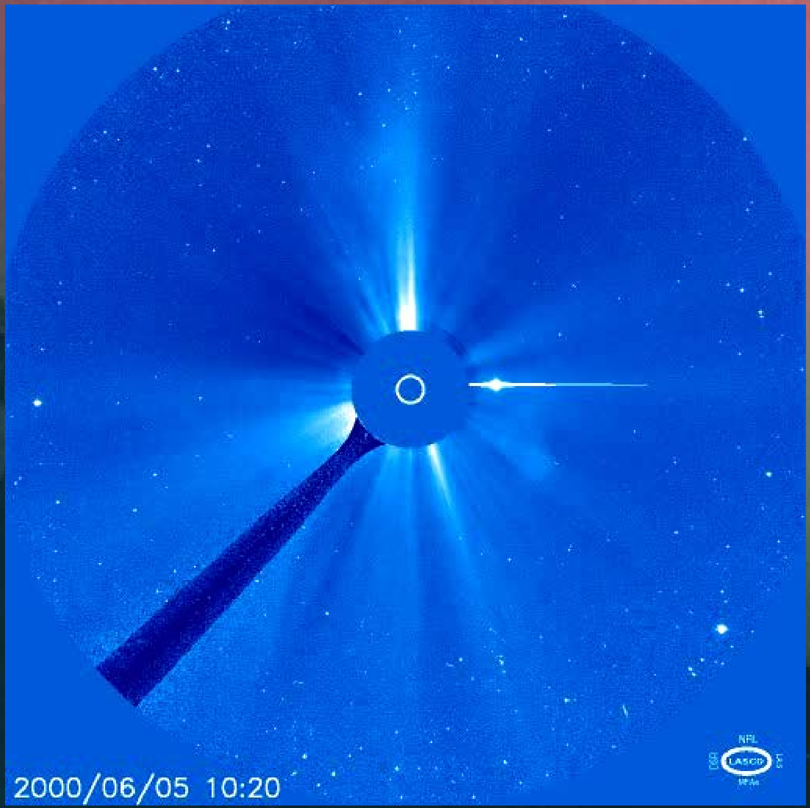
Coronal mass ejections: observations



First STEREO workshop
Paris
March 18 – 20, 2002

Rainer Schwenn
Max-Planck-Institut für Aeronomie
Lindau, Germany

The first CME observed in 1860?

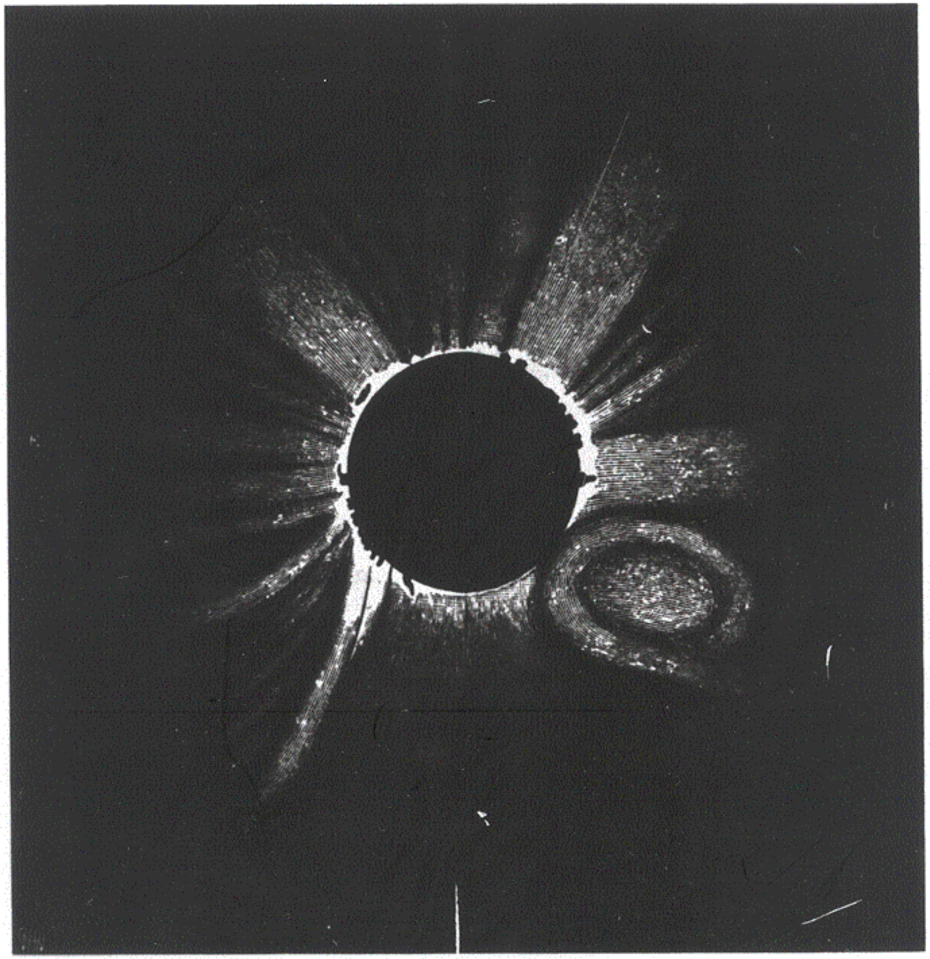


Fig. 2. Drawing of the corona as it appeared to Tempel at Torreblanca, Spain during the total solar eclipse of 18 July 1860 (Ranyard, 1879). South is at bottom, west at right

This early observation was not confirmed convincingly. However...

The first CMEs observed in modern times: OSO 7 (1971) and Skylab (1973)

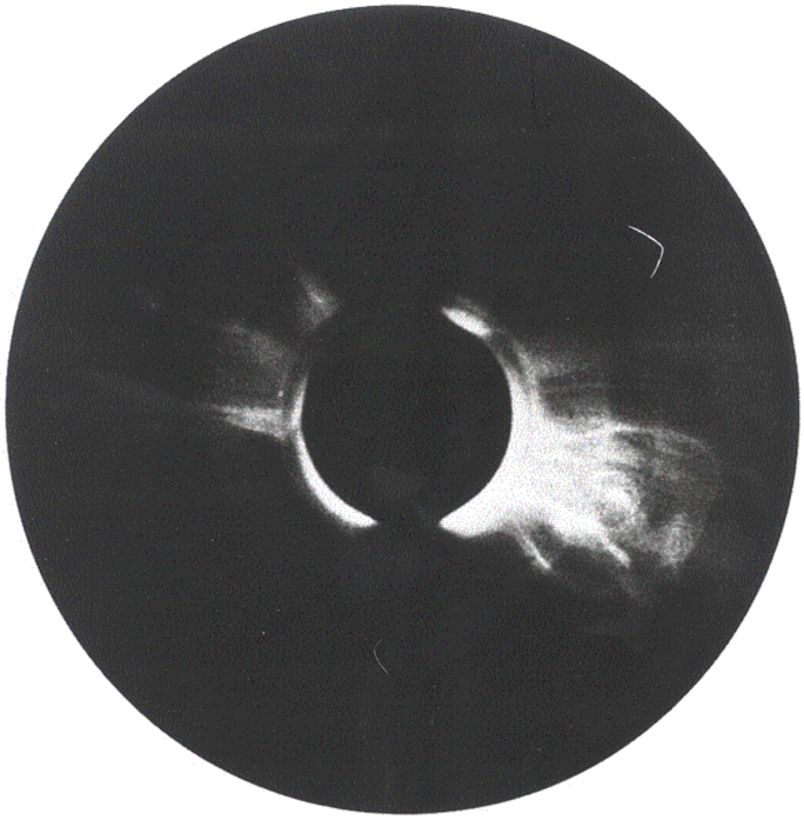
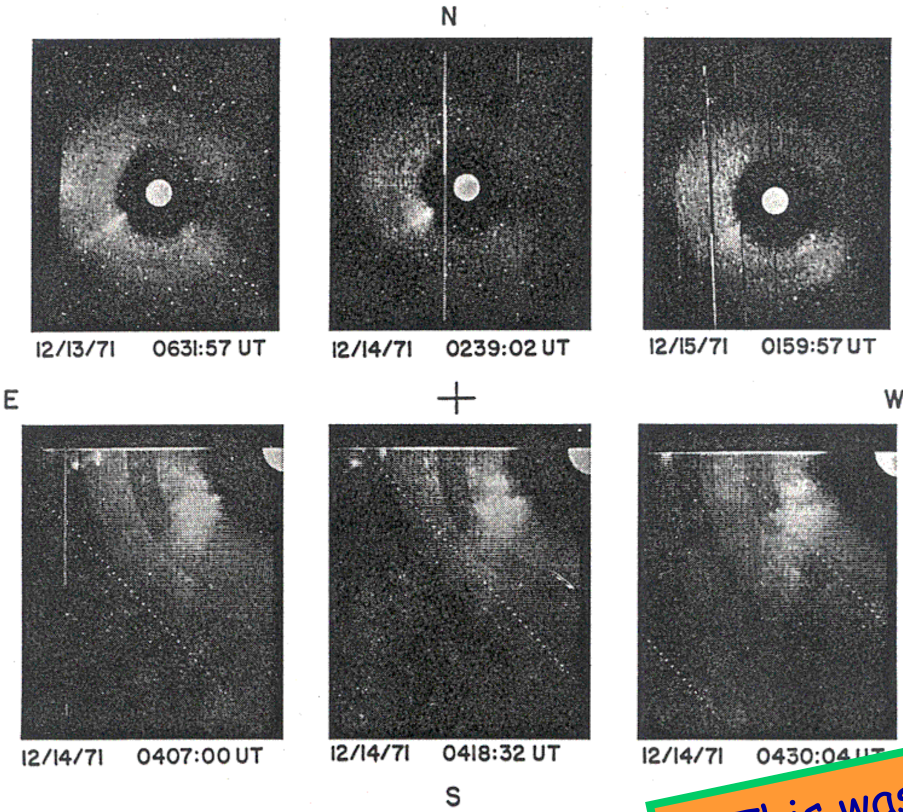


Fig. 1. Coronal photograph taken 0954 UT 10 June 1973 (11 min after Fig. 2 of MacQueen *et al.*, 1974) by HAO White Light Coronagraph Experiment on first NASA Skylab mission. Diameter of occulting disk is about 1.5 R_0. Transient feature at lower right (in northeast quadrant) was observed for about 30 min and moved outward with an apparent velocity of 450 km/s

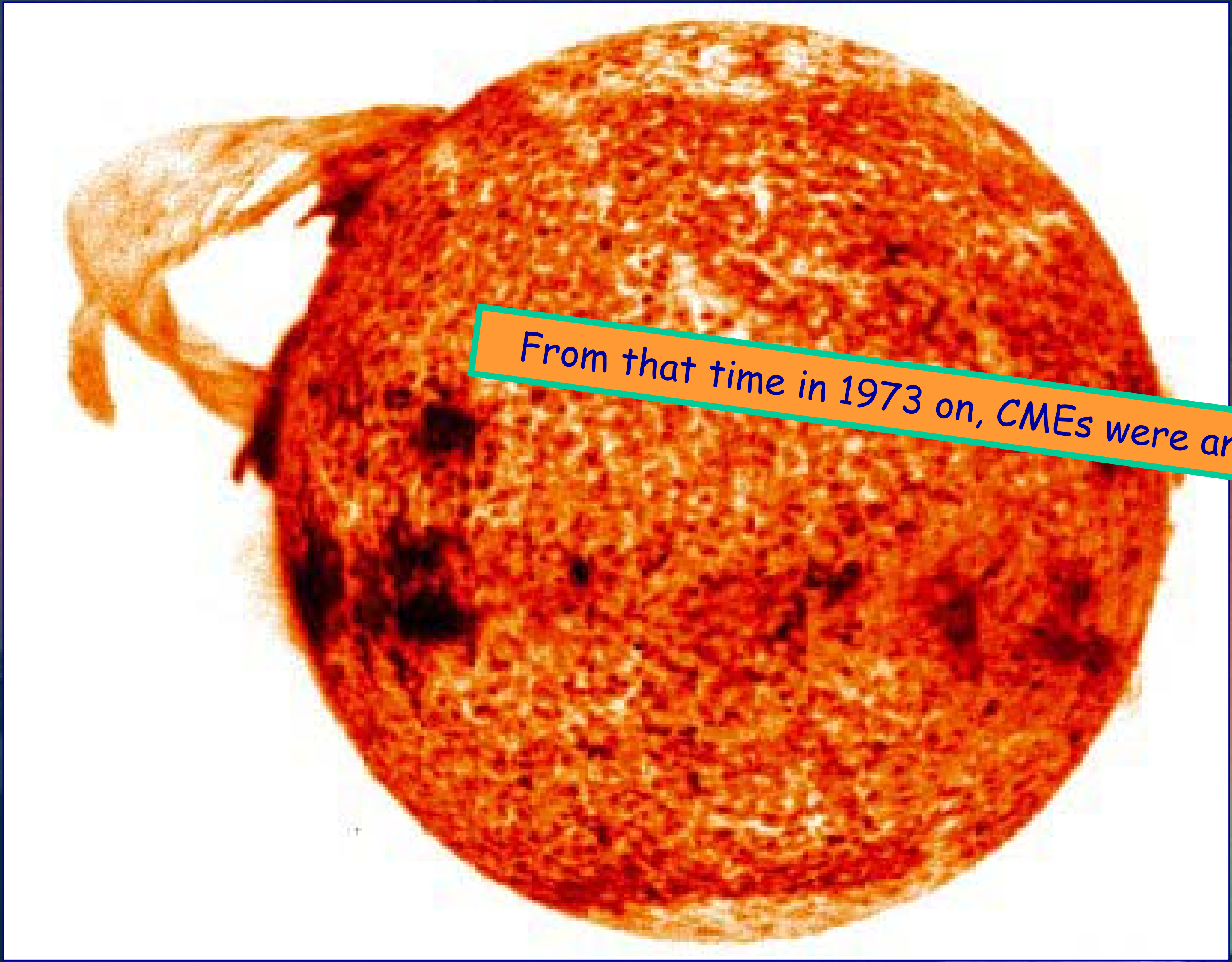
...the similarity with Skylab images obtained 113 years later is striking!



This was the first published „modern" CME event, observed 1971 from OSO 7.

A transient event in the outer corona was recorded on December 14, 1971 by the white-light coronagraph aboard NASA's seventh earth-orbiting solar observatory (OSO-7). The upper row of photographs shows coarse-resolution television pictures of the full field of the coronagraph. A dark central area is produced by an externally mounted occulting disk, whose support is indicated by the radial shadow to the right. Correct relative position and size of the occulted Sun are shown by the white disk. The disruption of the bright SE streamer, which began in the central picture of the upper row, was recorded with the full vidicon resolution during the next later orbit. At this time the quadrant of interest was transmitted to Earth at intervals eleven minutes apart, and produced the three lower photographs. Bright plasma clouds at the upper left of these pictures are moving outward at ≈ 1000 km s^{-1}. The field is covered by a polarizer which admits tangentially polarized light except for the annular bands concentric with the Sun, where the admitted vector is essentially radial.

(By courtesy of G. E. Brueckner, M. J. Koomen and R. Tousey, E. O. Hulbert Center for Space Research, U.S. Naval Research Laboratory.)



The most popular astronomical picture in history:
a huge prominence, seen in the He^{+} line (30.4 nm), from **Skylab** (1973)

CME? ...can't tell what it is, but if I see it I know it...

What, actually, is a CME?

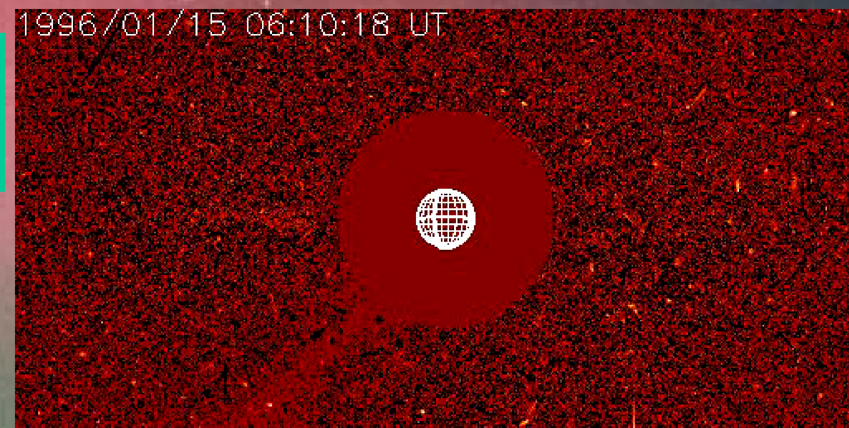
Definition of terms:

"We define a coronal mass ejection (CME) to be an observable change in coronal structure that

(1) occurs on a time scale of a few minutes and several hours and

(2) 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!

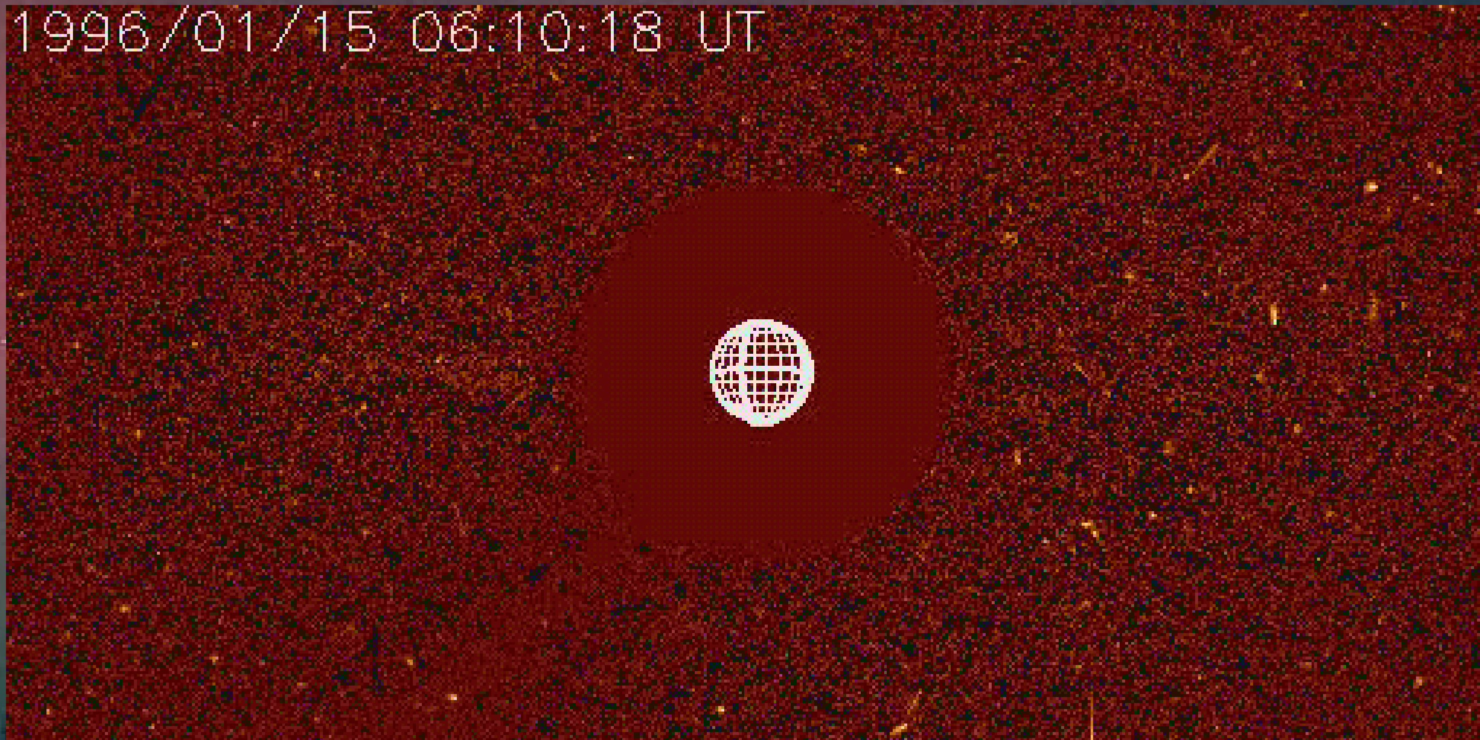


This definition is very fortunate in that

- it emphasizes the observational aspect,
- it stresses the transient event character,
- it does not infer an interpretation of the "feature" and its potential origin,
- in particular, it does NOT infer any conjunction with "coronal mass",
- it restricts the applicability of the term to the sun's proximity.

I would still prefer to call them SMEs, that avoids confusion...

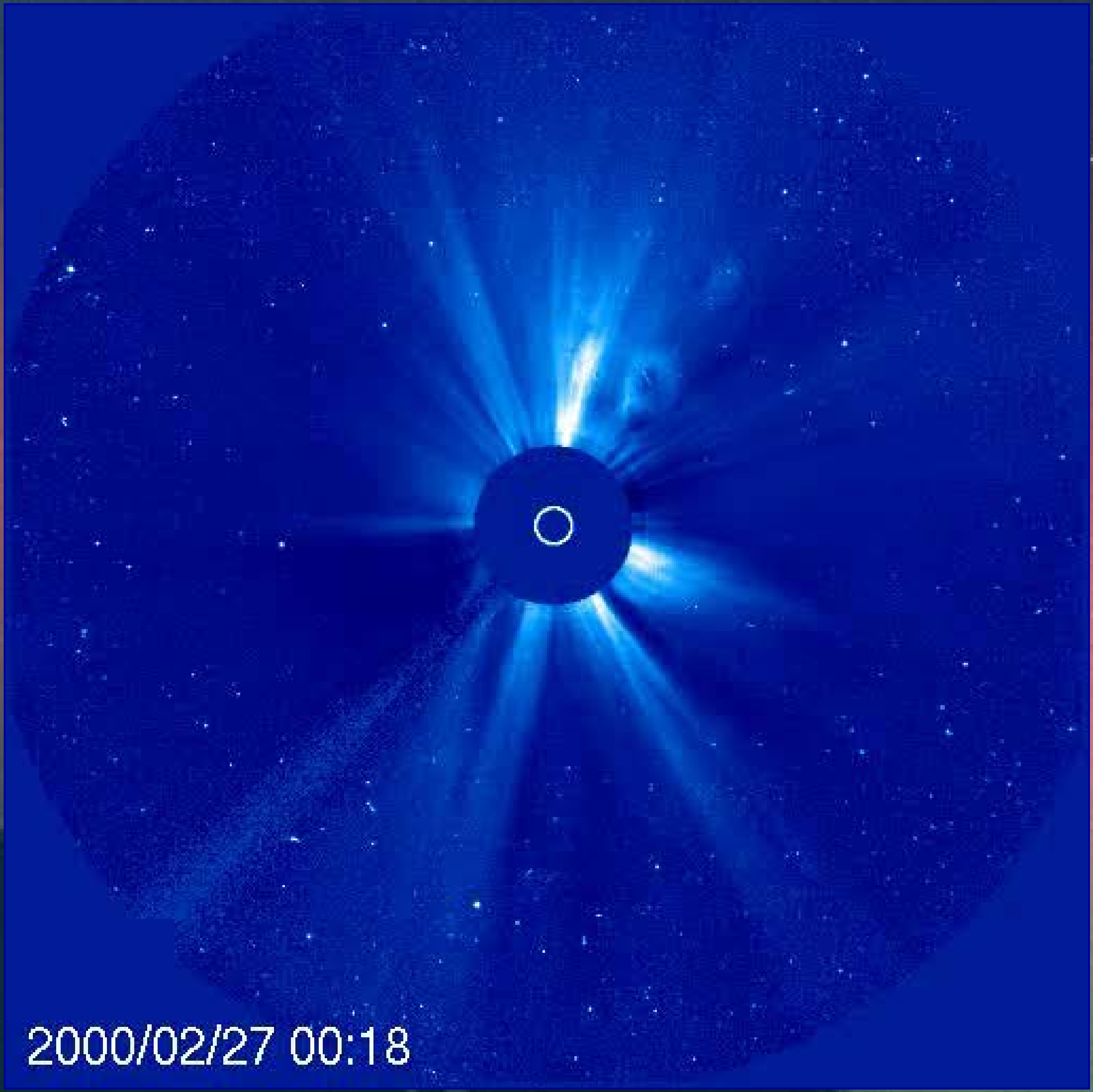
Coronal mass ejections (CMEs)

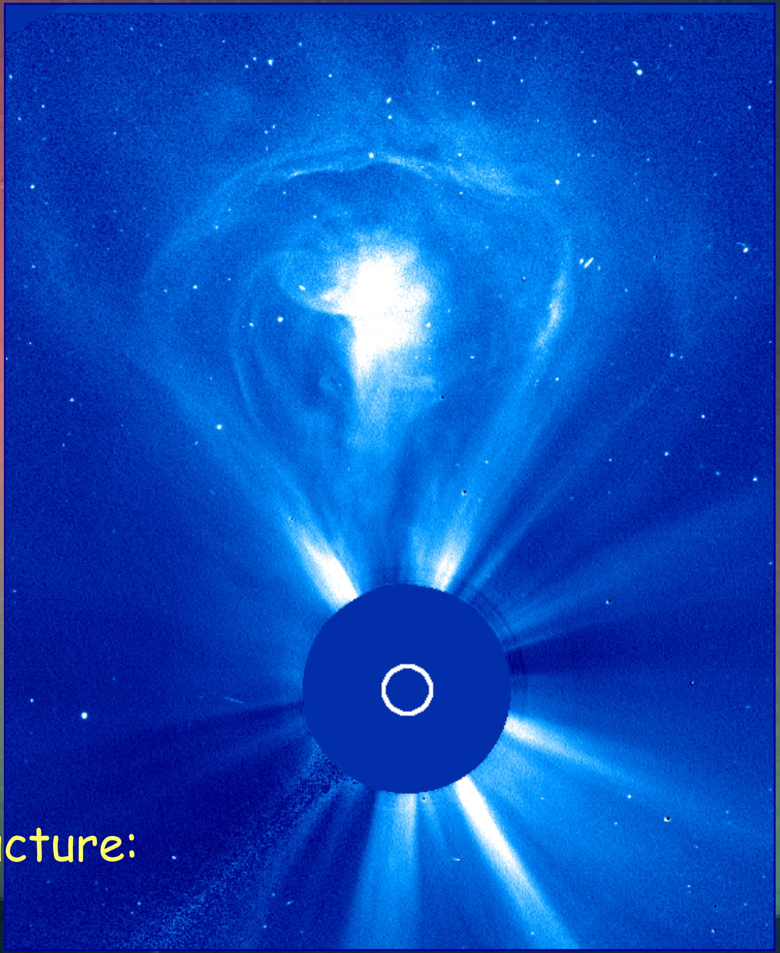


The CME of Jan 15, 1996, as seen by LASCO-**C3** on **SOHO**

Note the CME backside: first observational evidence for disconnection of the cloud!

Some CMEs are spectacular, indeed!

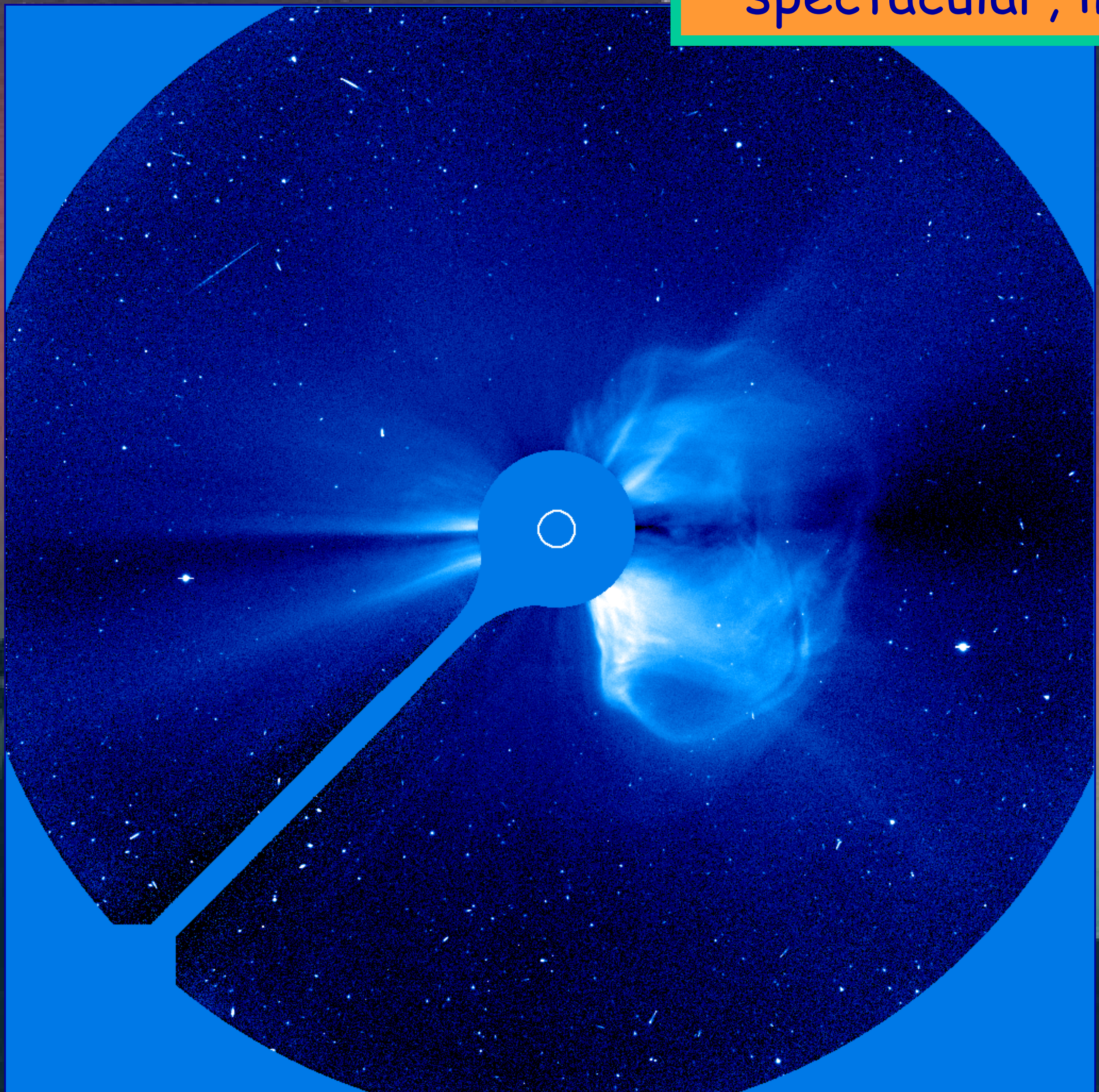




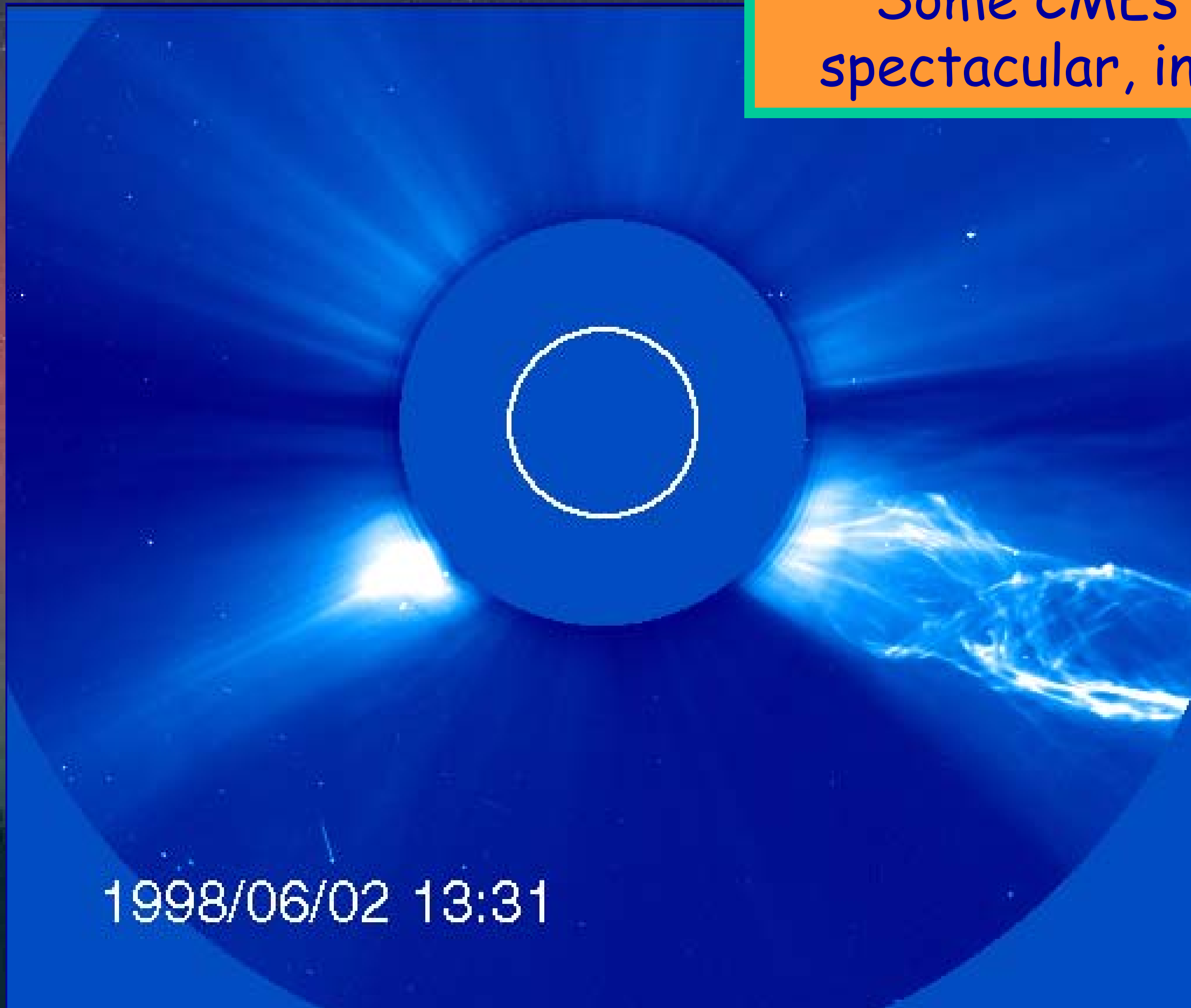
Most big CMEs show a characteristic 3-part structure:

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

Some CMEs are spectacular, indeed!

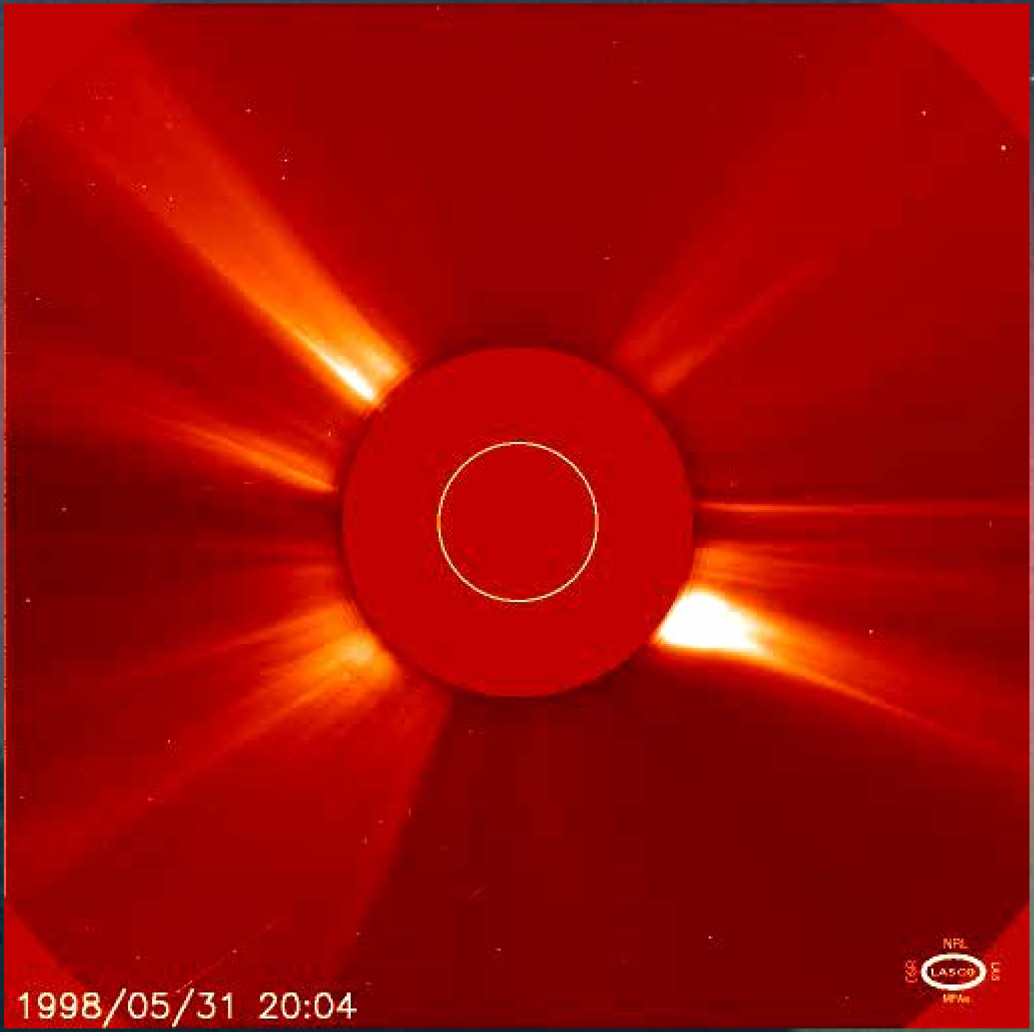


Some CMEs are spectacular, indeed!



A unique observation by **LASCO-C2**.
Note the helical structure of the prominence filaments!

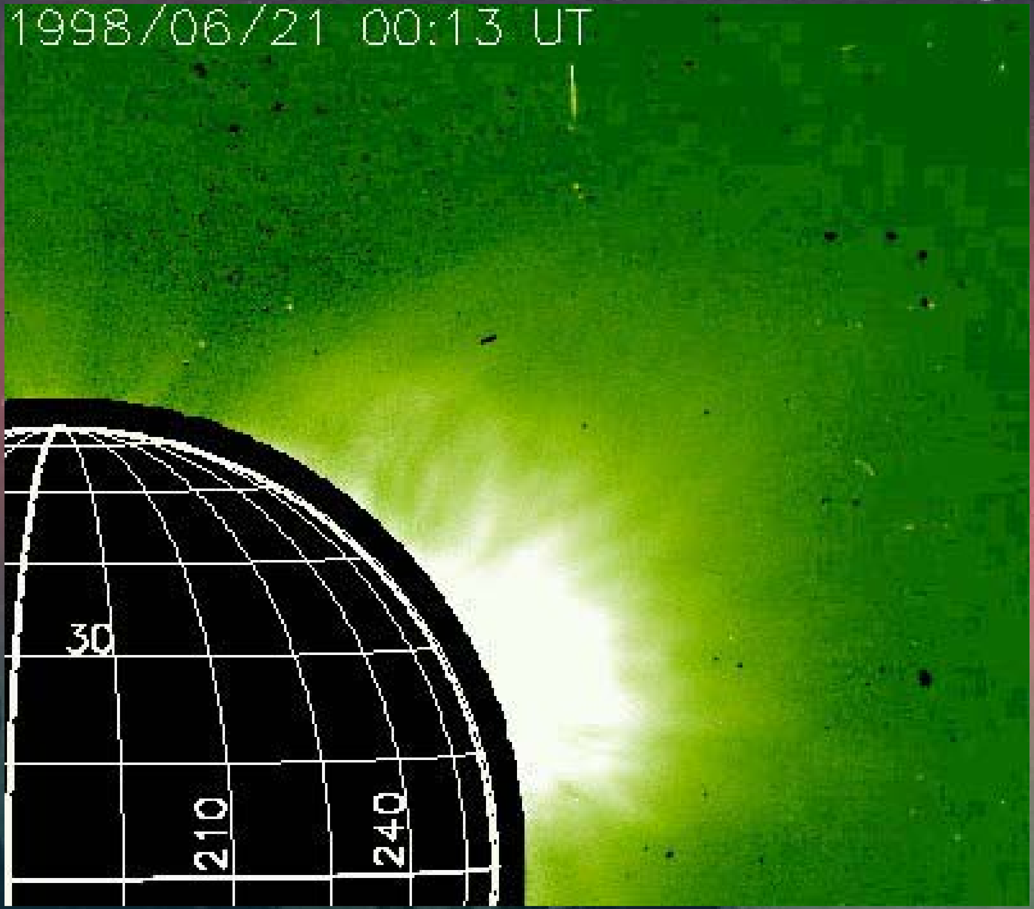
Some CMEs are spectacular, indeed!



The same CME,
seen as a quick-motion movie

Two small comets were evaporating near the Sun.
A few hours later a huge ejection occurred. Coincidence?
A unique observation by **LASCO-C2**.
Note the helical structure of the prominence filaments!

There is a huge variety of CMEs, including slow ones!



A "balloon-type" CME, observed by **LASCO-C1**, on June 21, 1998.

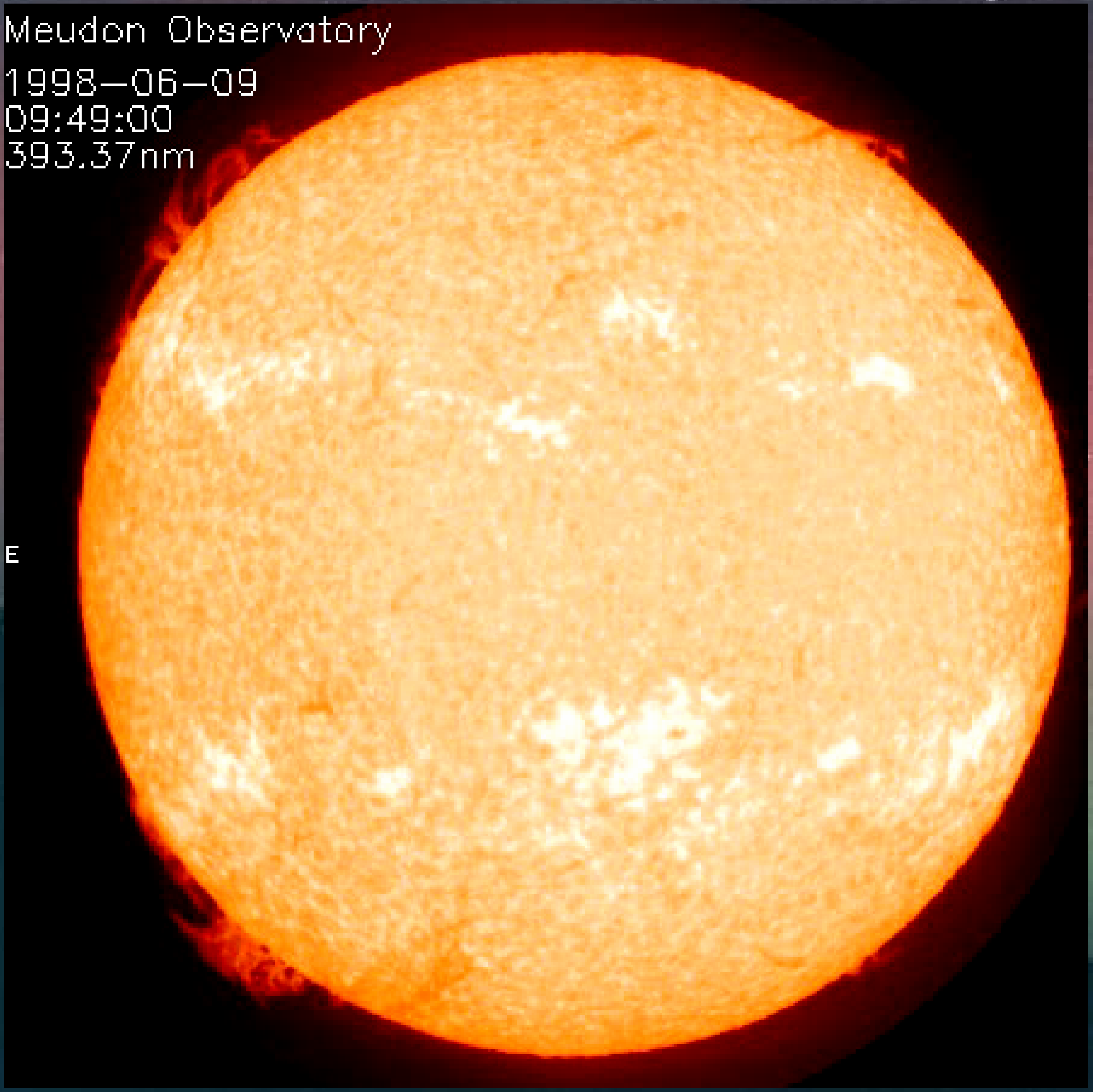
Note the 3-part structure:

1. bright outer loop,
2. dark void,
3. bright inner kernel

Srivastava et al., 1999

This balloon took some 30 hours to finally take off! It was the offspring of an eruptive prominence. The ejecta ran away at about the slow wind speed, probably no shock was associated with it.

There is a huge variety of CMEs, including slow ones!

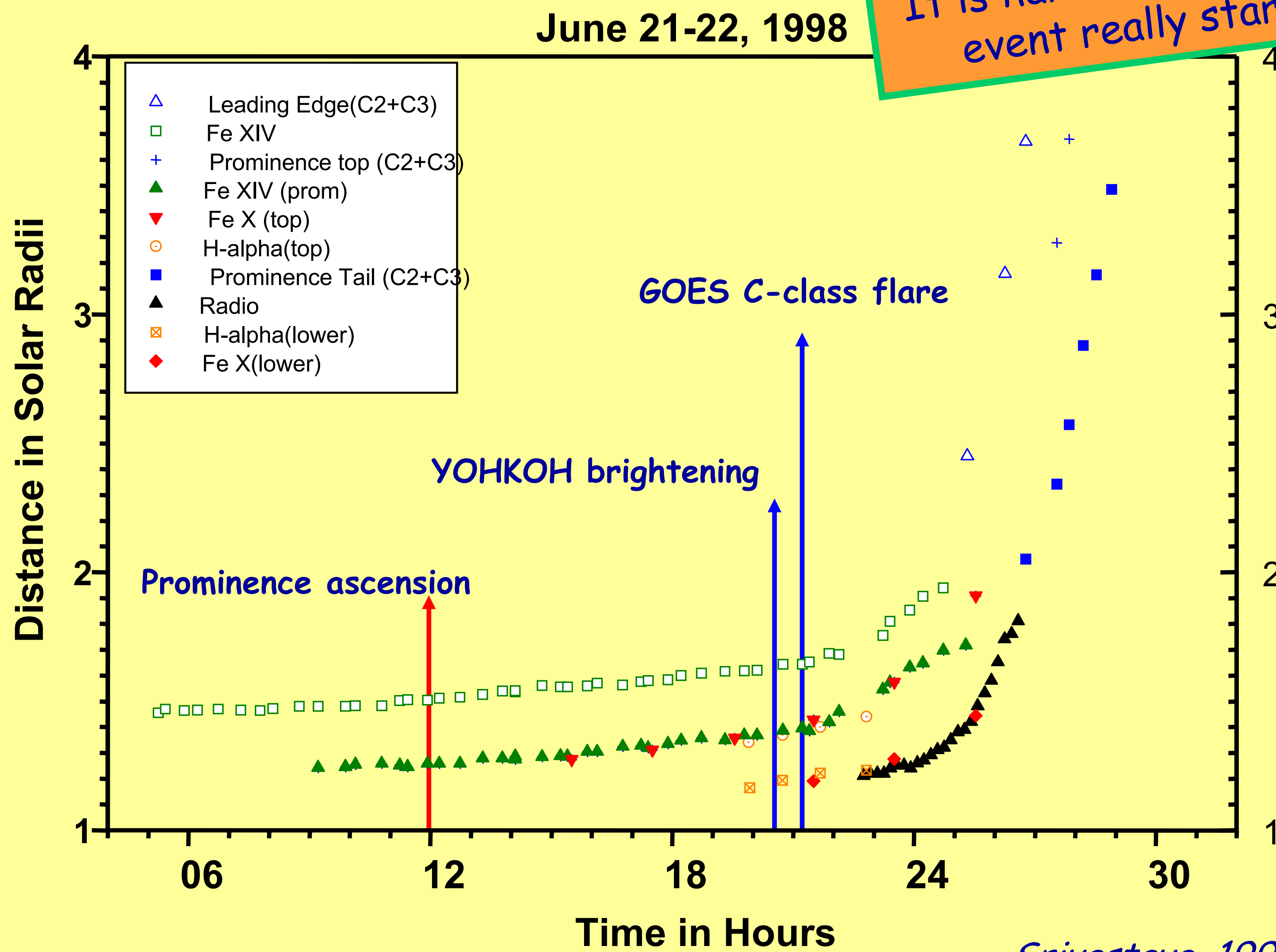


The filament had been observed in H-alpha and the K-line during its complete journey across the disk, before it finally erupted and led to the balloon type CME on June 21, 1998

Srivastava, 1999

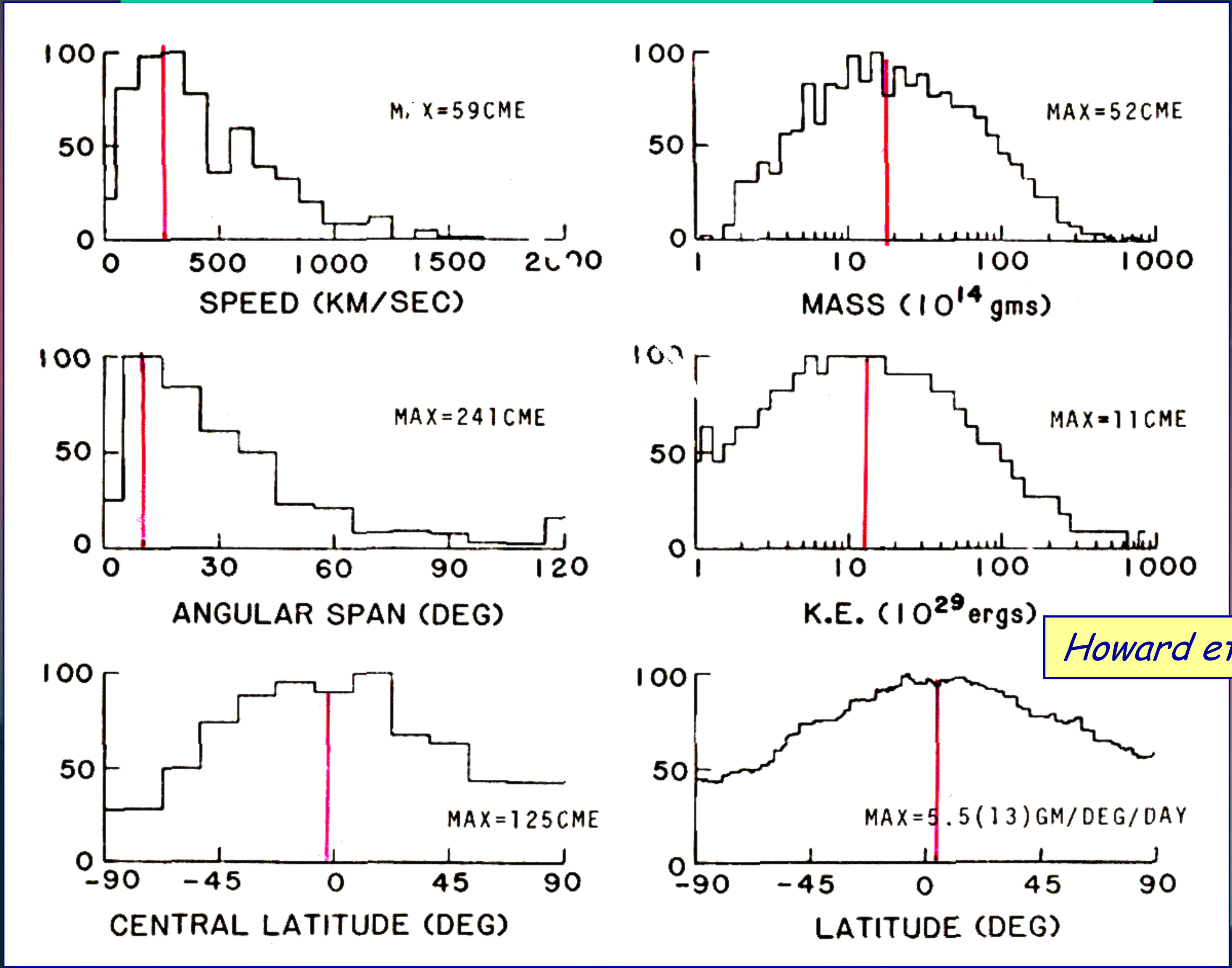
Initiation of a balloon type CME

It is hard to tell when this event really started !



Srivastava, 1999

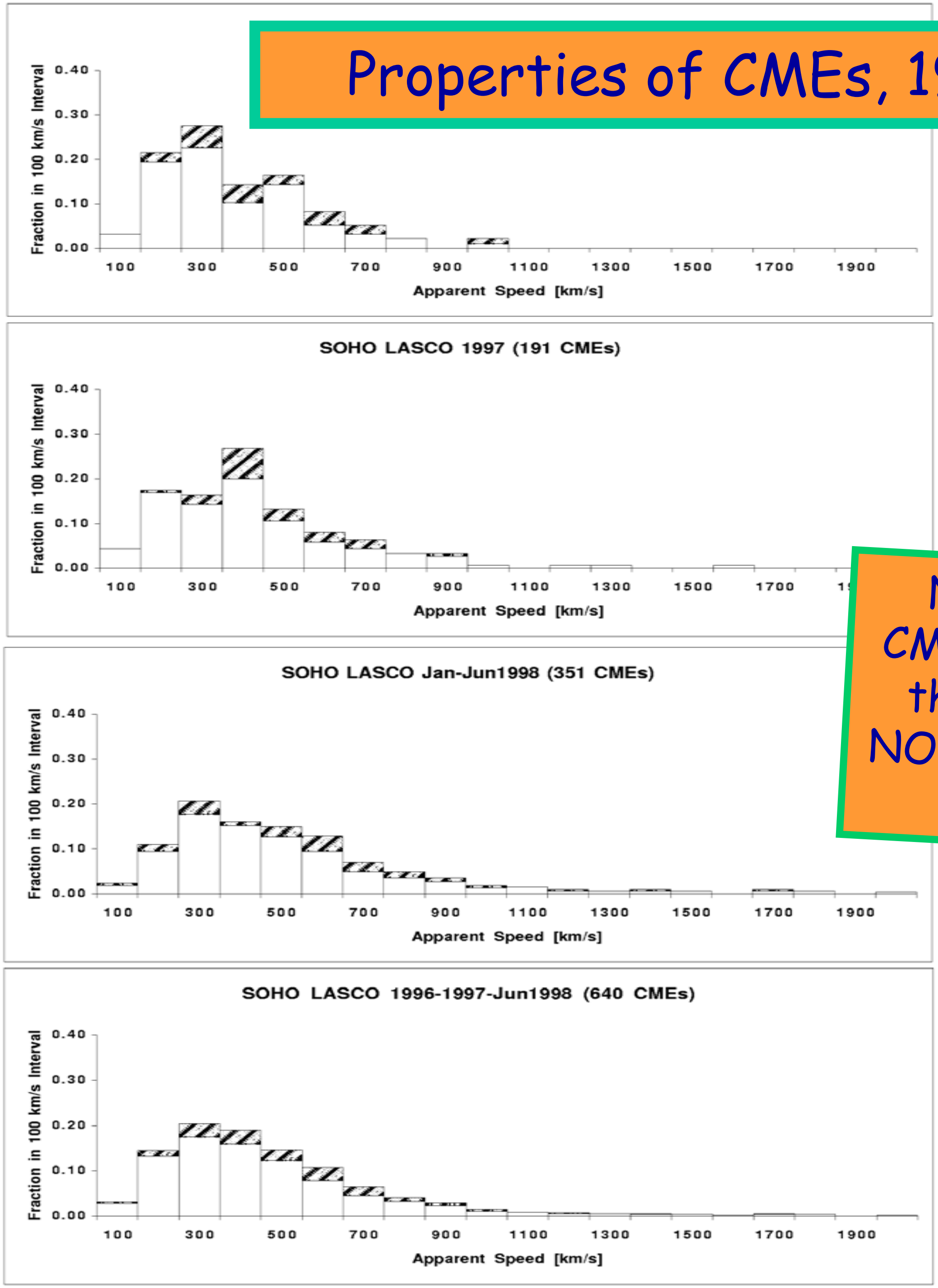
Properties of CMEs, 1979 to 1981



Howard et al., 1985

Statistical analysis of about 1000 CMEs observed by **SOLWIND**

Properties of CMEs, 1996 to 1998

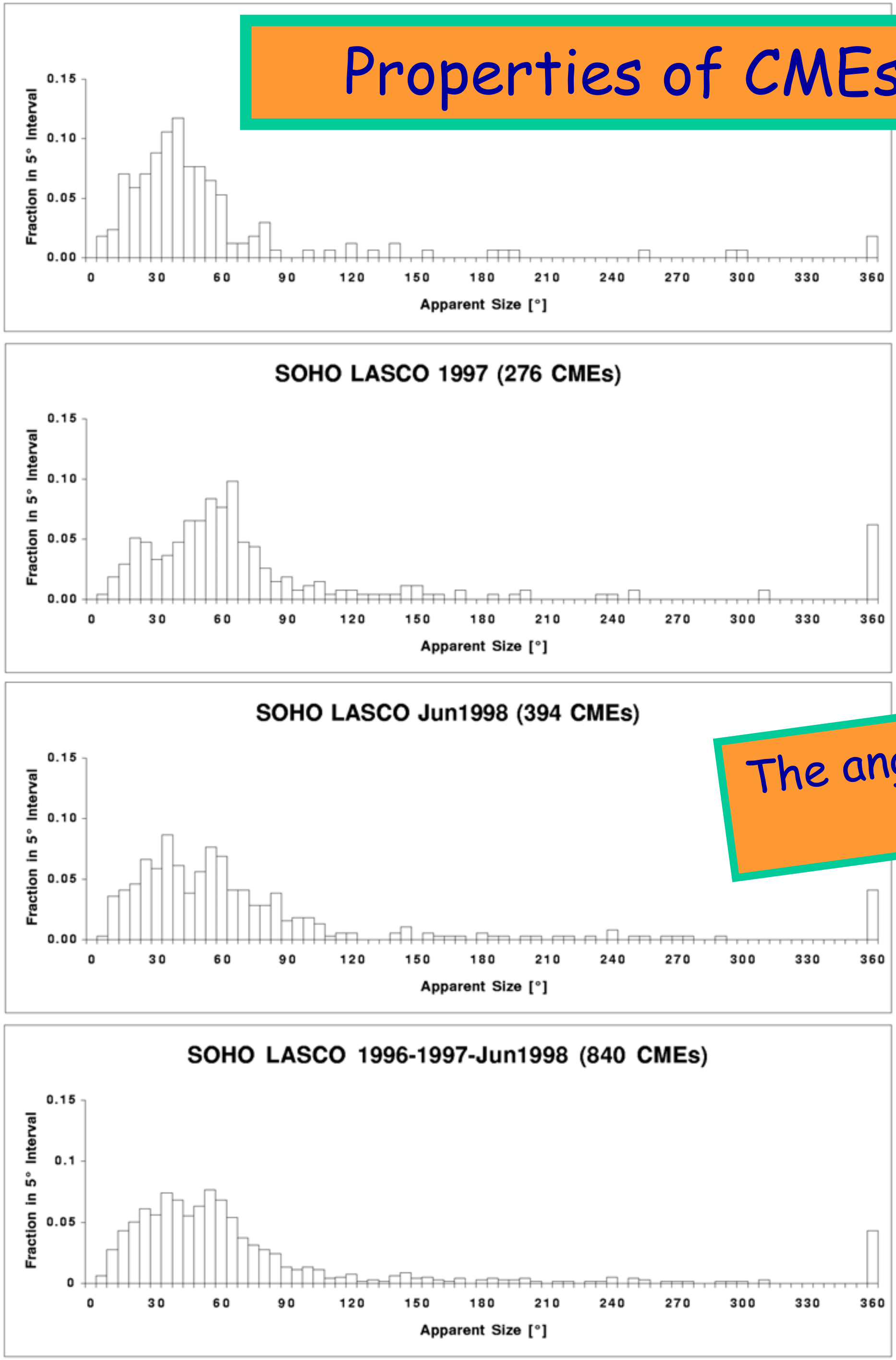


Note the small number of slow CMEs! The increased sensitivity of the modern instrumentation has NOT increased the number of slow, faint CMEs.

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

St.Cyr et al., 2000

Properties of CMEs, 1996 to 1998

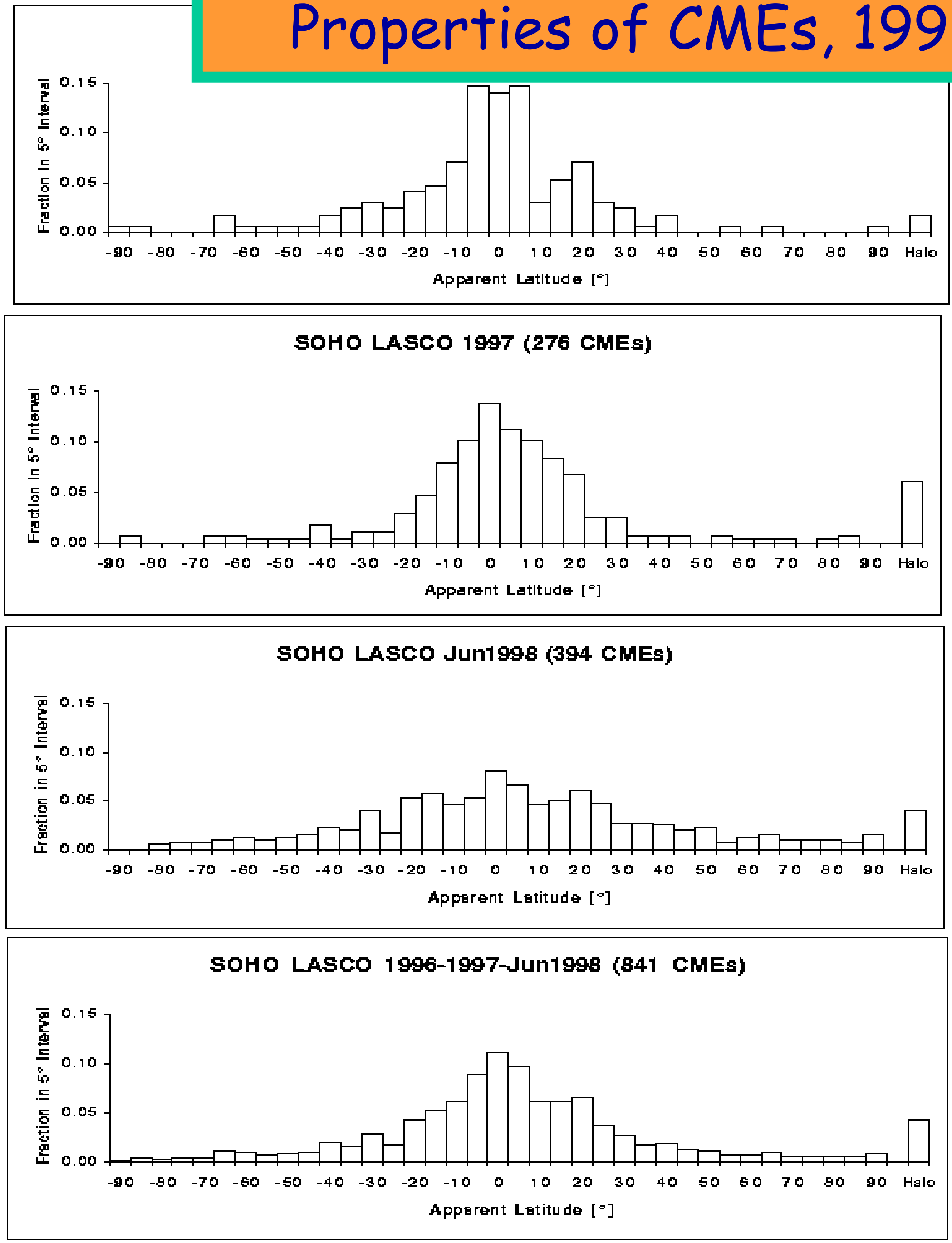


The angular size did not change much with rising solar activity

Apparent angular size of 840 CMEs

St.Cyr et al., 2000

Properties of CMEs, 1996 to 1998

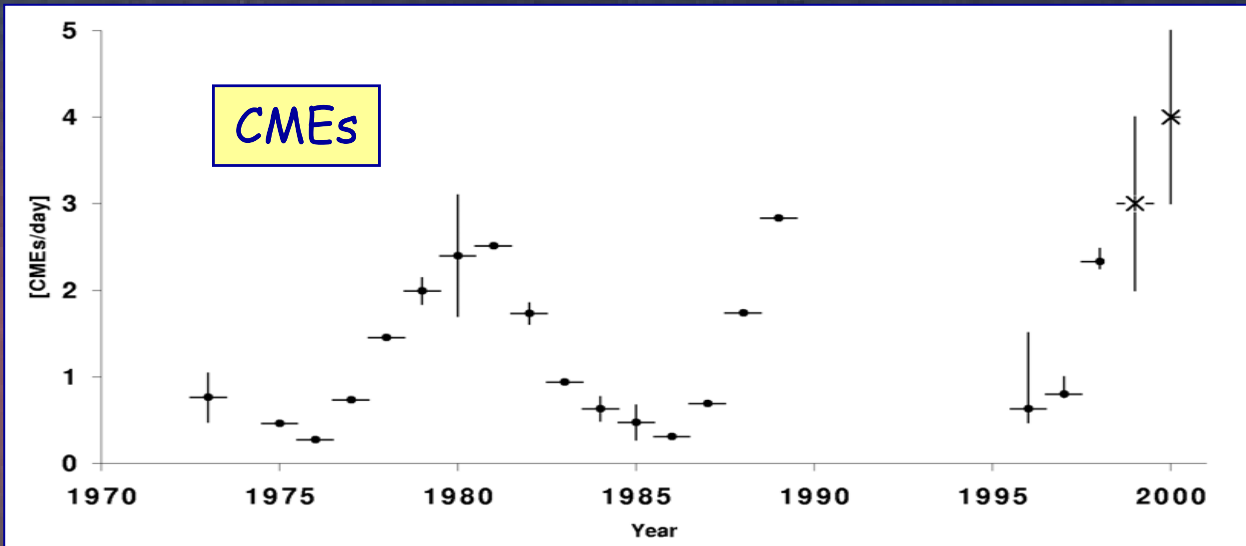


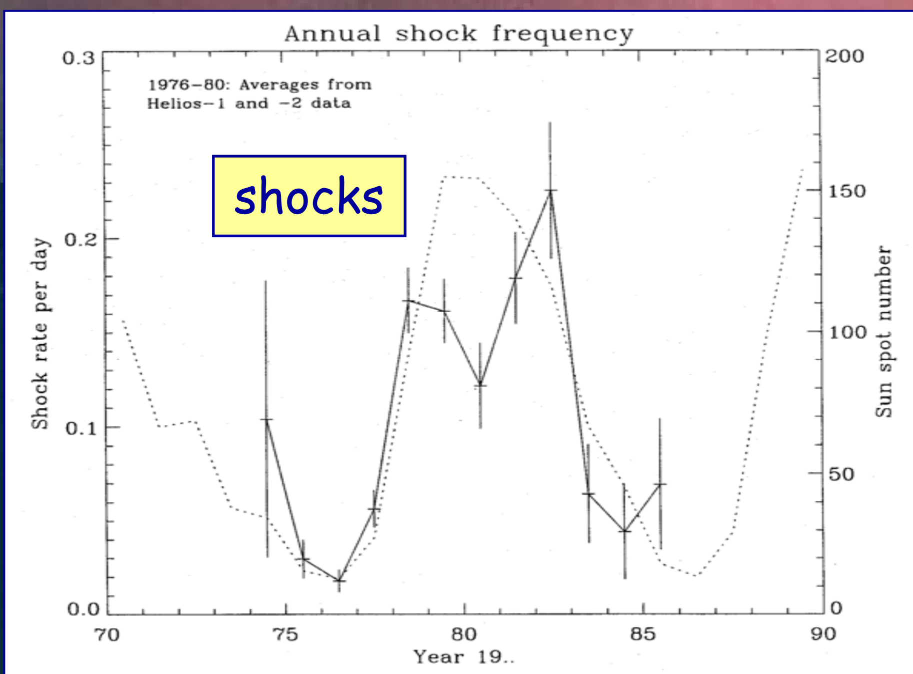
At activity minimum, there was a clear preference of equatorial latitudes for CME onset

The center latitudes of 841 CMEs

St.Cyr et al., 2000

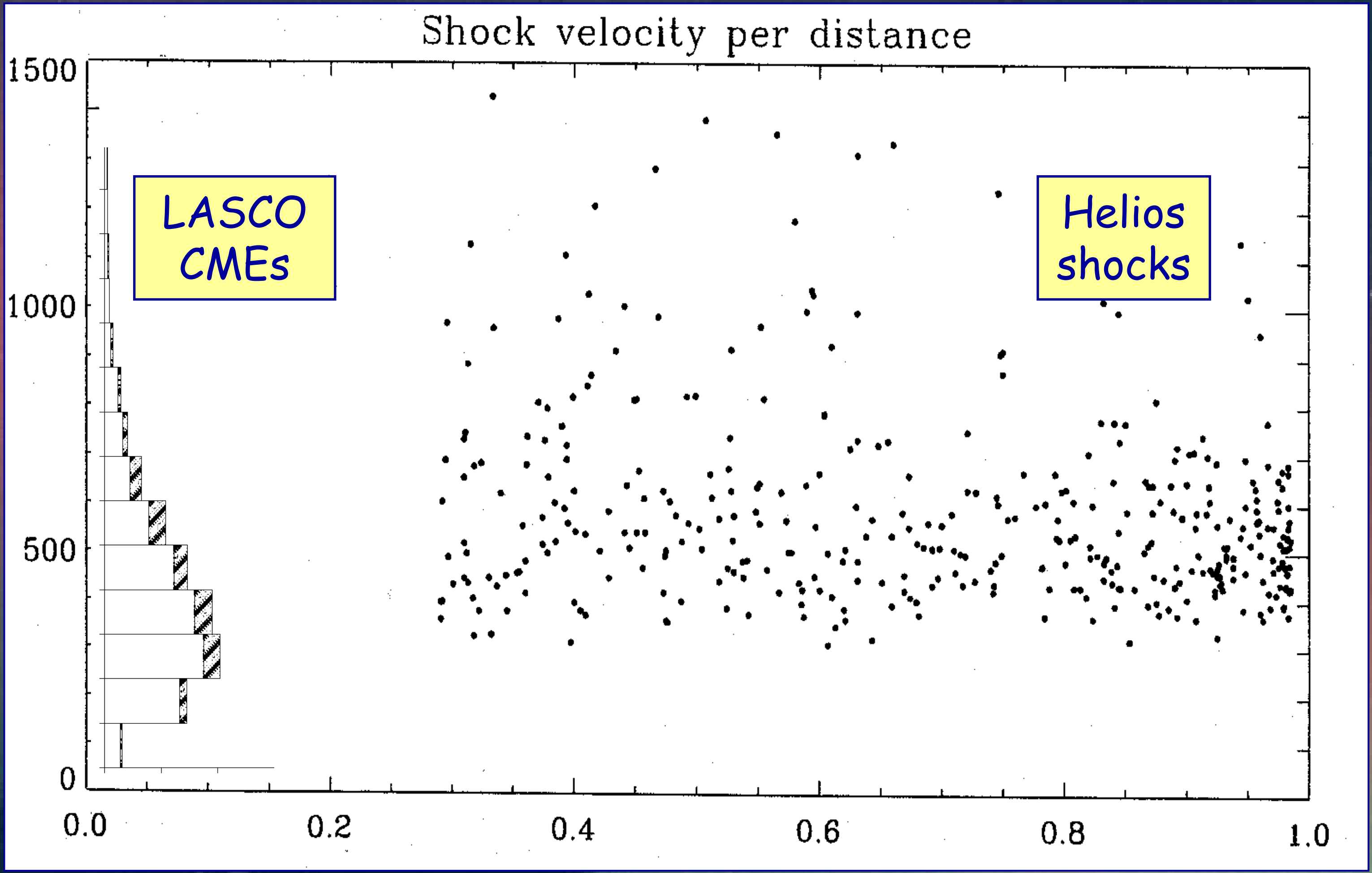
CMEs and shocks during 2 solar cycles





- Only one out of 10 CME shocks hits an *in-situ* observer!
- That means: the average cone angle of a shock front amounts to about 100^0,
- Remember that the average cone angle of CMEs is only 50^0.
- In other words: the shock fronts extend much further than the ejecta!

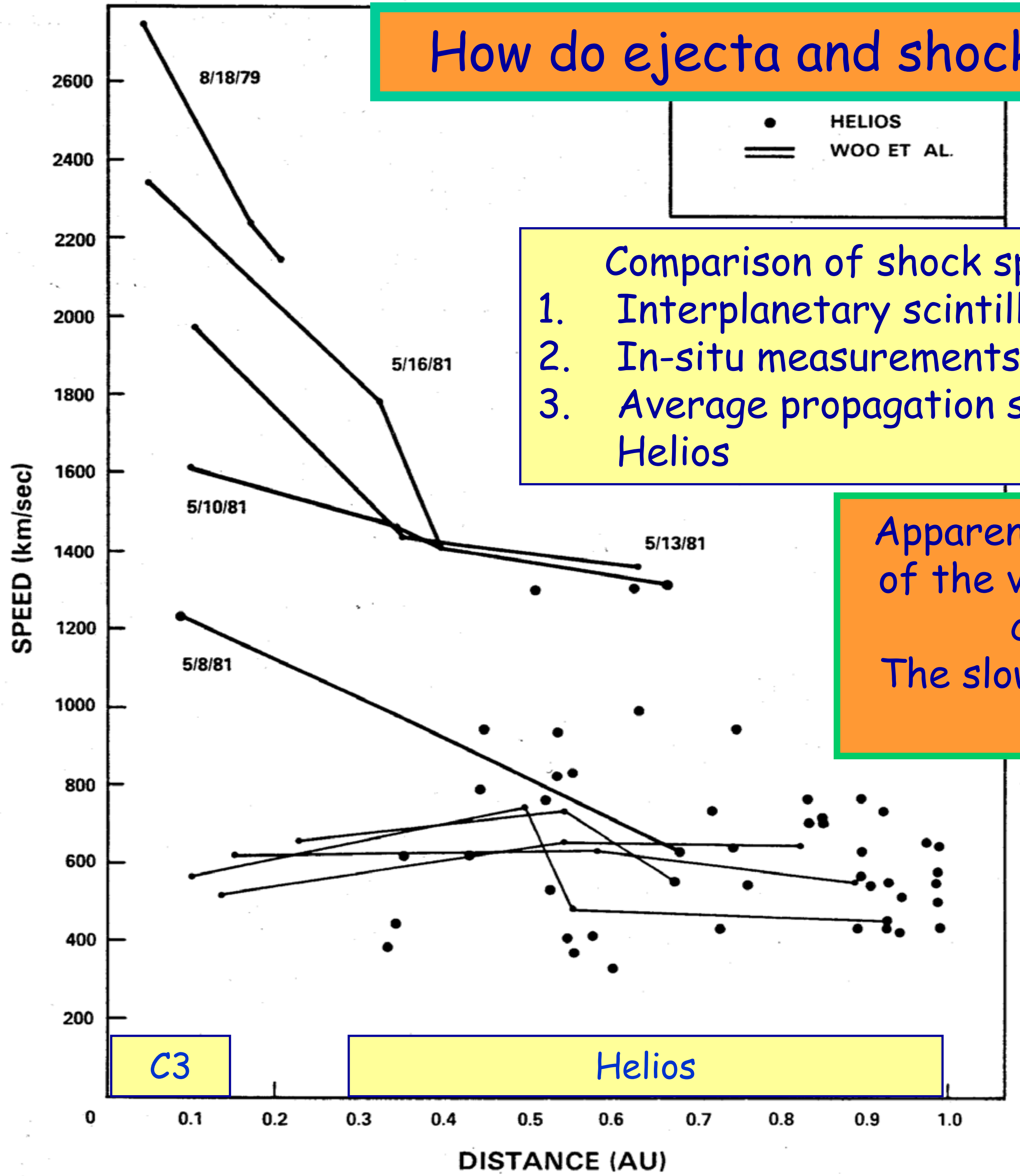
How do ejecta and shocks propagate?



Local speeds of about 400 shocks, observed between 0.3 and 1 AU by Helios from 1974 to 1986, compared to LASCO CME speeds.

The spread diminishes with increasing distance: fast ejecta are decelerated, the slow ones are accelerated and integrated into the slow solar wind.

How do ejecta and shocks propagate?



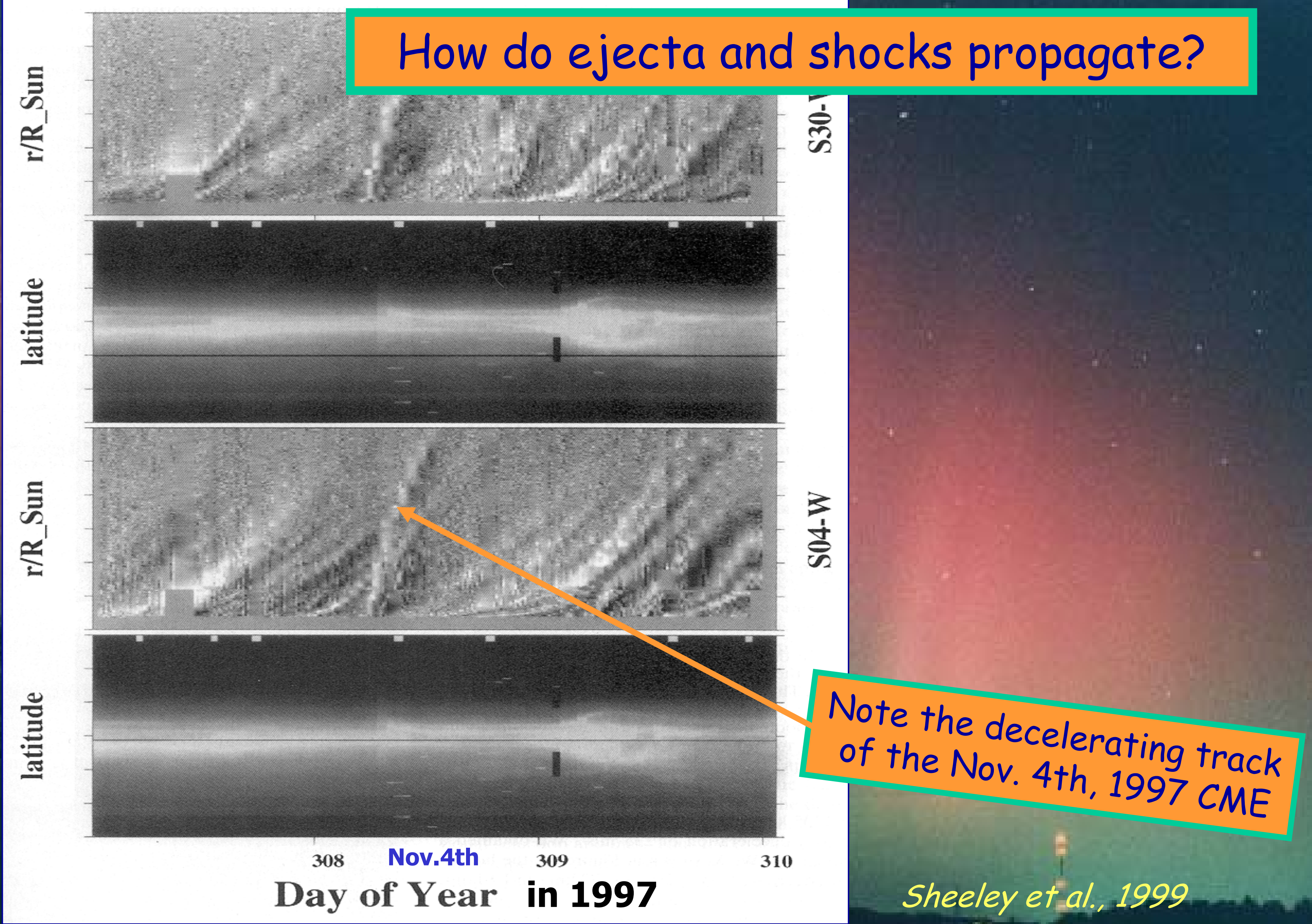
Comparison of shock speeds determined by

1. Interplanetary scintillation technique (IPS),
2. In-situ measurements by Helios,
3. Average propagation speeds between Sun and Helios

Apparently, strong deceleration of the very fast events occurs close to the sun.
The slow ones are decelerated more gradually.

Woo et al., 1985

How do ejecta and shocks propagate?



Sheeley et al., 1999

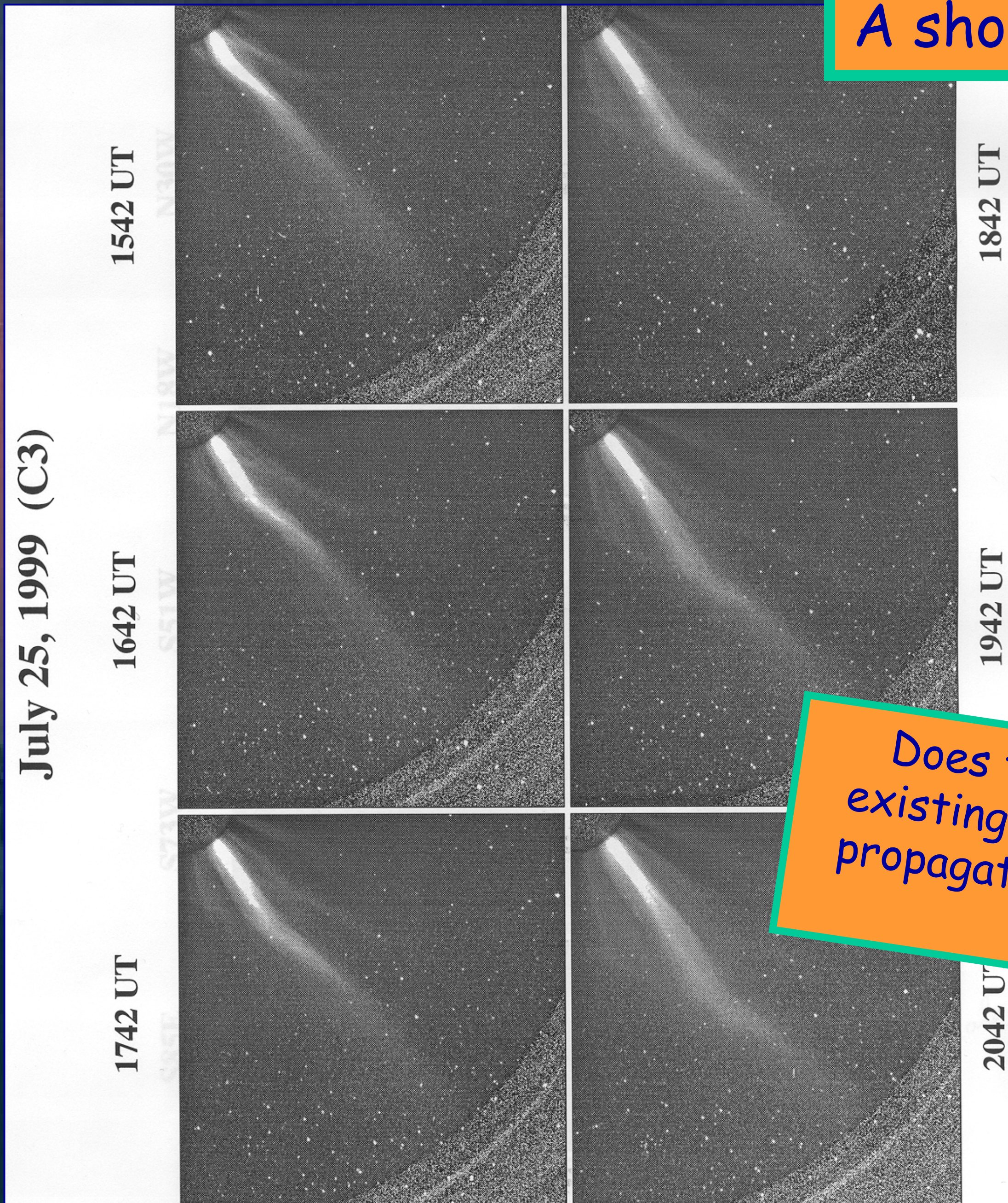
Brightness distributions in limited latitudinal slices plotted vs radial distance reveal acceleration/deceleration of features in the corona, e.g. CMEs

CMEs and shock waves near the Sun

Where is the shock with respect to the CME?
Why can't we see it, even with our most sensitive instruments?

What is this feature (in the NW): a density wave driven by the subsequent CME?

A shock wave near the Sun?



Does this moving kink in the pre-existing radial features indicate the propagation of an otherwise invisible shock wave?

Sheeley et al., 1999

Tracers of shock waves: Radio type II bursts

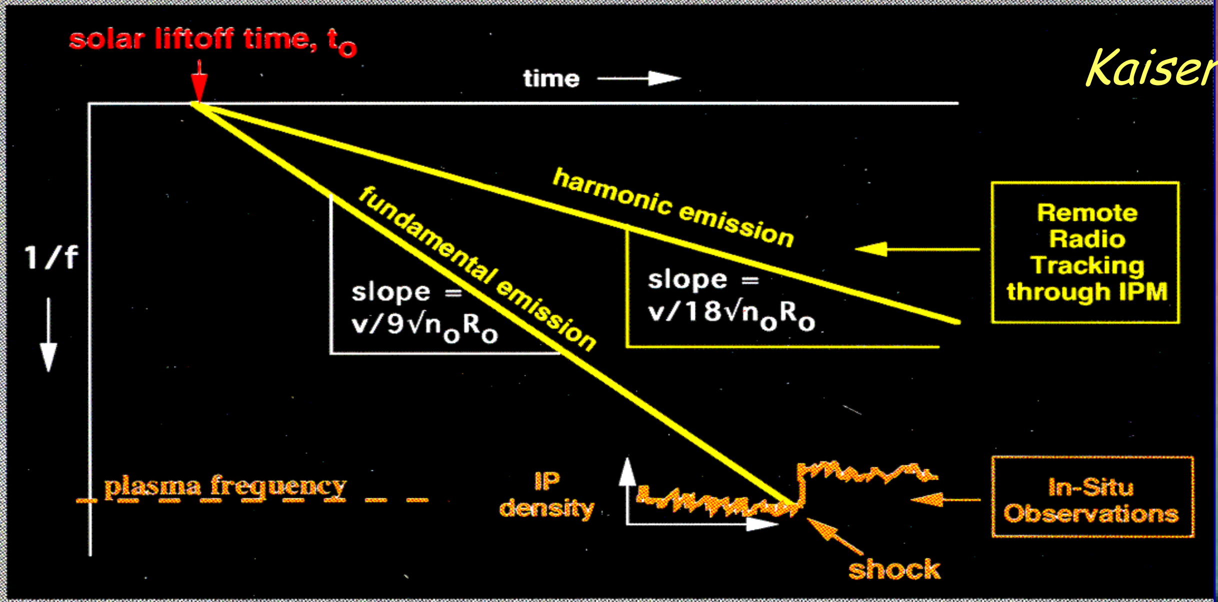
$n \sim 1/R^2 \xrightarrow{f = 9\sqrt{n}} f \sim 1/R$

$1/f \sim R \approx v\,(t - t_o)$

v = shock speed (assumed ~ constant)

t_o = solar liftoff time

<u>Dynamic properties</u> of the radio source are more <u>directly</u> indicated by plotting the radio data as <u>1/f versus time</u>

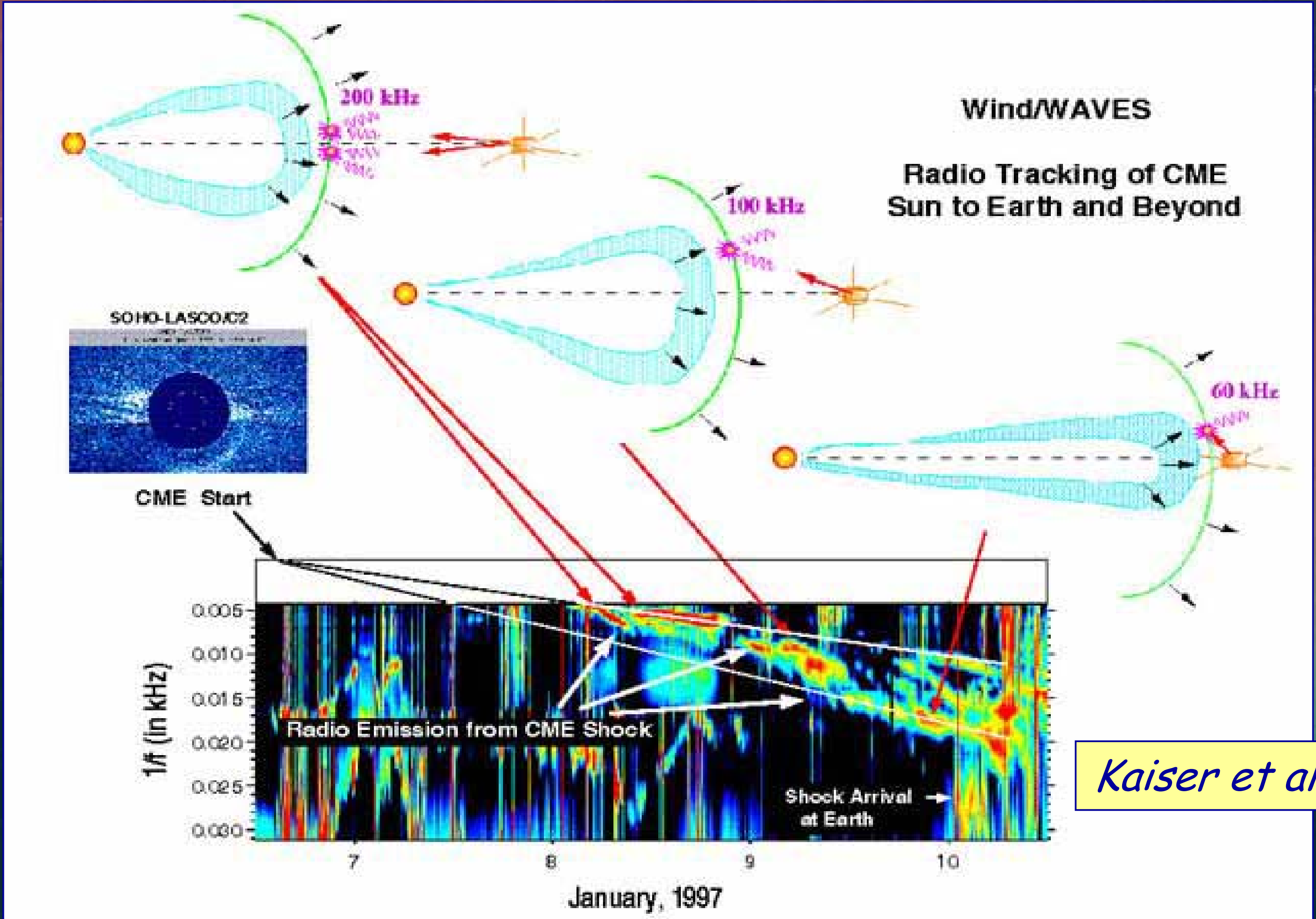


Kaiser et al., 1998

- slope of lines gives $v/\sqrt{n_o R_o}$, $R_o = 1.5 \times 10^8$ km
- intercept of lines gives t_o
- in-situ observations give n_o and v

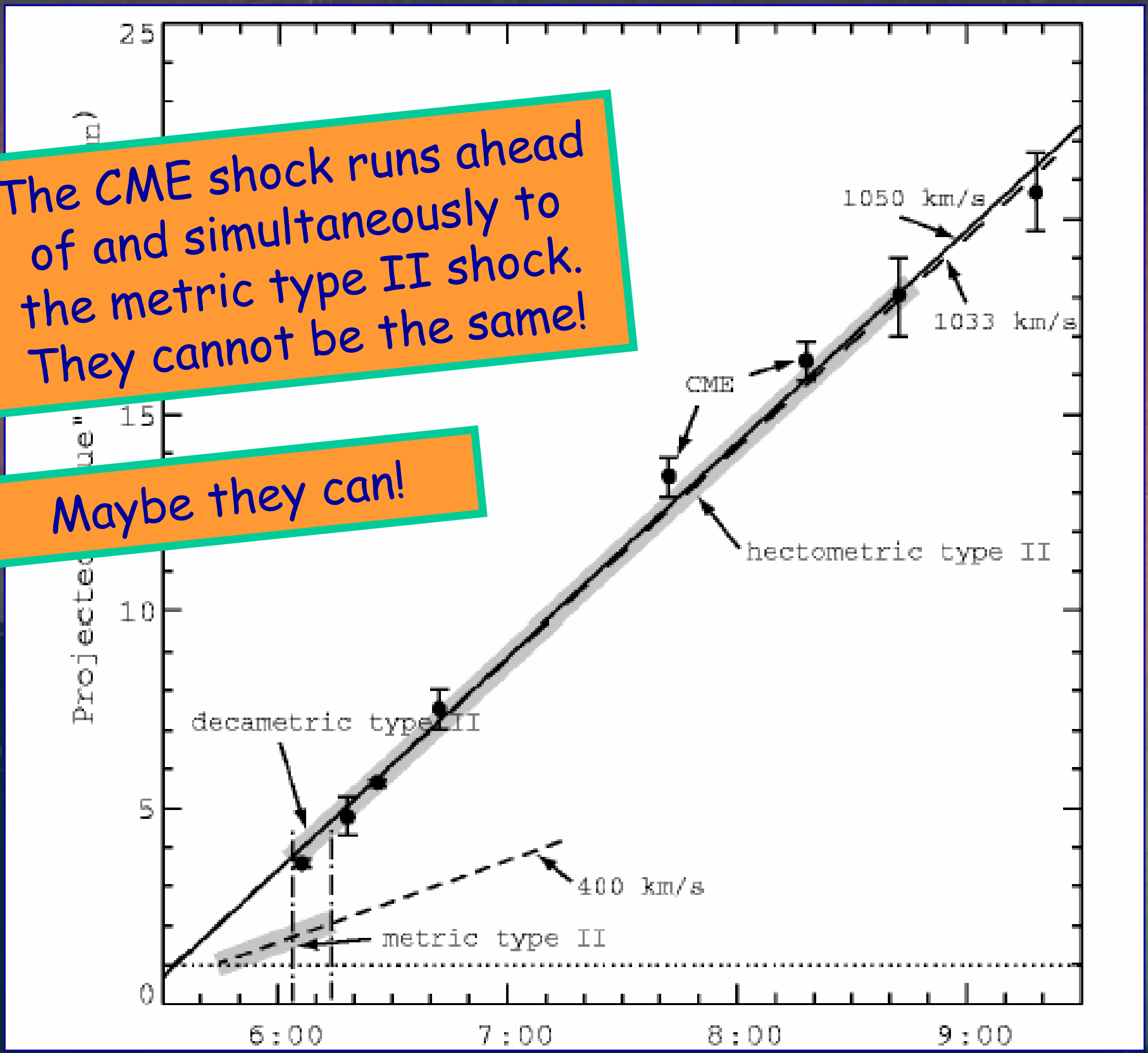
Propagation of shock waves from the Sun towards Earth

Where and how are they accelerated/decelerated?
Answers might come from radio wave observations,
especially for improving space weather forecasts.



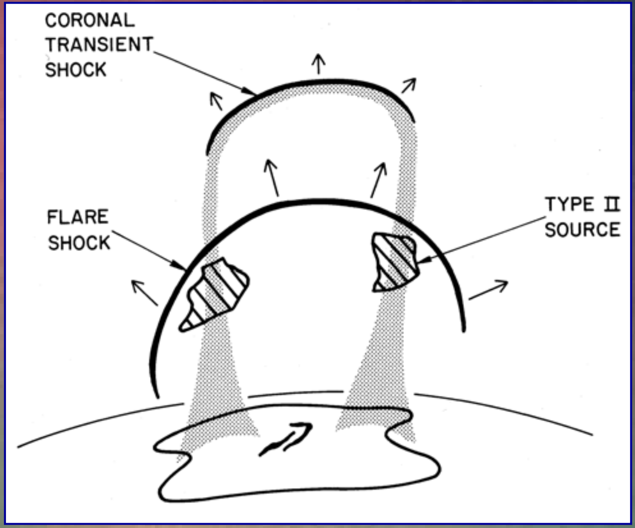
Kaiser et al., 1998

Radio bursts as remote sensors of shock waves



The CME shock runs ahead of and simultaneously to the metric type II shock. They cannot be the same!

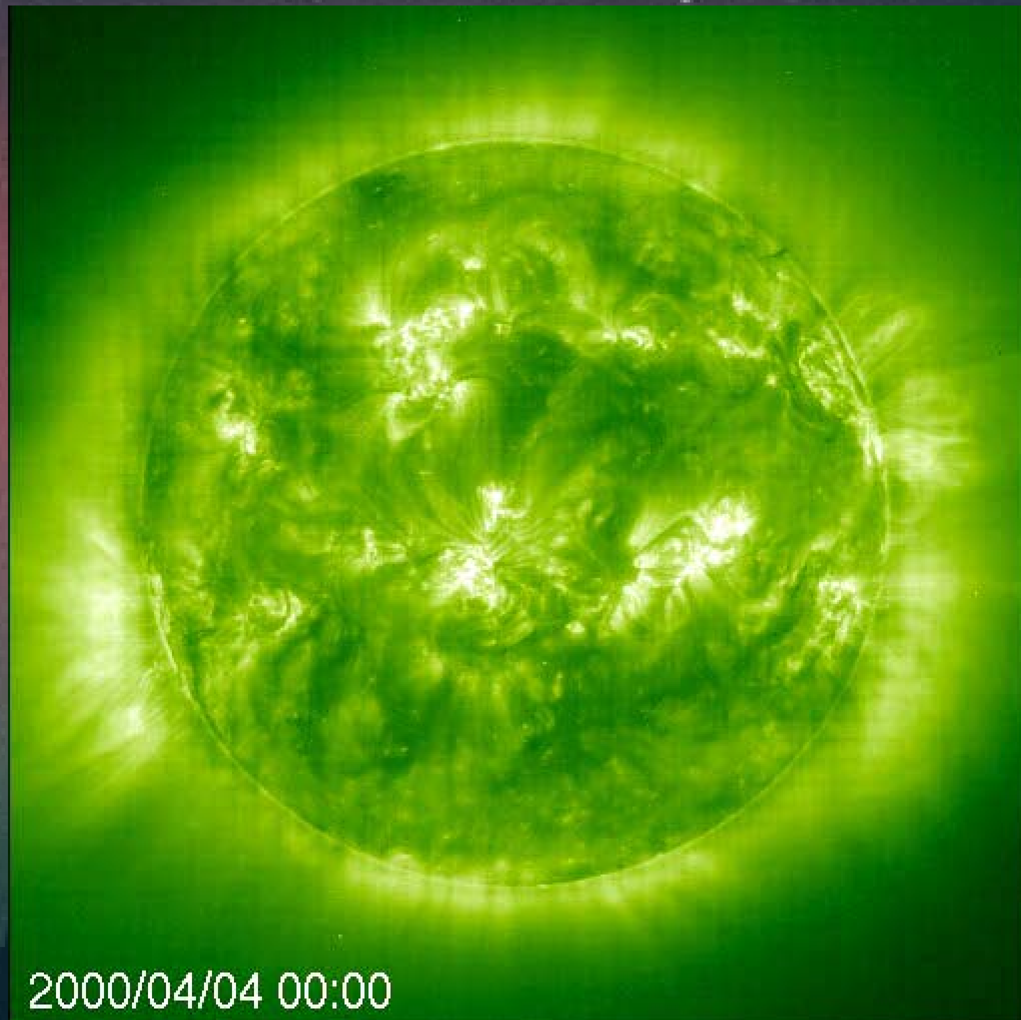
Maybe they can!



Reiner et al., 2000

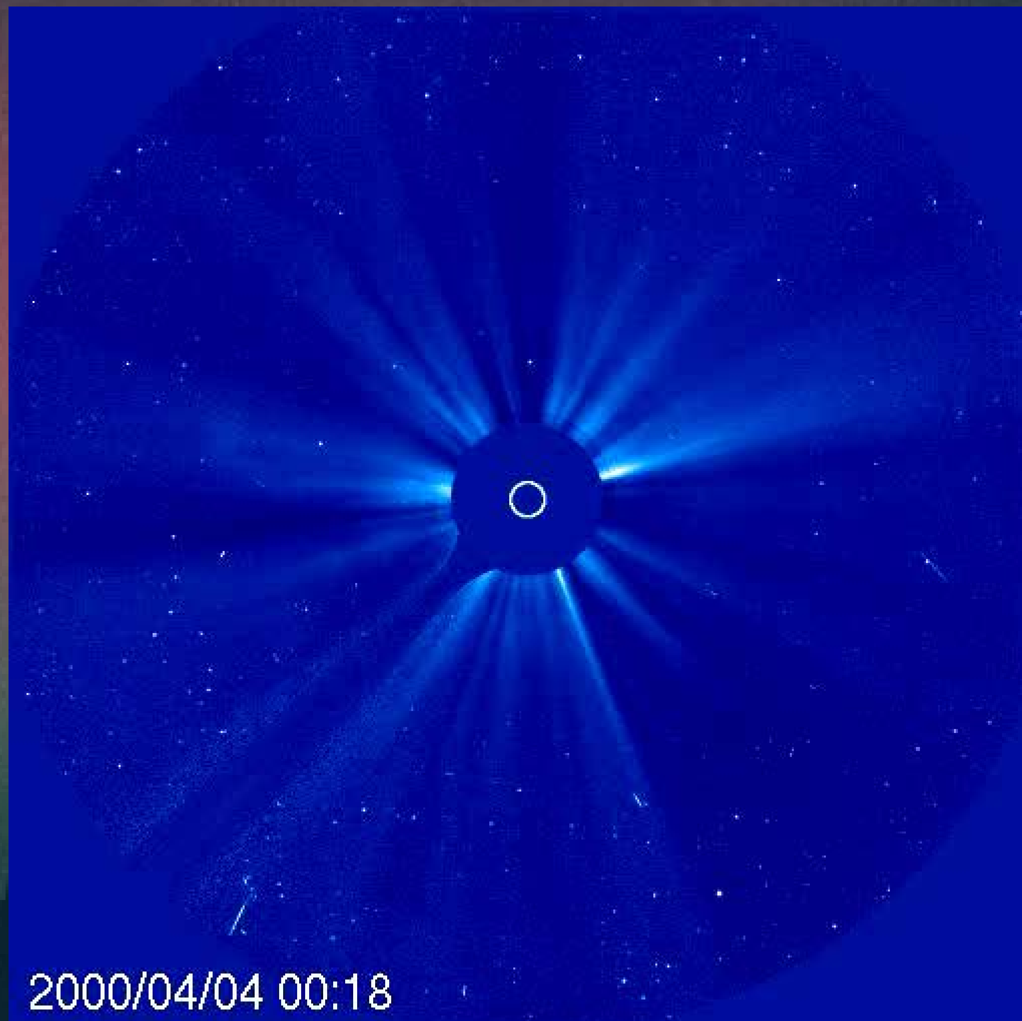
Height-time diagram of the May 3rd, 1999, CME, as determined from **LASCO**, and from drift rates of type II radio emission.

The events of April 4, 2000



Based on EIT images, none of the several events seemed worth particular attention ...

The events of April 4, 2000



... nor did the halo CME alert the predictors

Date: Thu, 6 Apr 2000 19:01:23 +0000 (GMT)

From: Simon Plunkett

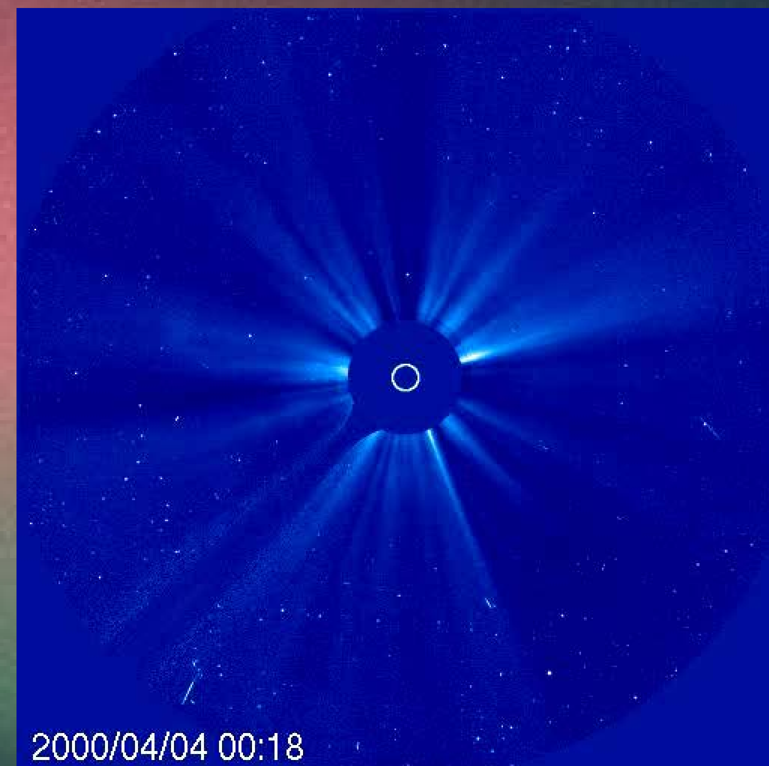
Subject: Halo CME on 2000/04/04

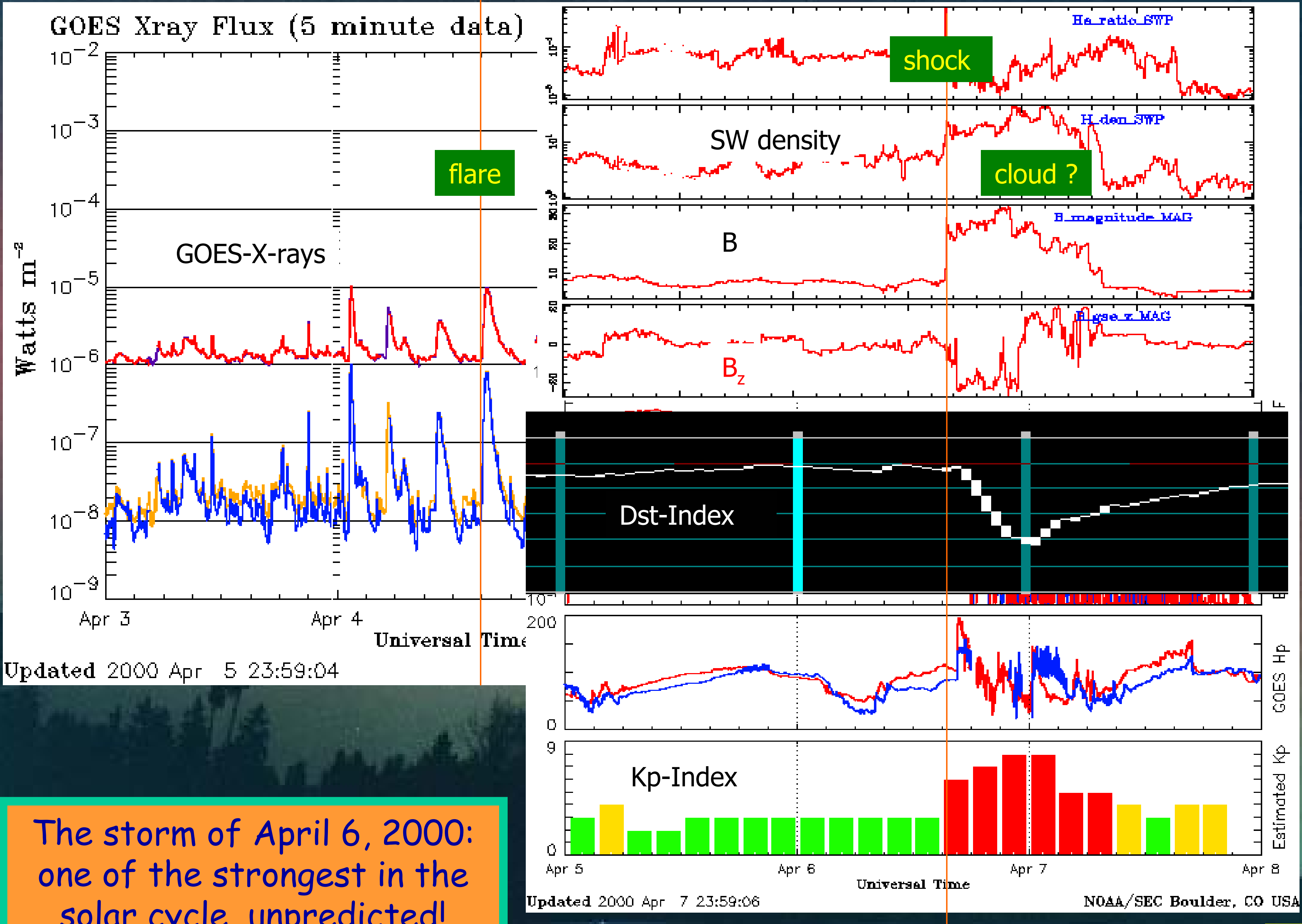
The event of April 4, 2000, unnoticed at first…

LASCO and EIT observed a full halo event on 2000/04/04. This is presumably the cause of the shock that was observed at ACE today. The CME was first observed in a C2 frame at 16:32 UT, following a data gap of about ninety minutes. The leading edge of the CME had already left the C2 field of view at this time. Measurements in C3 indicate a plane-of-sky speed of 984 km/s at PA 260 (W limb). The event was brightest and most structured ov er the West limb, where a bright core was observed behind the leading edge. The appearance was more diffuse and fainter in the east.

EIT observed a C9 flare in AR 8933 (N18 W58) at 15:24 UT, that was probably associated with this flare. A large area of dimming between AR 8933 and AR 8935 (S07 W34) was also observed in EIT around the same time.

Apologies for the late delivery of this message. I was on travel earlier this week and did not see the event until today.





The storm of April 6, 2000: one of the strongest in the solar cycle, unpredicted!

The April 4./6. 2000 events

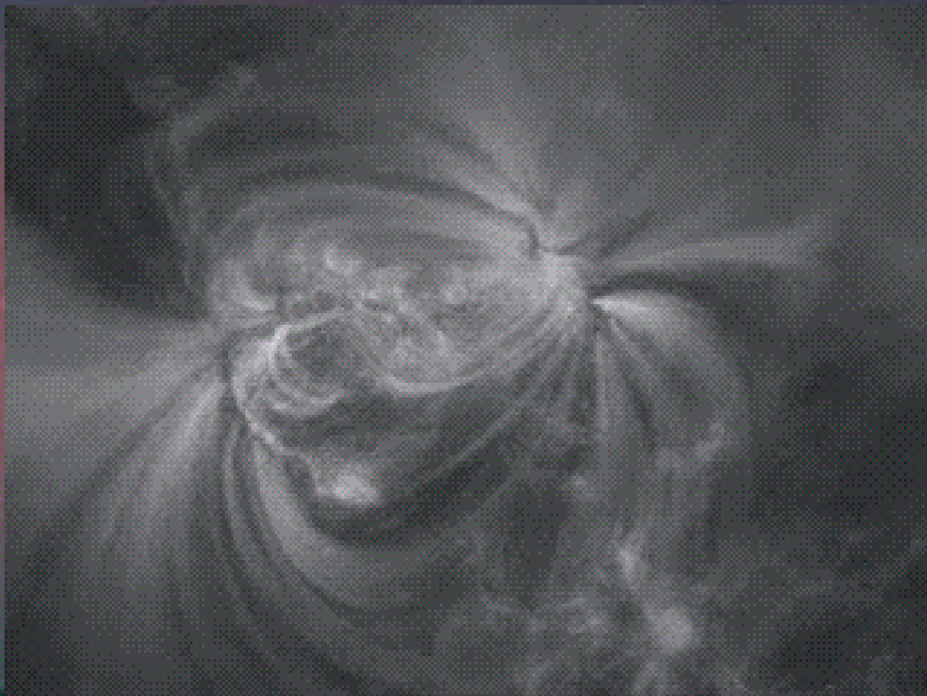
C 9.8 flare:	April 4, 16:37
Arrival of energetic particles at 1 AU:	none
Shock at 1 AU:	April 6, 16:02
Travel time:	47.5 hours
Initial CME speed:	980 km/s
Average travel speed:	880 km/s
Shock speed at 1 AU:	810 km/s
Kp max:	8
Dst min:	-310 nT

The biggest storm of the present solar cycle, caused by a middle-class solar event - that's what I call "geoefficient"...!

Conclusions: Don't trust observers and predictors: they might be lacking relevant data or ignoring them, or they are biased, or on vacations, or...

Aurora in Essen, Germany, on April 7, 2000 at 01:00

A never ending discussion: flares vs CMEs

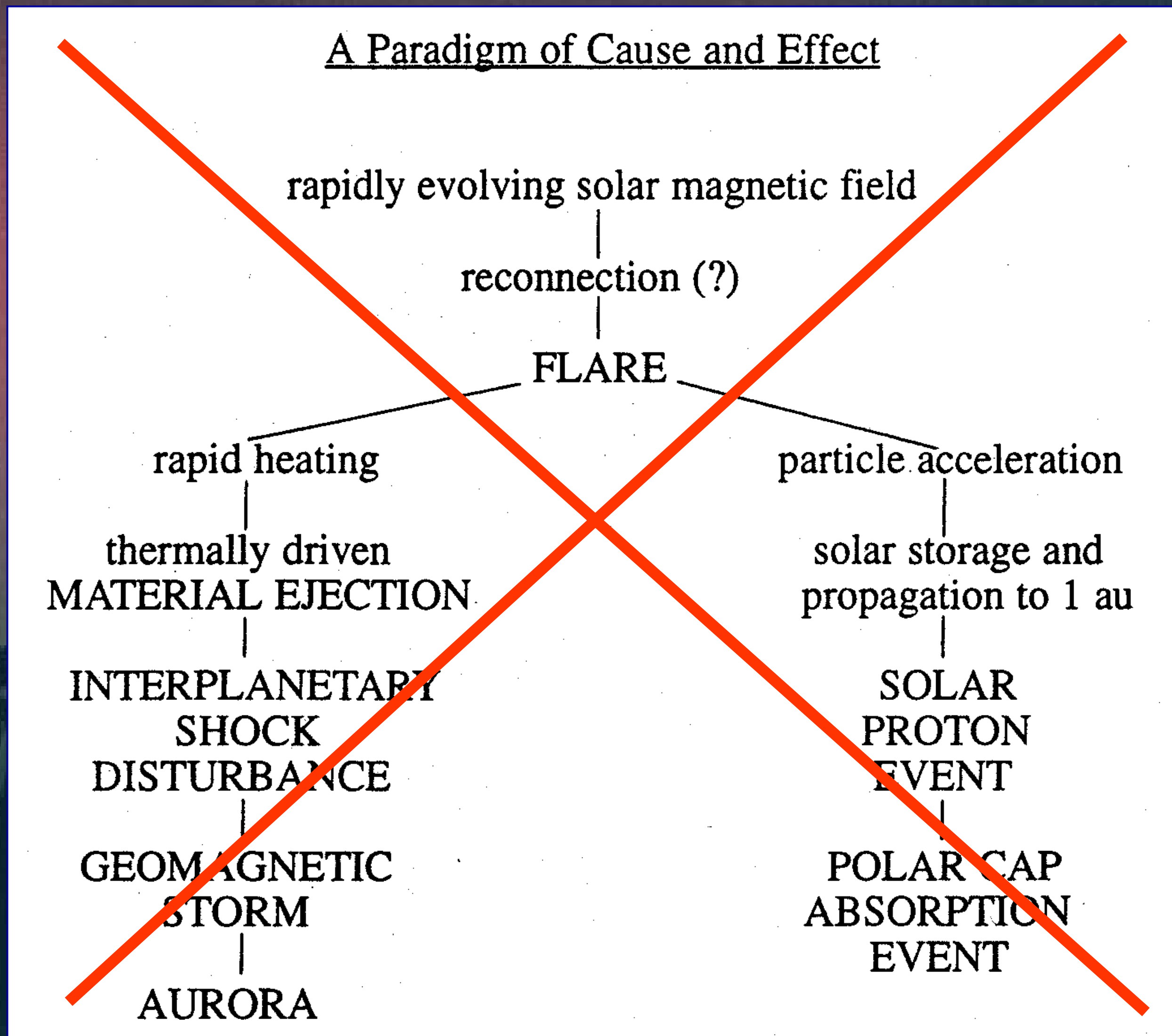


A solar flare, as observed by **TRACE**

CMEs, as observed by LASCO C3

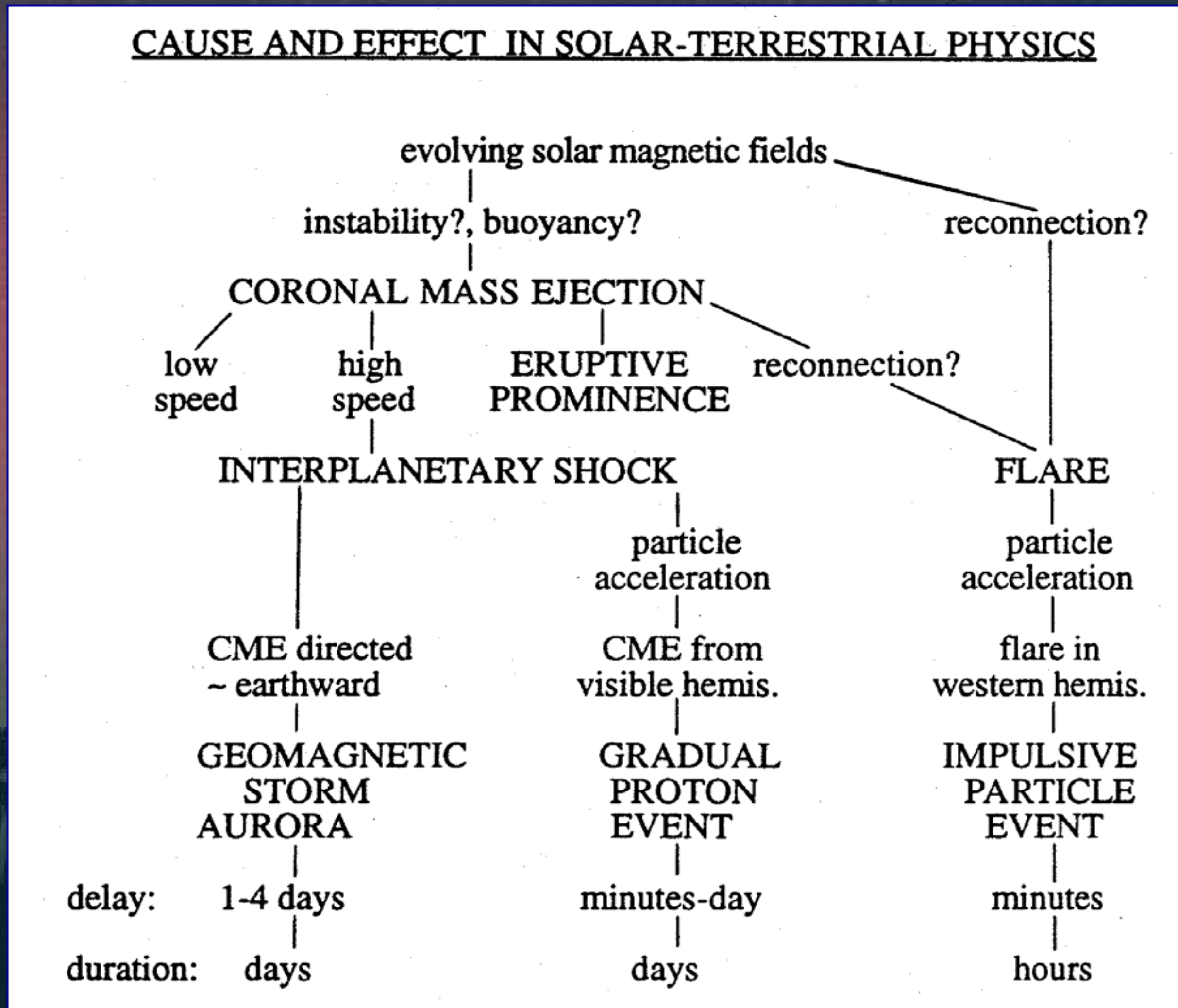
One the cause of the other?

The “old” paradigm: the “solar flare myth”



Gosling, 1993

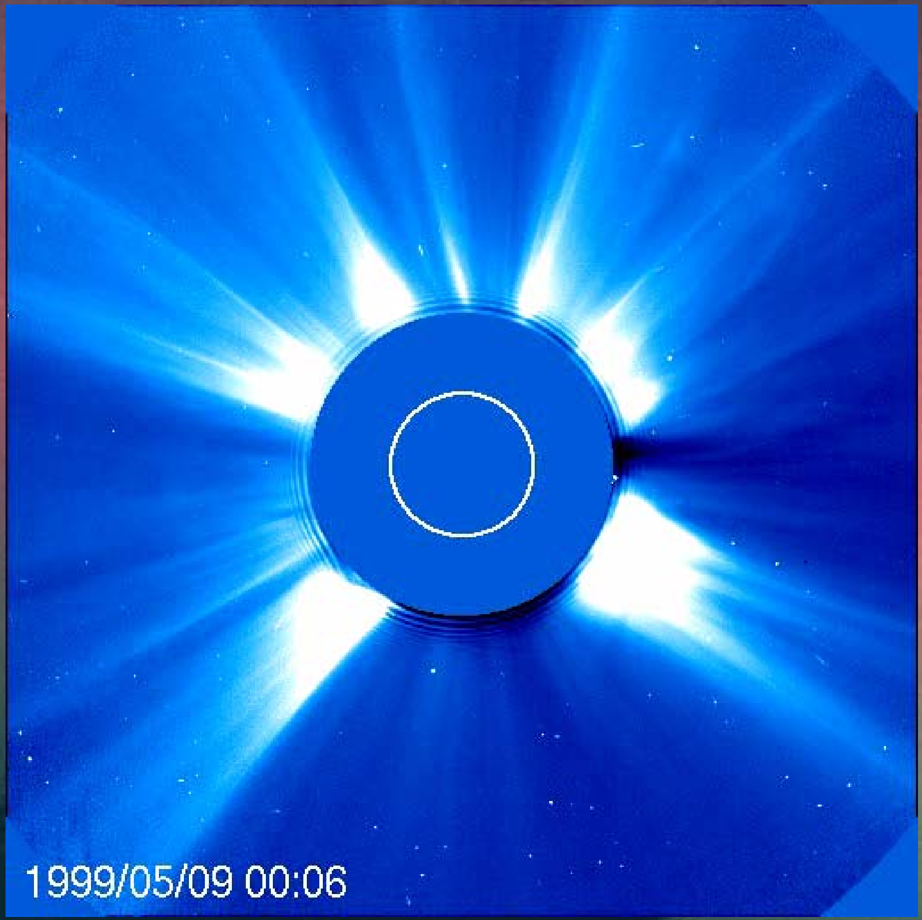
The modern paradigm



Gosling, 1993

Flares and CMEs are probably symptoms of a more basic **"magnetic disease"** of the Sun (*Harrison)*

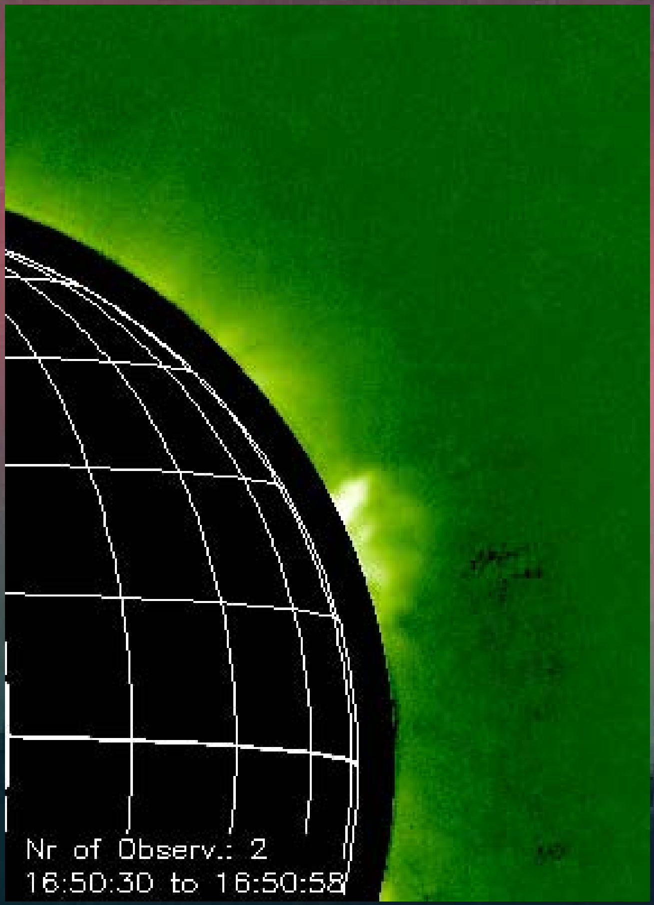
Explosive onset of a CME

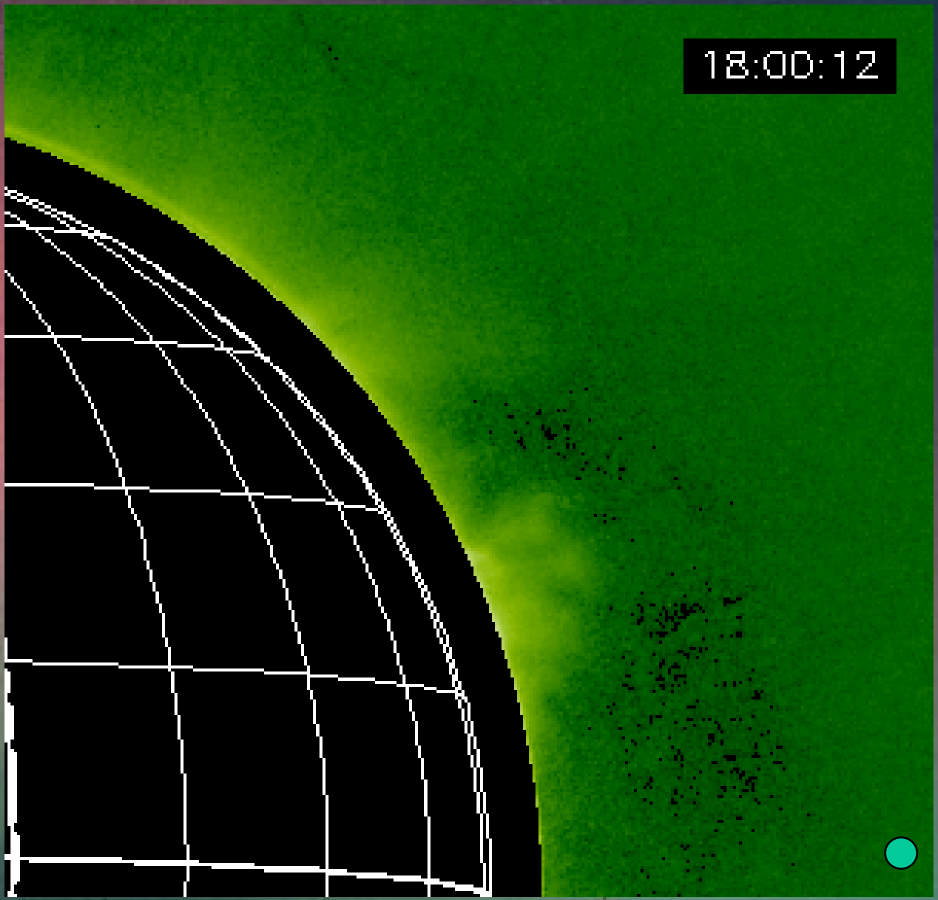


A CME seen by LASCO C2 on SOHO on May 9, 1999

For this CME we were lucky to observe the onset in unprecedented detail, using data from several instruments: MICA, SUMER, EIT

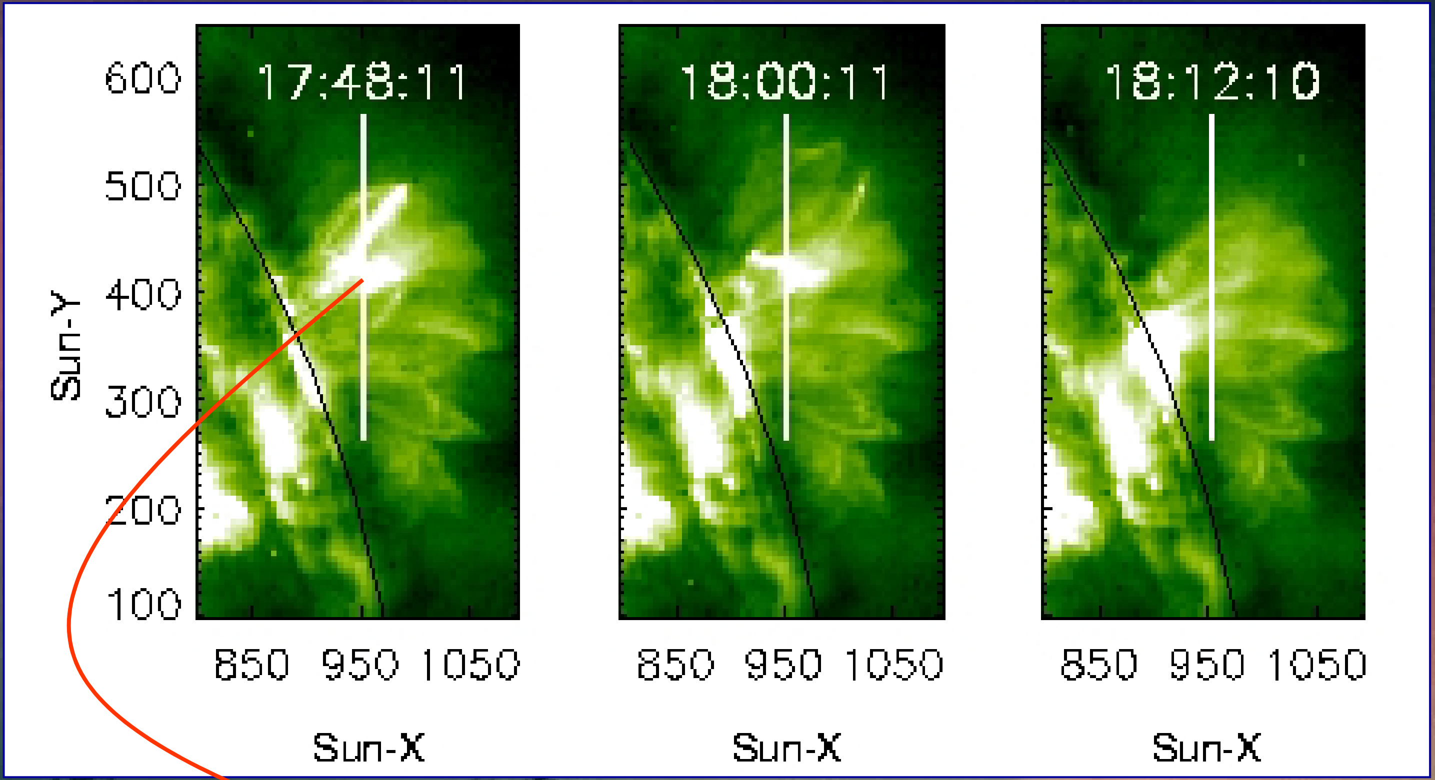
The onset of a fast CME (600 km/s) was revealed!





The MICA coronagraph observed the CME onset on May 8, 1999 in the green Fe XIV line. Pictures were taken every half minute!

The onset of a fast CME (600 km/s) was revealed!



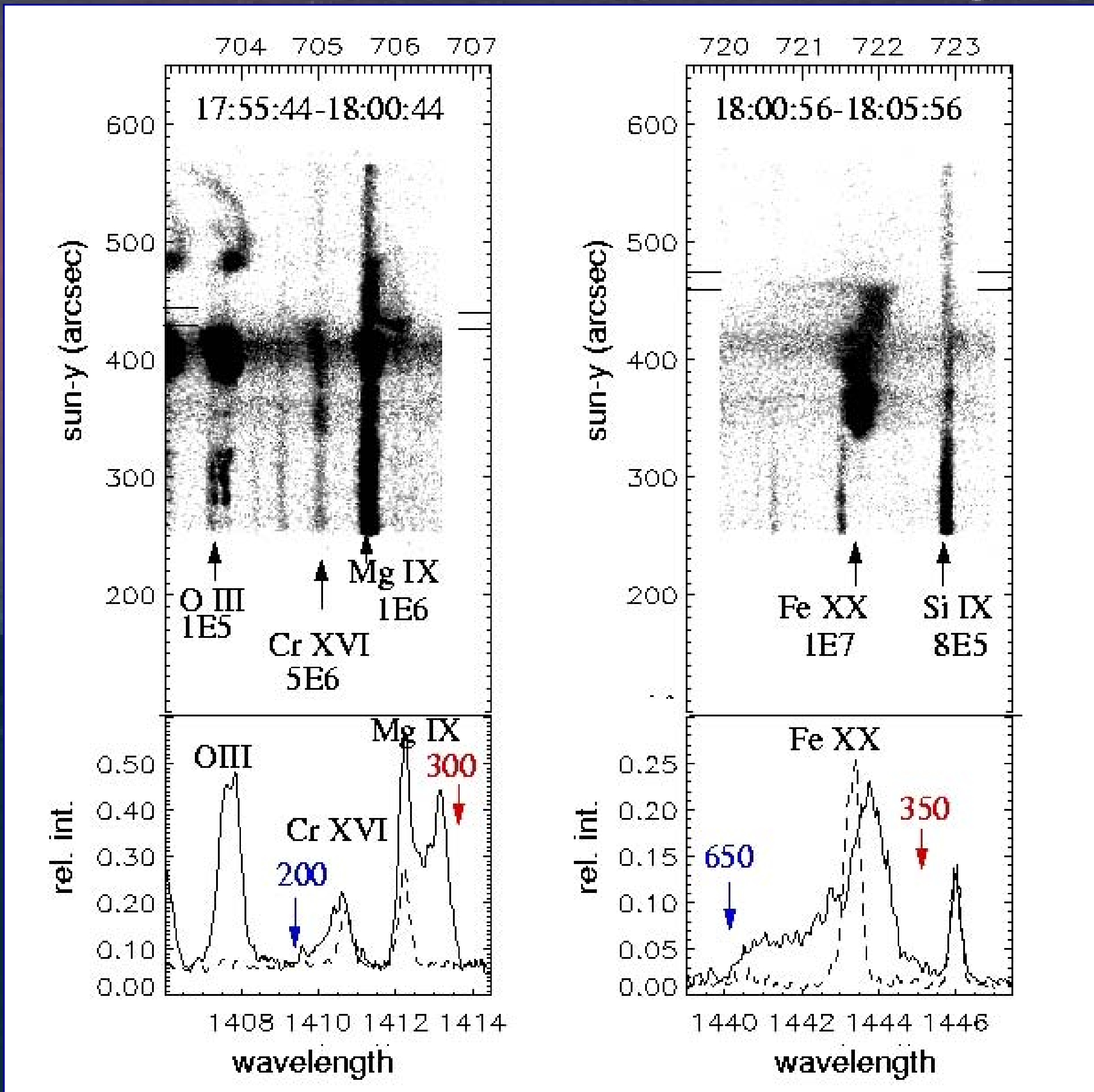
EIT images, taken every 12 minutes, show but the scenario

SUMER slit (1 sec x 300 sec)

Innes et al., 2000

SUMER happened to take UV spectra in the "right" location. Pure chance!

The onset of a fast CME (600 km/s) was revealed!

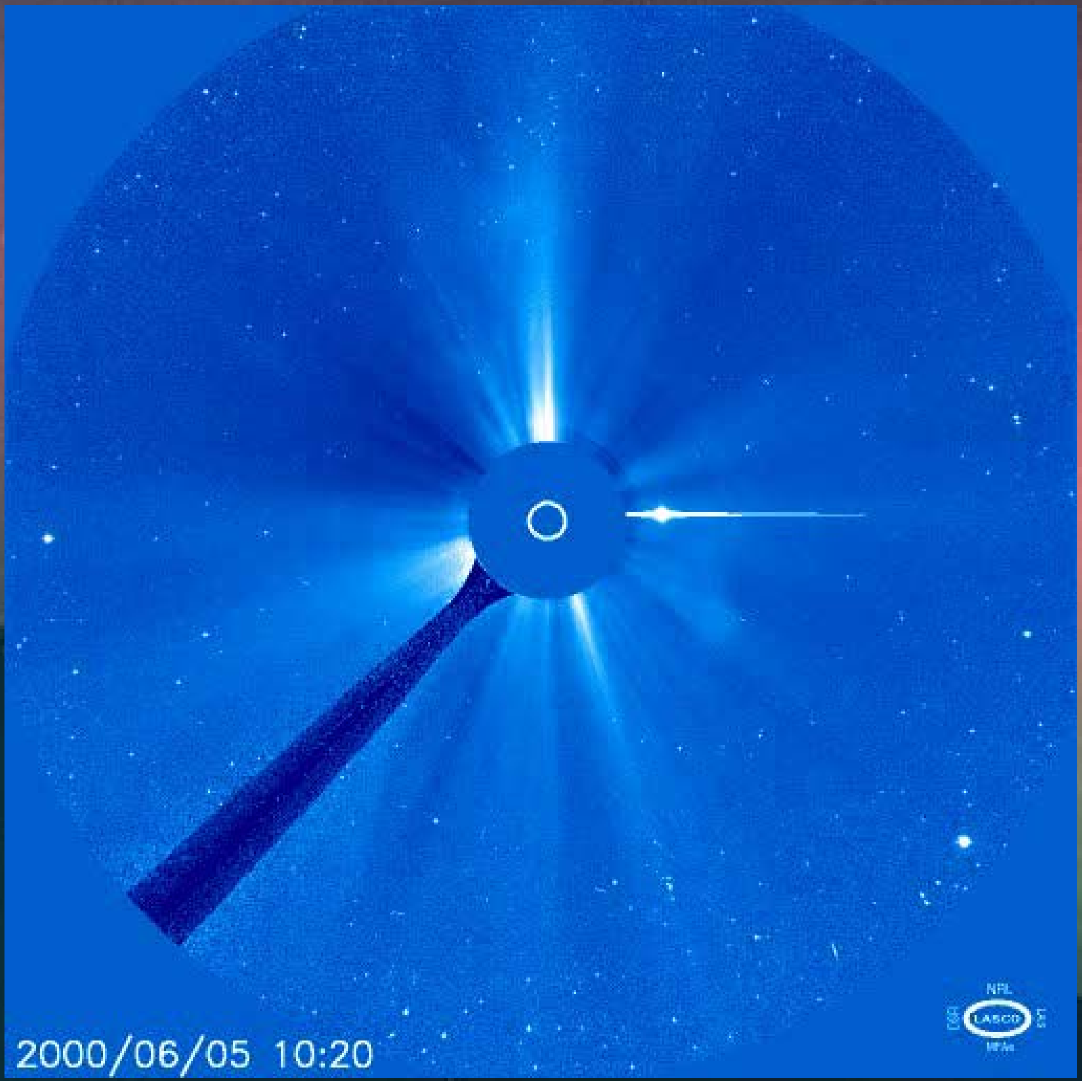


Expansion speeds up to 600 km/s in all directions were measured. That indicates 3-D explosive reconnection at a site in the corona.

Line-of-sight plasma flow observations using SUMER spectra.

Innes et al., 2000

Limb CMEs and „halo“ CMEs

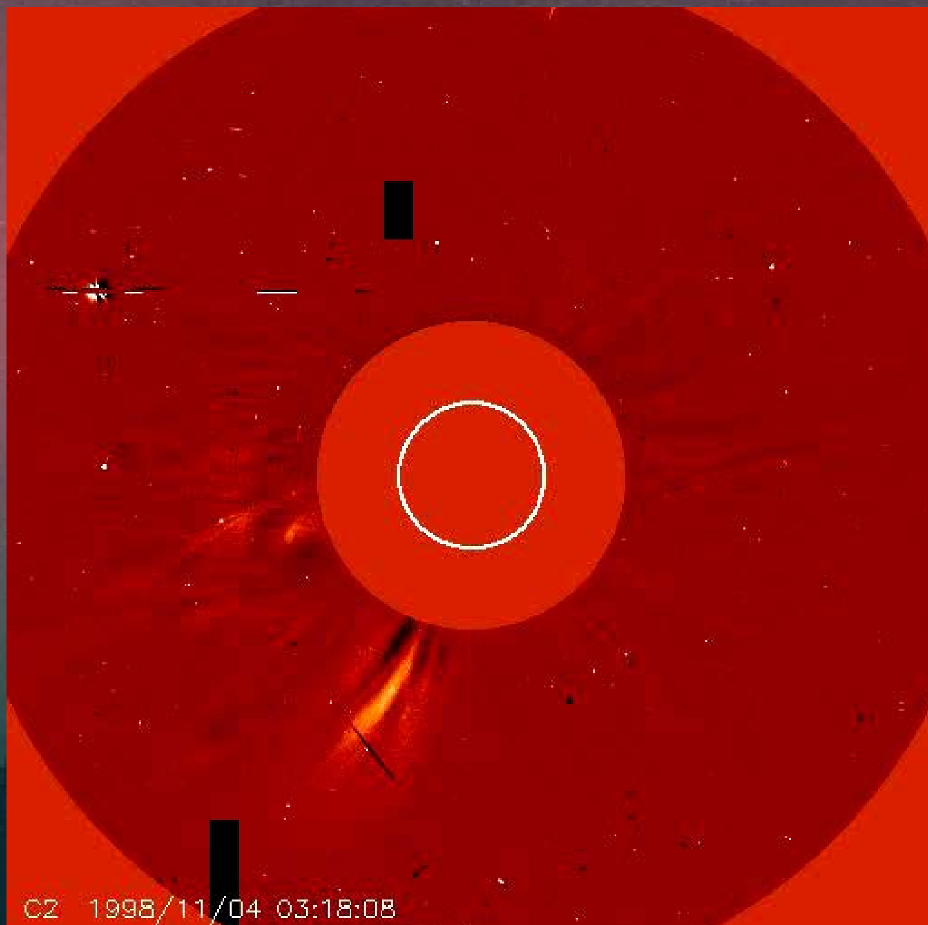


A series of dramatic CMEs observed by LASCO C3 on SOHO

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

Halo CMEs: a new quality from SOHO

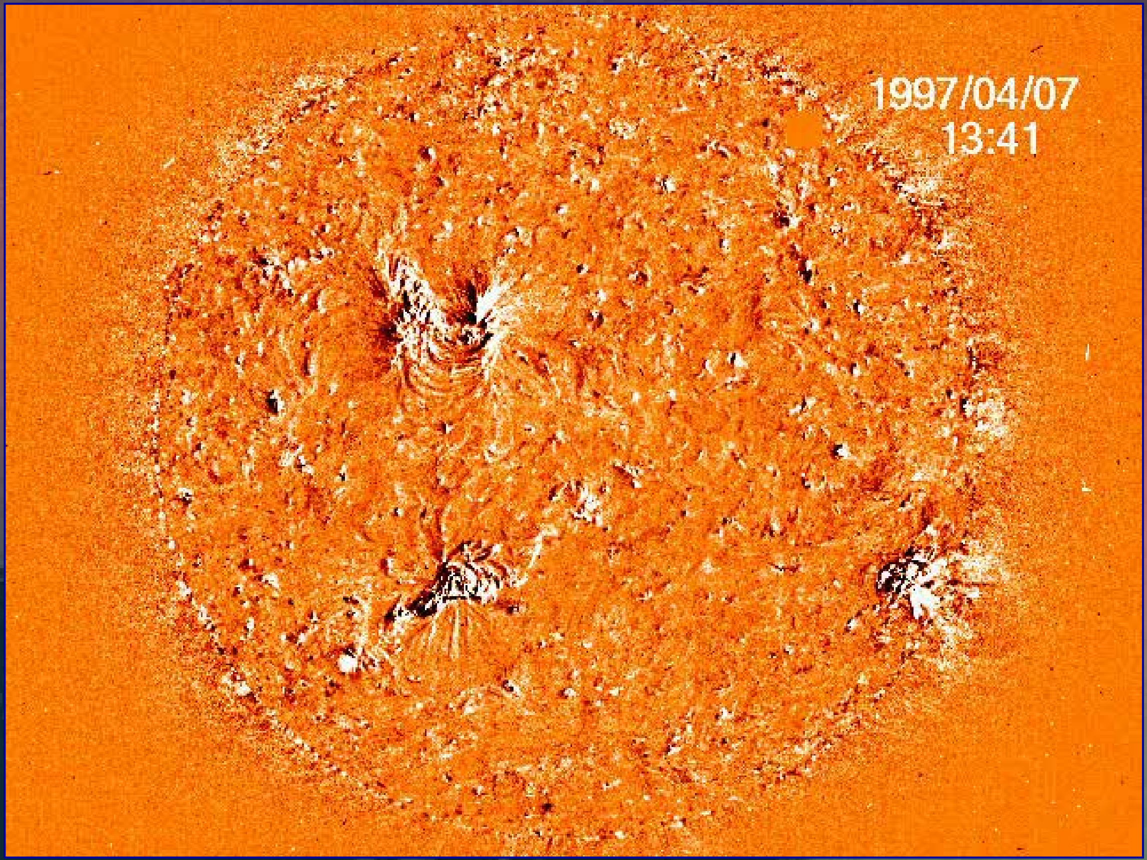
We can now watch earthward pointed CMEs early on



A classical "halo" CME,
observed by **LASCO-C2**
on 4.11.1998

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

A SOHO discovery: EIT waves



A pressure wave (EIT wave) in the solar atmosphere, pushed by a flare on 7.4.1997.
In conjunction, there was a halo CME launched towards Earth.

In H-alpha, similar features had been seen long ago: “Moreton-waves”.
They are not the same!

EIT waves and coronal shock waves

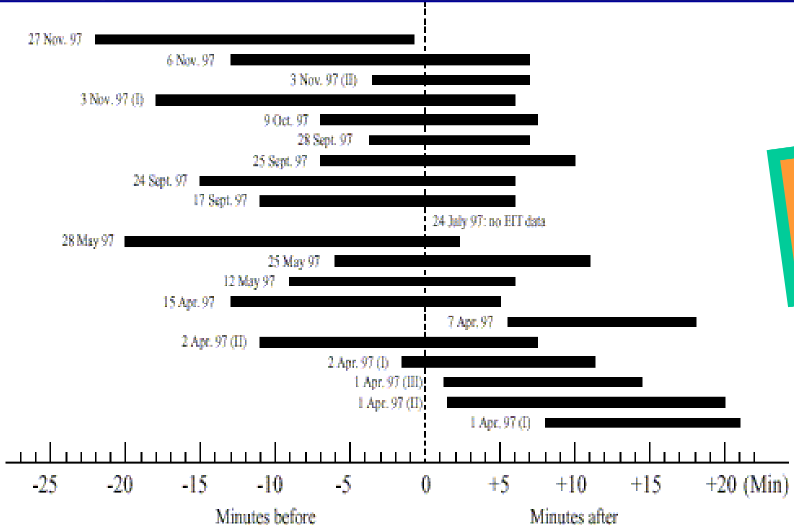


Fig. 2. EIT wave onset related with the start of associated type III bursts (indicating the start of the impulsive flare phase). The start time of the type III bursts is zero on the time axis

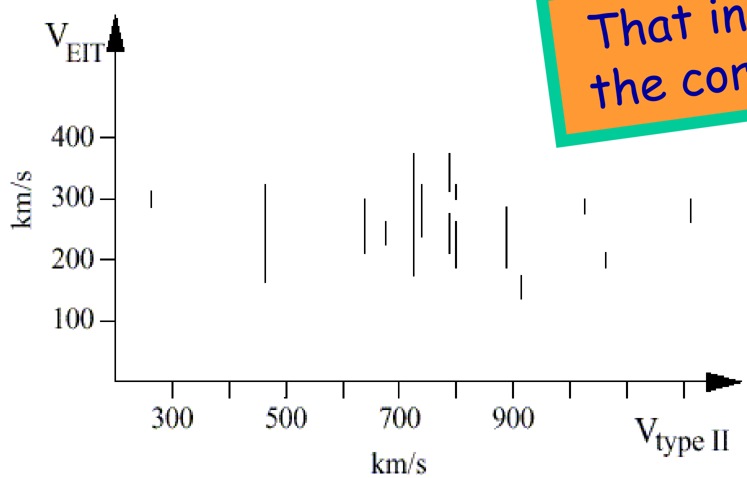


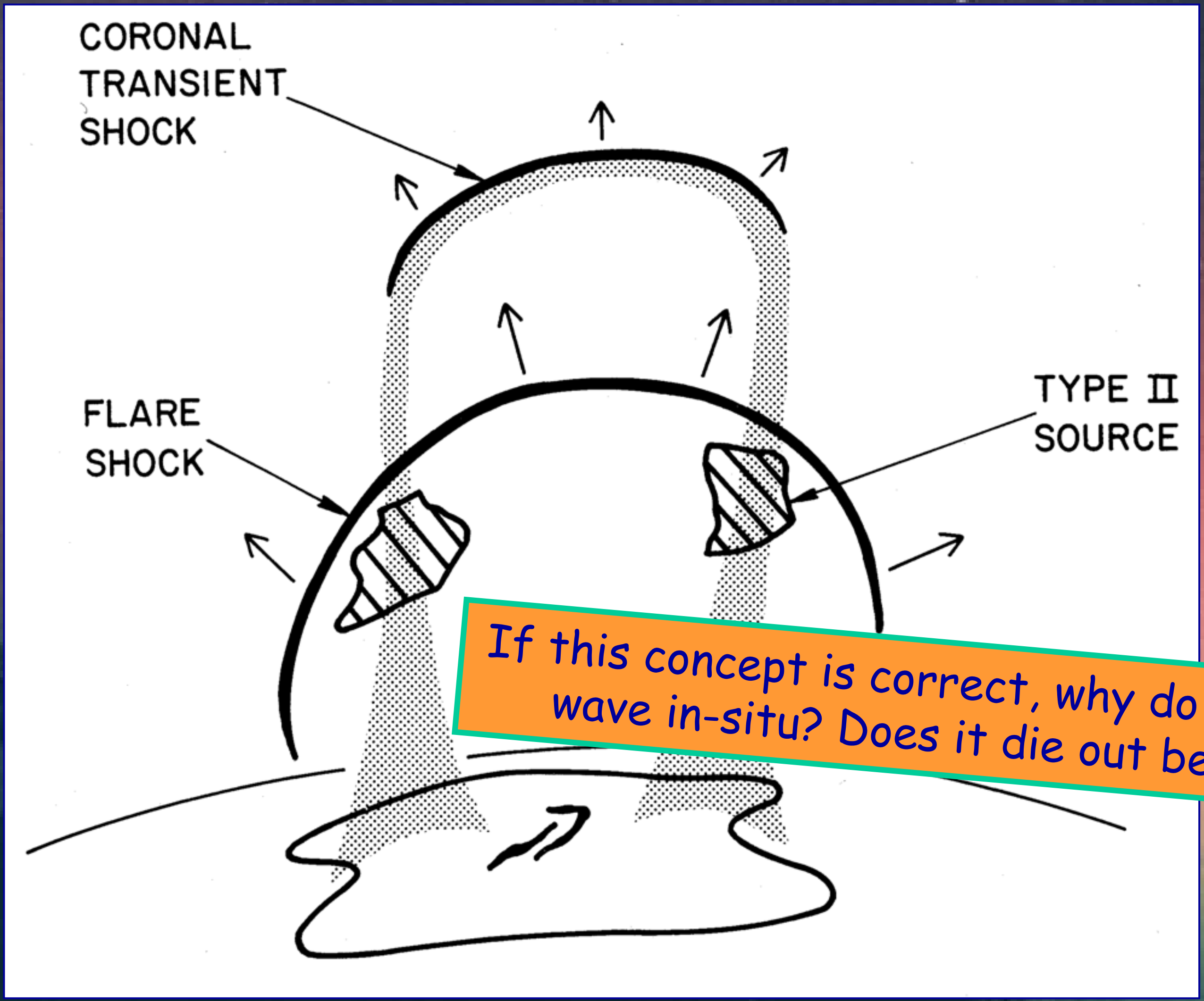
Fig. 3. The speed relation between EIT waves and type II bursts

EIT waves are usually much slower than type II waves

That indicates that the EIT-waves are NOT the coronal shock waves causing radio bursts

Klassen et al., 2000

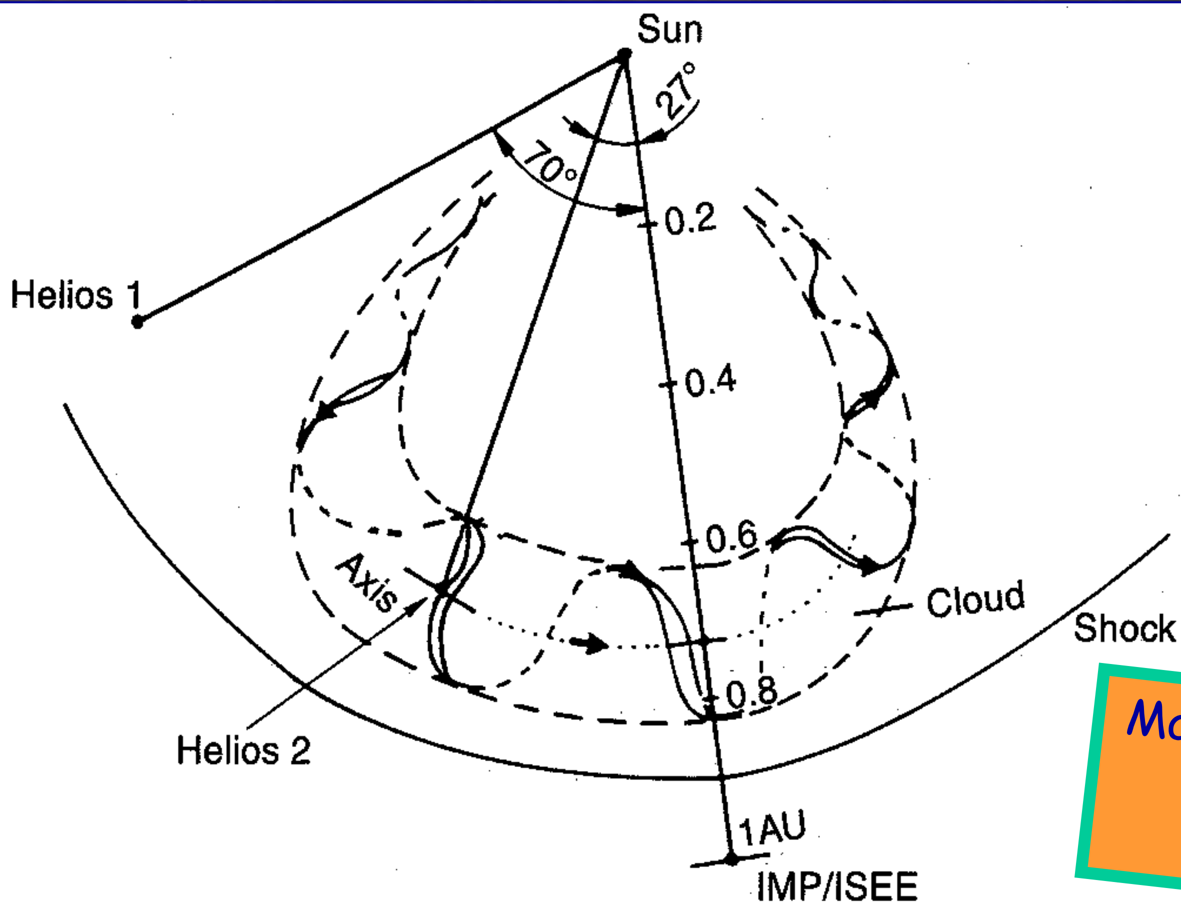
Radio signals („bursts") as remote sensors



If this concept is correct, why do we never see the blast wave in-situ? Does it die out before it reaches us?

The "two-shock concept": a CME driven shock wave runs ahead of a flare generated blast wave

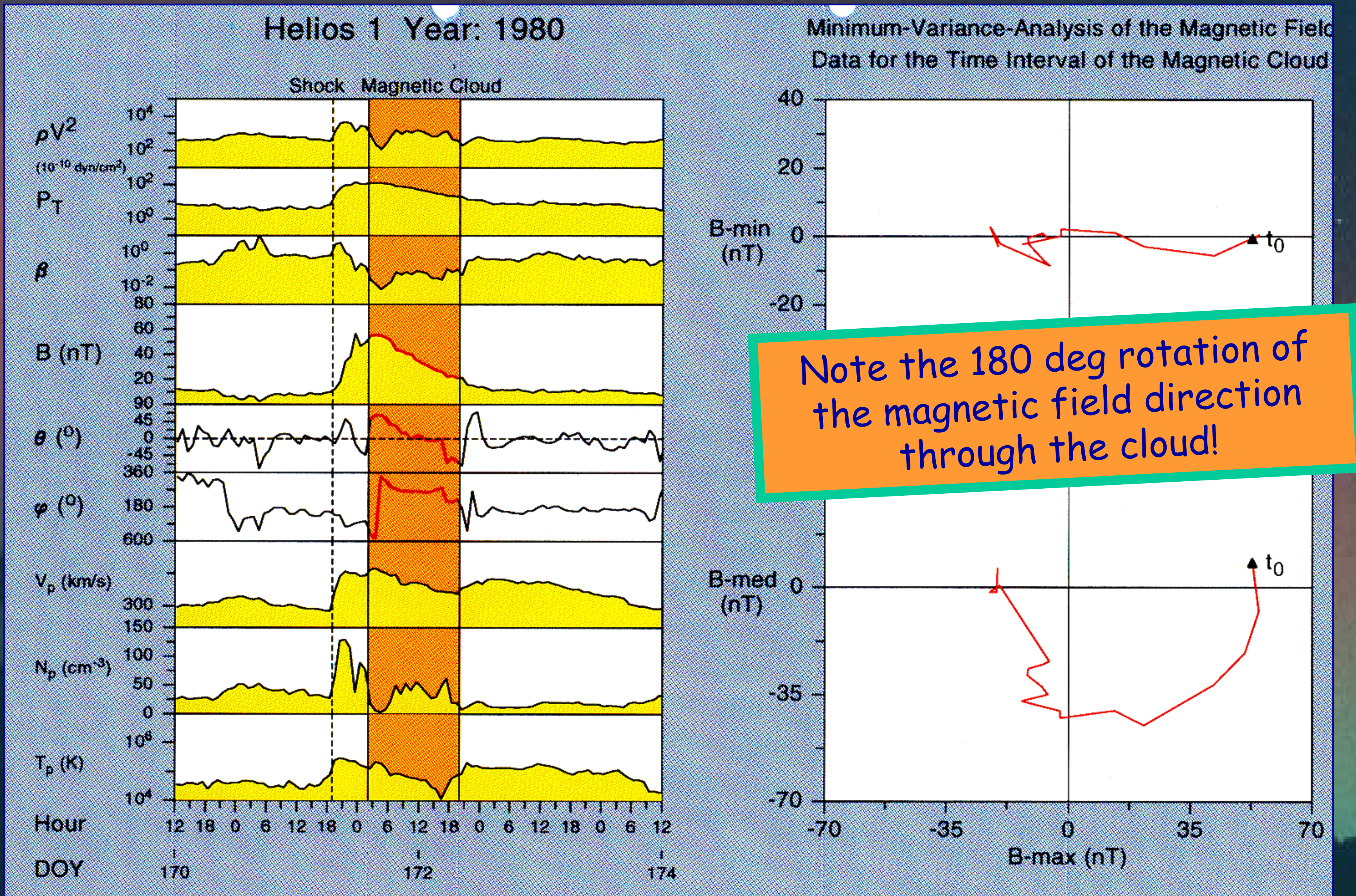
Ejected plasma clouds in space



Sketch showing the possible large-scale geometry of the MC observed by Helios 2 and IMP/ISEE in April 1979 (see Fig. 10) based on results of the MVA of the magnetic field data. Helios 1 did observe the shock, but not the MC. *Arrows* denote the orientation of the magnetic field lines at the cloud's outer boundaries and on its axis

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

Ejected plasma clouds in space

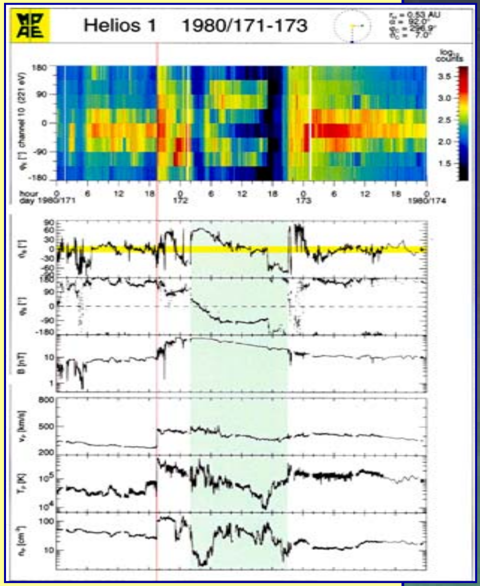


A typical "magnetic cloud", following a fast shock wave

Ejected plasma clouds in space

The signatures of plasma clouds/driver gas with respect to the ambient solar wind:

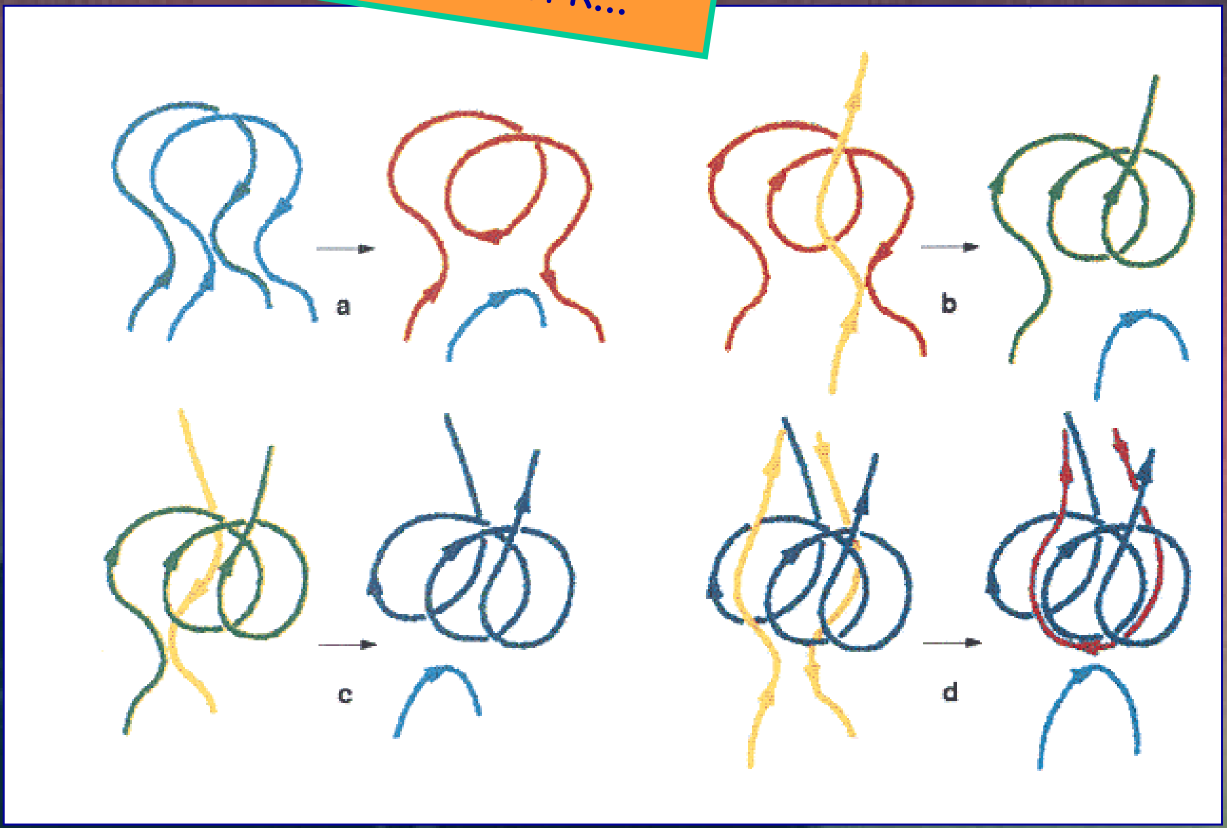
- ion and electron temperature depressions,
- tangential discontinuities in density, temperatures, and field,
- helium abundance enhancements (up to 30 %!),
- unusual ionization states (Fe^{16+}, He^{+}, etc),
- counterstreaming of energetic electrons and protons,
- counterstreaming of suprathermal electrons (BDEs),
- magnetic cloud signatures:
  - anomalous field rotation,
  - strong magnetic field,
  - very low plasma beta,
  - low variance of the magnetic field.



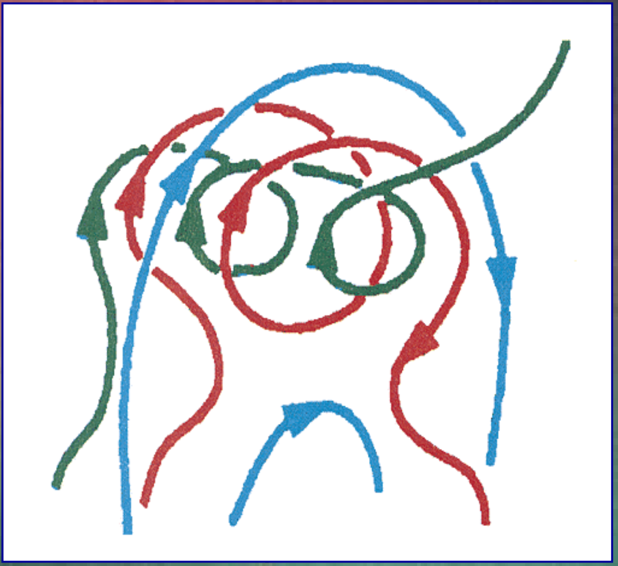
Usually, only a subset of these signatures is observed.

Ejected plasma clouds in space

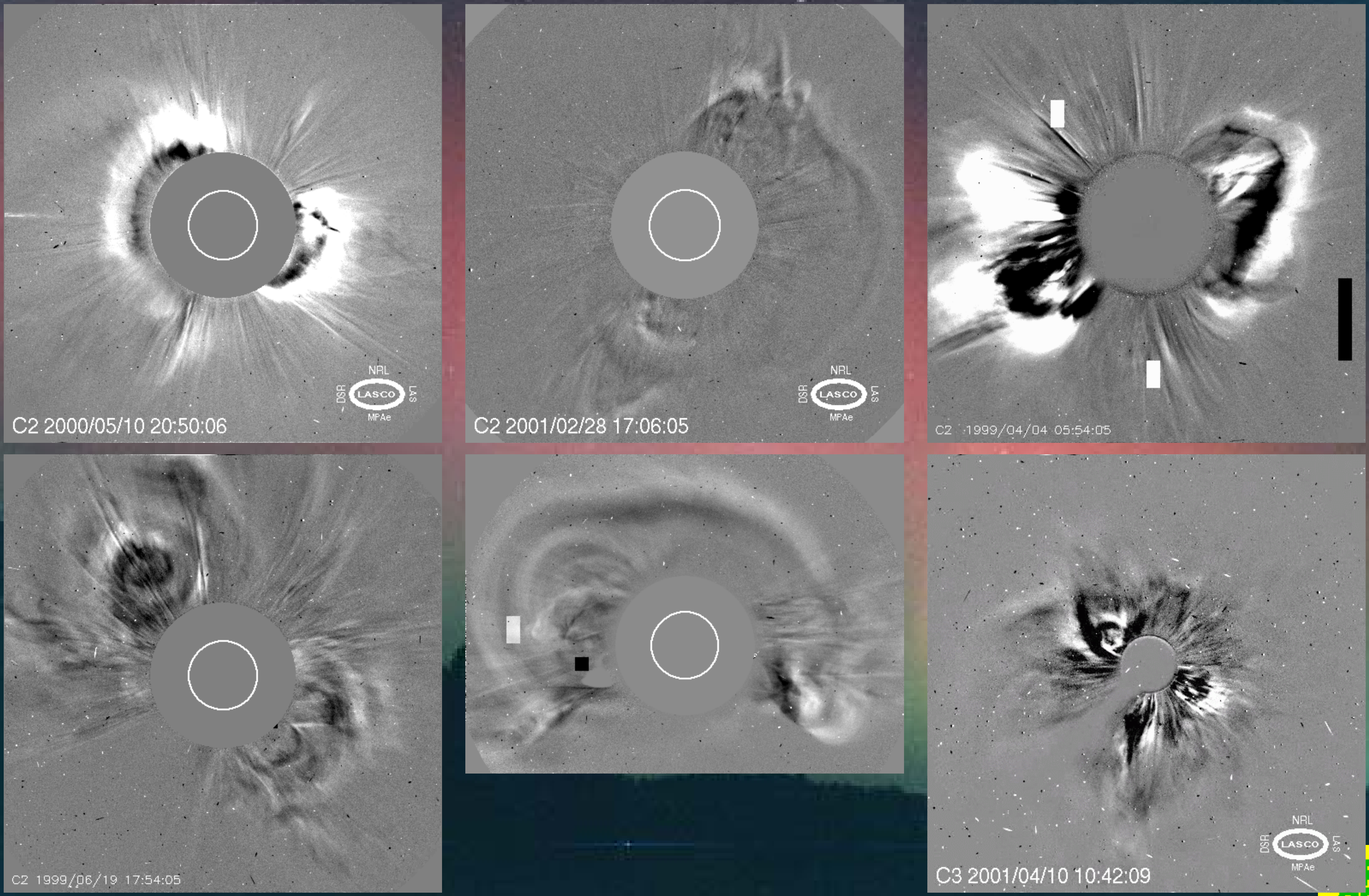
Another artist at work...



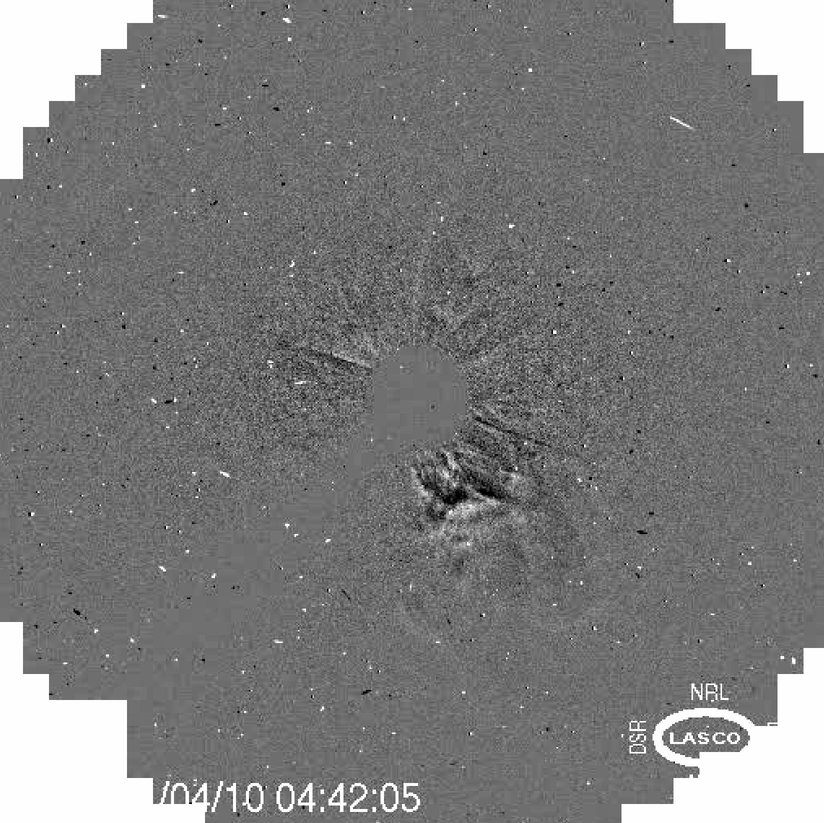
Topologies of 3D reconnection

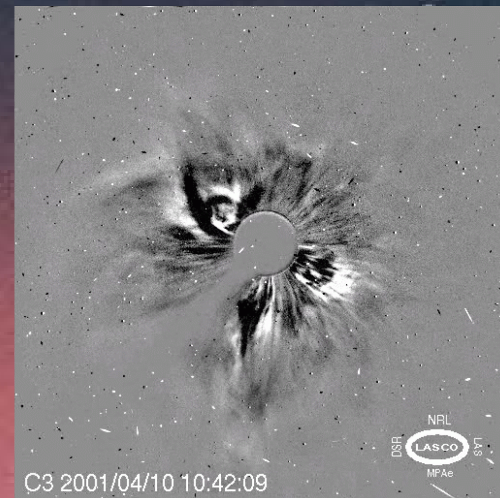


Do global or sympathetic CMEs exist?

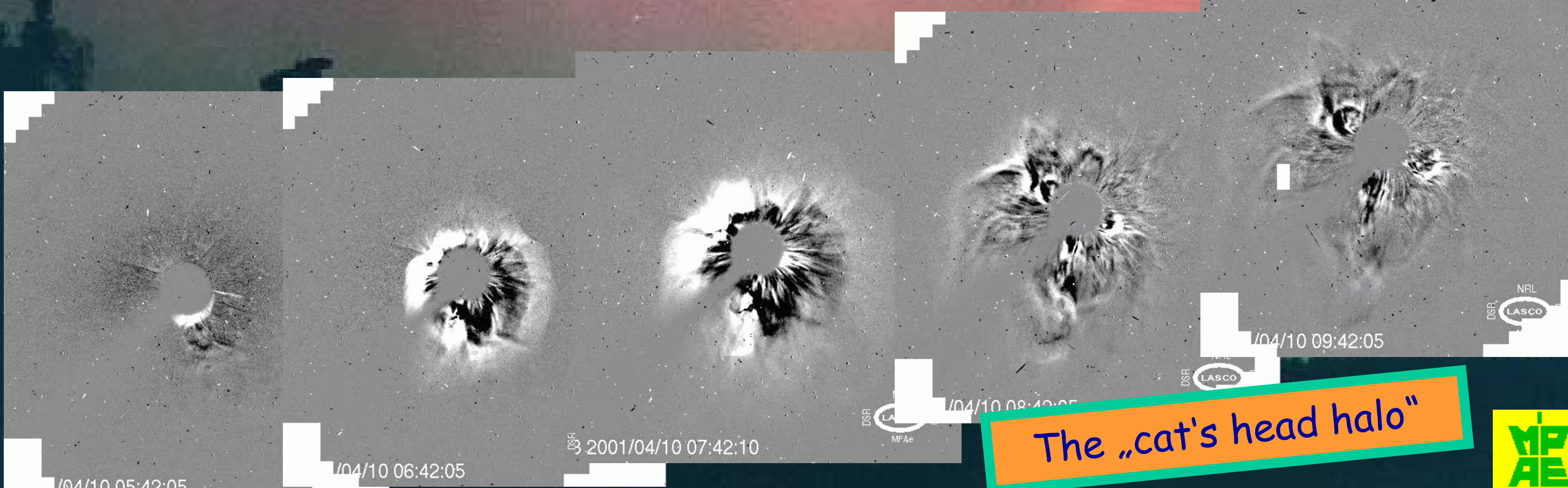


Global or sympathetic CMEs ?



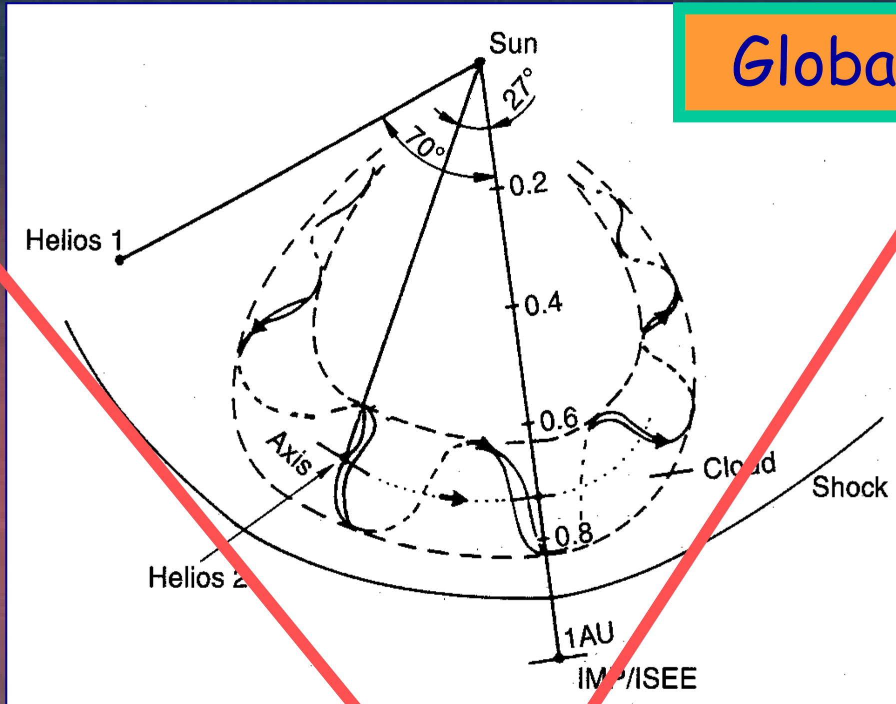


A perfect halo CME with symmetric lobes enclosed

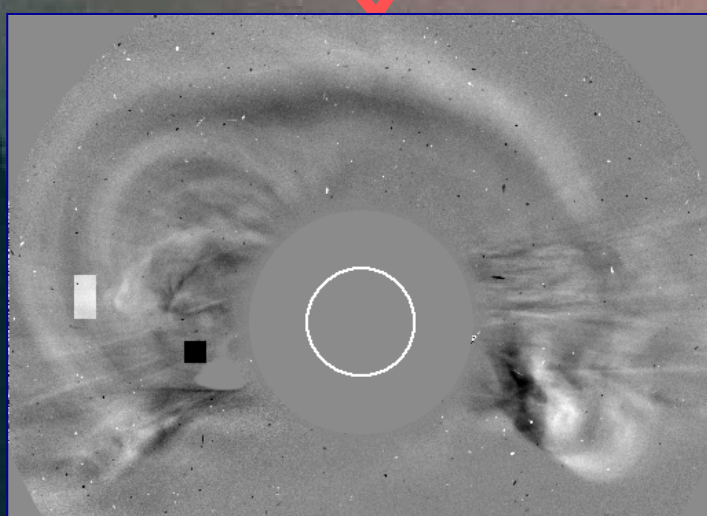


The „cat's head halo"

Global or sympathetic CMEs ?

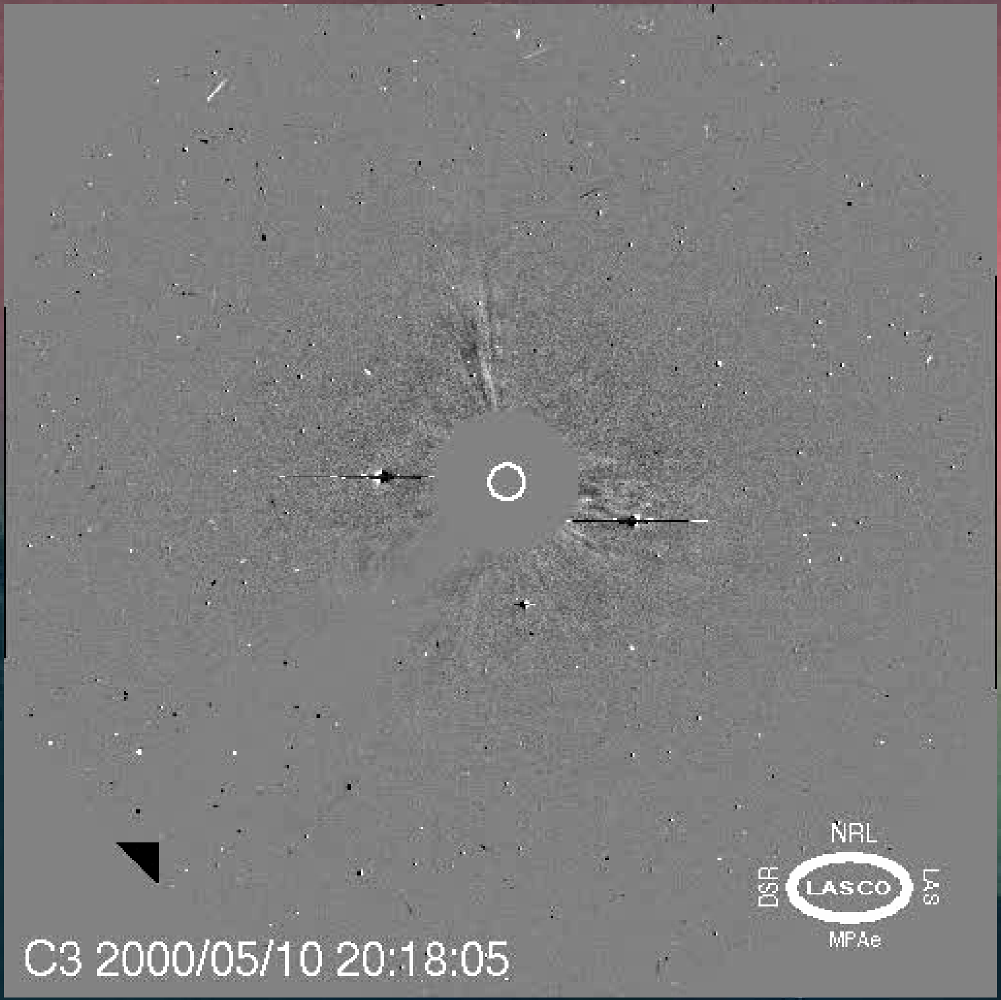


The lobes are due to a projection effect!



An extended flux rope CME seen from the front or the back side.
Note the 2D rope structure and the engulfing 3D halo CME structure.

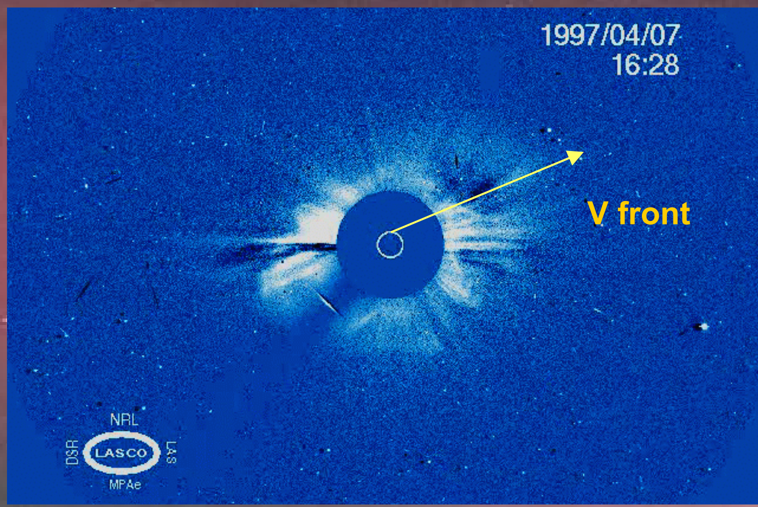
CME mythology: do global CMEs or sympathetic CMEs exist?

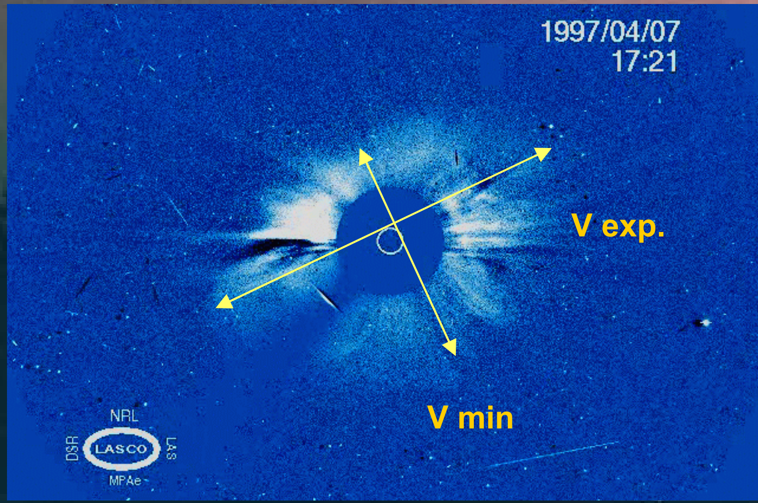


My answer is: No.

They are probably just head-on flux rope halo CMEs.
Let's see what they look like from different perspectives, i.e., SMIE, STEREO, SDO, and Solar Orbiter.

How to predict travel times of halo CMEs?





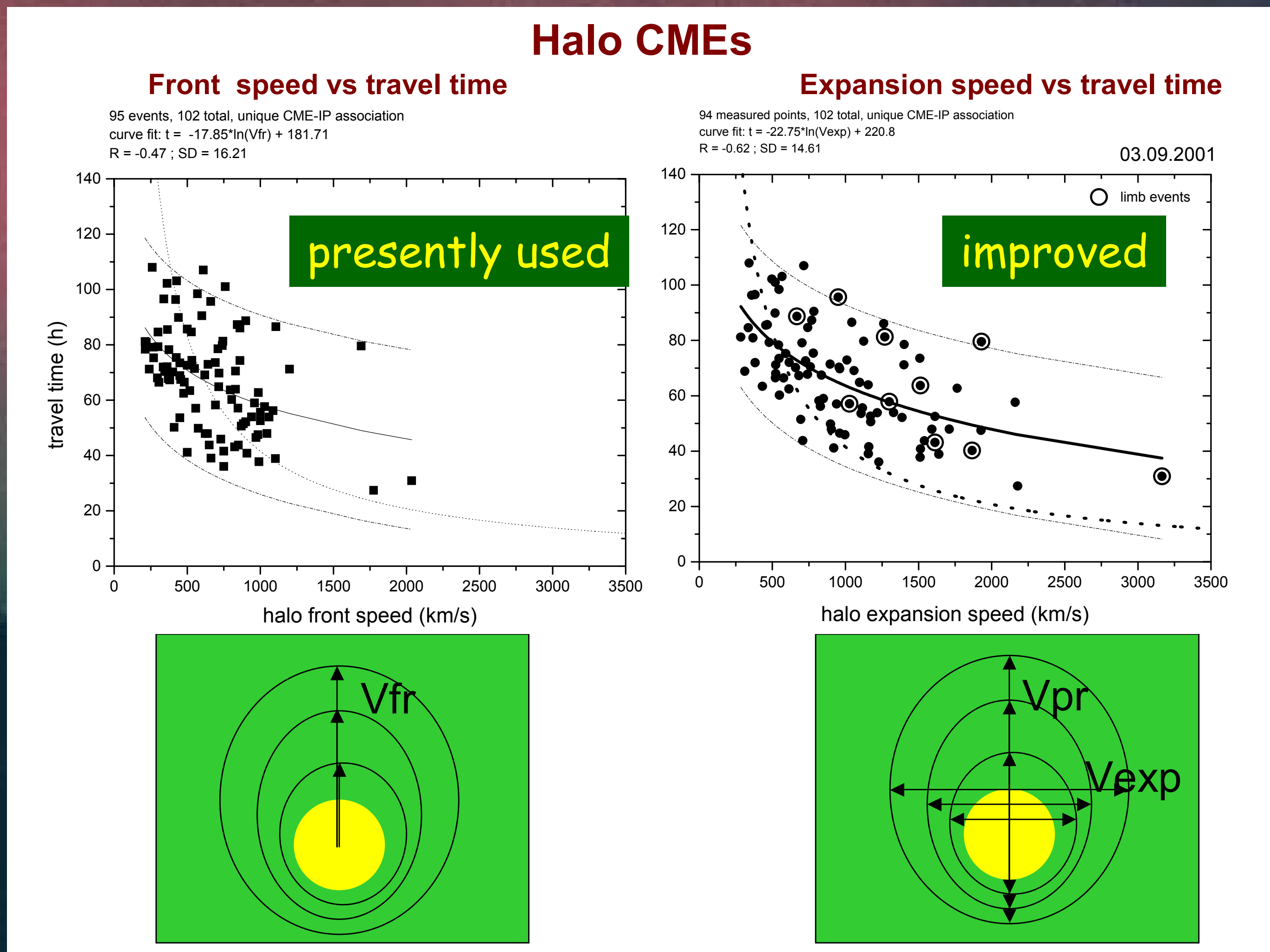
The apparent „front speed" v_{front} depends on the ejection direction.

As a better proxy for the unknown speed component towards Earth, we try to use the „expansion speed" v_{exp} and derive an empirical relation.

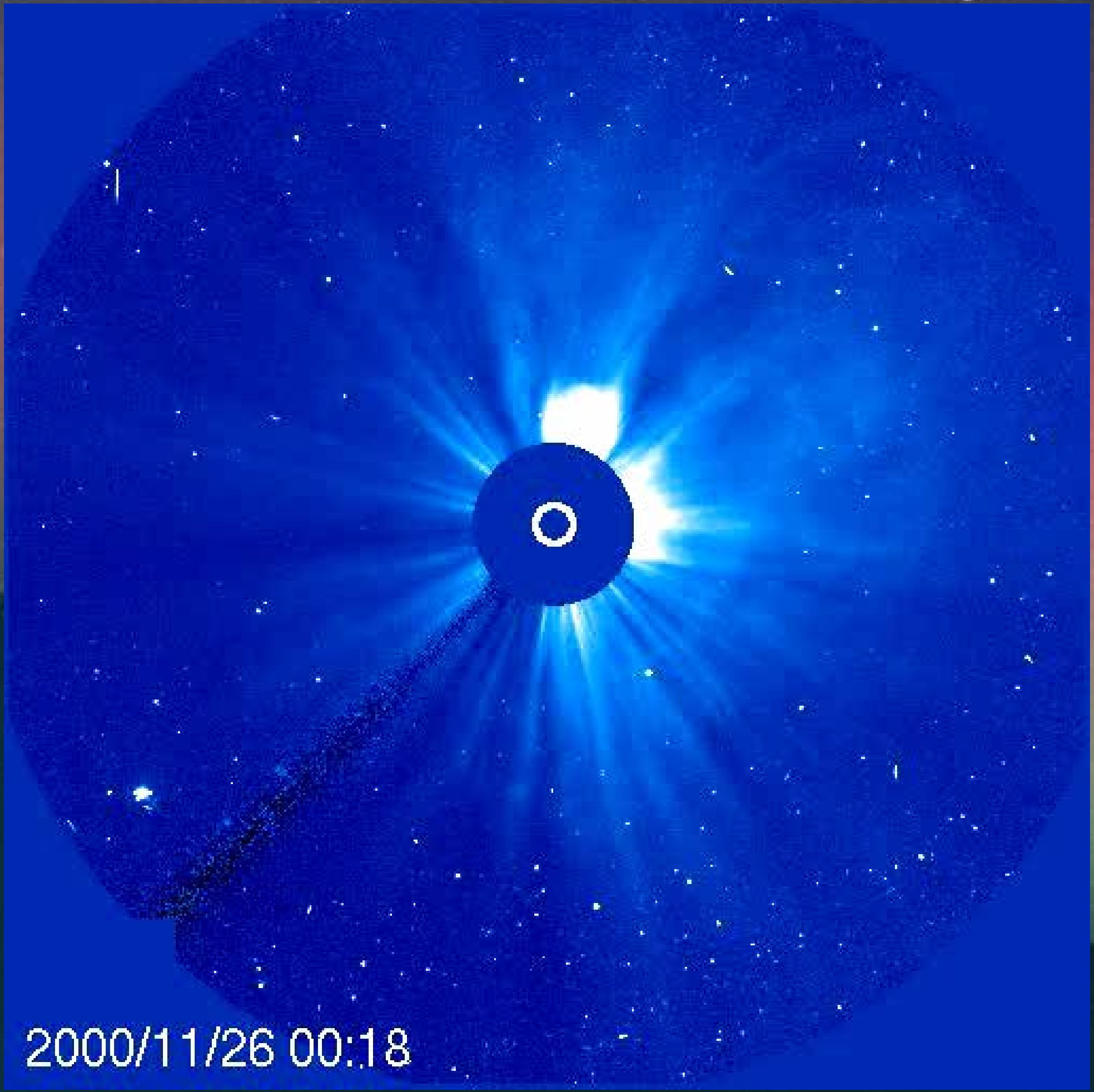
How to predict travel times of halo CMEs?

For 95 cases, the halo expansion speed and the travel times to 1 AU were determined

An empirical function was derived: **an improved prediction tool!**



Close relatives of "global" CMEs: Cannibals!



2 succeeding halo CMEs, "cannibalizing" a limb CME

Gopalswamy, 2000

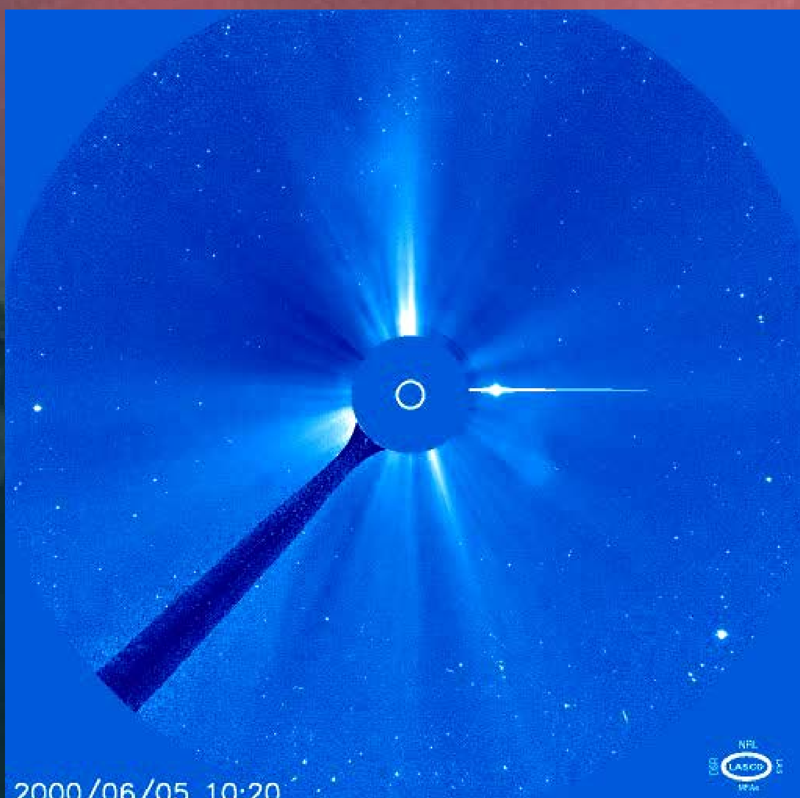
Let's see what they look like from different perspectives, i.e., SMIE, STEREO, SDO, and Solar Orbiter!

Questions to be addressed in the future:

- Where are the shock fronts relative to the CME?
- How does the 3 part CME structure transform into what is encountered *in-situ*?
- Types of CMEs: continuous spectrum or qualitative differences?
- Acceleration/deceleration profiles from Sun to Earth?
- Can proxy data be found for predicting arrival and effects at Earth?
- How to predict CMEs/flares before they occur (time, location, strength, topology)?

The STEREO mission is the next logical step for finding the answers

Coronal mass ejections: observations



First STEREO workshop
Paris
March 18 – 20, 2002

Rainer Schwenn
Max-Planck-Institut für Aeronomie
Lindau, Germany