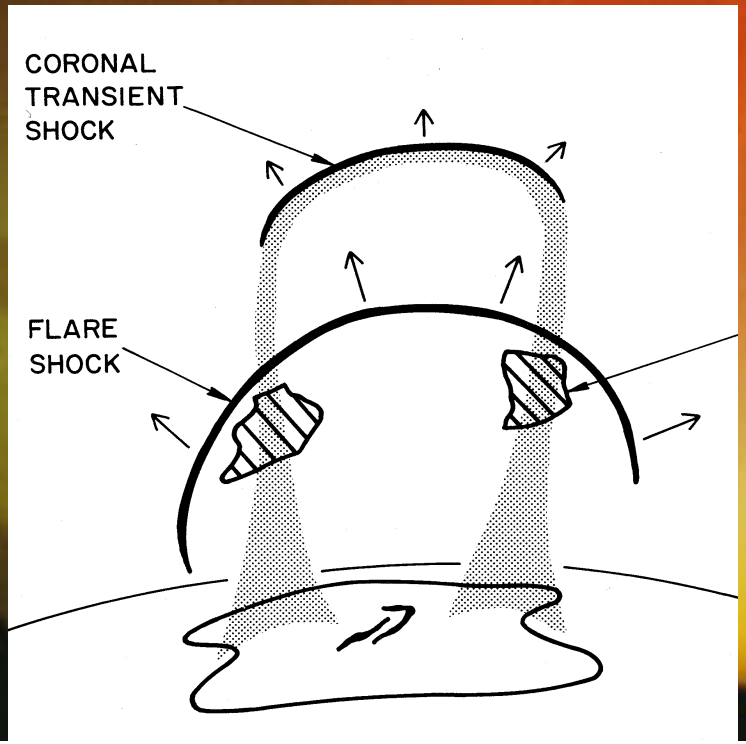
What exa…

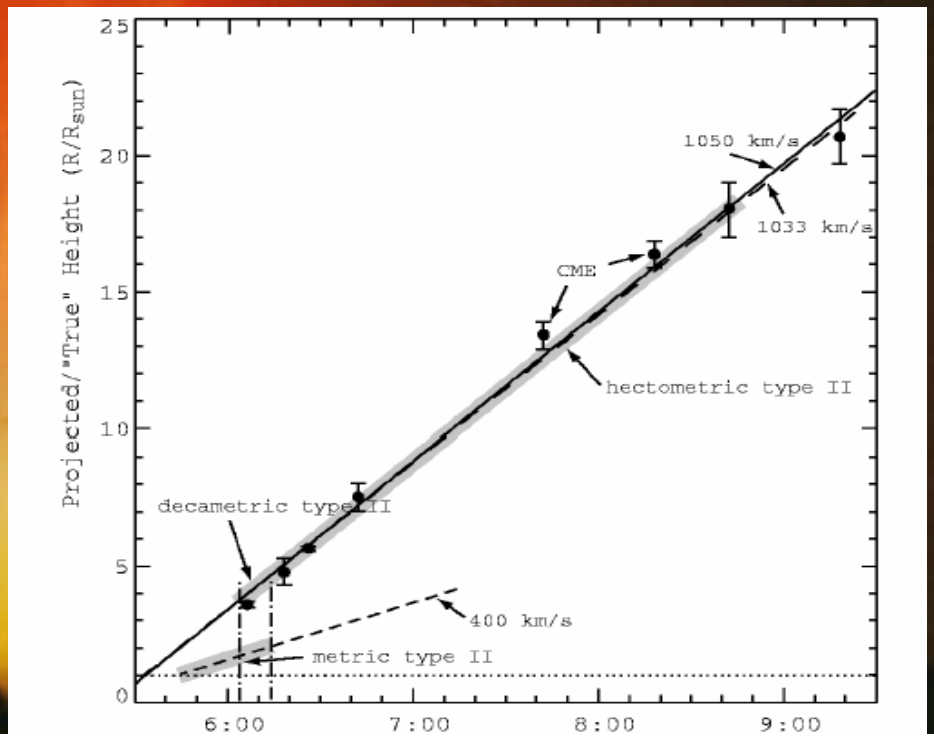




Shock waves from flares and CMEs

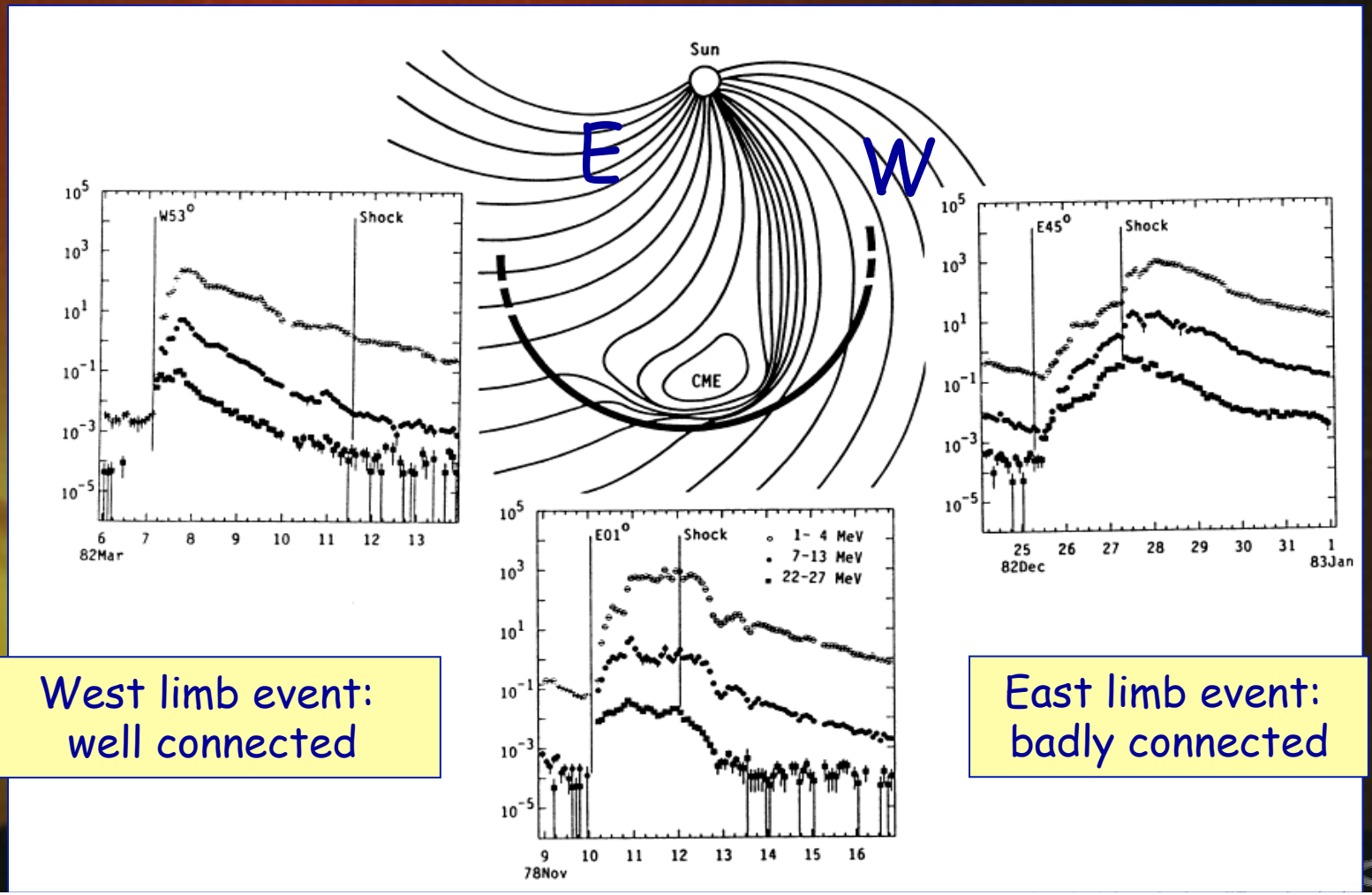
- Where are shock waves actually being formed?
- Are shocks from flares blast waves, qualitatively different from driven CME shocks?
- Moreton- and EIT waves, coronal dimmings, radio type II&III bursts, energetic particles – is there a consistent scenario? ^





Particle acceleration (SEPs)

Where, when and how are particles accelerated?
What is the seed population for SEPs?



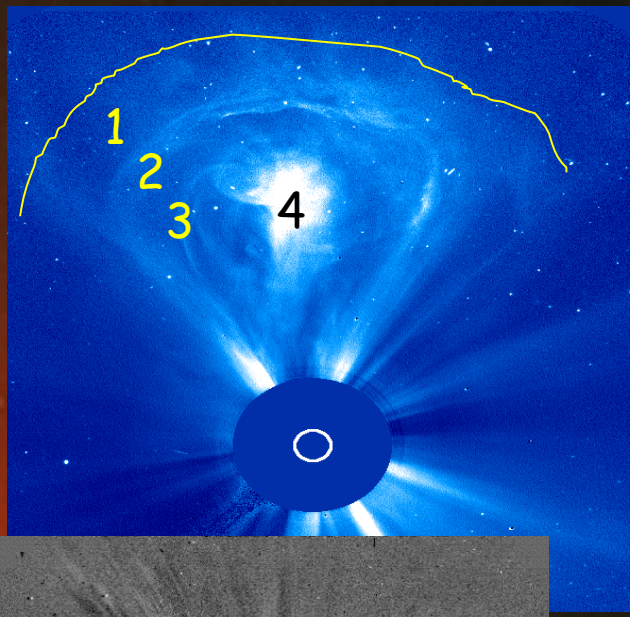
West limb event:
well connected

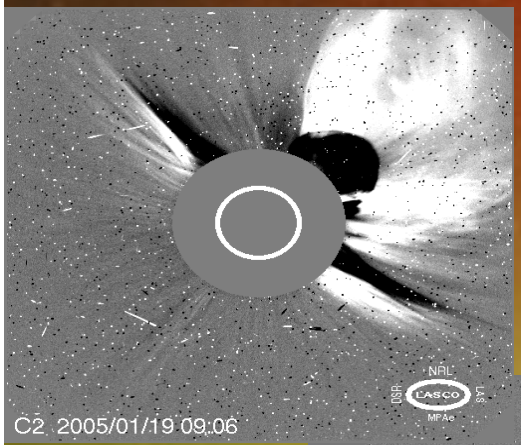
East limb event:
badly connected

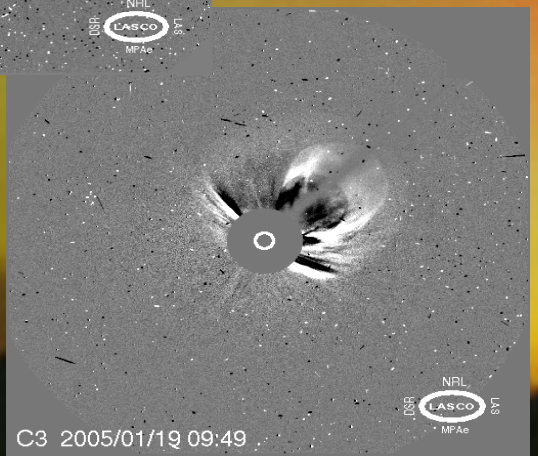
Topology of CMEs

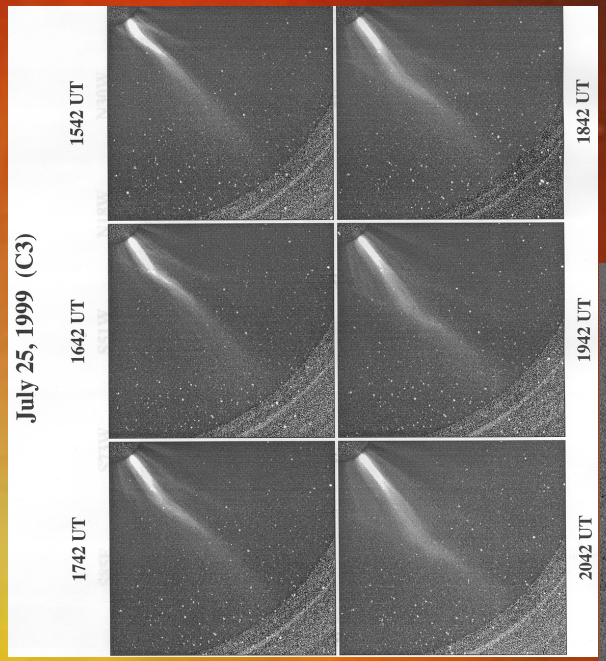
Where would a shock front be in coronagraph images? How far ahead of the bright loop and how far extended?

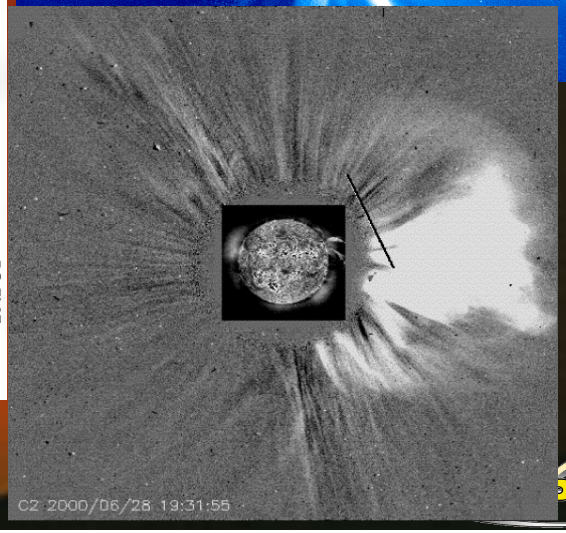
The majority of CMEs has a clearly discernible 4-part structure. Str.1 and the shock itself remain invisible.





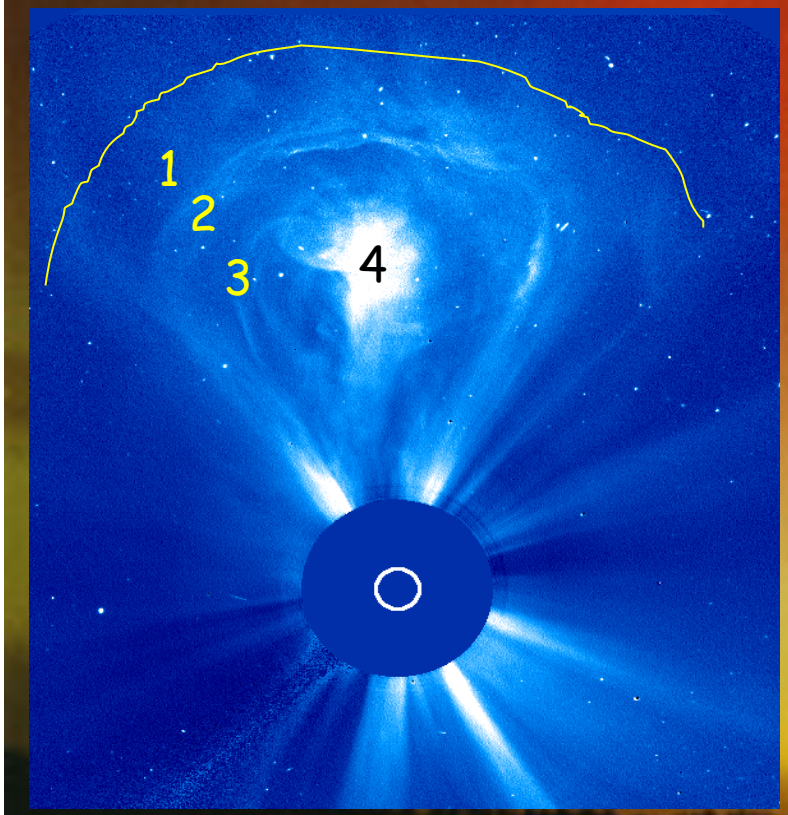


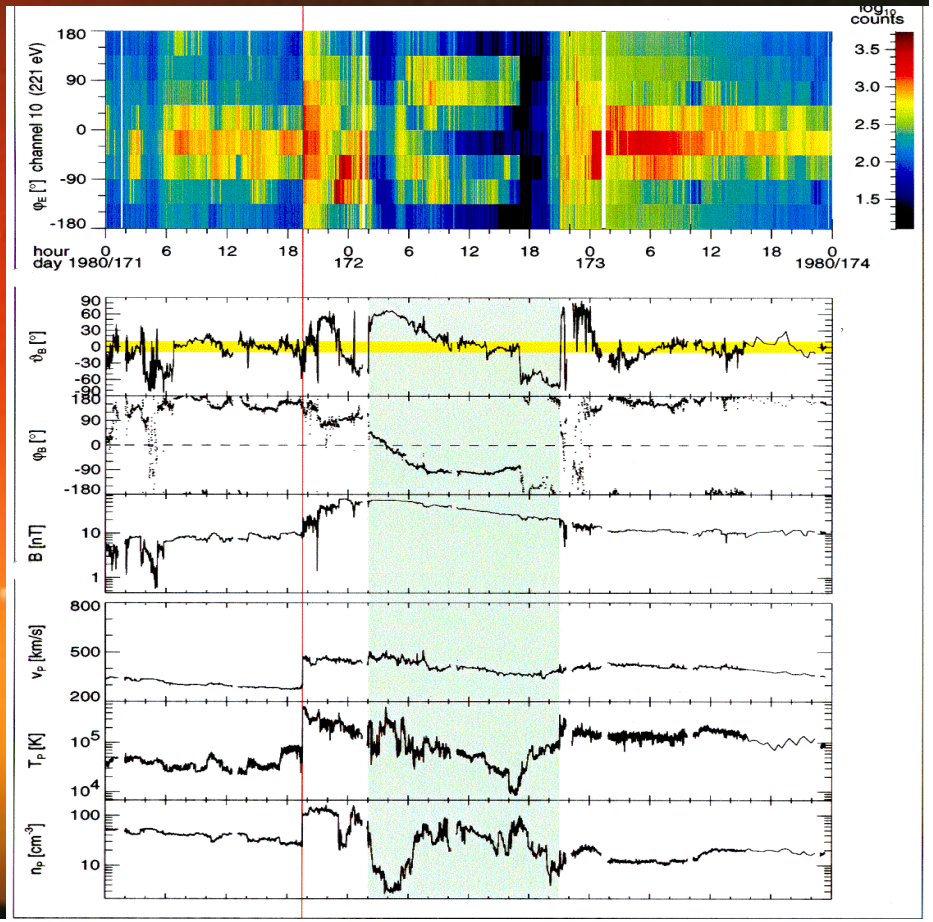




The transformation of CMEs into ICMEs

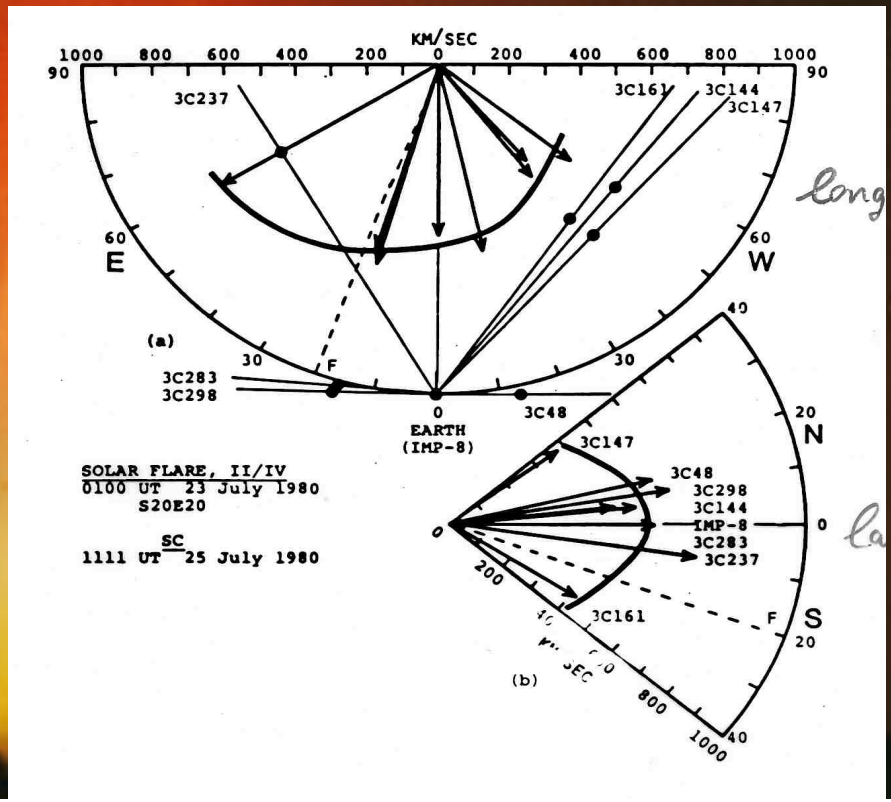
How is the multi-part CME structure transformed into the two-part ICME structure?





The extent of shock fronts, ejecta, and SEP fluxes

How far around the Sun do shocks, ICMEs and SEP fluxes extend?
How irregular are the shockfronts due to local shock speeds?
Are shock fronts continuous surfaces all ?
Acceleration & deceleration processes throughout the heliosphere?

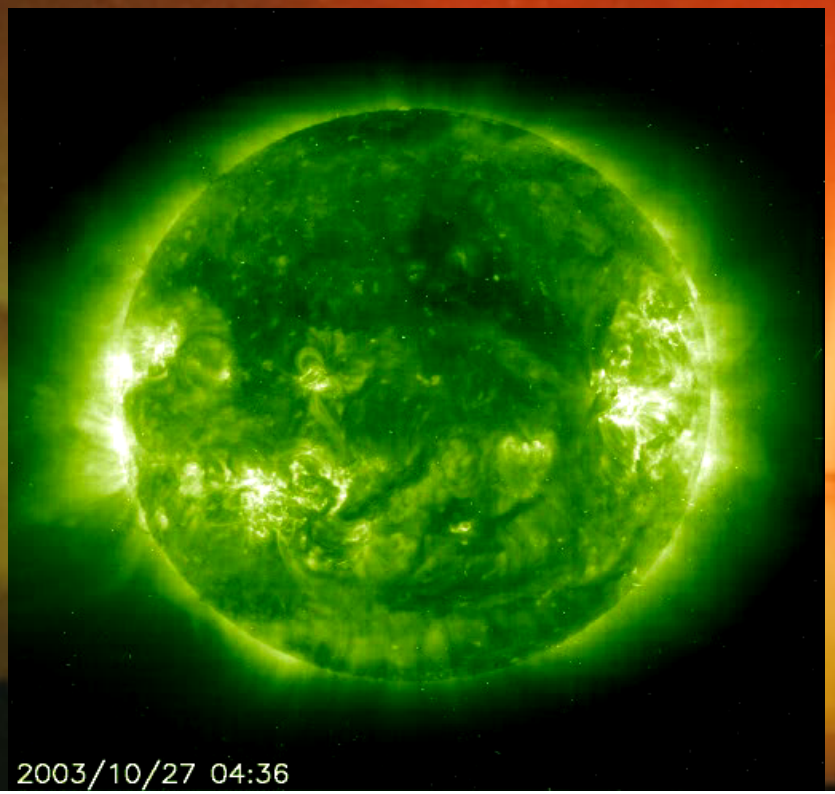


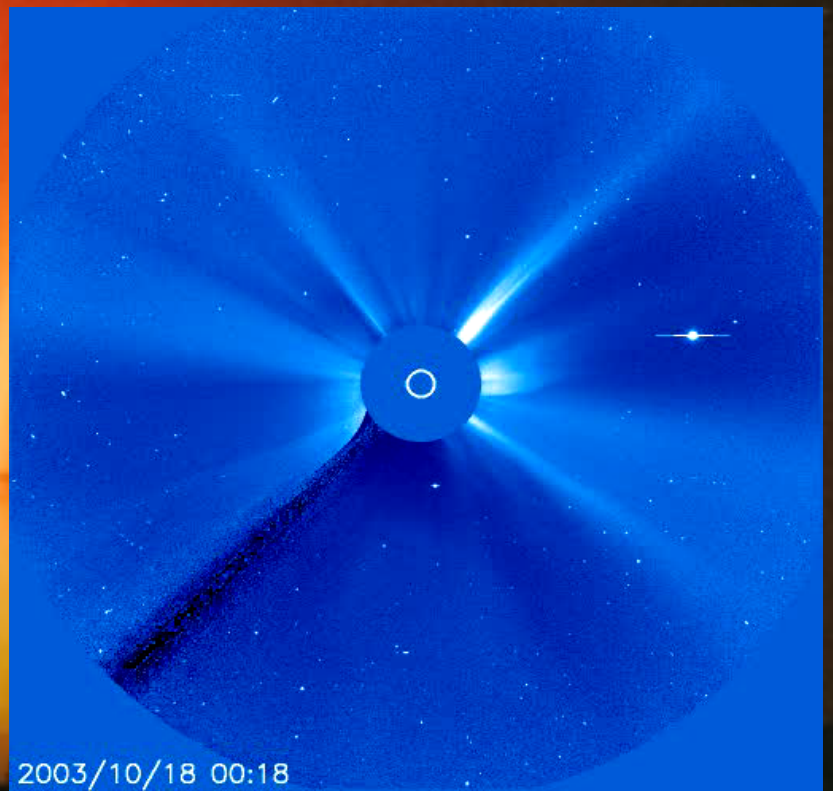
Space weather predictions are still terribly uncertain!

We cannot predict eruptions before they occur

We cannot predict the propagation time of ICMEs towards Earth

We do not yet have a unique handle on what determines geo-efficiency.





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