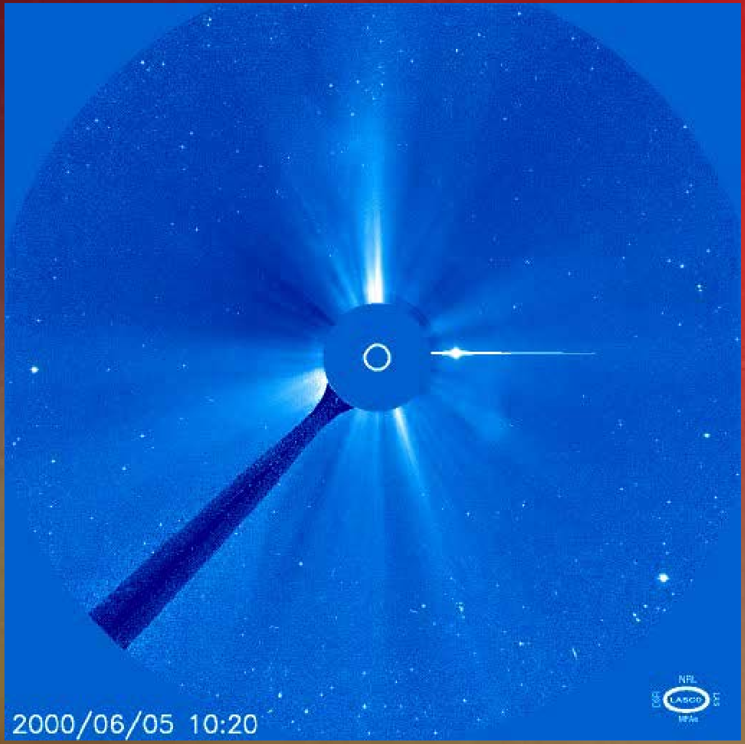
The Solar Origins of Space Weather

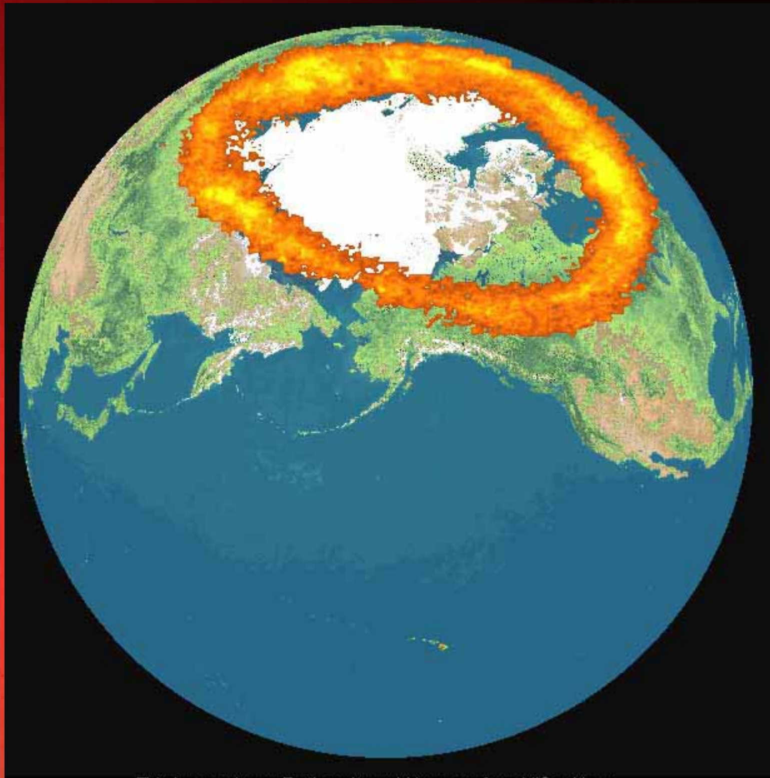
STP-10/CEDAR 2001 Joint Meeting
June 17 to 22, 2001
Longmont, Colorado



Rainer Schwenn
Max-Planck-Institut für Aeronomie
Katlenburg-Lindau

Space Weather!

Northern lights,
Aurora!



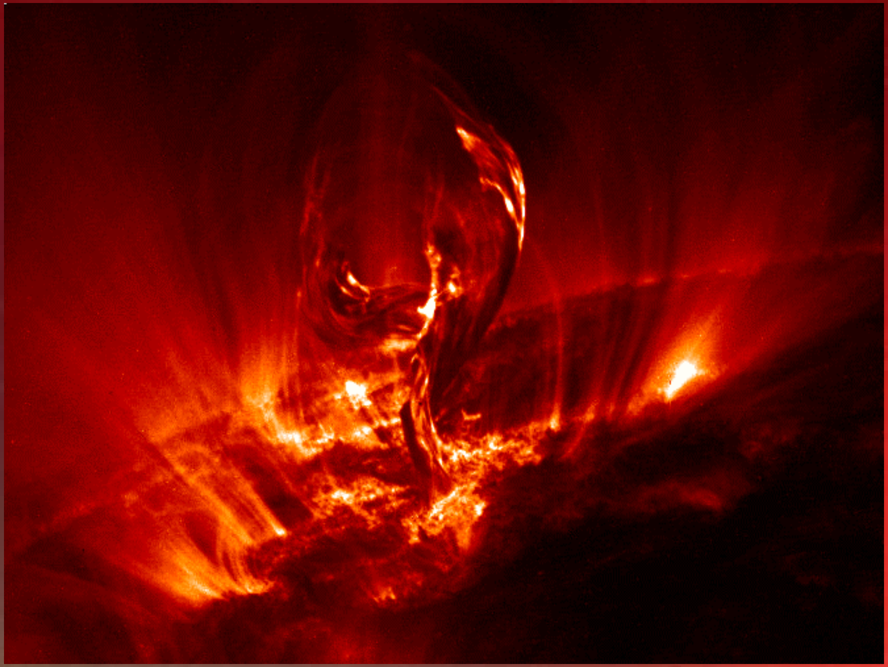
This image shows Earth as it would be seen from VIS, with an image of the northern aurora superimposed on an image of the Earth from March 25, 1996.

PJM Public Service
Step Up Transformer

Severe internal damage caused by the space storm of 13 March, 1989.

Space "storms" may cause severe damage to, e.g., power systems on earth!

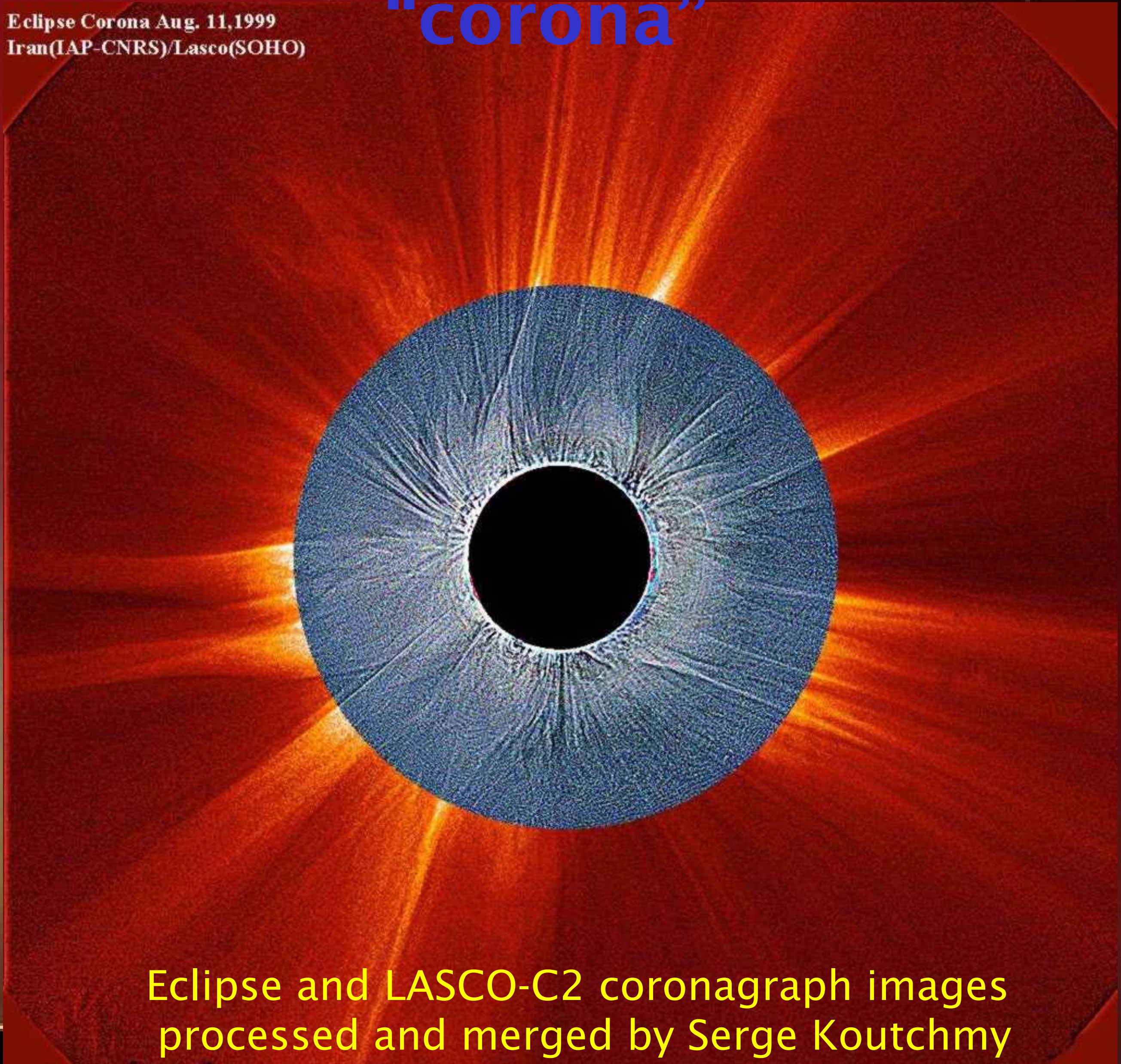
The Sun as the driver of Space Weather



Major geomagnetic storms may cause

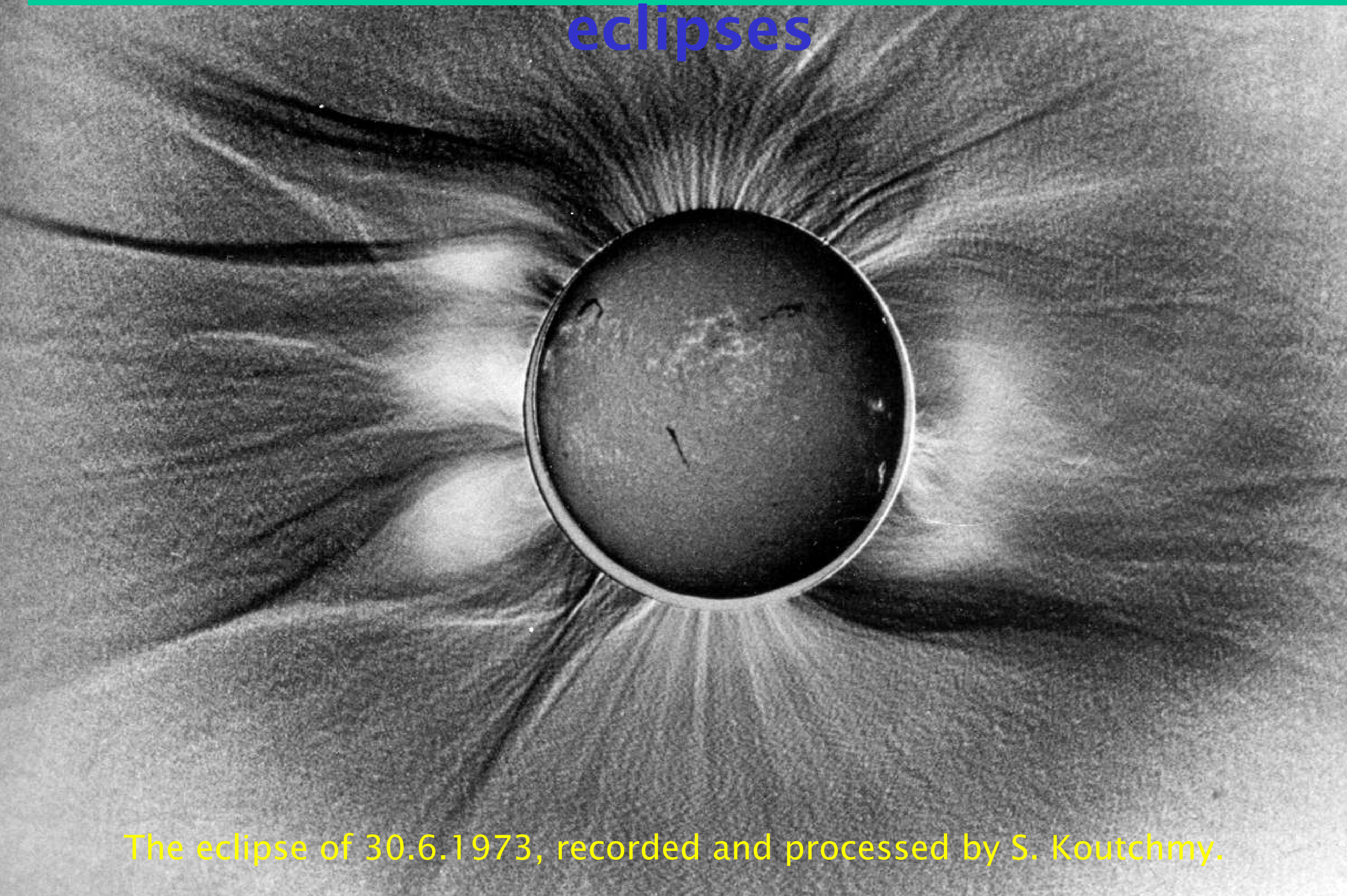
- bright aurorae, down to low latitudes,
- damage to high voltage lines in arctic regions,
- anomalous corrosion of oil pipelines in arctic regions,
- damage to long distance communication cables,
- malfunction of magnetic compasses,
- damage to satellites and satellite systems,
- effects on biological systems.

The Sun’s huge atmosphere, the “corona”



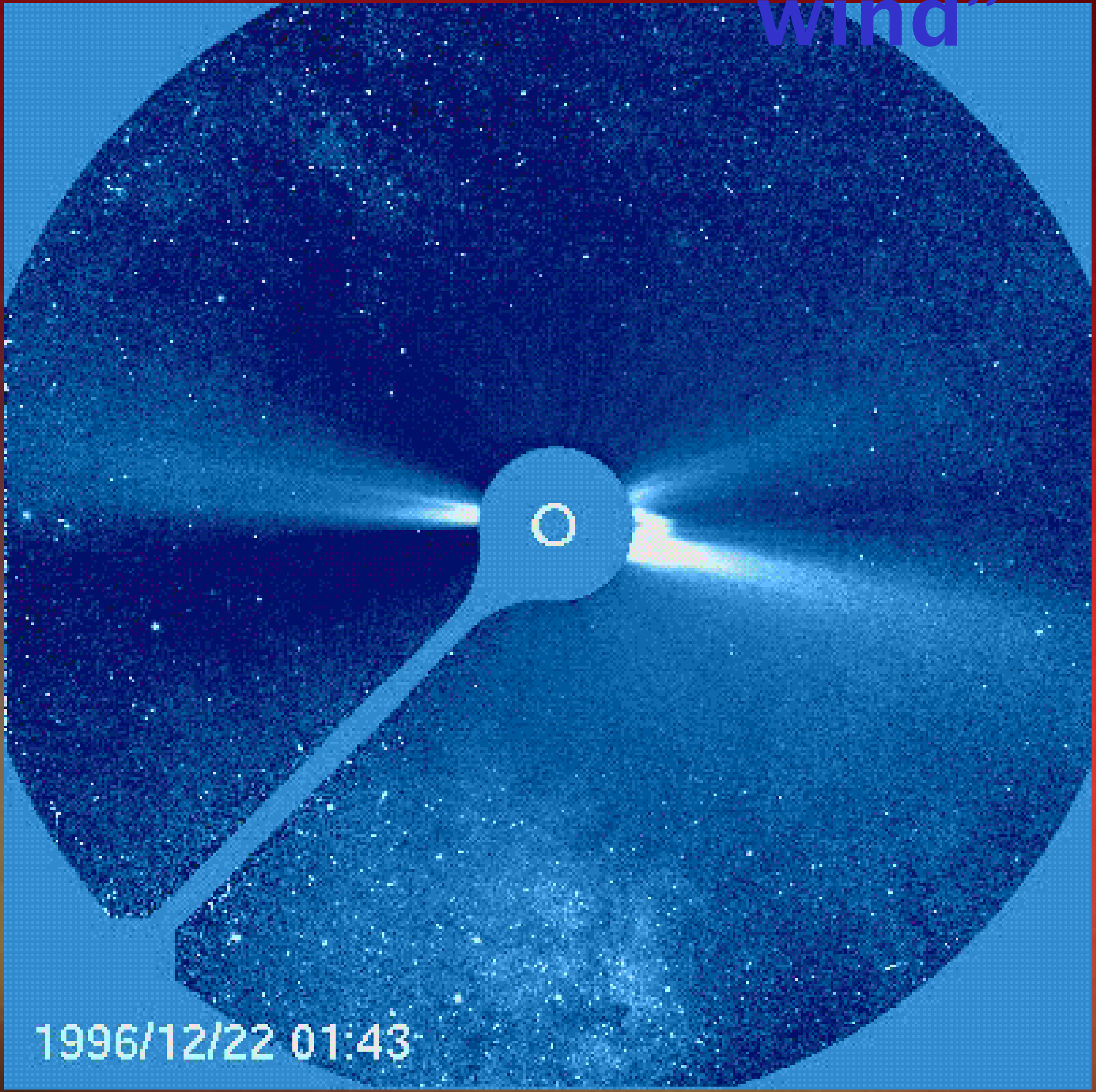
Eclipse and LASCO-C2 coronagraph images processed and merged by Serge Koutchmy

The Sun’s corona, well-known from eclipses



The eclipse of 30.6.1973, recorded and processed by S. Koutchmy.

The corona evaporates the “solar wind”



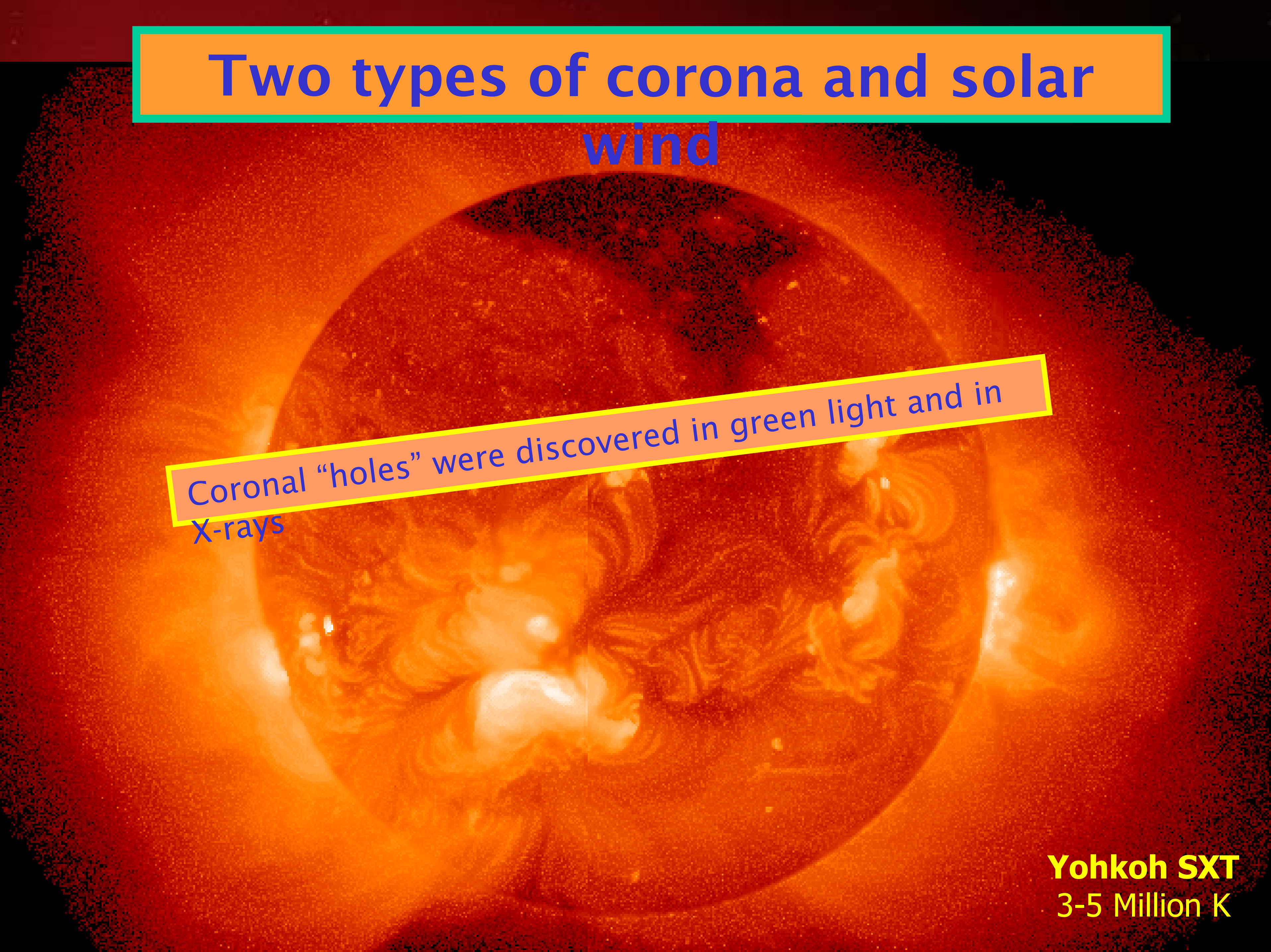
Never seen before: the „smoke clouds“ near the equatorial plane are due to inhomogeneities in the solar wind, which thus becomes visible

Note further:

- The moving star field,
- Our milky way which the sun traverses righ at Christmas,
- A little comet plunging into the sun and evaporating

Christmas 1996: **LASCO-C3** shows the sun (though occulted) as a star amongst others in its own galaxy, the milky way!

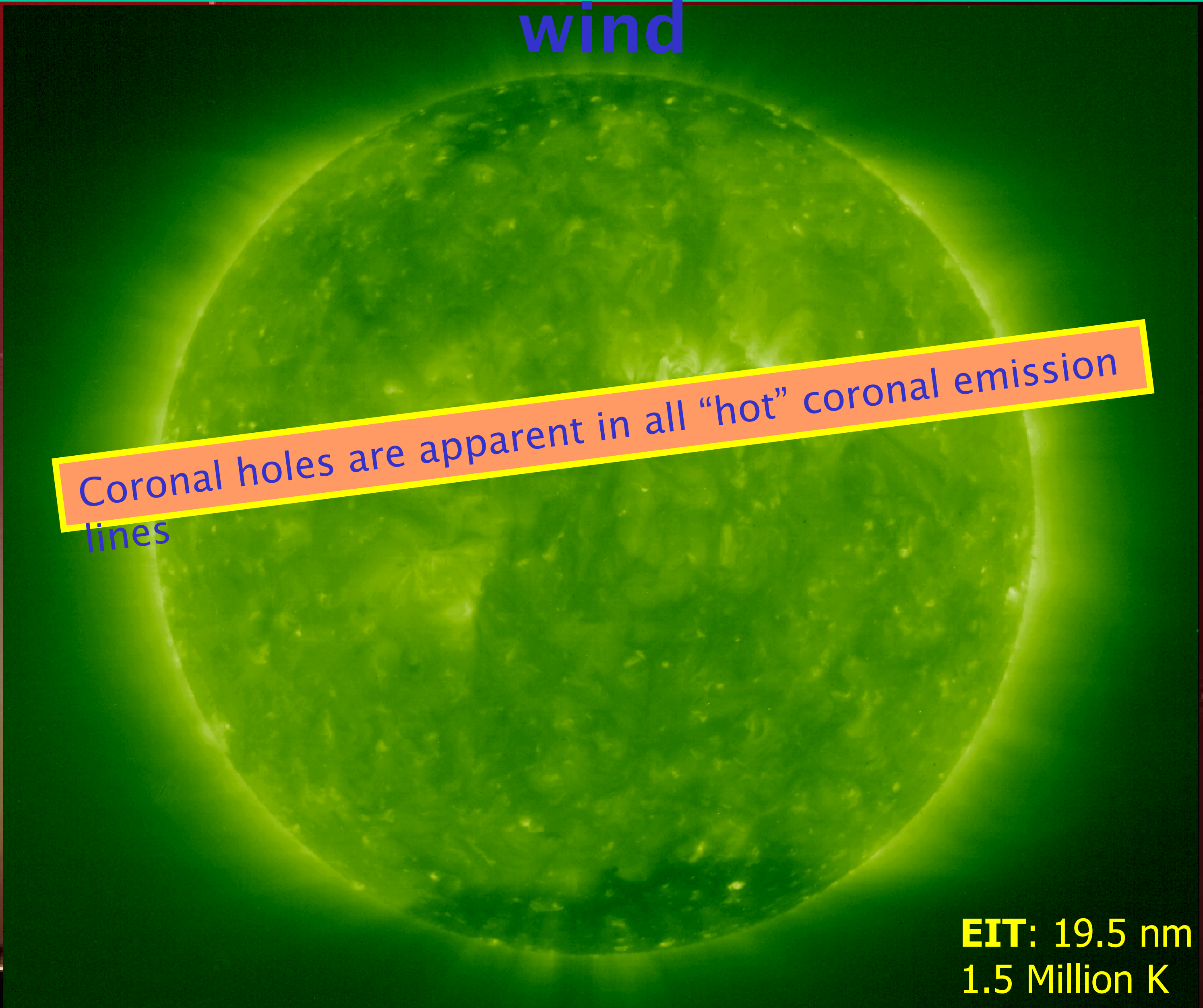
Two types of corona and solar wind



Coronal “holes” were discovered in green light and in X-rays

Yohkoh SXT
3-5 Million K

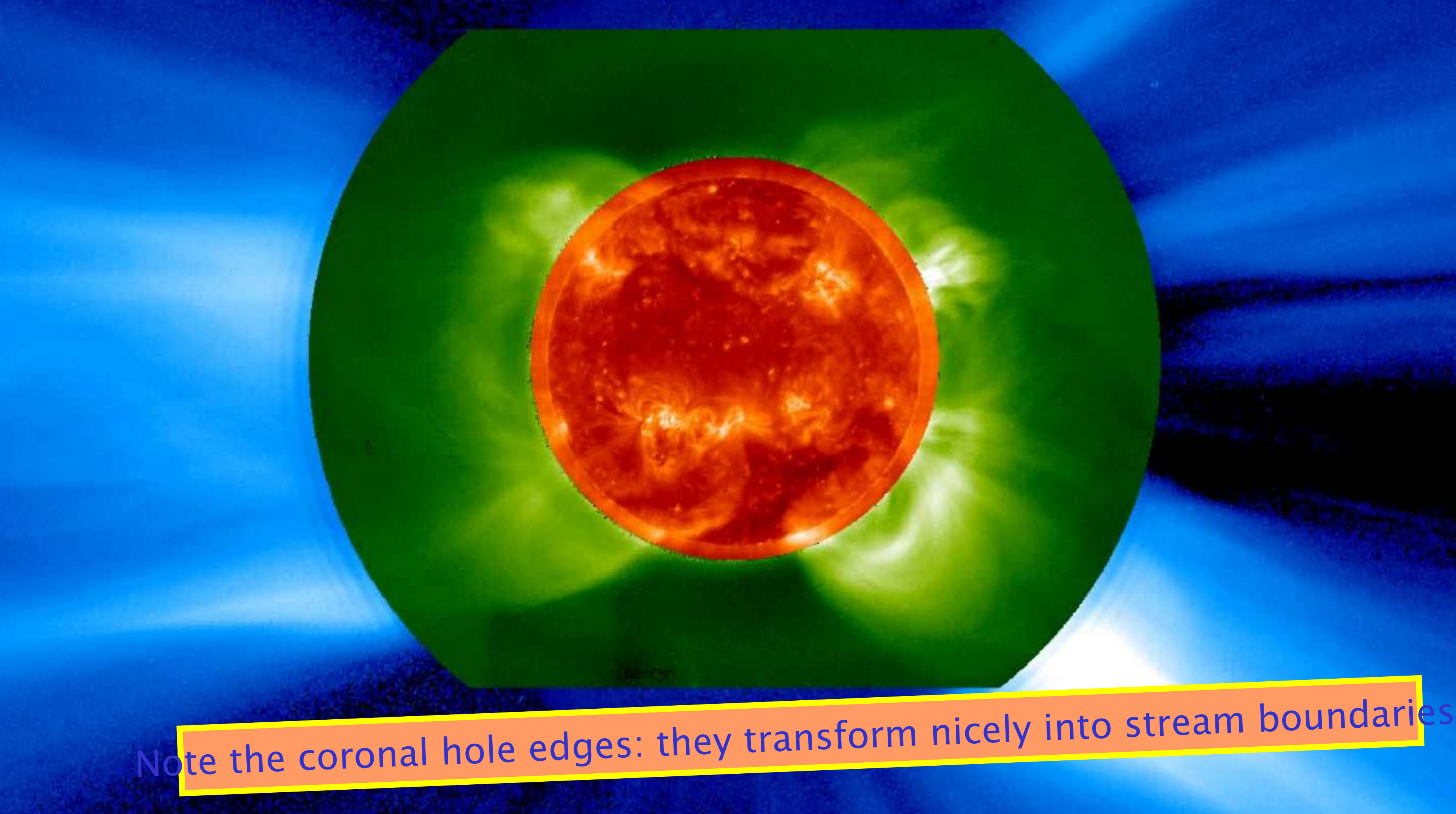
Two types of corona and solar wind



Coronal holes are apparent in all “hot” coronal emission lines

EIT: 19.5 nm
1.5 Million K

The two states of corona and solar wind

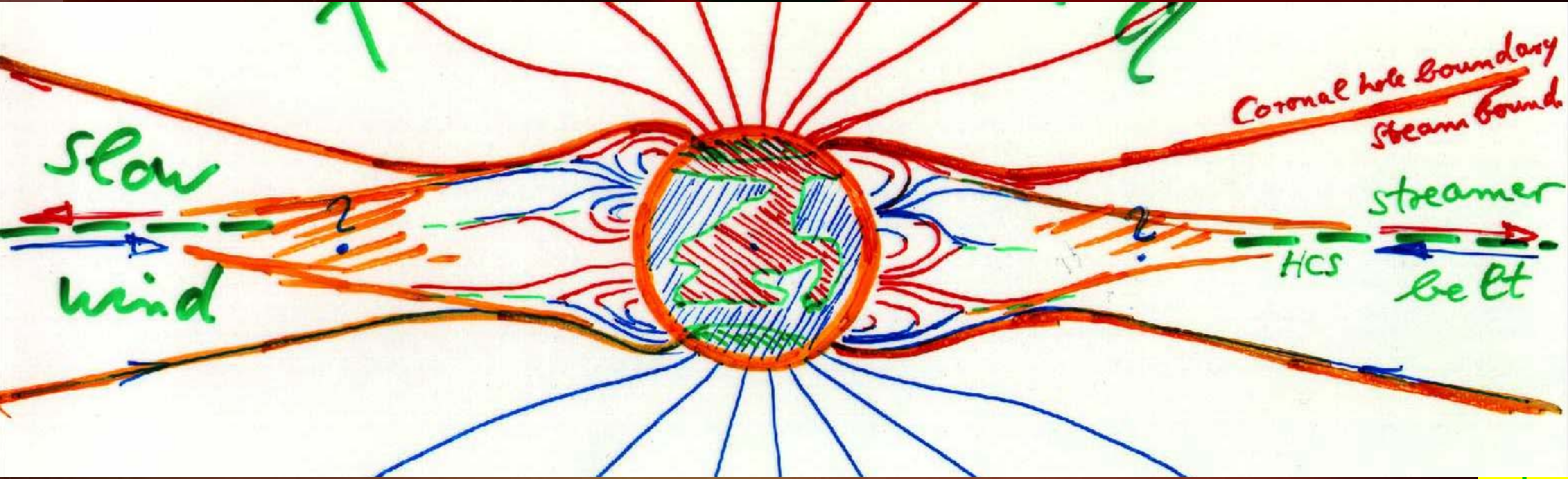


Note the coronal hole edges: they transform nicely into stream boundaries

The corona of the active sun (1998), viewed by **EIT** and **LASCO-C1/C2**

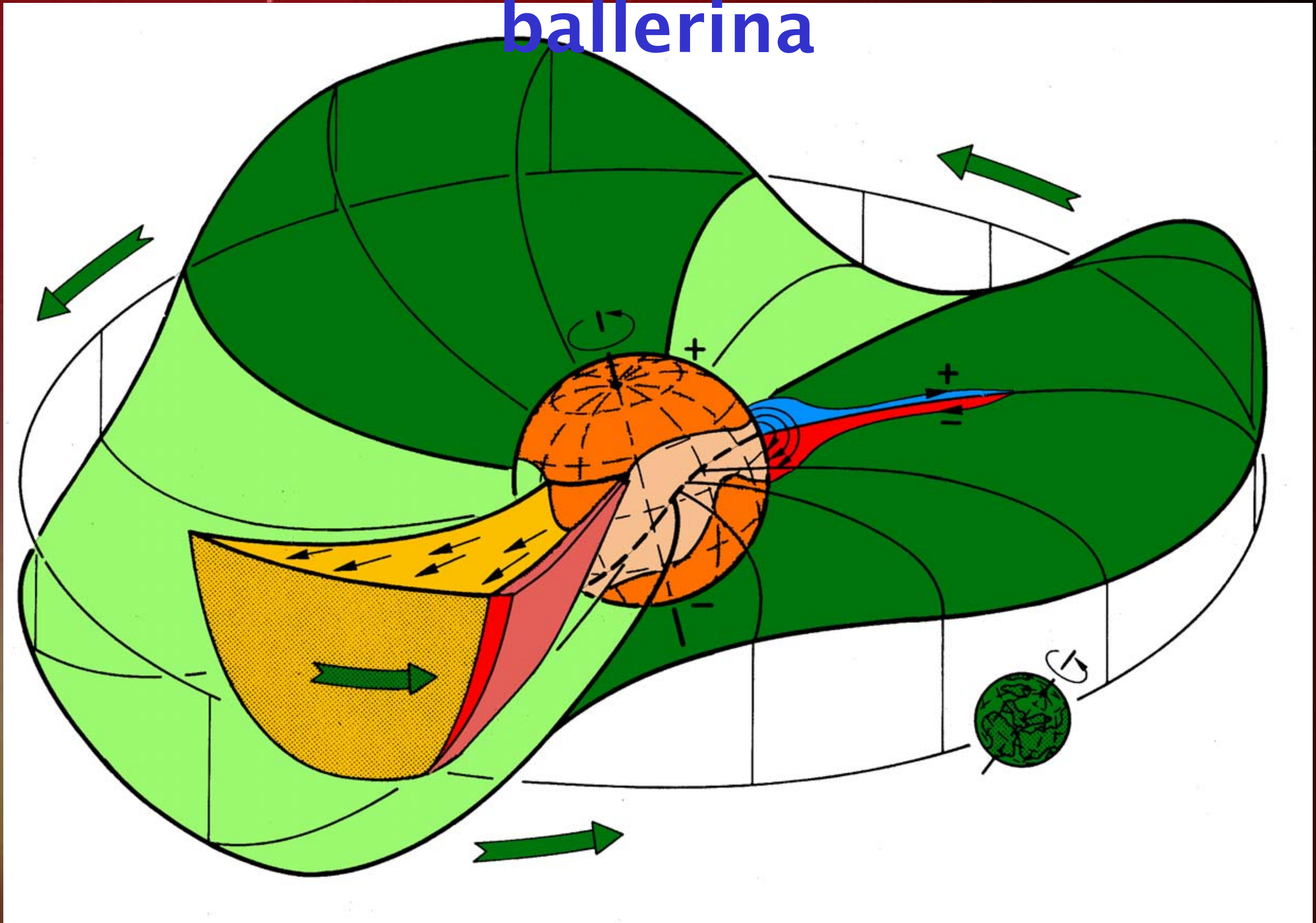
The "quiet" Sun and its minimum corona

LASCO C1/C2, on 1.2. 1996



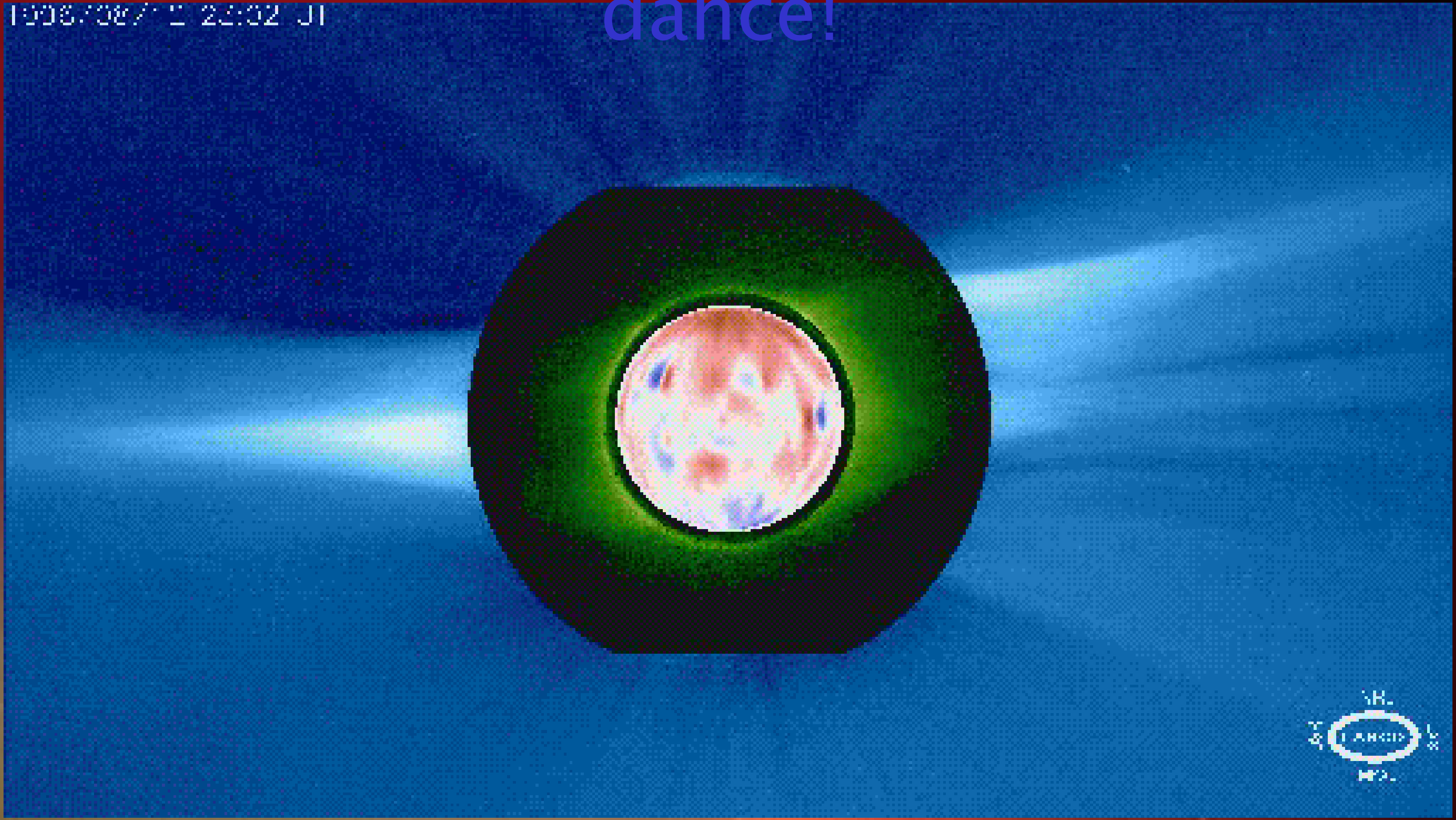
A model of the corona at activity minimum in early 1996 and its topology

The Sun is a spinning ballerina



The "ballerina" model, according to *Alfvén, 1977*.

See the ballerina Sun dance!



The sun and its corona at solar activity minimum
during the Whole Sun Month (WSM) in 1996,
seen by the **LASCO C1/C2** coronagraphs on **SOHO**
and the **WSO** magnetograph

The two types of solar wind

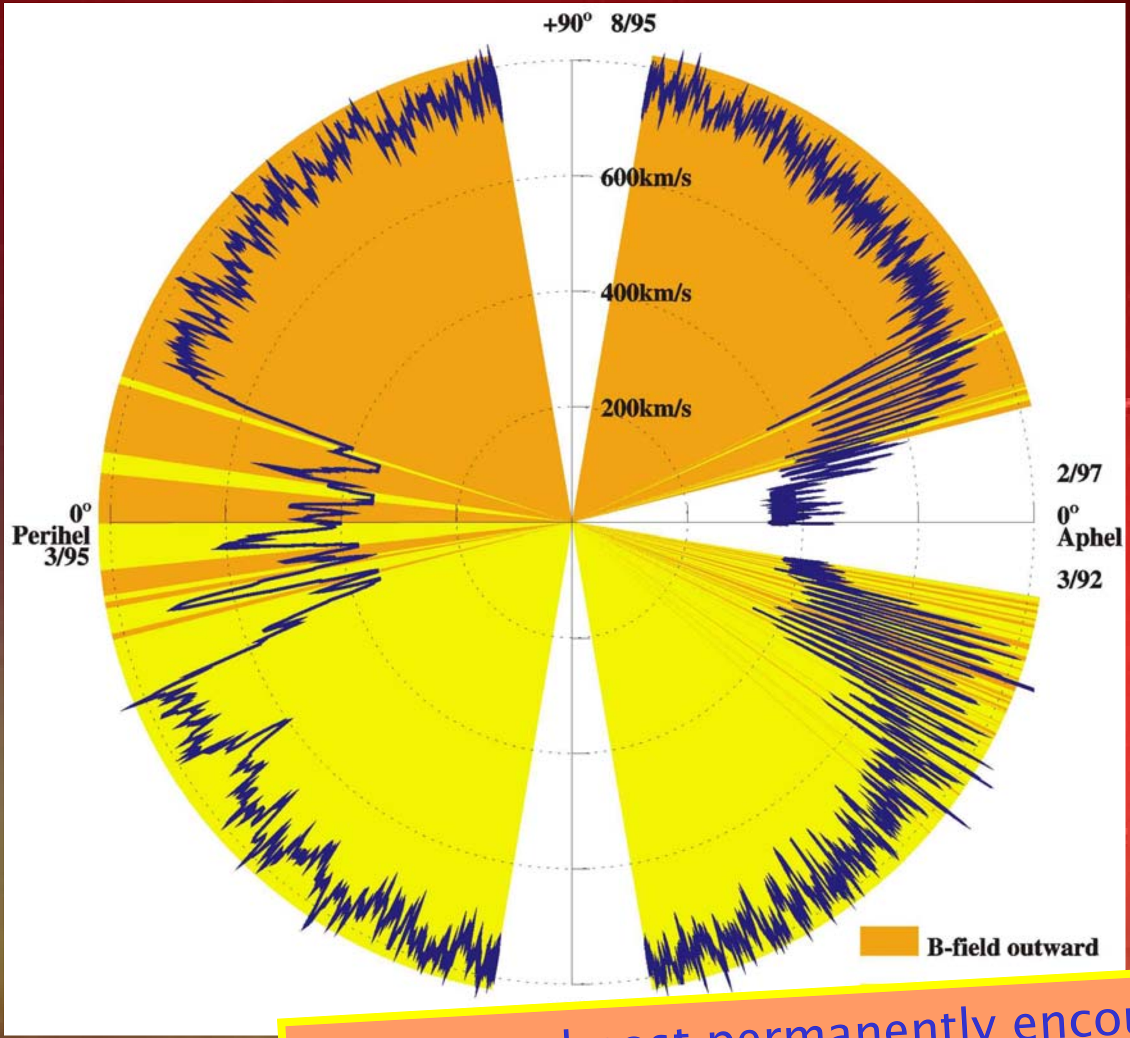
1.Fast wind in high speed streams

High speed	400-800 kms^{-1}
Low density	3 cm^{-3}
Low particle flux	2×10^{8} cm^{-2} s^{-1}
Helium content	3.6%, stationary
Source	coronal holes
Signatures	stationary for long times (weeks!), all streams are alike.

2.Low speed wind of "interstream" type

Low speed	250-400 kms^{-1}
High density	10.7 cm^{-3}
High particle flux	3.7×10^{8} cm^{-2} s^{-1}
Helium content	below 2%, highly variable
Source	helmet streamers near current sheet, at activity minimum
Signatures	generally very variable, sector boundaries imbedded.

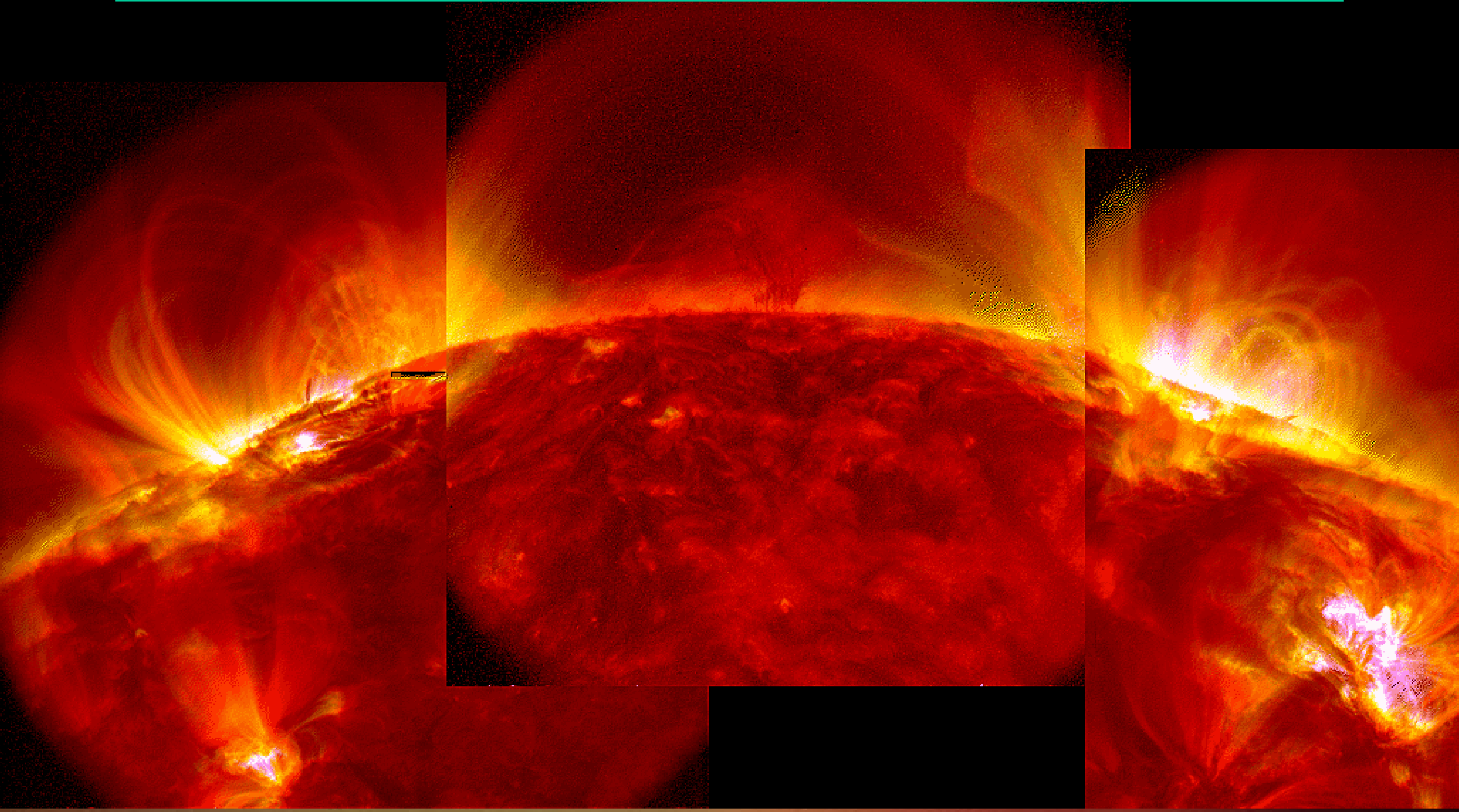
The Sun as the driver of Space Weather



Ulysses observations of solar wind speed and magnetic sector structure, observed during a full execliptic orbit around solar activity minimum.

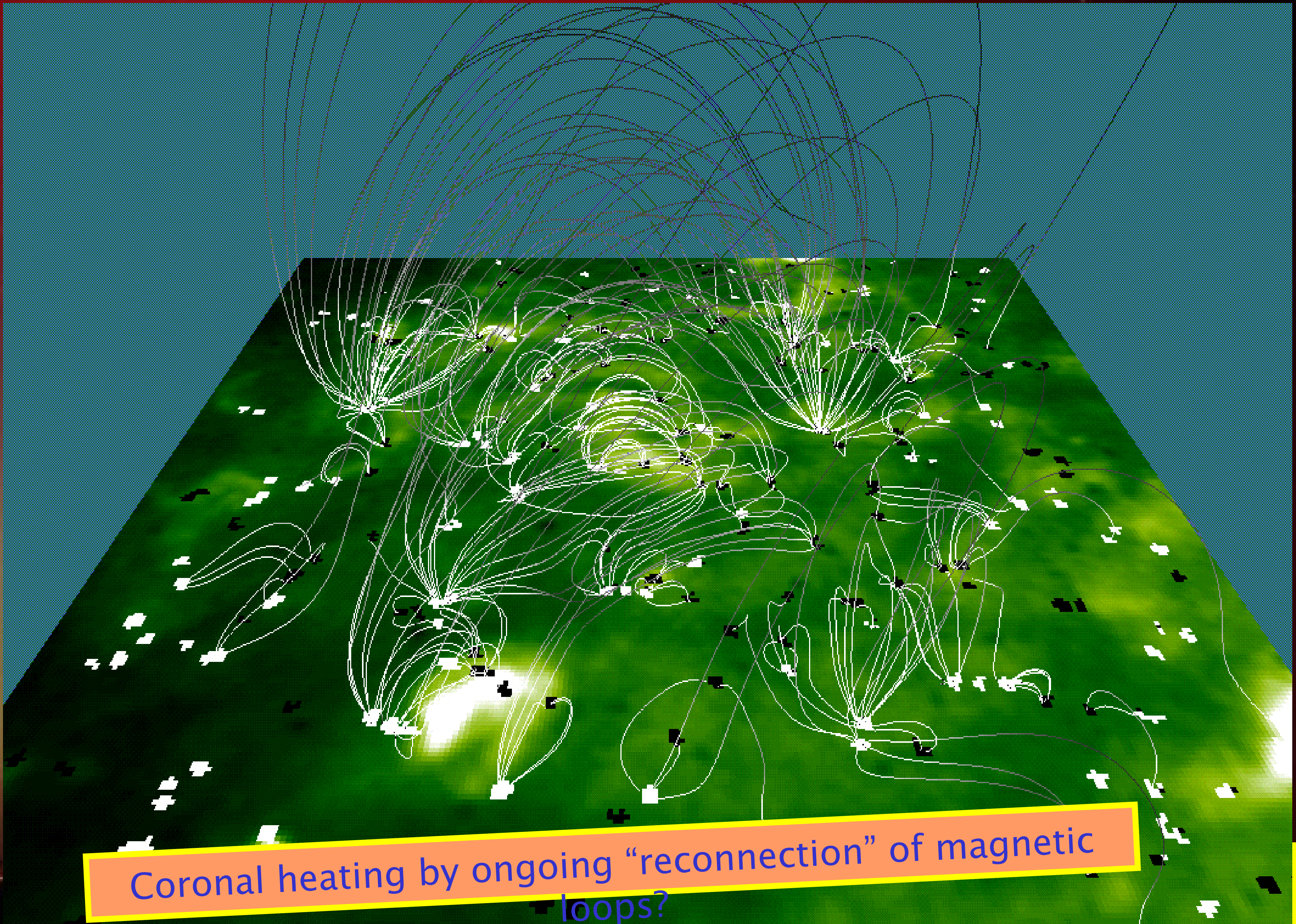
Ulysses was almost permanently encountering fast solar wind, except from a narrow, near-equatorial belt of slow solar wind, thus confirming earlier measurements (e.g., from IPS, Helios).

The corona as a “magnetic carpet”



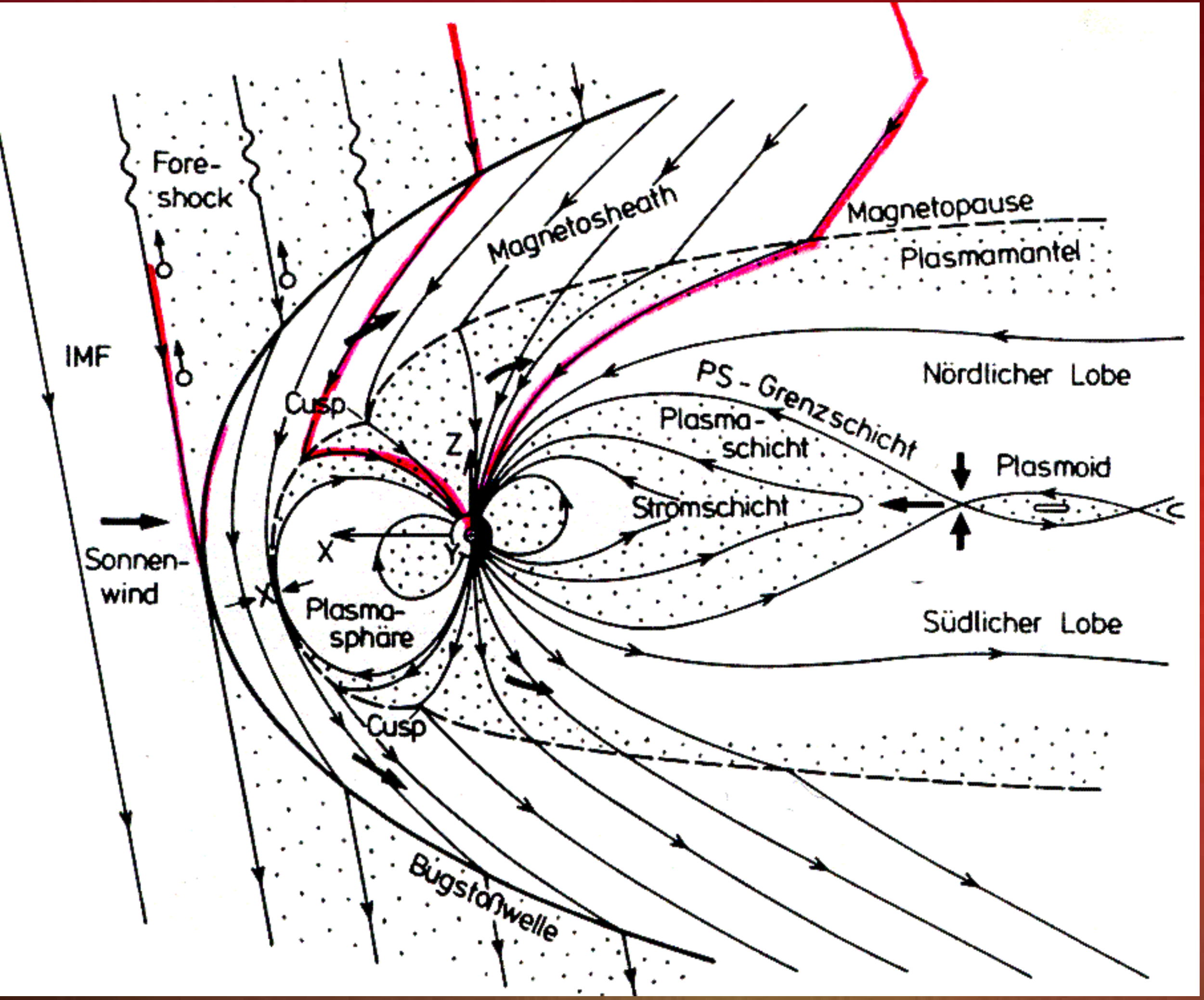
TRACE makes us wonder: how fine are the magnetic structures? In other words: what are the relevant scales of the basic physical processes?

The corona as a "magnetic carpet"



Coronal heating by ongoing "reconnection" of magnetic loops?

What makes geospace vulnerable? B_z south!

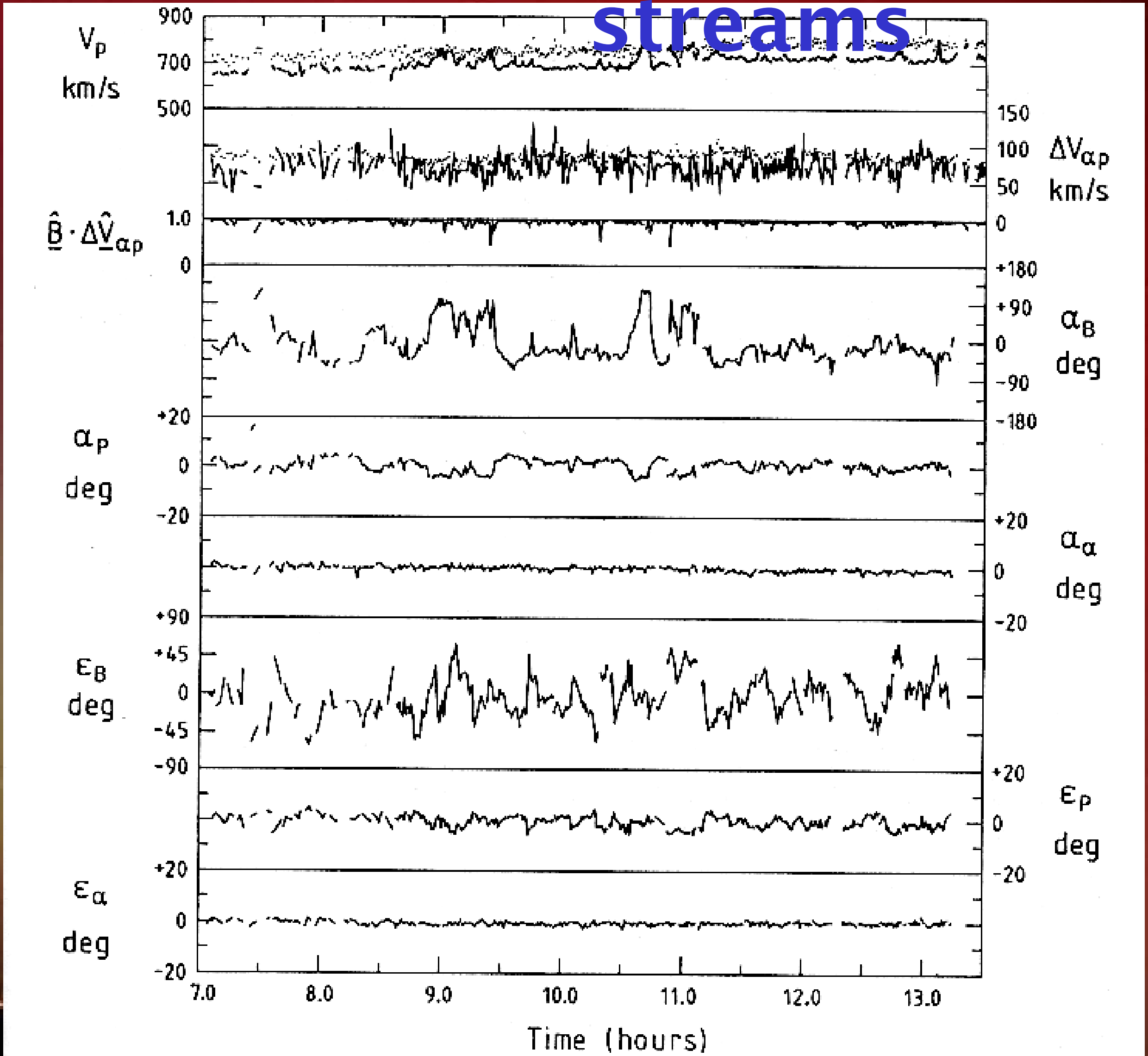


Magnetic reconnection at the frontside of the magnetosphere occurs, when the interplanetary B_z turns south, i.e. antiparallel to the Earth’s intrinsic field.

Charged particles can now penetrate from outer space way down into the polar ionosphere.

How to obtain B_z south?

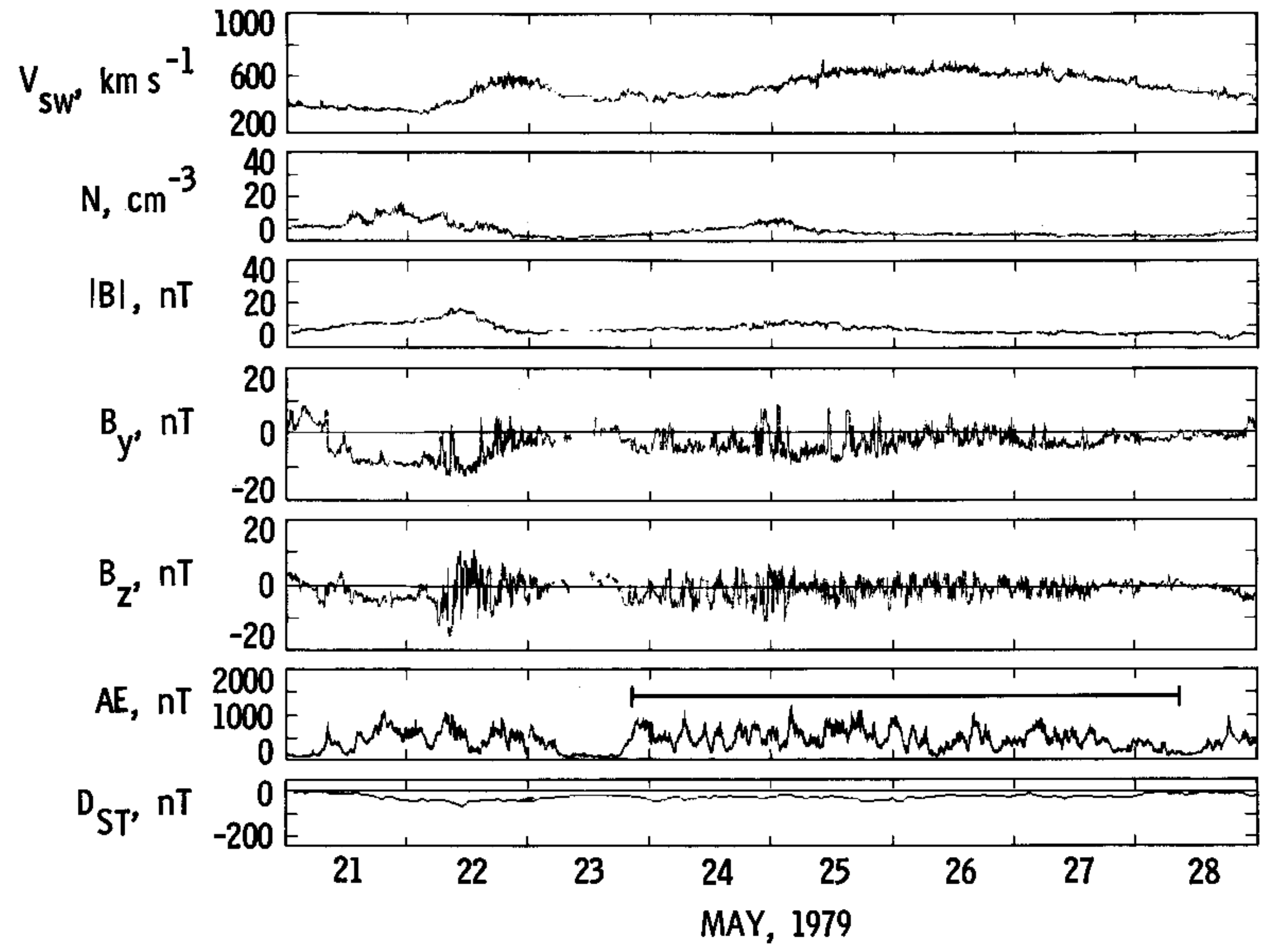
1. By Alfvén waves in high speed streams



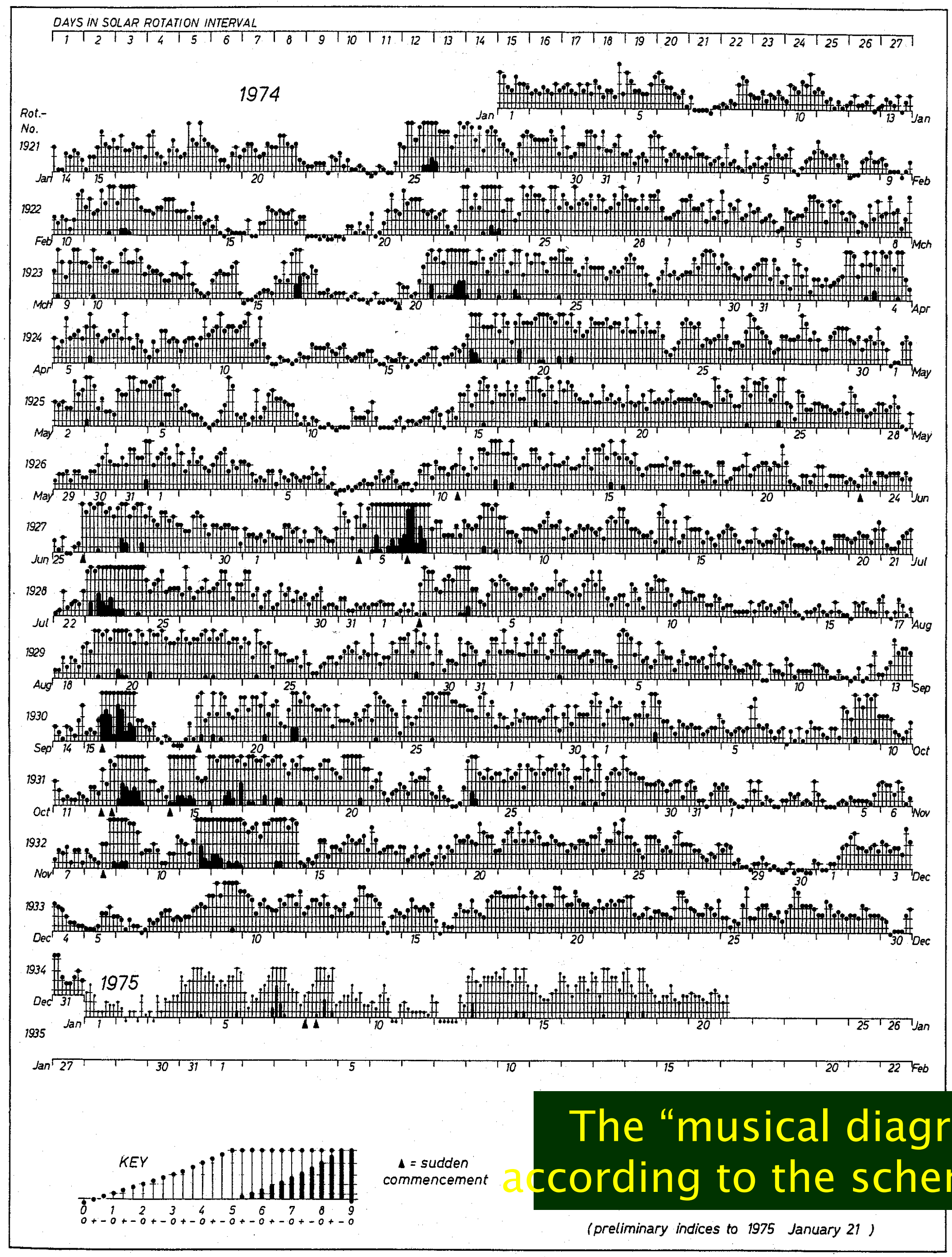
Alfvén waves cause substantial deflections in both: flow direction and magnetic field.

That is the origin of north-south field excursions in high speed wind streams

High speed streams – M-regions!



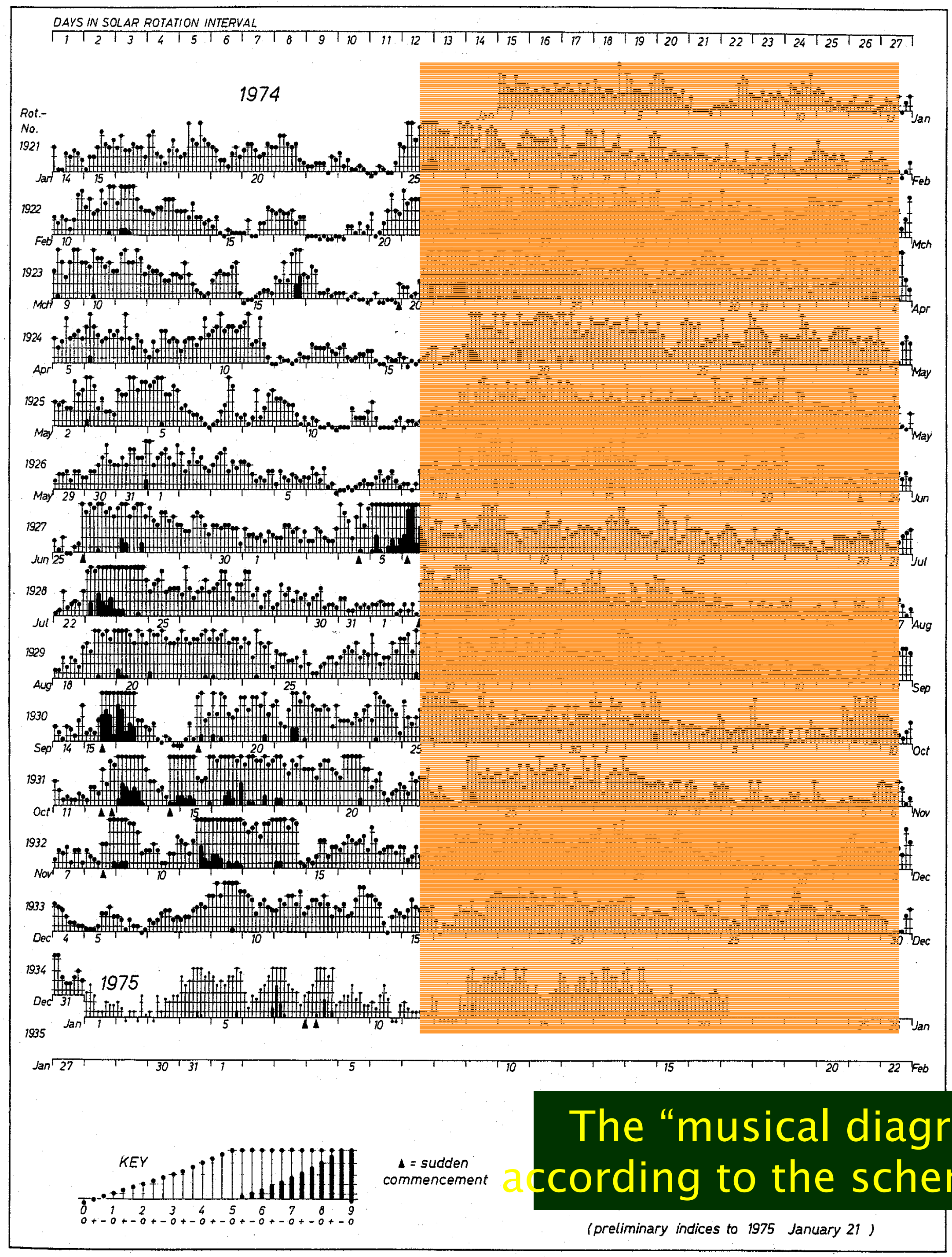
Alfvén waves occur usually in high speed streams. Their magnetic excursions include B_z-components which cause mild geomagnetic effects. That's the answer: the high speed streams are the "M-regions"!



Often ignored: High speed streams from coronal holes (i.e. the inactive” sun) also cause (moderate) activity:

They are the “M-regions”!

The “musical diagram” of geomagnetic activity, according to the scheme introduced by Bartels (1930



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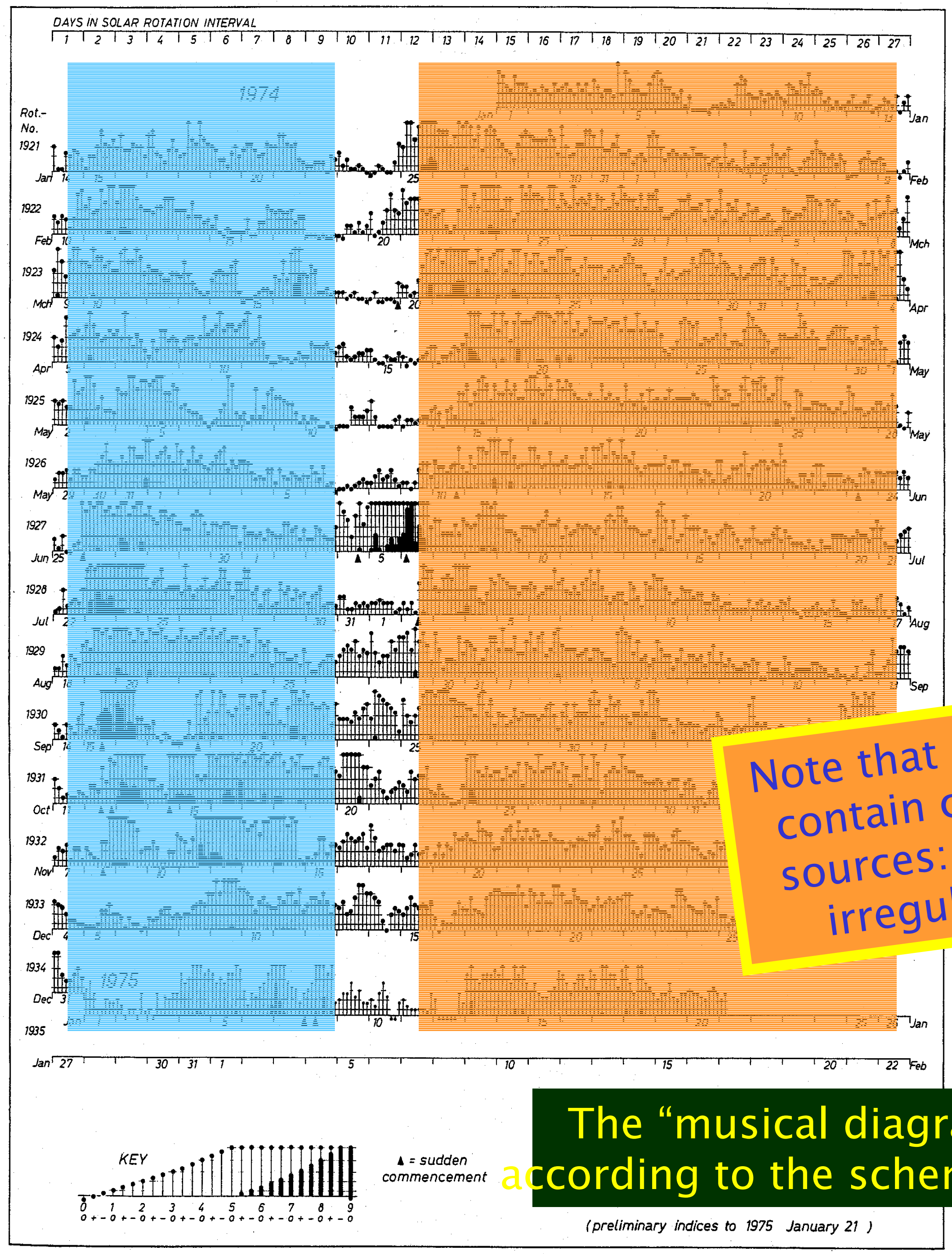
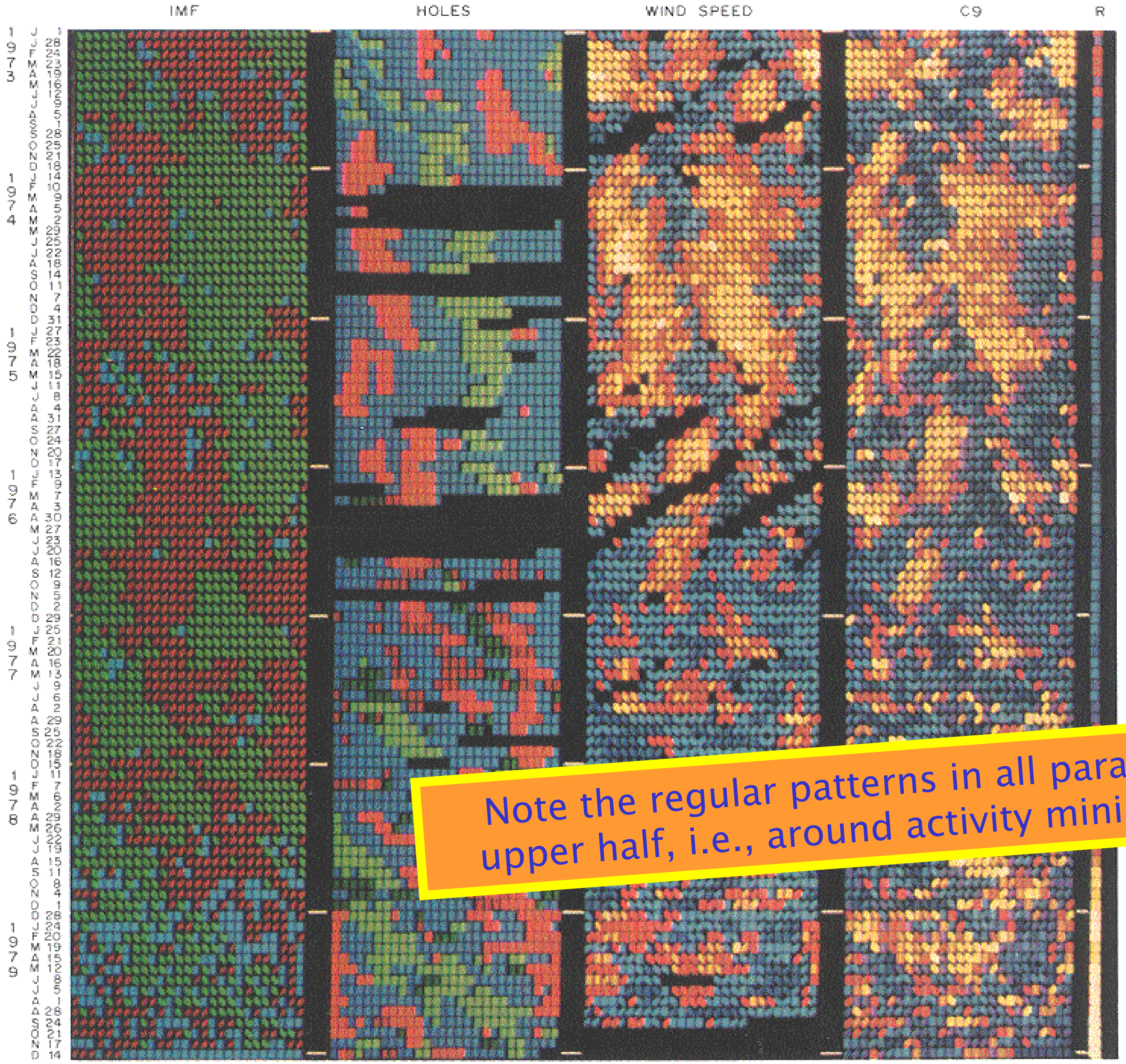


Often ignored: High speed streams from coronal holes (i.e. the inactive" sun) cause (moderate) activity:

They are the "M-regions"!

Note that geomagnetic indices such as Kp contain contributions from two contrary sources: the regular "M-regions" and the irregularly appearing strong storms!

The "musical diagram" of geomagnetic activity, according to the scheme introduced by Bartels (1930



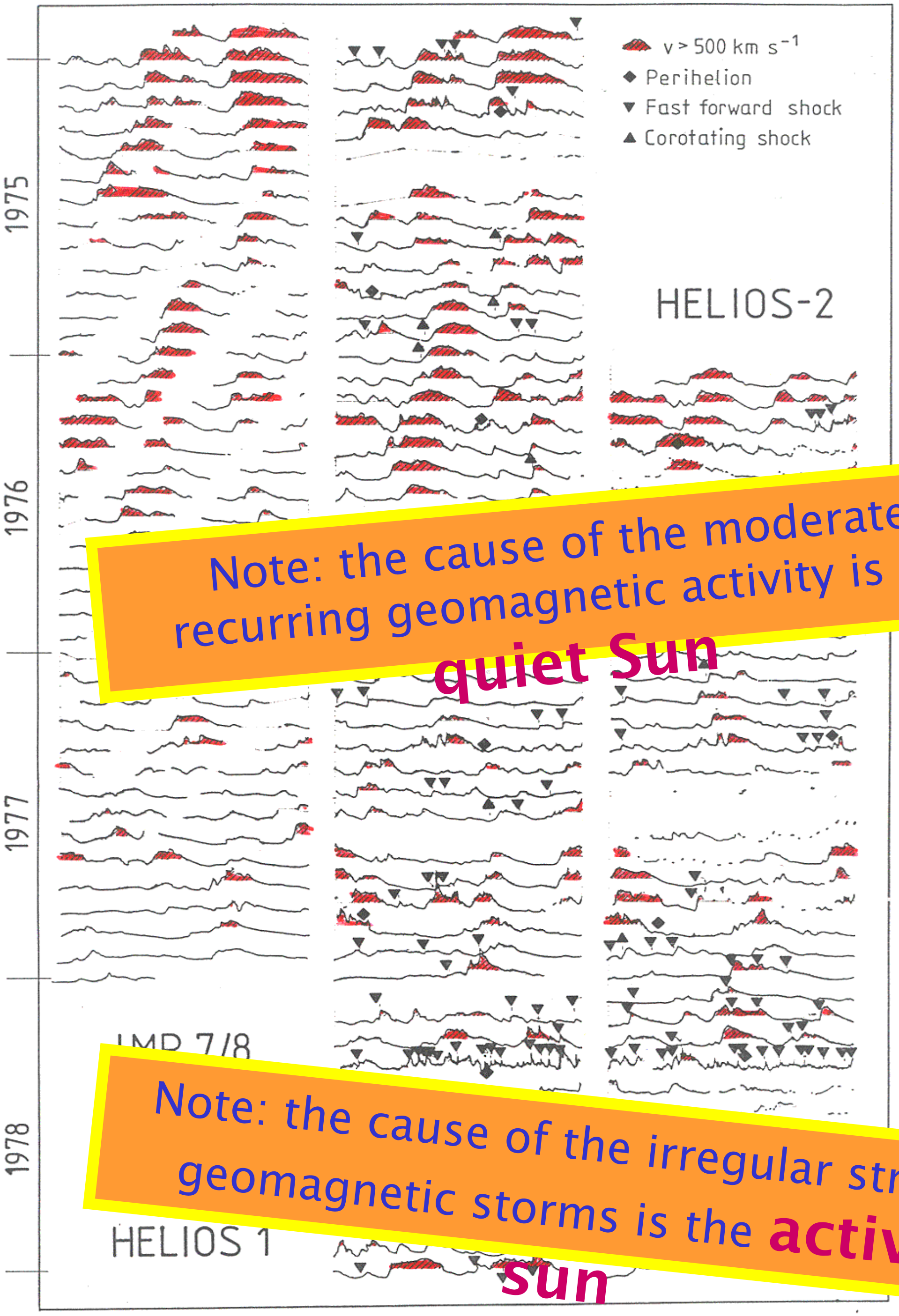
7 years of data, arranged by solar rotations:

- IP Magnetic field,
- Coronal holes,
- Solar wind speed
- Geomagntic index.

Note the regular patterns in all parameters in the upper half, i.e., around activity minimum in 1975.

The solar wind stream structure, observed by the Helios and IMP spacecraft around the activity minimum in 1976

The recurrent high-speed streams which caused a similar M-region pattern

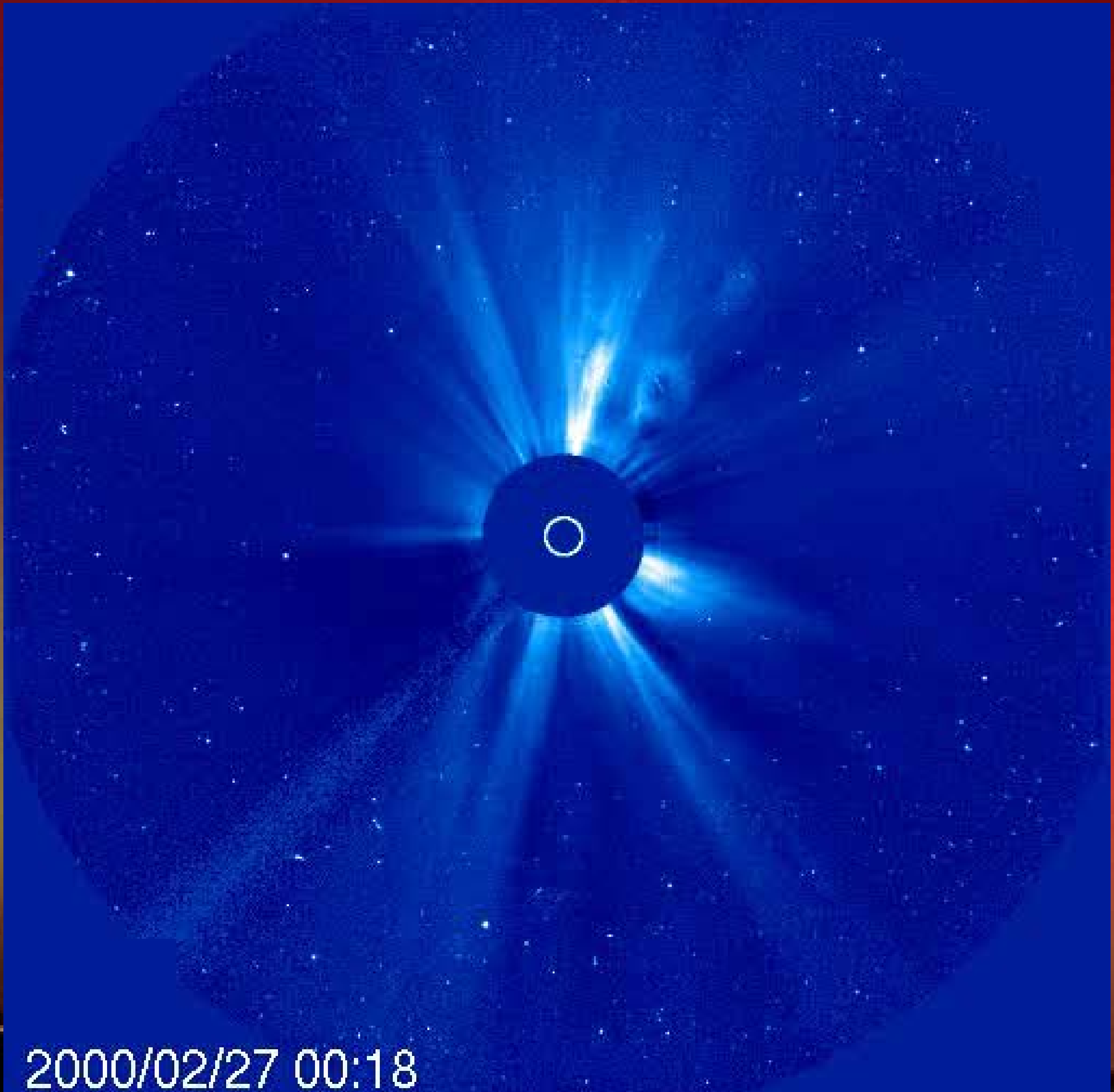


Note: the cause of the moderate, recurring geomagnetic activity is the **quiet Sun**

Note: the cause of the irregular strong geomagnetic storms is the **active sun**

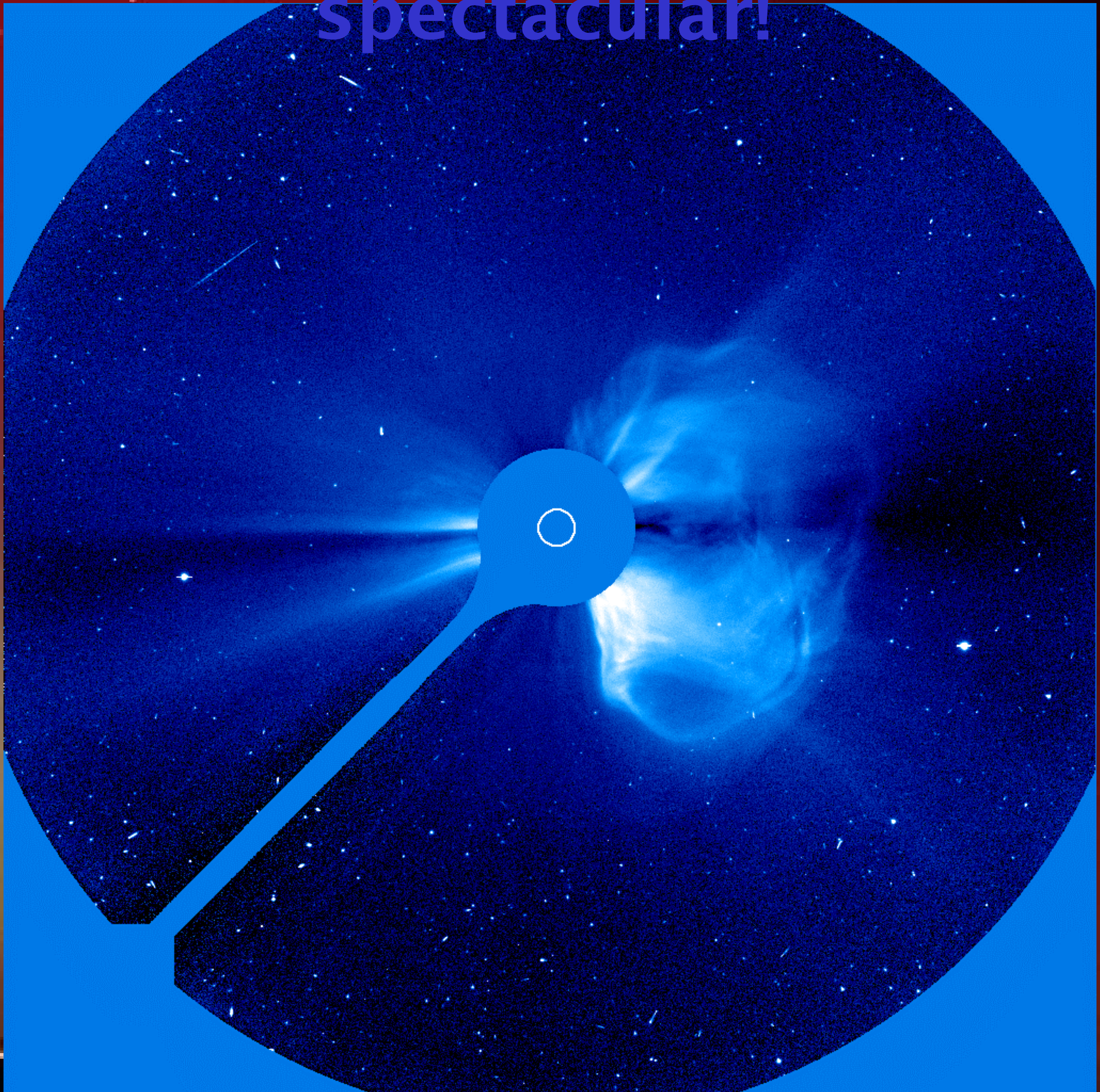
With increasing solar activity (in 1978), many transient events destroyed any regular solar wind structure

How to obtain B_z south?
2. Here comes the the active Sun!

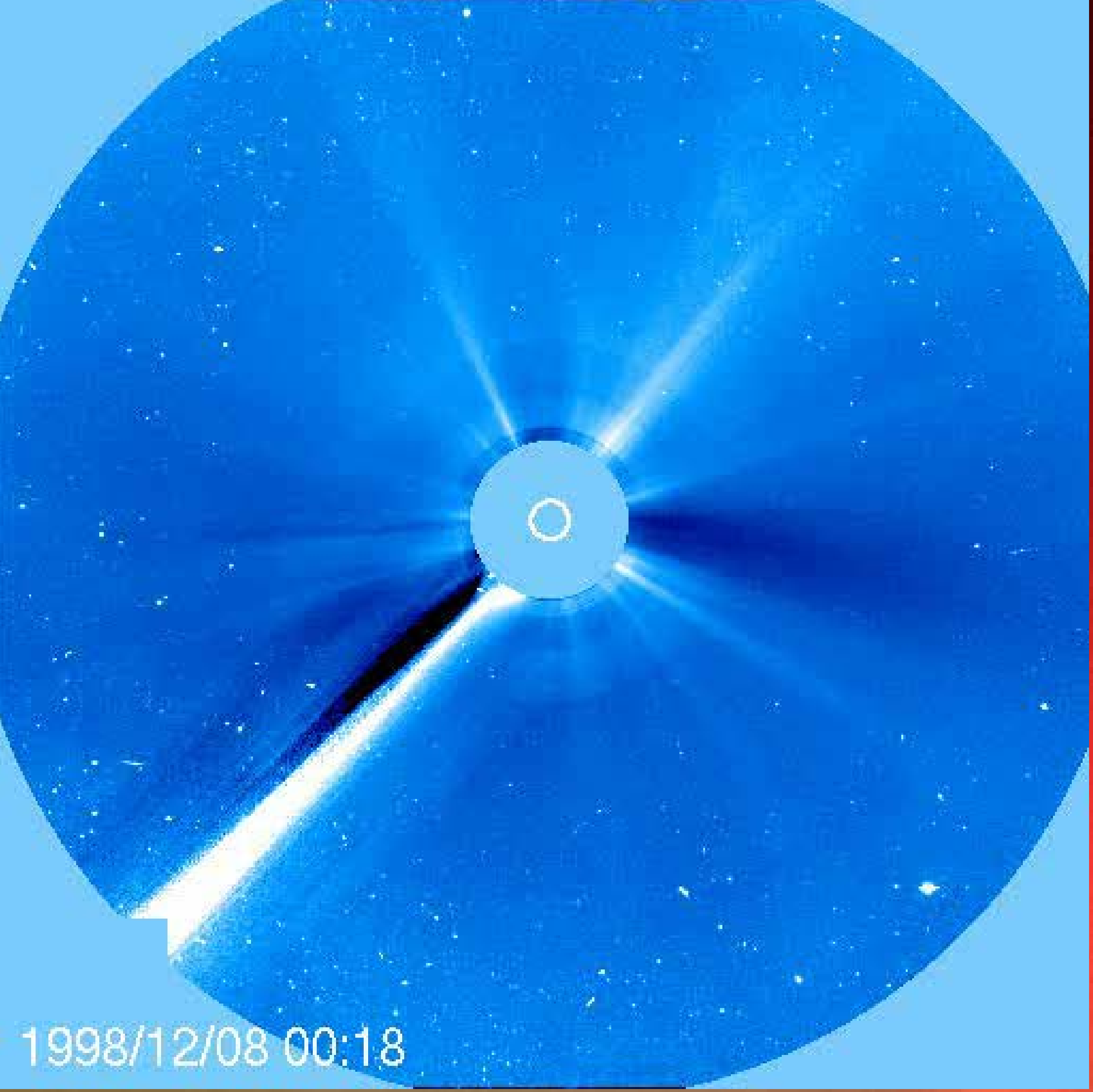


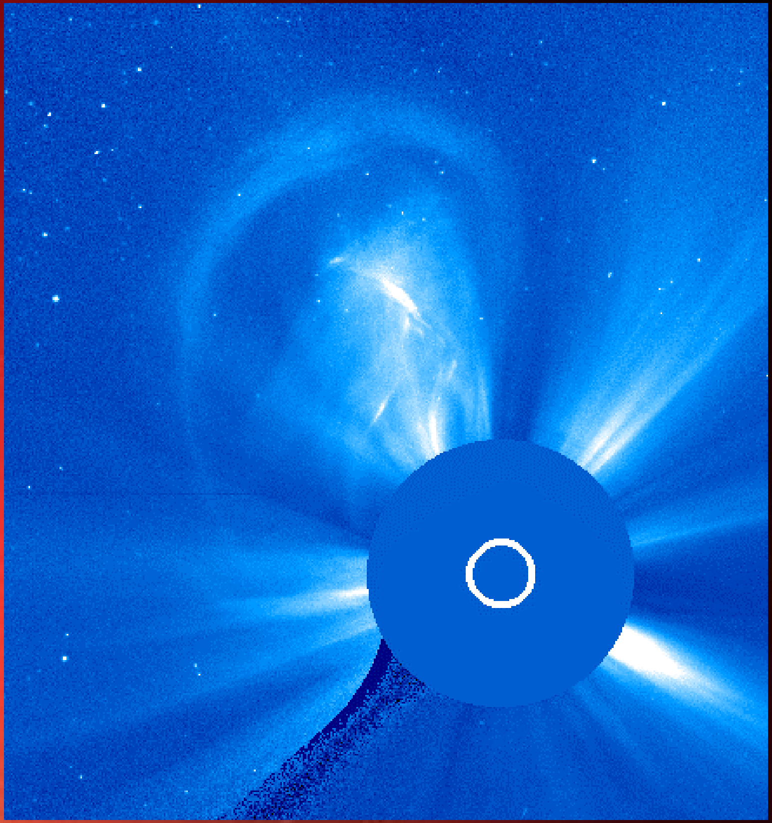
Most dramatic effects;
“Coronal mass ejections”
(CMEs)

Some CMEs are really spectacular!



Some CMEs are spectacular!

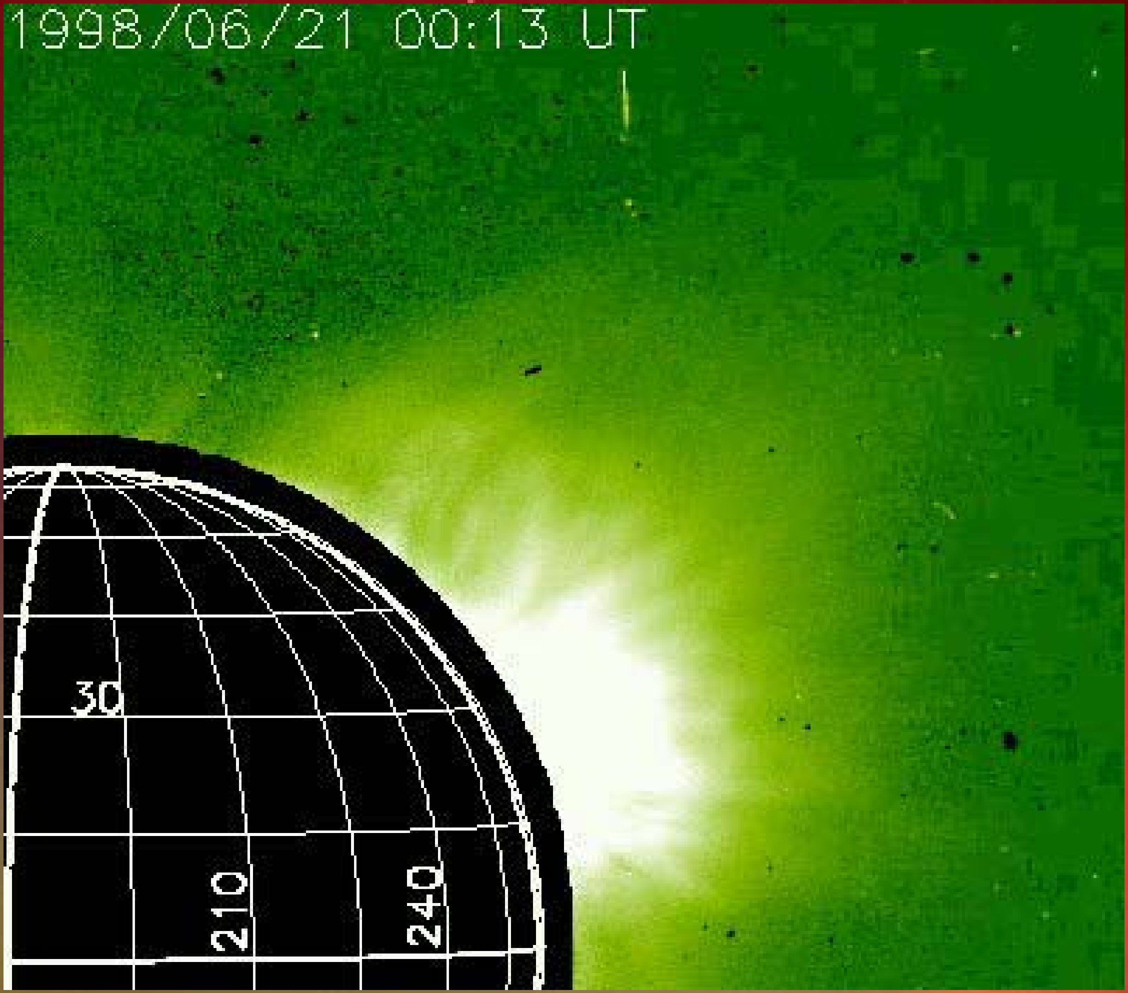




Most big CMEs show a characteristic 3-part structure:

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

There is a huge variety of CMEs



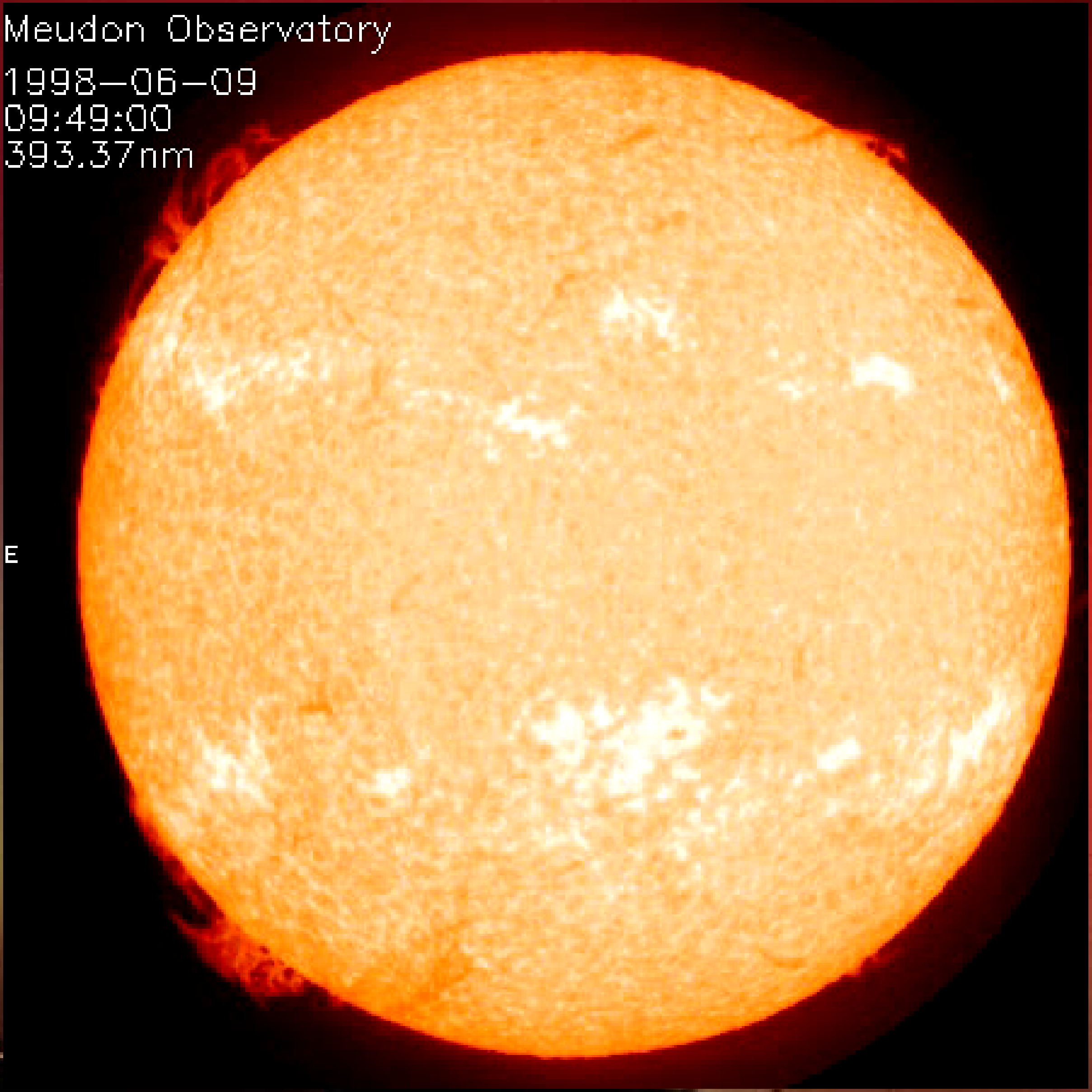
Here comes a “balloon-type” CME, observed by **LASCO-C1** , on June 21, 1998.

It also shows the characteristic 3-part structure:

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

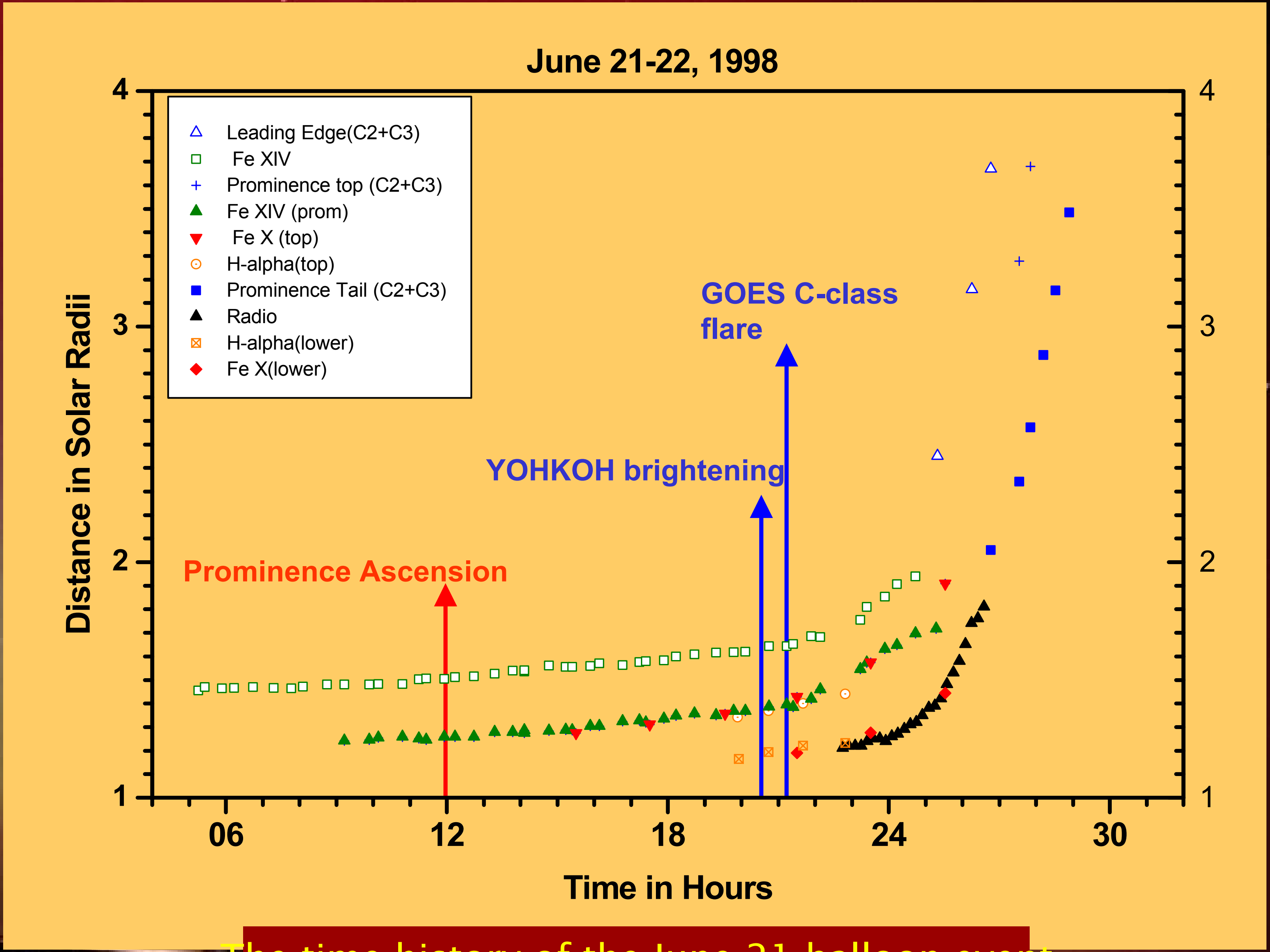
This balloon took some 30 hours to finally take off!
It was the offspring of an eruptive prominence. It ran away at about the slow wind speed, probably no shock was associated with it.

There is a huge variety of CMEs



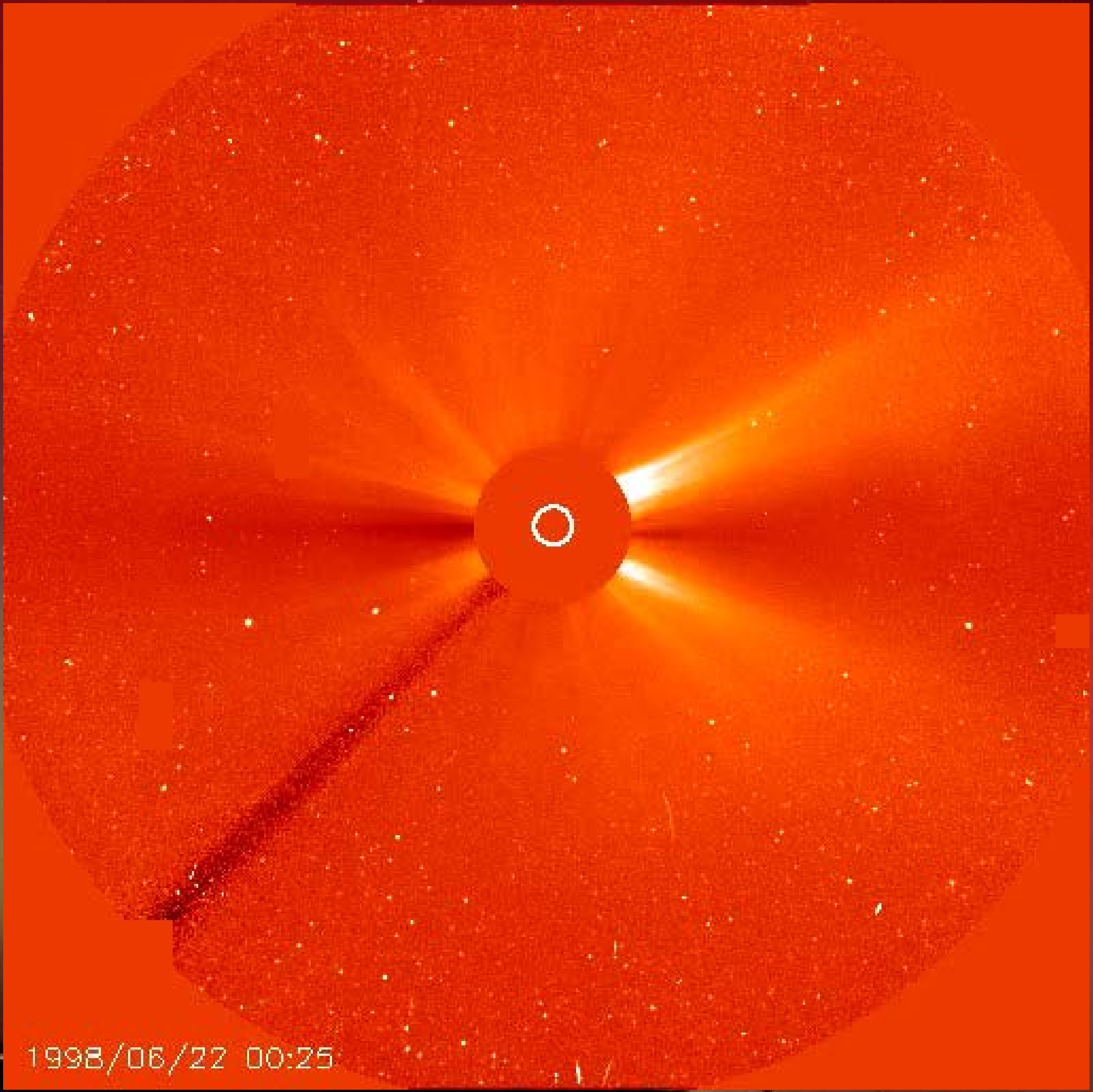
The filament had been observed in H-alpha and the K-line during its complete journey across the disk, before it finally erupted and led to the balloon type CME on June 21, 1998

There is a huge variety of CMEs



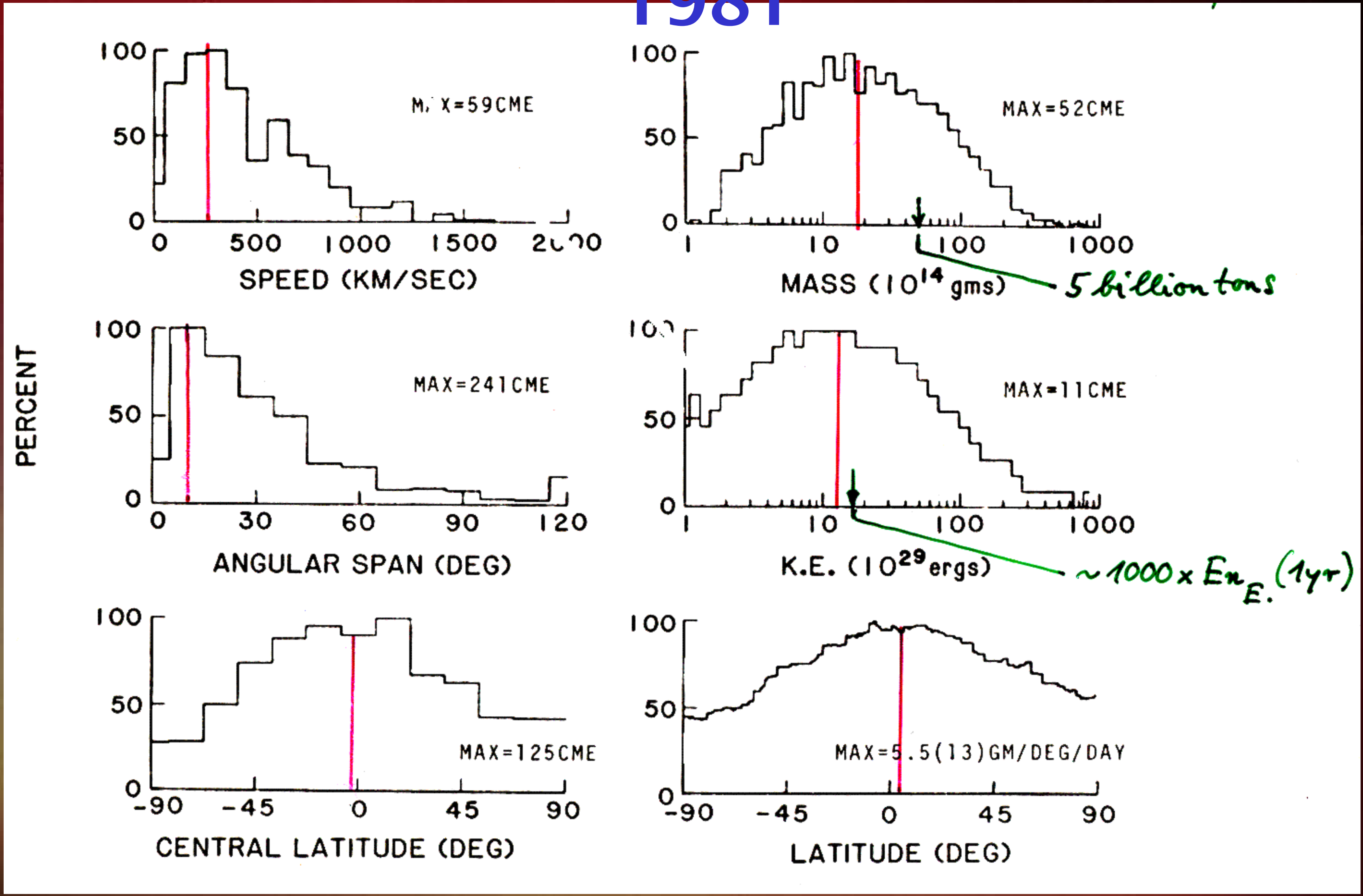
The time history of the June 21 balloon event

There is a huge variety of CMEs



This is what the balloon-type CME finally looked like!

Properties of CMEs, 1979 to 1981

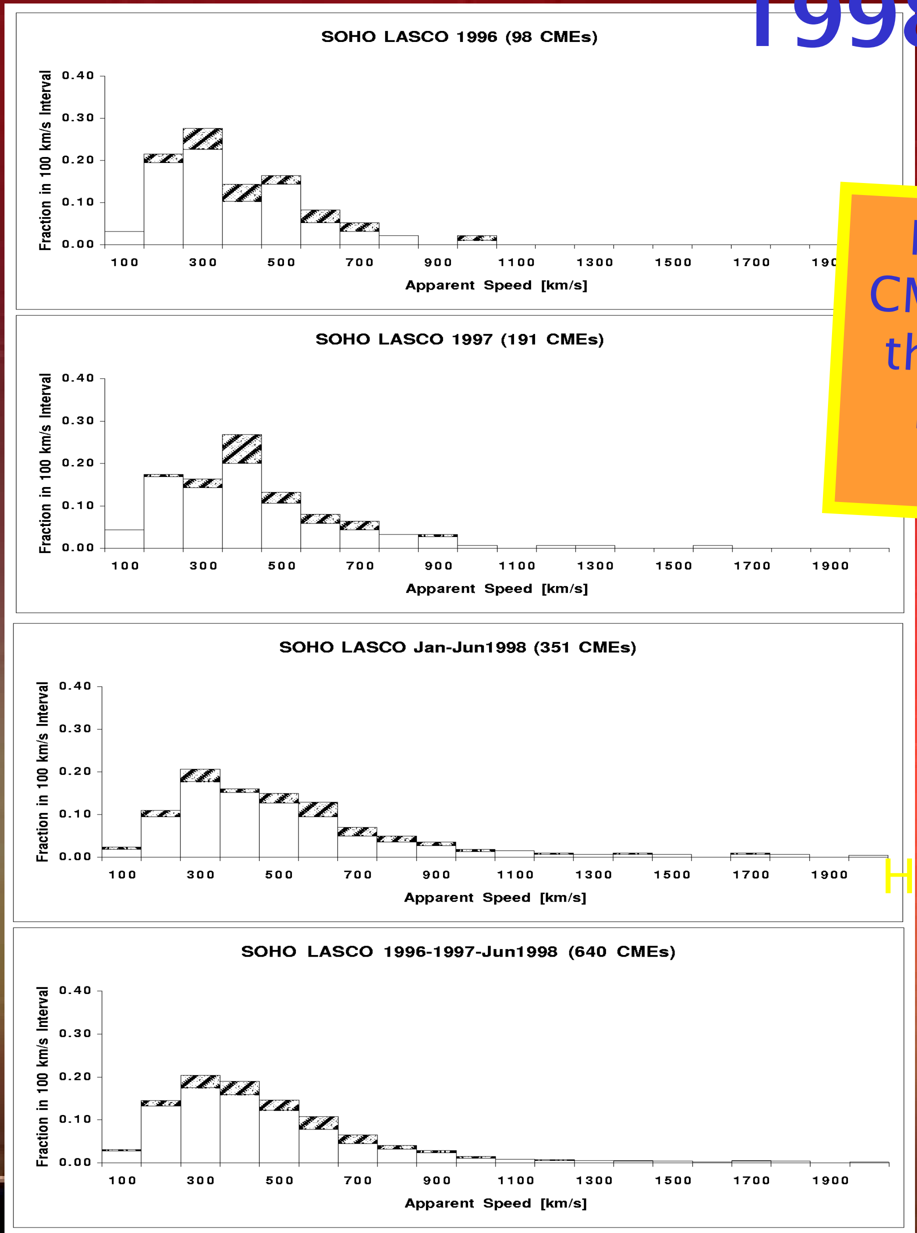


5 billion tons

~1000 x $En_{E.}$ (1yr)

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

Properties of CMEs, 1996 to 1998



SOHO LASCO 1996 (98 CMEs)

SOHO LASCO 1997 (191 CMEs)

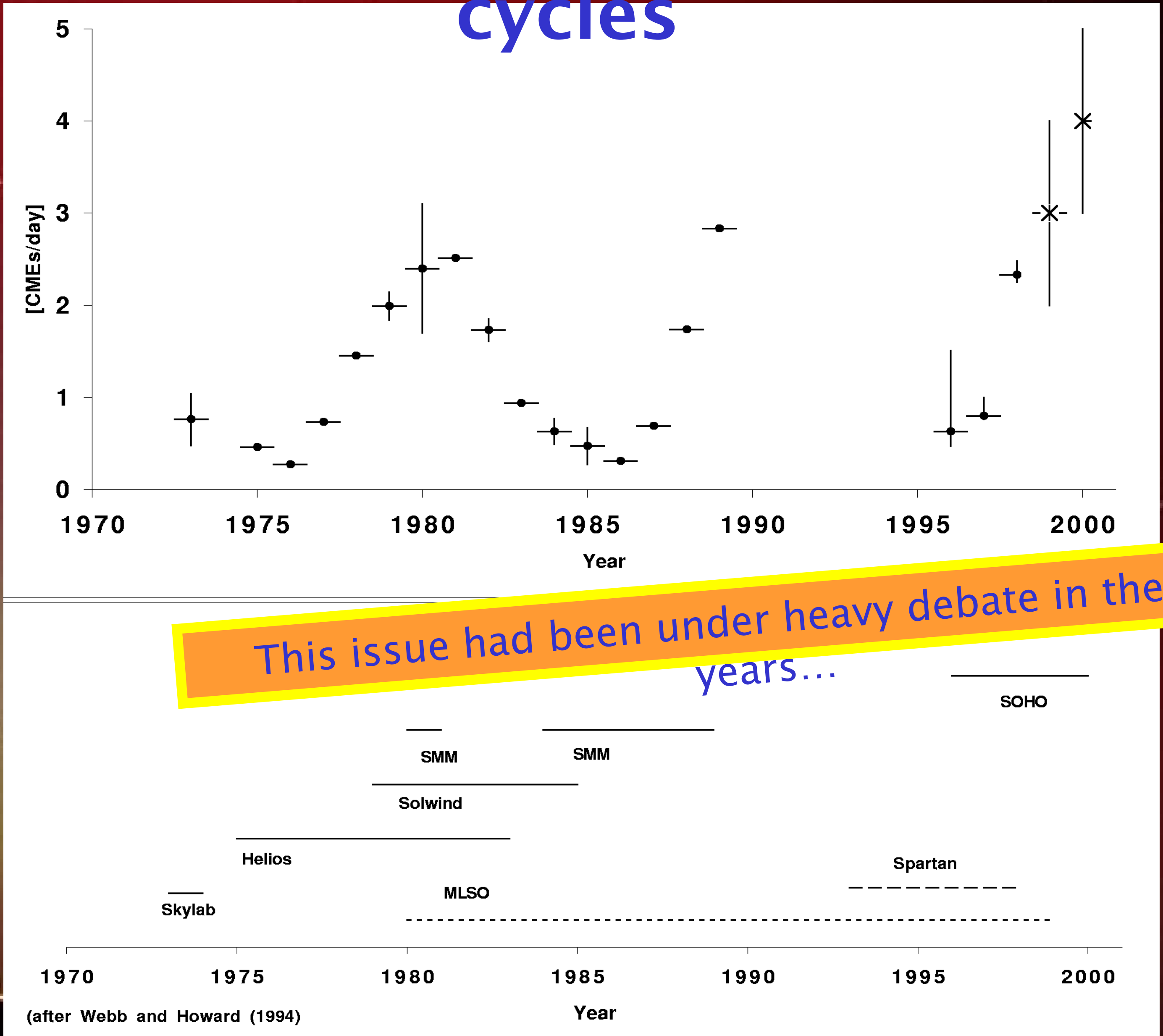
SOHO LASCO Jan-Jun1998 (351 CMEs)

SOHO LASCO 1996-1997-Jun1998 (640 CMEs)

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**

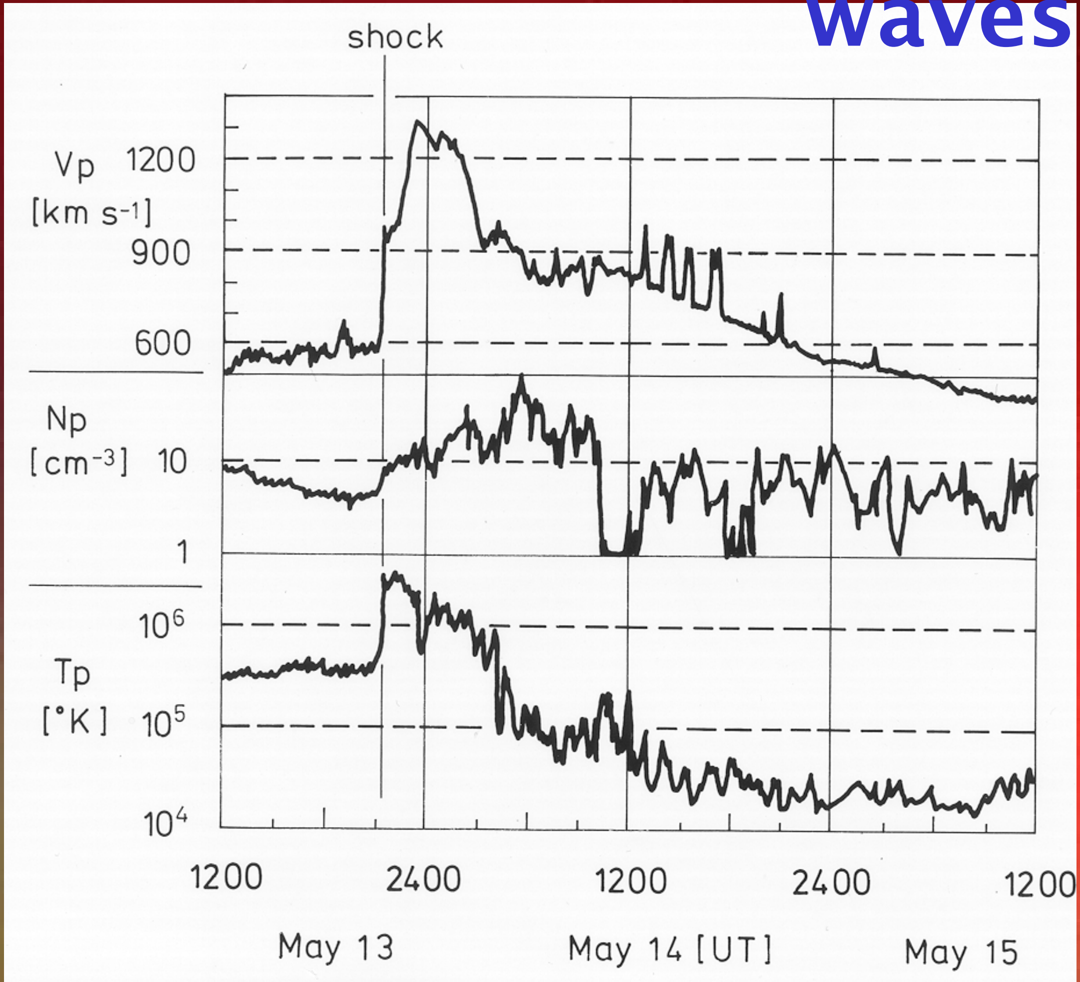
The daily number of CMEs in 2 solar cycles



(after Webb and Howard (1994))

This issue had been under heavy debate in the early years…

Fast CMEs drive interplanetary shock waves

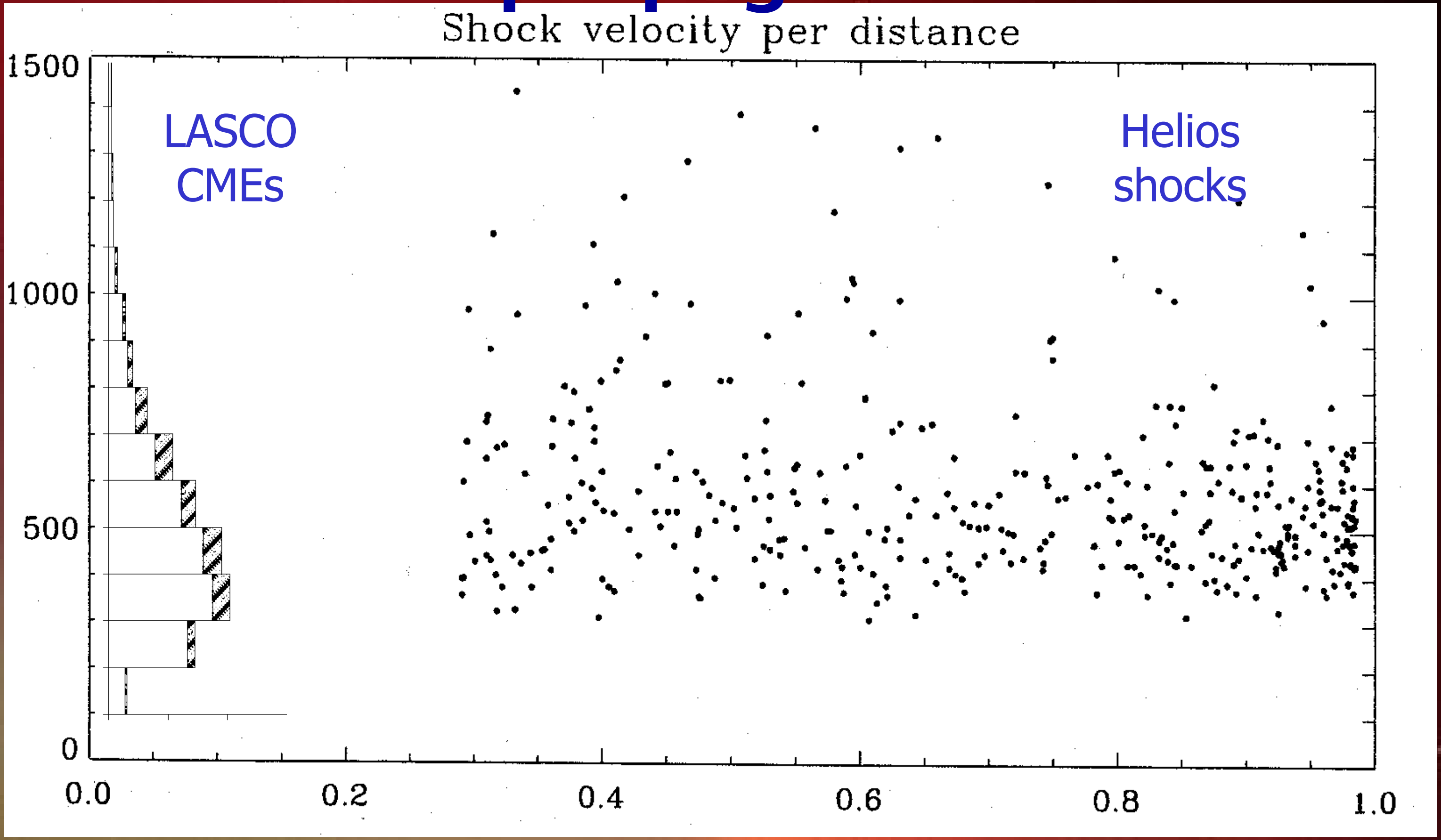


A very fast interplanetary shock wave, as seen by **Helios** in 1978

These are typical CME products in the interplanetary medium:

- no more 3-part structure,
- just shocked “sheath” plasma (compressed and heated),
- and sometimes “driver gas”

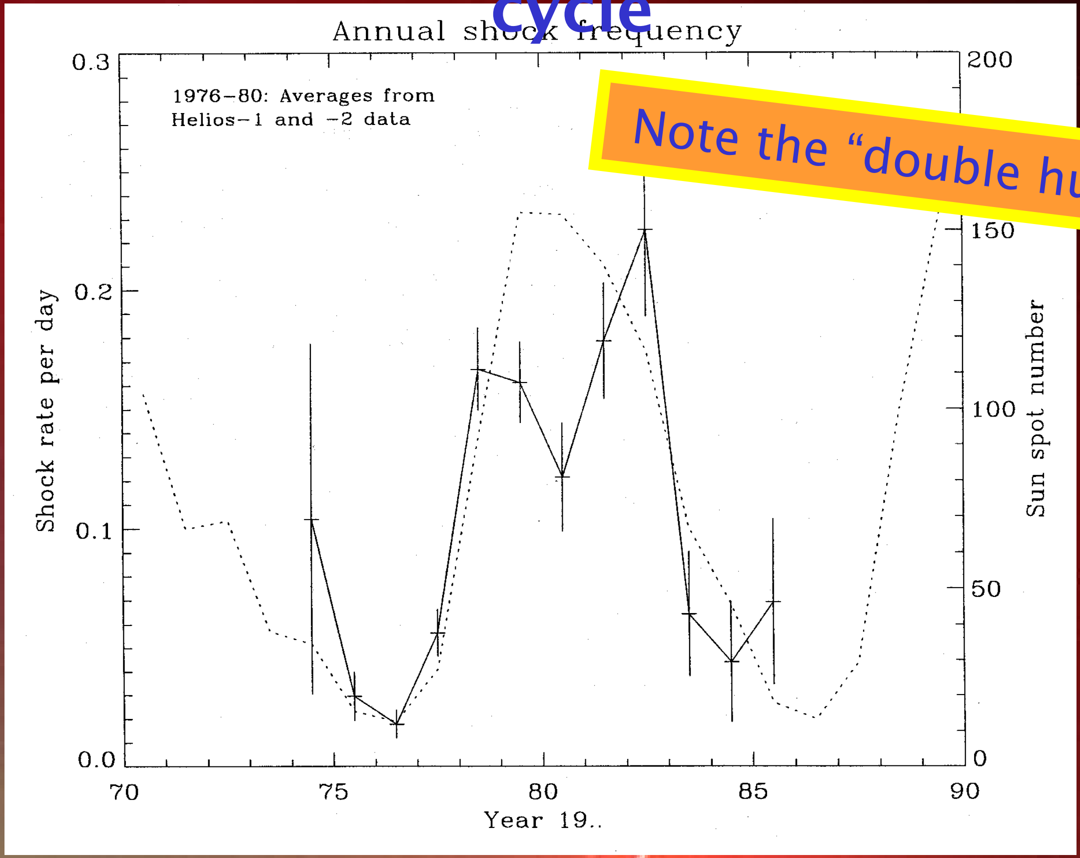
How do ejecta and shocks propagate?



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

Apparently, there is no significant deceleration beyond 0.3 AU. It must occur closer to the sun!

The daily number of shocks in a typical solar cycle

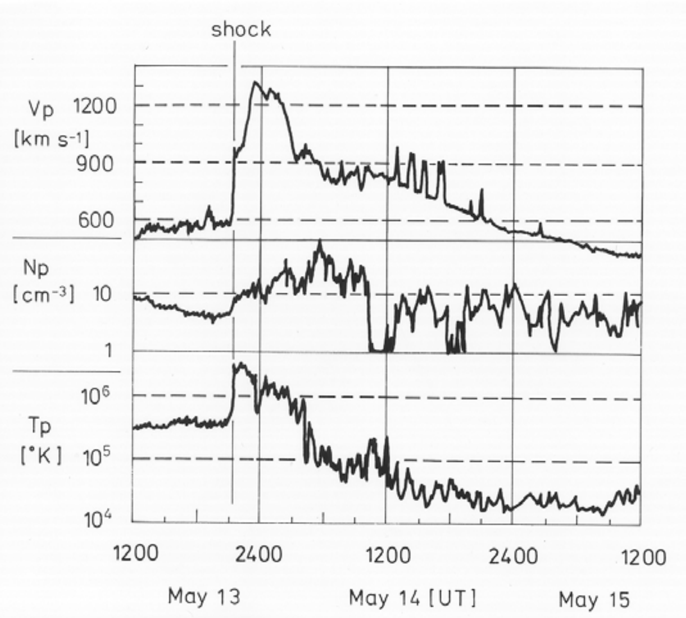


Note the “double hump” distribution!

The daily shock rate, based on 400 shocks observed by the Helios solar probes in 12 years.

The number of shocks noted by an observer in the ecliptic plane is about 10% of the total CME rate. That means: every tenth CME shock hits the earth!

Further: the average cone angle of shock fronts amounts to about 100^0.



Fast CMEs drive shock waves way through the heliosphere

A very fast interplanetary shock wave, as seen by **Helios** in 1978

Results from correlations between CMEs and interplanetary shocks:

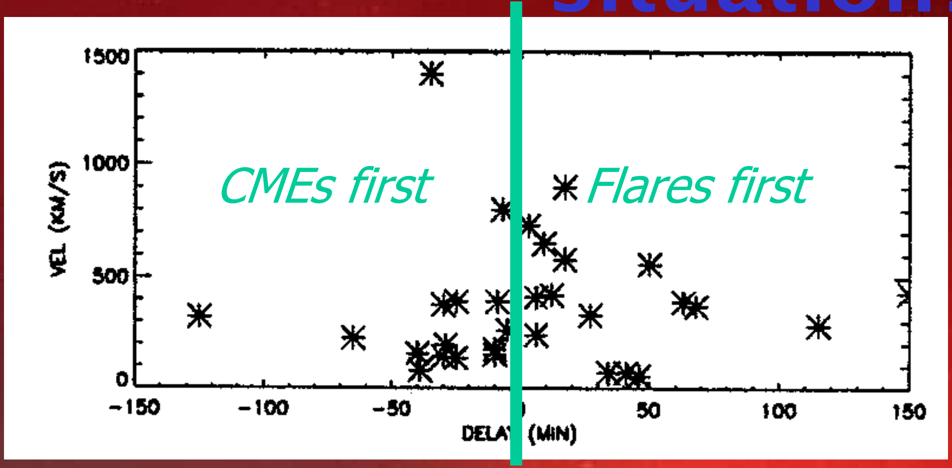
- an observer within the angular span of a fast (>400 km/s) CME has a 100% chance to be hit by a fast shock wave, and vice versa:
- every shock (except at CIRs) can be traced back to a fast CME.

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

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.

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



Time separation between flares and correlated CMEs

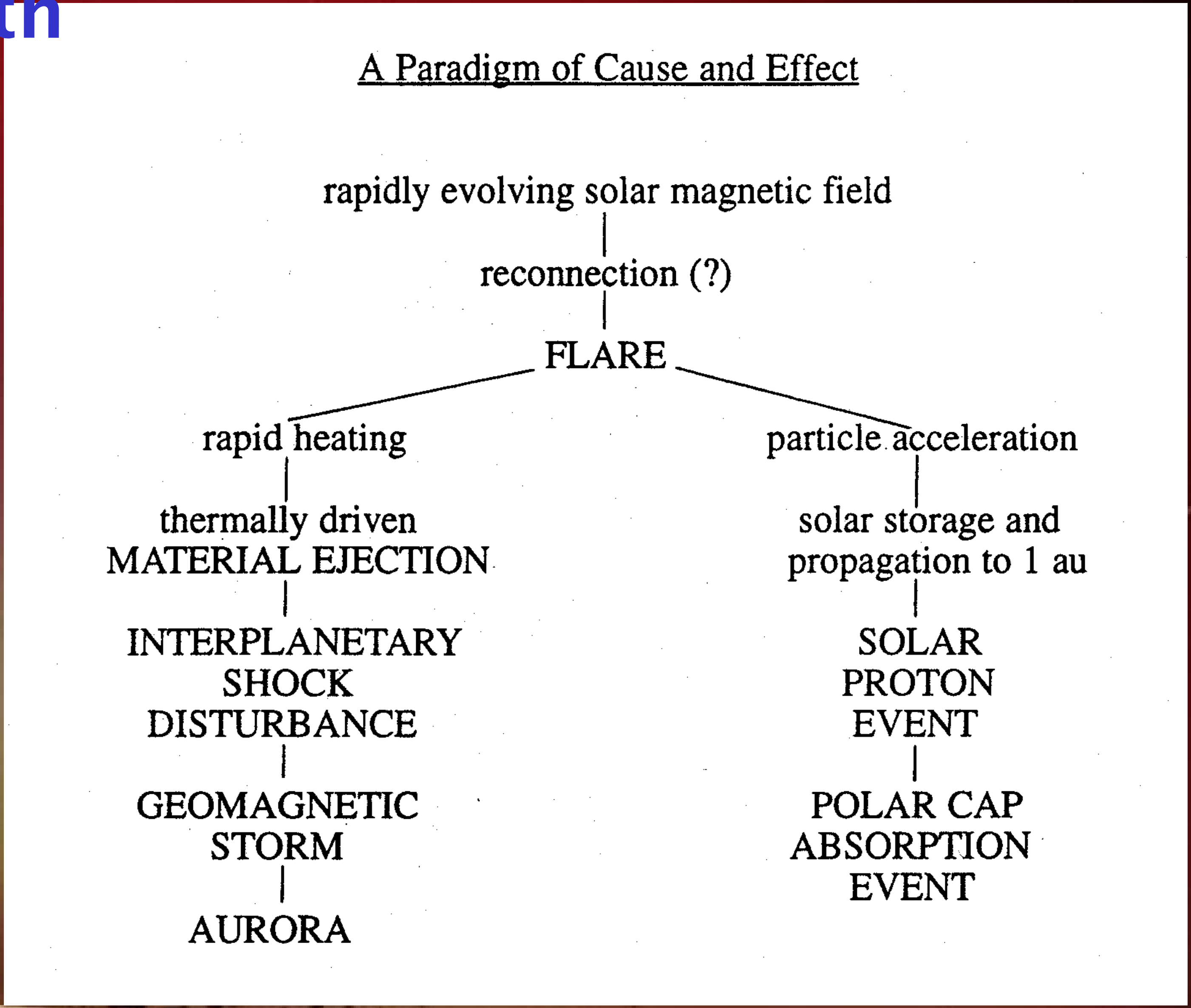
The simple but important conclusions from these studies:
Flares occurring after their associated CMEs cannot be their cause, quite logically.

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

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!”

The “old” paradigm: the solar flare myth



A Paradigm of Cause and Effect

rapidly evolving solar magnetic field

reconnection (?)

FLARE

rapid heating

thermally driven
MATERIAL EJECTION

INTERPLANETARY
SHOCK
DISTURBANCE

GEOMAGNETIC
STORM

AURORA

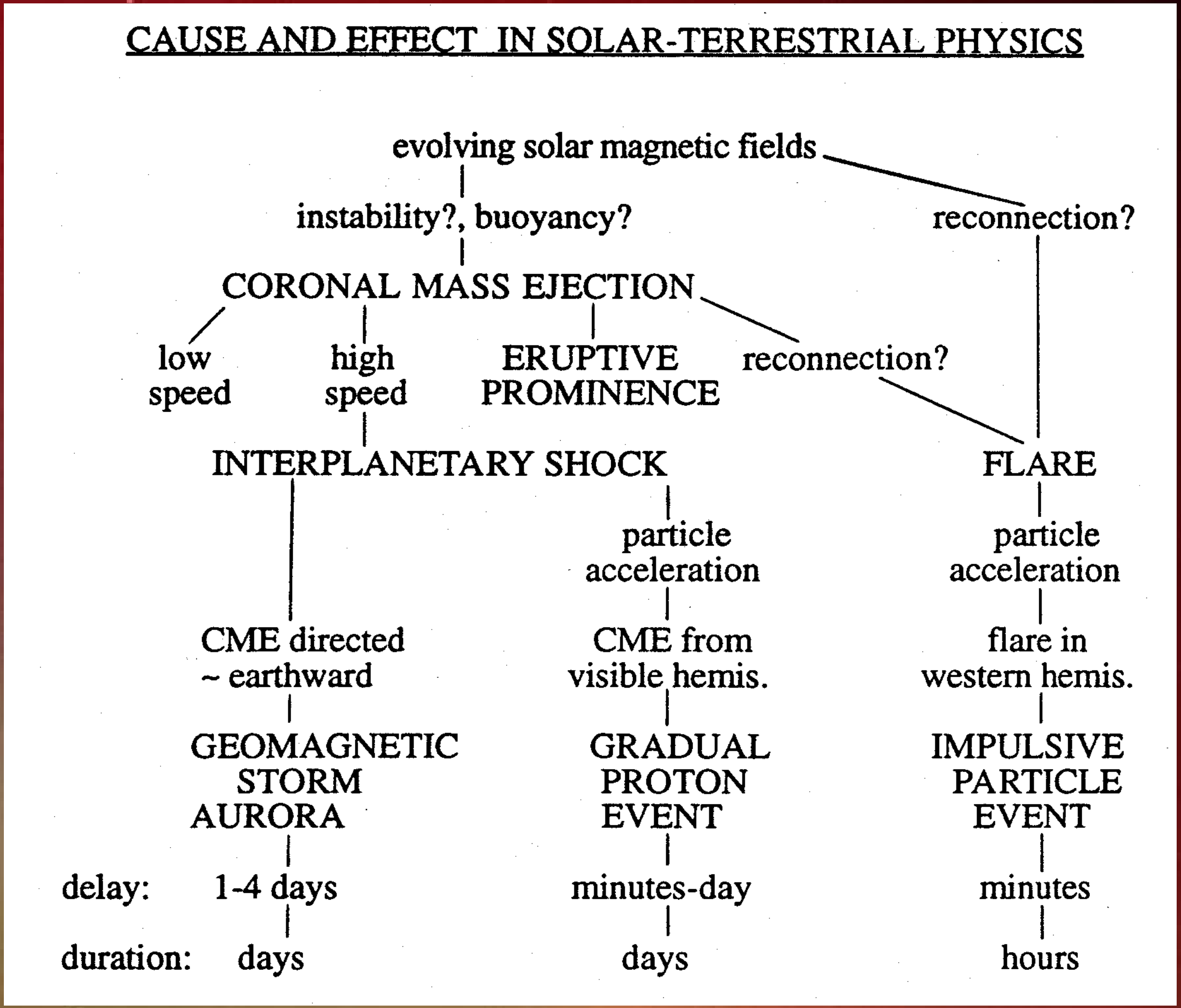
particle acceleration

solar storage and
propagation to 1 au

SOLAR
PROTON
EVENT

POLAR CAP
ABSORPTION
EVENT

The modern paradigm



CAUSE AND EFFECT IN SOLAR-TERRESTRIAL PHYSICS

evolving solar magnetic fields

instability?, buoyancy?

reconnection?

CORONAL MASS EJECTION

low speed

high speed

ERUPTIVE PROMINENCE

reconnection?

INTERPLANETARY SHOCK

FLARE

particle acceleration

particle acceleration

CME directed ~ earthward

CME from visible hemis.

flare in western hemis.

GEOMAGNETIC STORM AURORA

GRADUAL PROTON EVENT

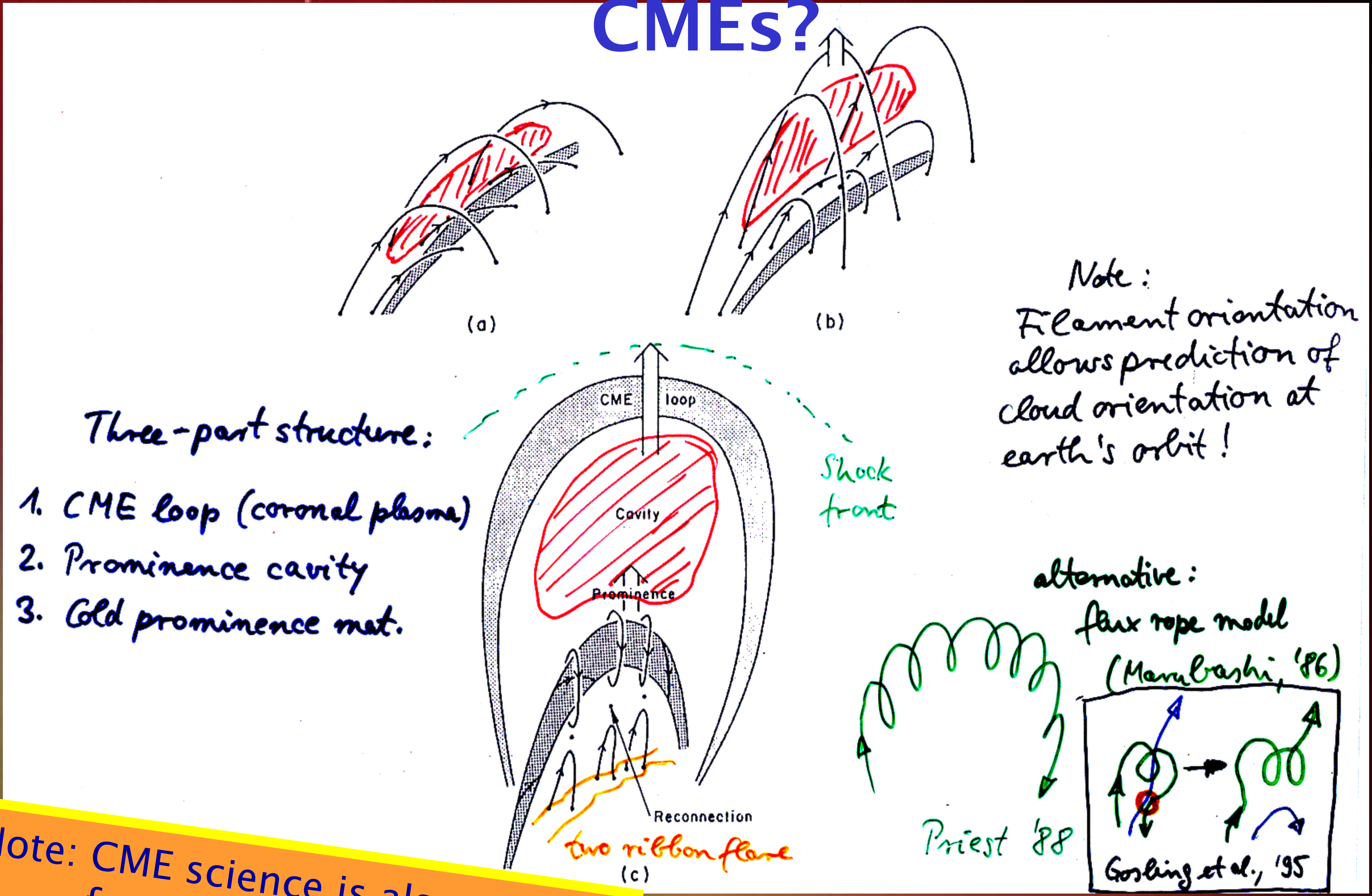
IMPULSIVE PARTICLE EVENT

delay: 1-4 days | minutes-day | minutes

duration: days | days | hours

However, the very big events have everything: flares, radio bursts, CMEs, shock waves, energetic particles, etc, within a few minutes. Causes and effects? Remain to be disentangled...

Why does B_z turn south in CMEs?



Three-part structure:

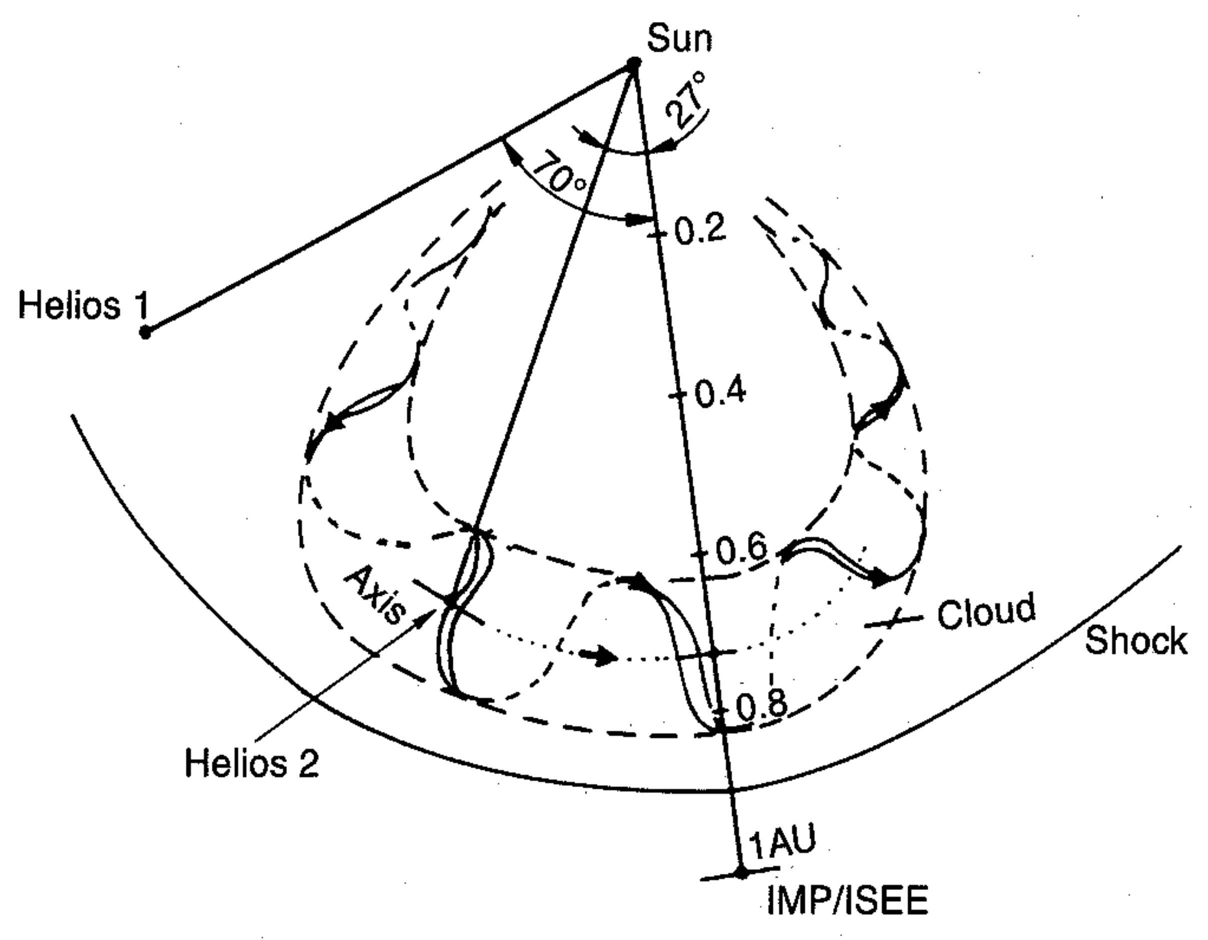
1. CME loop (coronal plasma)
2. Prominence cavity
3. Cold prominence mat.

Note:
Filament orientation allows prediction of cloud orientation at earth's orbit!

alternative:
flux rope model
(Marubashi, '86)

Note: CME science is also a field for creative artists...

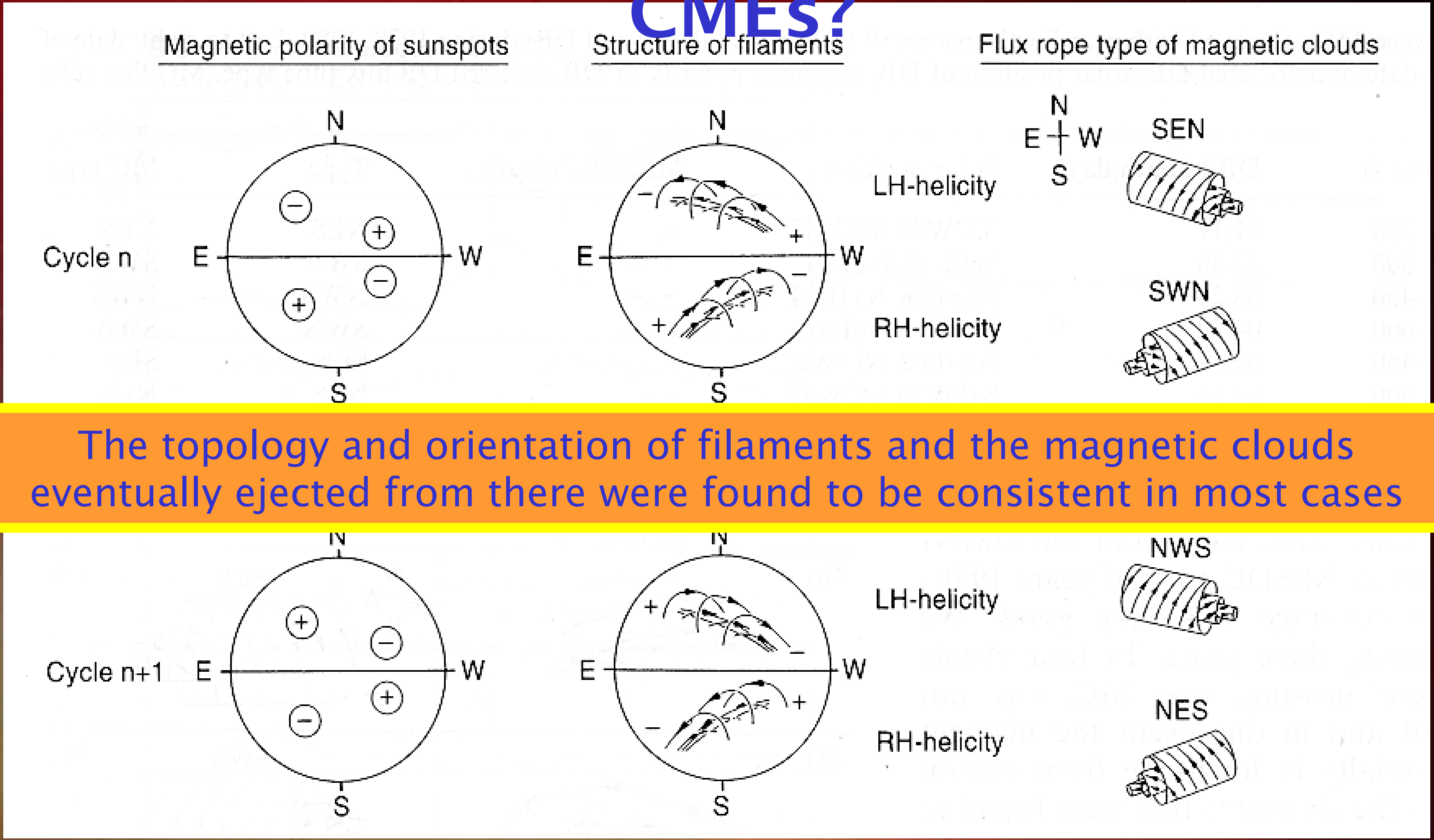
Why does B_z turn south in CMEs?



When a flux rope passes an observer, he may encounter B_z south fields at times

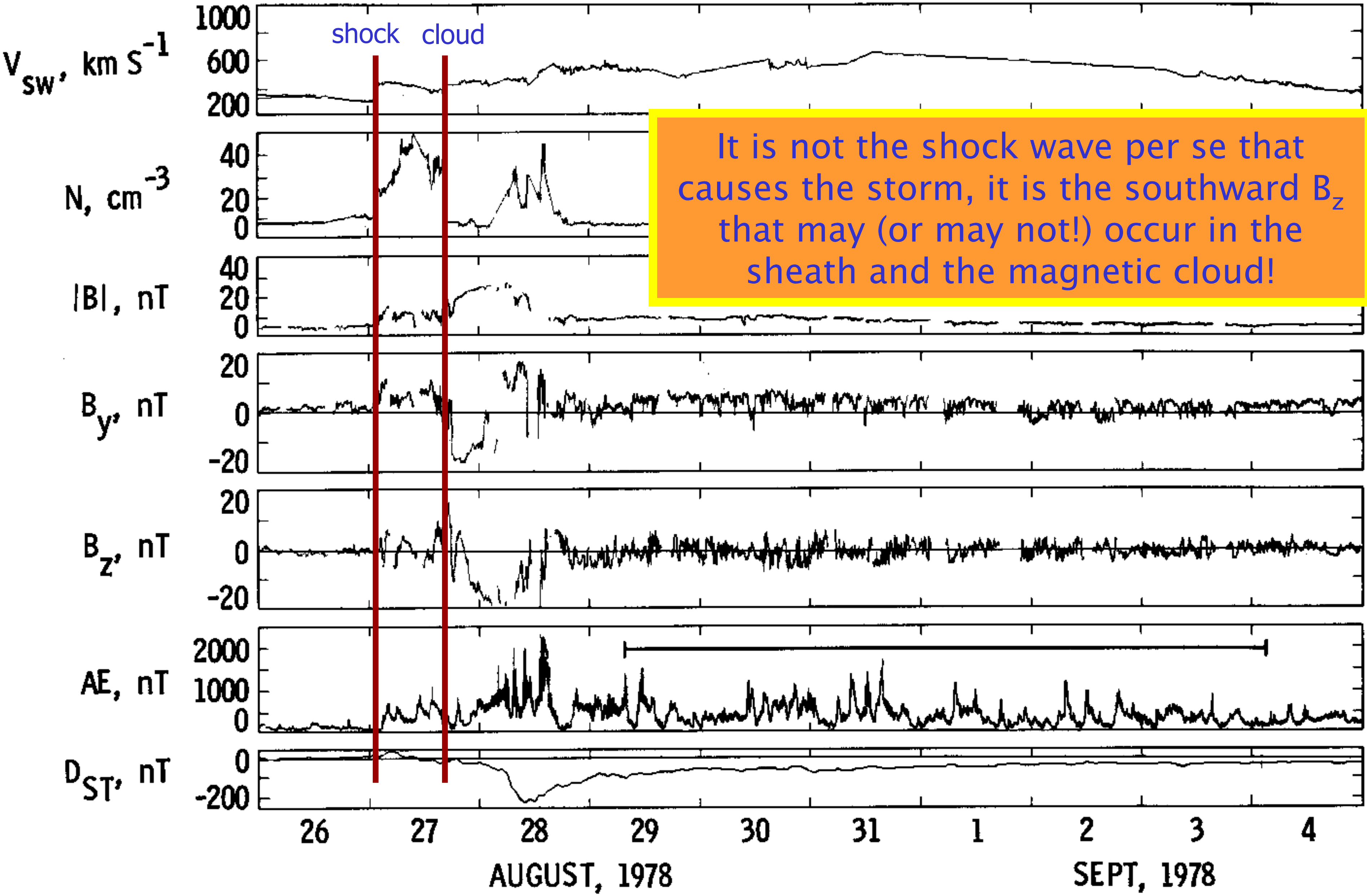
The flux rope topology of a magnetic cloud in interplanetary space.

Why does B_z turn south in CMEs?



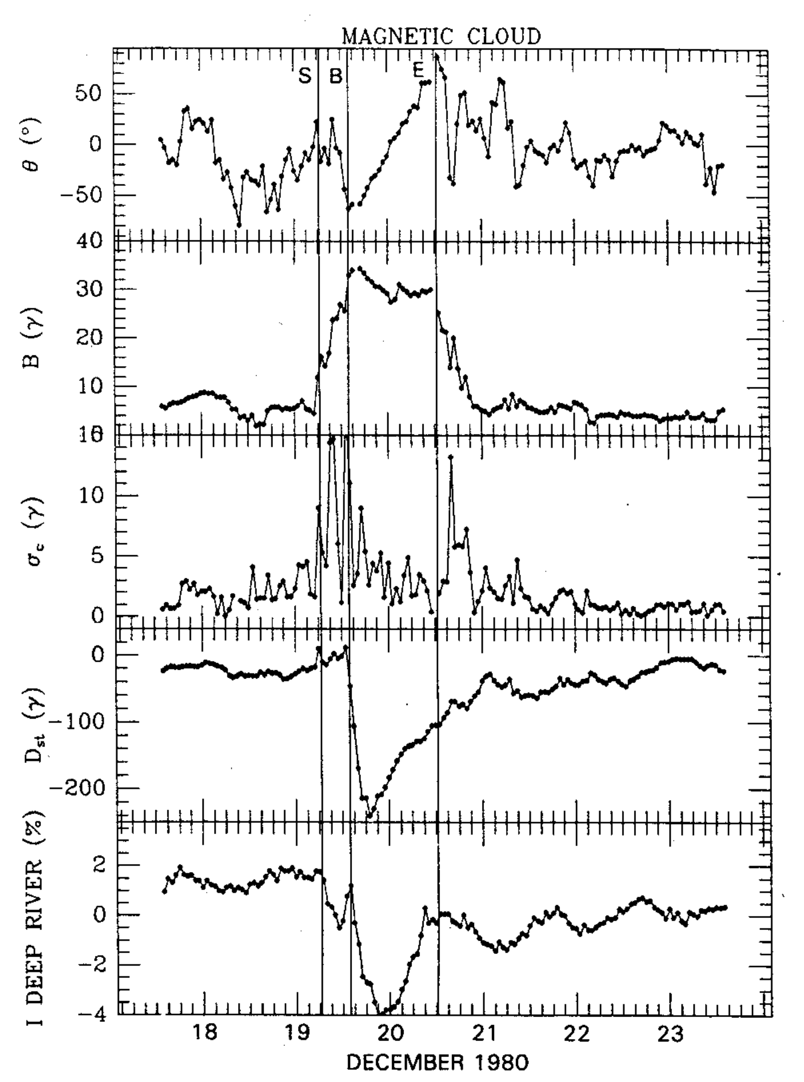
The topology and orientation of filaments and the magnetic clouds eventually ejected from there were found to be consistent in most cases

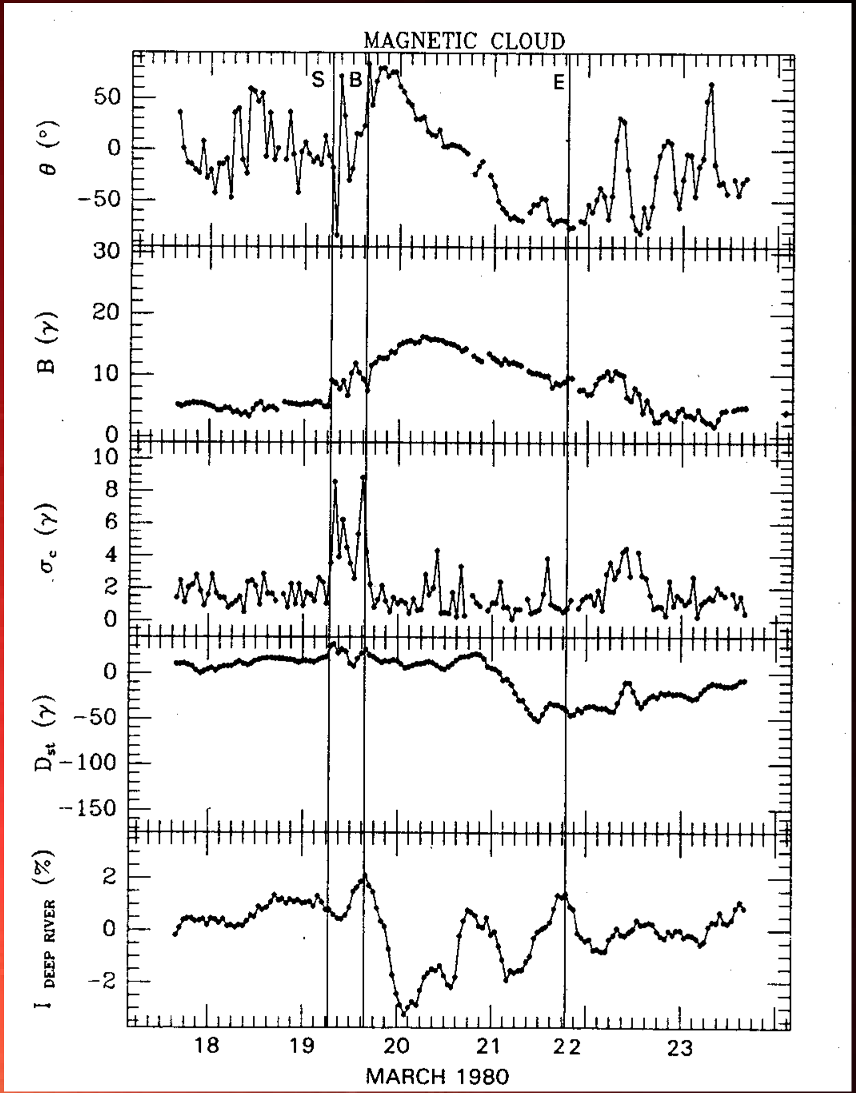
The flux rope topologies of magnetic clouds in interplanetary space.
All 4 types are observed and correspond well to their filament sources
But their geoefficiency differs dramatically!



It is not the shock wave per se that causes the storm, it is the southward B_z that may (or may not!) occur in the sheath and the magnetic cloud!

Relation of a strong geomagnetic storm with the arrival of a magnetic cl



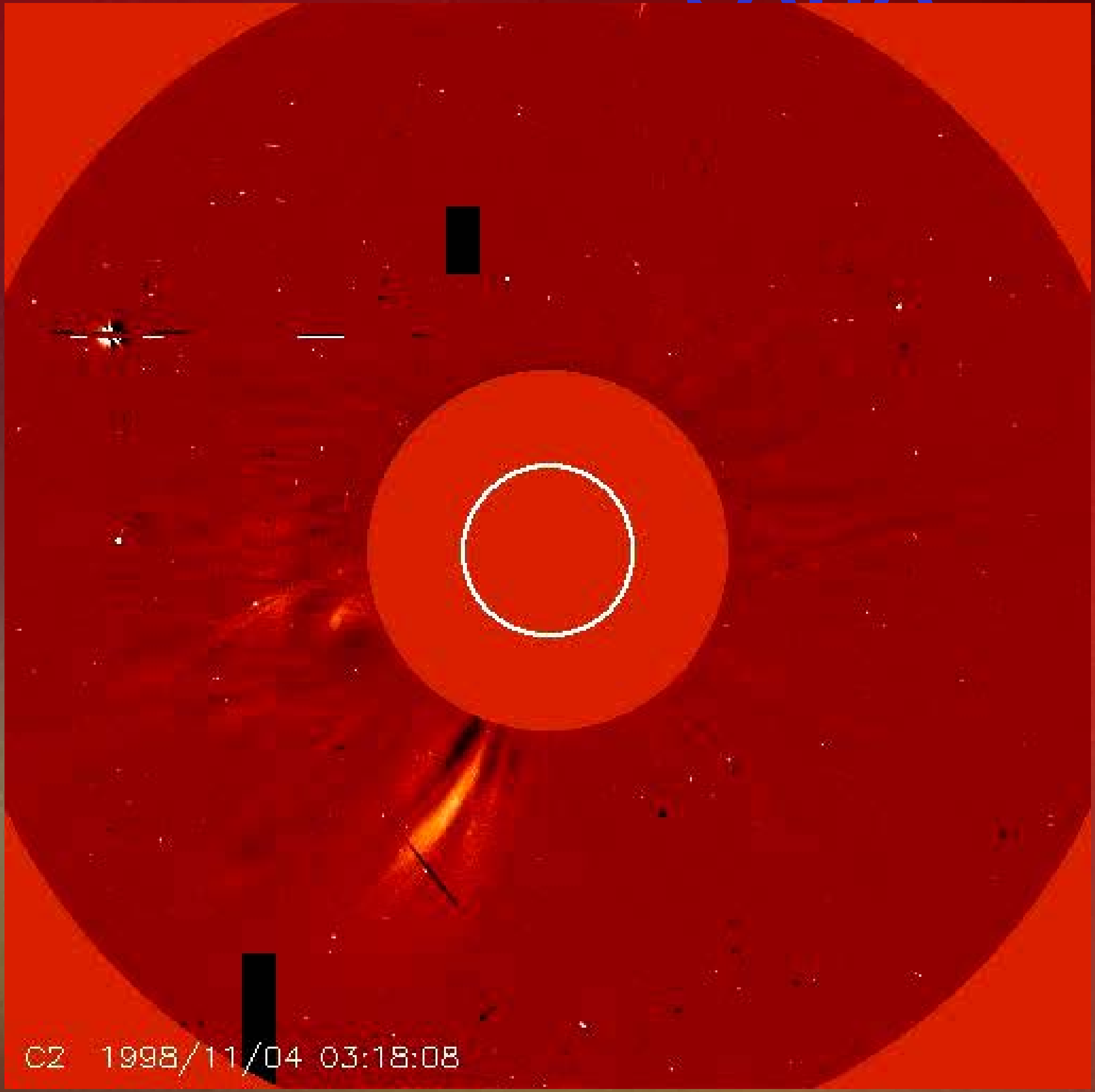


A SEN cloud at 1 AU

A NES cloud at 1 AU

Note how different the geomagnetic response is, despite the similarity of both: the cloud pattern and the Forbush decrease!

Halo CMEs: a new quality from SOHO



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

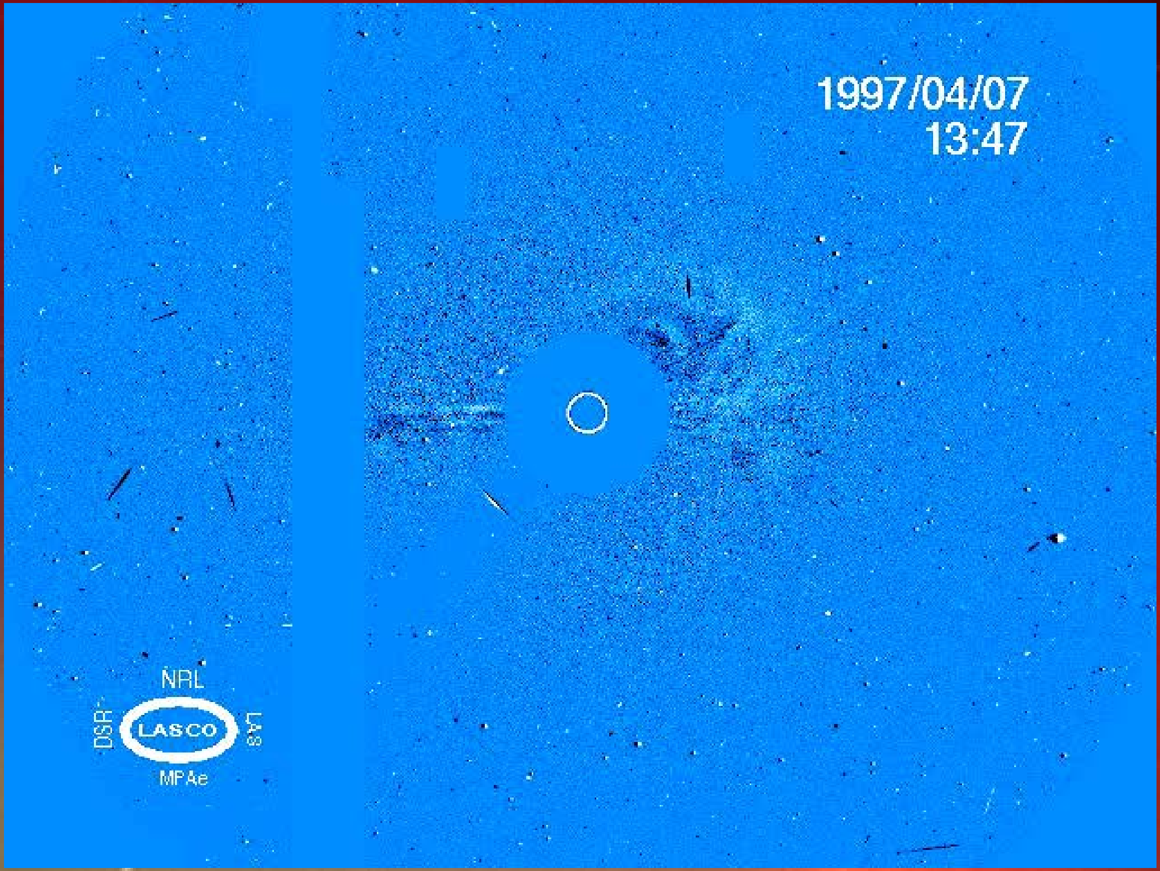
Towards or away from Earth? That knowledge would grant space weather predictions a new quality

Front or backside: a new quality from SOHO

A pressure wave (EIT Wave) in the solar atmosphere, pushed by a flare on 7.4.1997.
It launched a halo CME towards earth and caused a geomagnetic storm on 10.4.97.

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

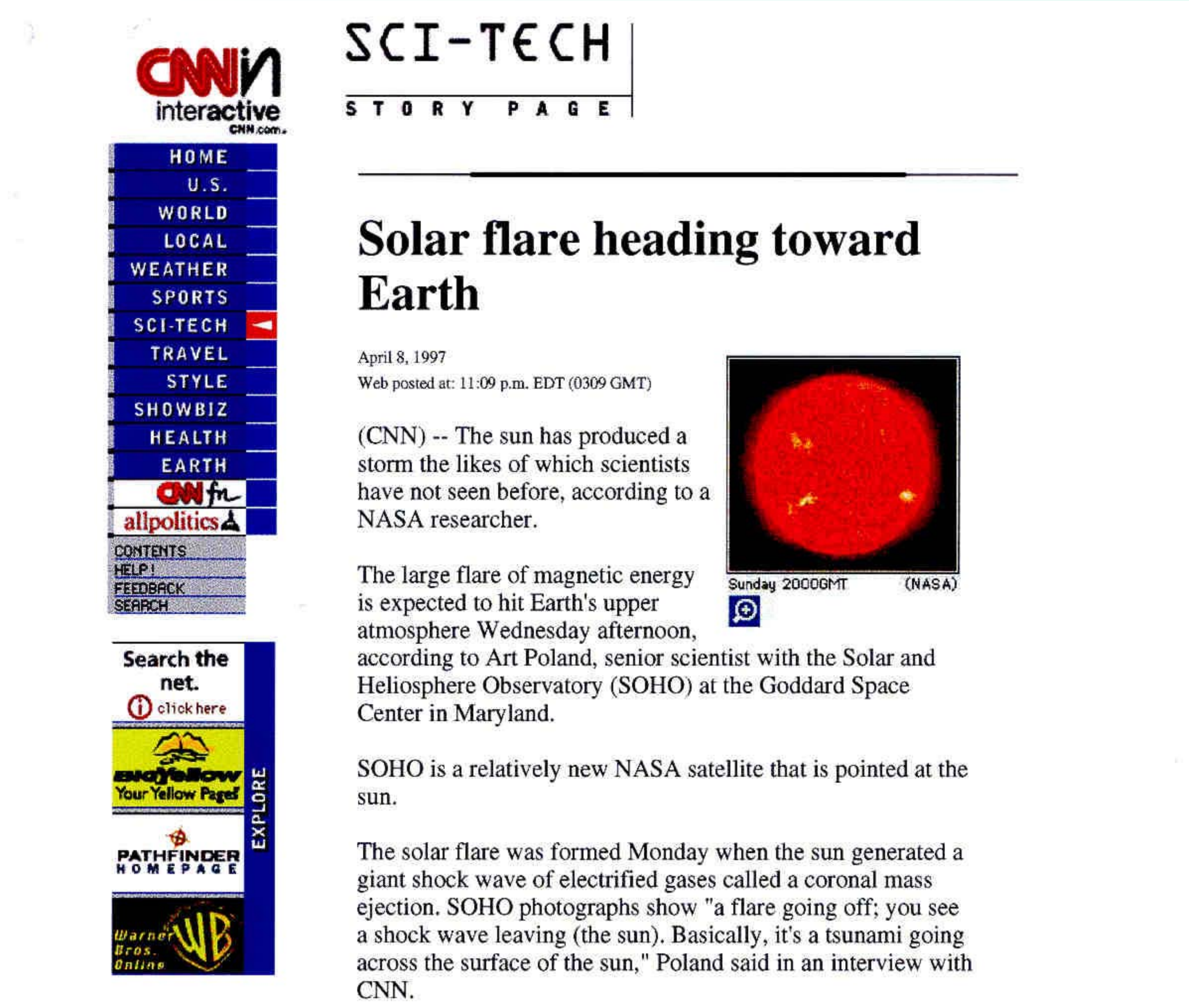
Halo CMEs: a new quality from SOHO



The Halo CME of April 7, 1997, observed by **LASCO-C3**

This event caused:
- a NASA press conference on April 8, 1997,
- CNN to show this very movie on April 9, 1997,
- a tremendous press activity in the USA,
- the „Bildzeitung“ in Germany to put it onto the front page on April 10, 1997,

Halo CMEs: a new quality from SOHO



Solar flare heading toward Earth

April 8, 1997
Web posted at: 11:09 p.m. EDT (0309 GMT)

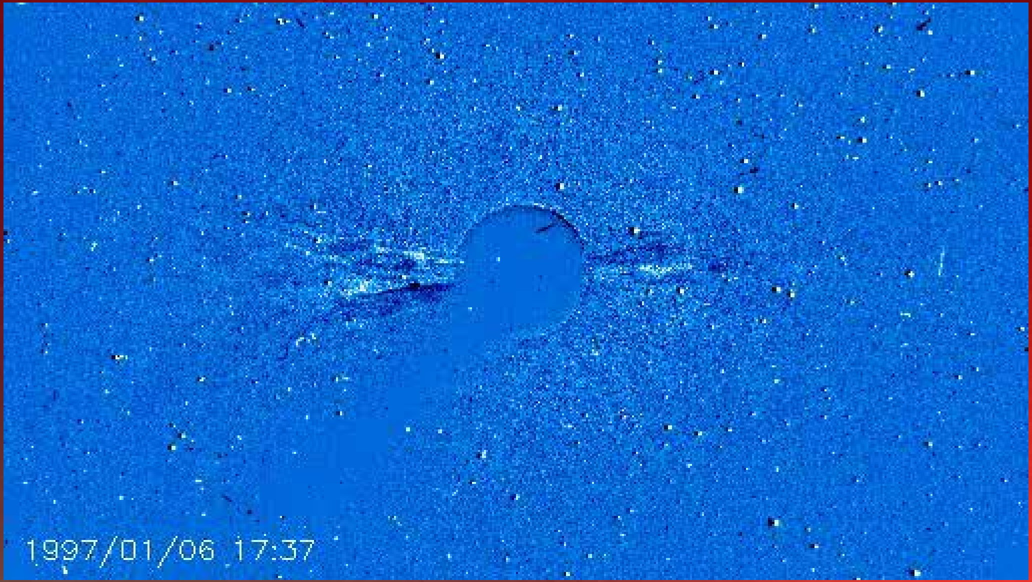
(CNN) -- The sun has produced a storm the likes of which scientists have not seen before, according to a NASA researcher.

The large flare of magnetic energy is expected to hit Earth's upper atmosphere Wednesday afternoon, according to Art Poland, senior scientist with the Solar and Heliosphere Observatory (SOHO) at the Goddard Space Center in Maryland.

SOHO is a relatively new NASA satellite that is pointed at the sun.

The solar flare was formed Monday when the sun generated a giant shock wave of electrified gases called a coronal mass ejection. SOHO photographs show "a flare going off; you see a shock wave leaving (the sun). Basically, it's a tsunami going across the surface of the sun," Poland said in an interview with CNN.

The first halo CME observed by LASCO



The famous January 6, 1997, event,
(during an ISTP meeting...)

Eruptive prominence Jan.6,
14:00
Shock at 1 AU Jan.10,
00:10
Travel time: 78.5
hours
Average travel speed 530

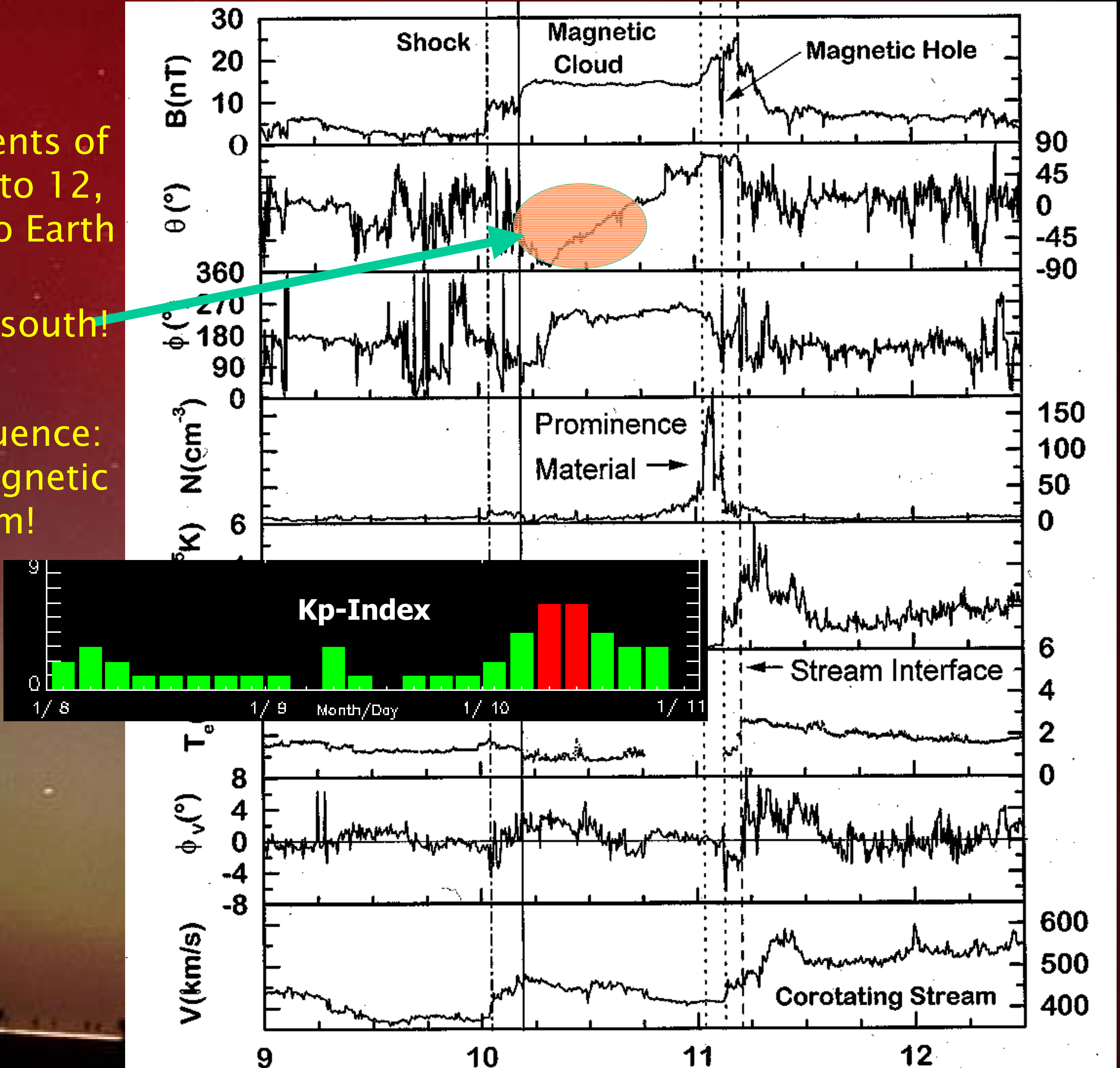
Although it was a really faint, slow, and unspectacular CME, it caused most dramatic effects in geospace, but not before Jan. 11!

6

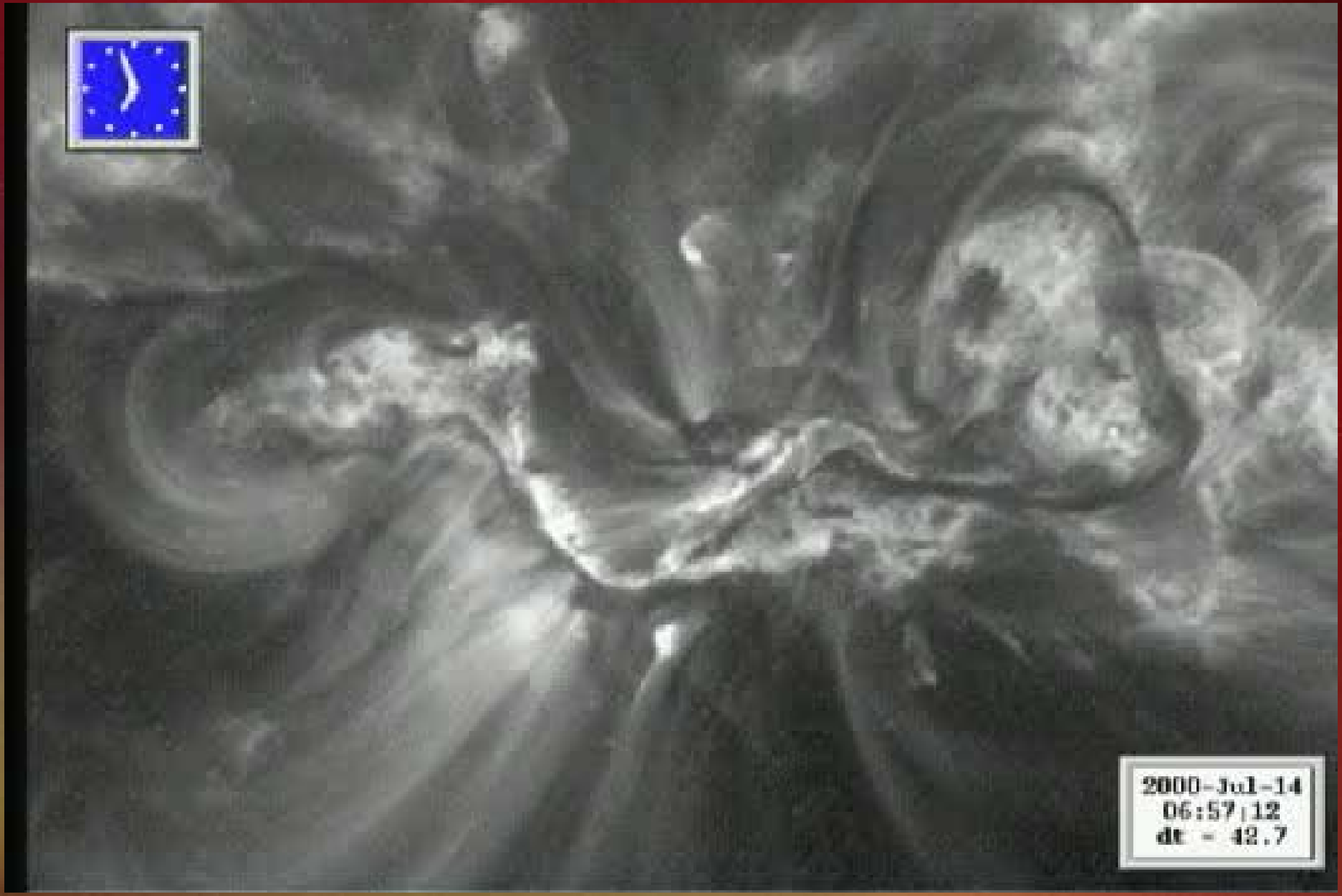
The events of Jan. 9 to 12, close to Earth

B_z turns south!

Consequence: a geomagnetic storm!

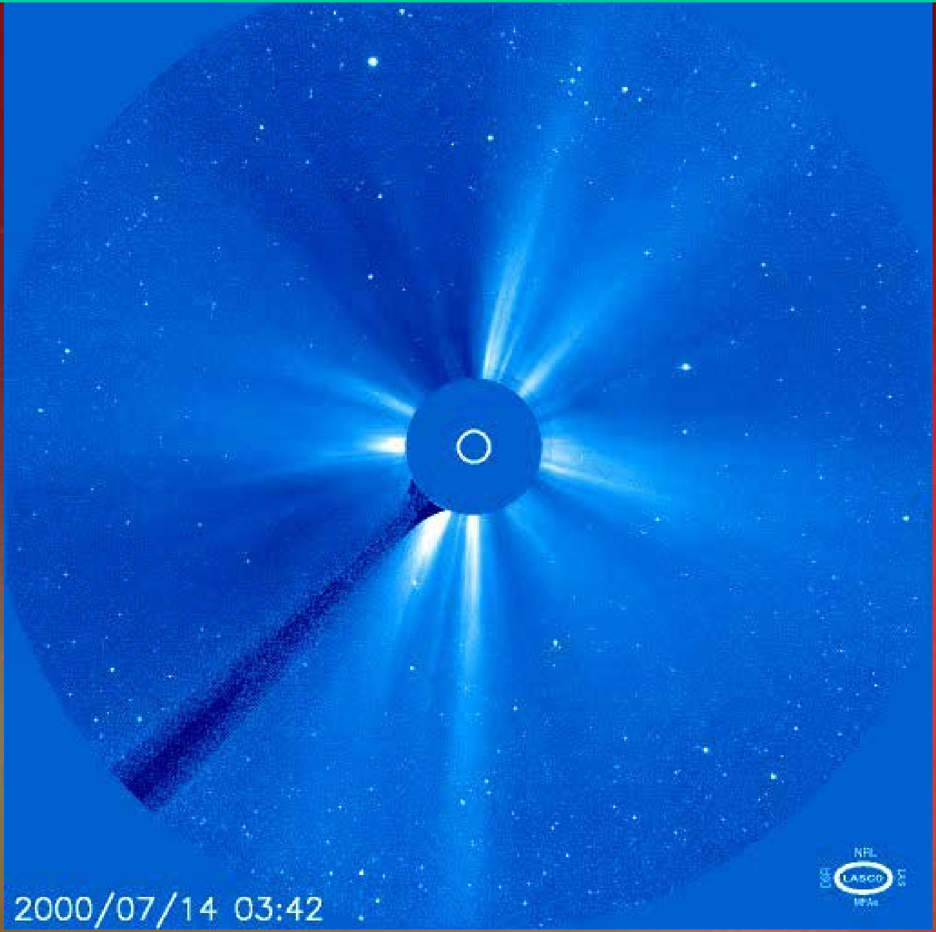


The “Bastille event”, with all blows and whistles: July 14, 2000.



The biggest flare of the present solar cycle, observed by **TRACE** on July 14, 2000.

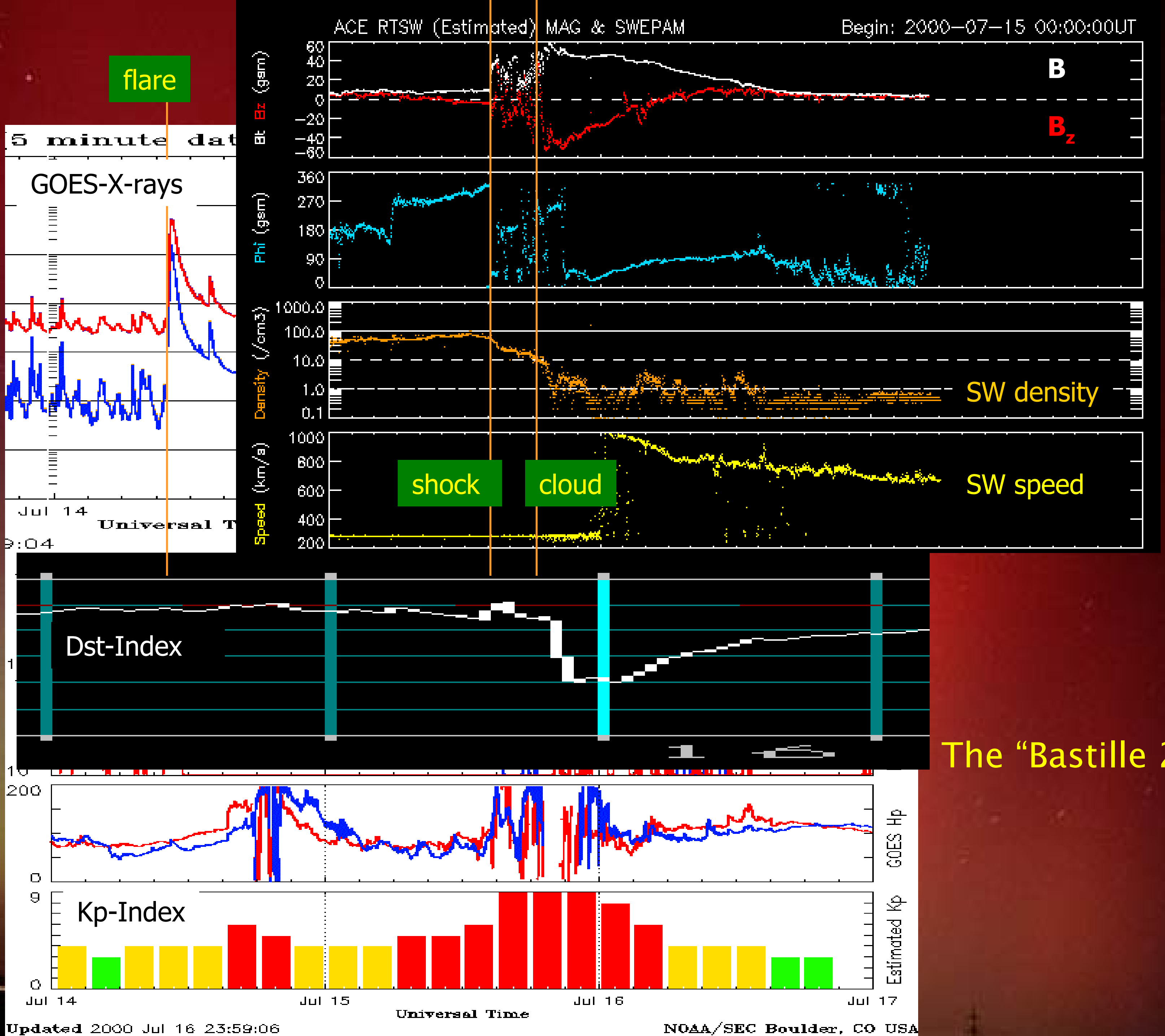
The "Bastille event", with all blows and whistles: July 14, 2000



An optical telescope as a Cosmic Ray detector...!

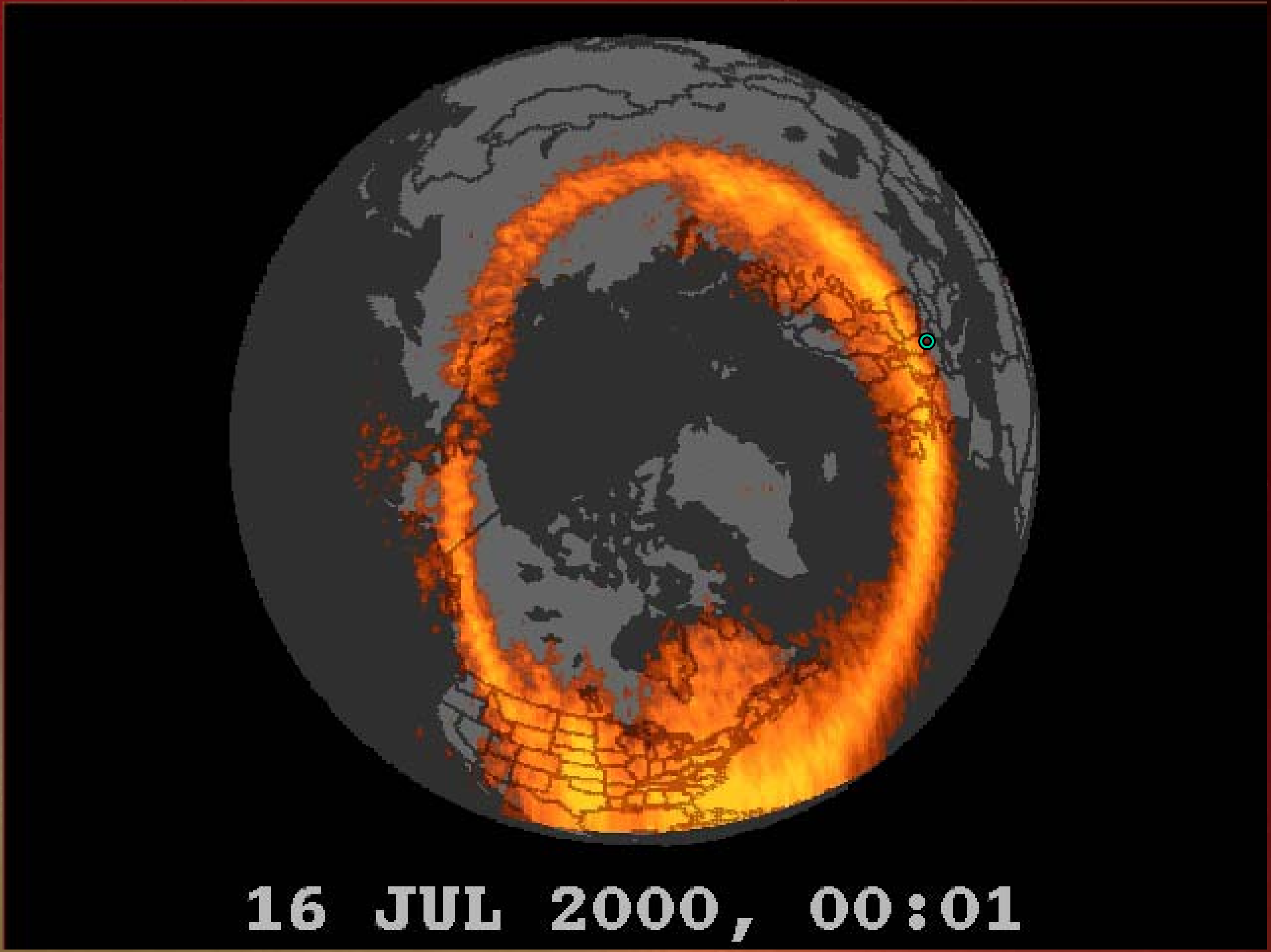
The huge solar mass ejection on July 14, 2000, observed by **LASCO-C3**.

The "snow shower" is due to particles, accelerated to extremely high speeds during the ejection. They penetrate the instrument walls and let the CCD scintillate.

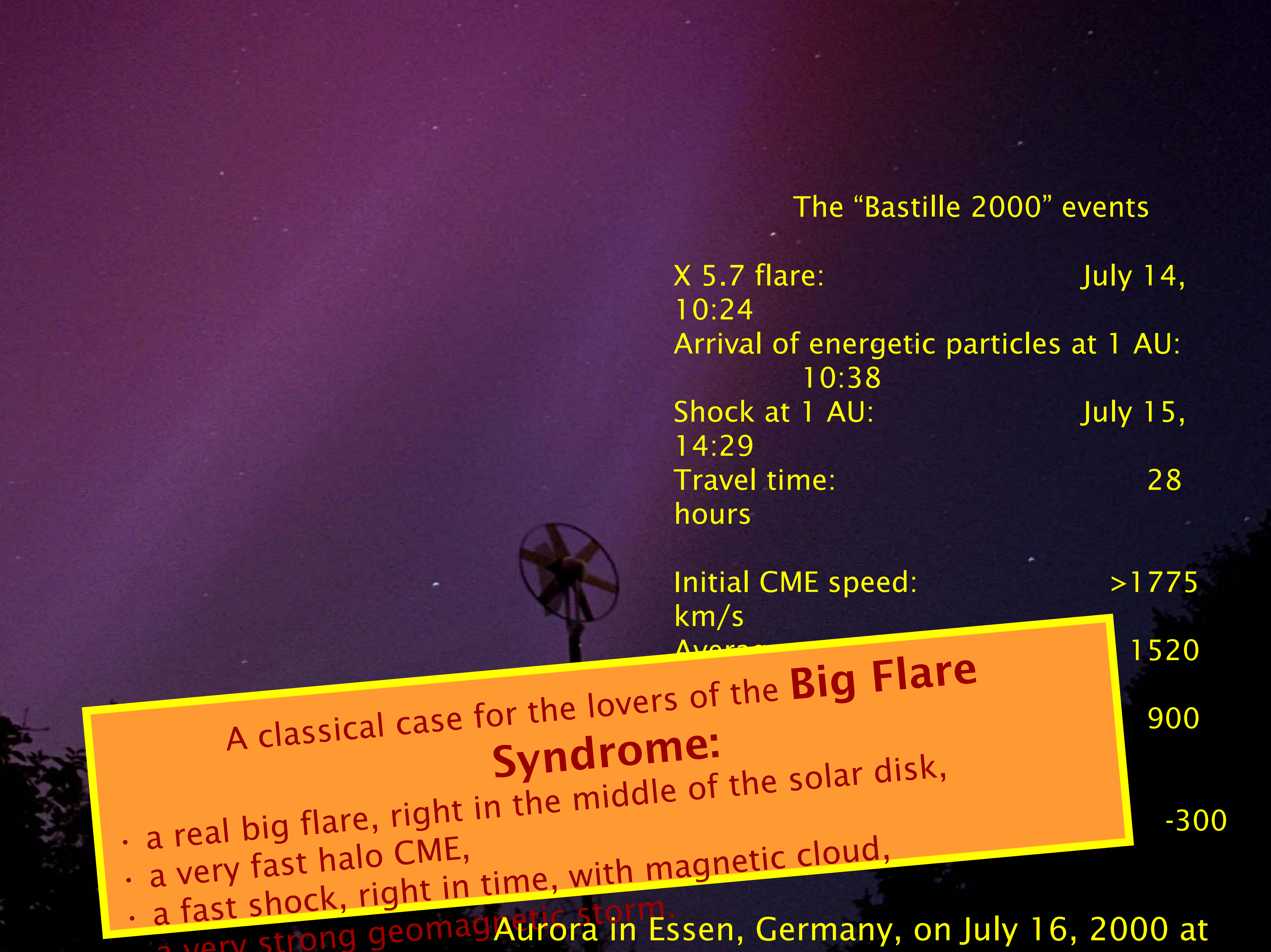


The “Bastille 2000” events

The “Bastille event”: its effects at Earth



That was the auroral oval on July 16, 2000:
aurorae all over the USA and even middle Europe!



The "Bastille 2000" events

X 5.7 flare: July 14, 10:24
Arrival of energetic particles at 1 AU: 10:38
Shock at 1 AU: July 15, 14:29
Travel time: 28 hours

Initial CME speed: >1775 km/s
Avera 1520
900
-300

A classical case for the lovers of the **Big Flare Syndrome:**

- a real big flare, right in the middle of the solar disk,
- a very fast halo CME,
- a fast shock, right in time, with magnetic cloud,
- a very strong geomagnetic storm.

Aurora in Essen, Germany, on July 16, 2000 at

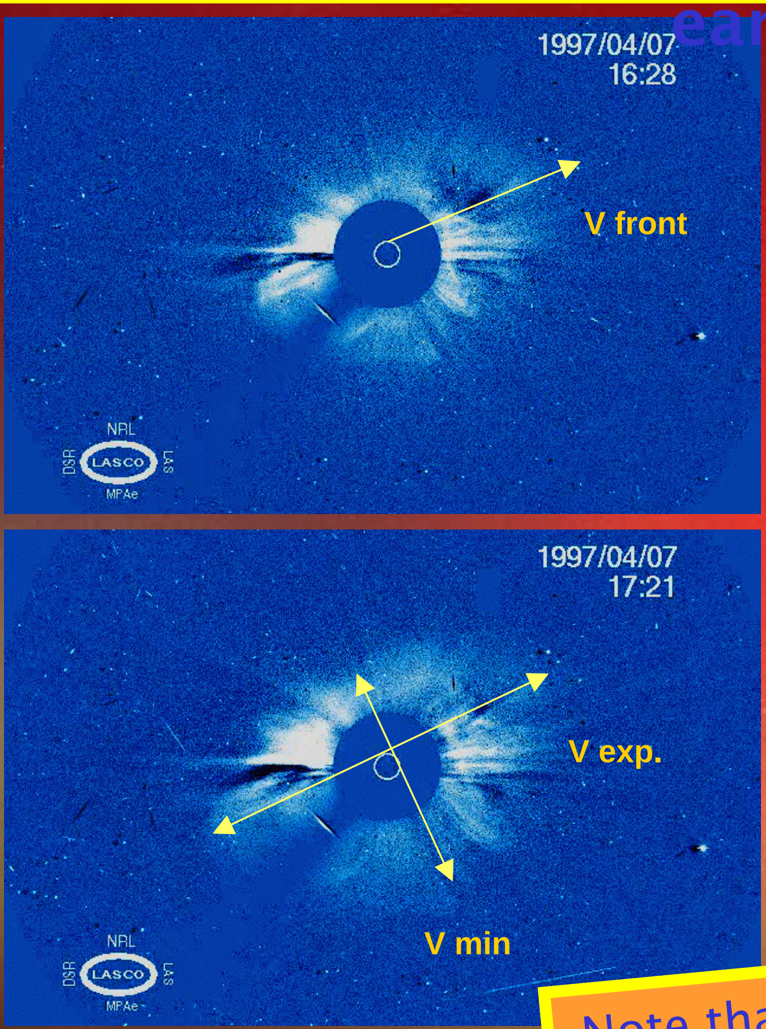
The “Bastille event”: its effects on satellites

14-16 July 2000: proton event & geomagnetic storm, Ap*=192, Dst min = -300 nT

- **ASCA** (Advanced Satellite for Cosmology and Astrophysics) – lost attitude fix resulting in solar array misalignment and power loss, satellite probably lost
- **GOES-8 & -10** – SEM Electron sensor problems, power panels
- **ACE** (Advanced Composition Explorer) – Temporary SW and other sensor problems
- **WIND** – Permanent (25%) loss of primary transmitter power & Temporary loss of Sun and star sensors
- **SOHO** (also **YOHKOH** & **TRACE**) – High energy protons obscure solar imagery
- **GEO** and **LEO** Satellites – S/C orientation problems during MPE

How to predict travel times of halo CMEs?

We cannot measure the speed towards the earth!



Trying to characterize a halo CME:

- use pairs of images from C2 andC3,
- determine speed of outermost front:
- determine maximum expansion speed
- also: minimum expansion speed

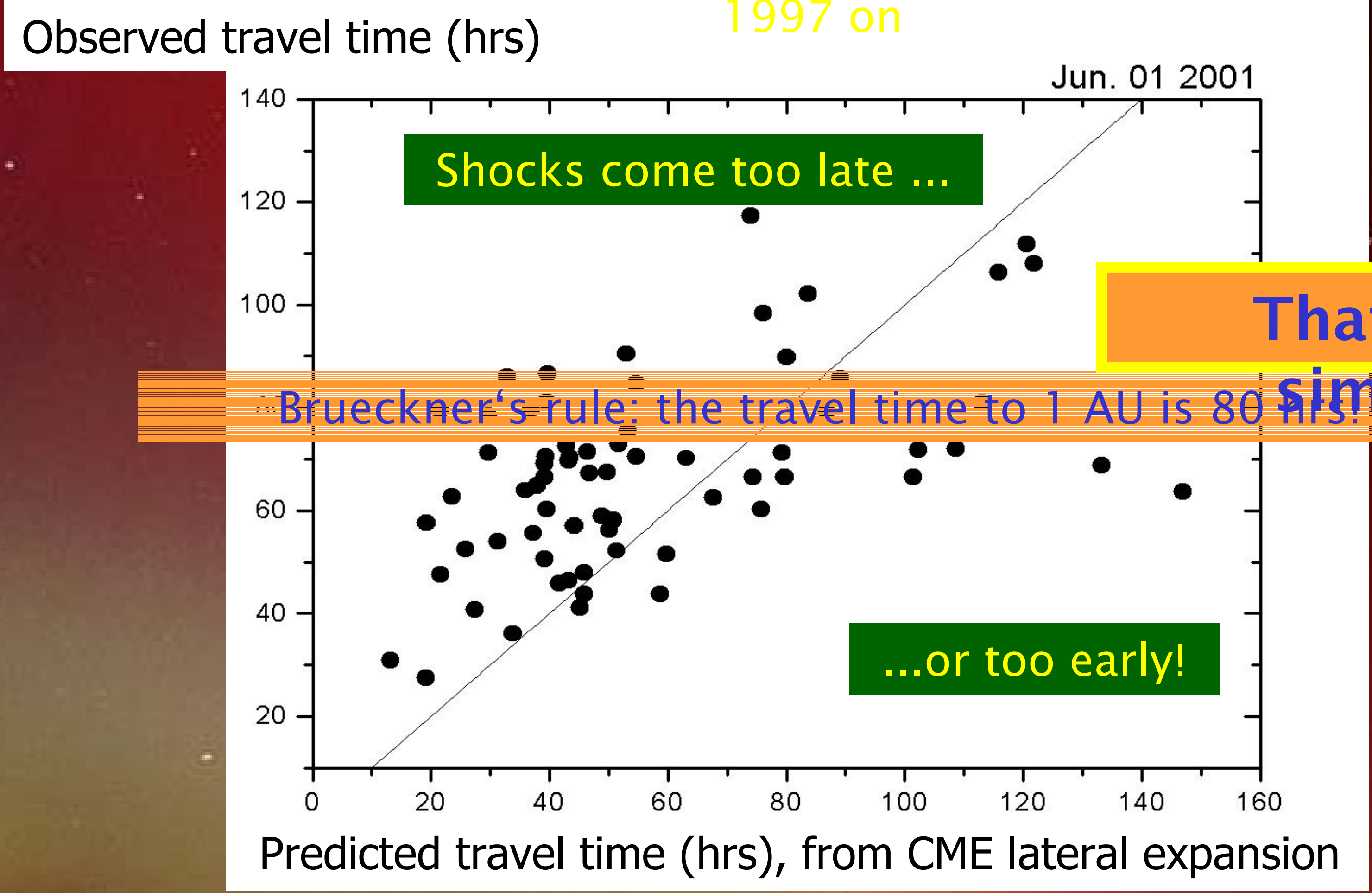
Note though: often the expansion speed varies dramatically between the first appearance above the C2 occulter and the outer edge of C3.

The „travel time“ of a CME is the time difference between the first appearance in C2 and the arrival of the associated

Note that the travel time does NOT give a handle on potential geo-efficiency!

Comparing predictions with reality…

We have analyzed about 200 halo CMEs and their shocks at 1 AU, from 1997 on



Shocks come too late ...

...or too early!

Brueckner‘s rule: the travel time to 1 AU is 80 hrs!

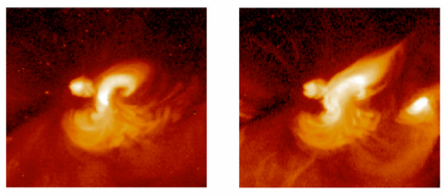
That’s too simple…

Conclusion as of today:

We have not yet found the optimum prediction tool...

Research topics for the future:

- How to predict CMEs/flares before they occur?



Sigmoids?

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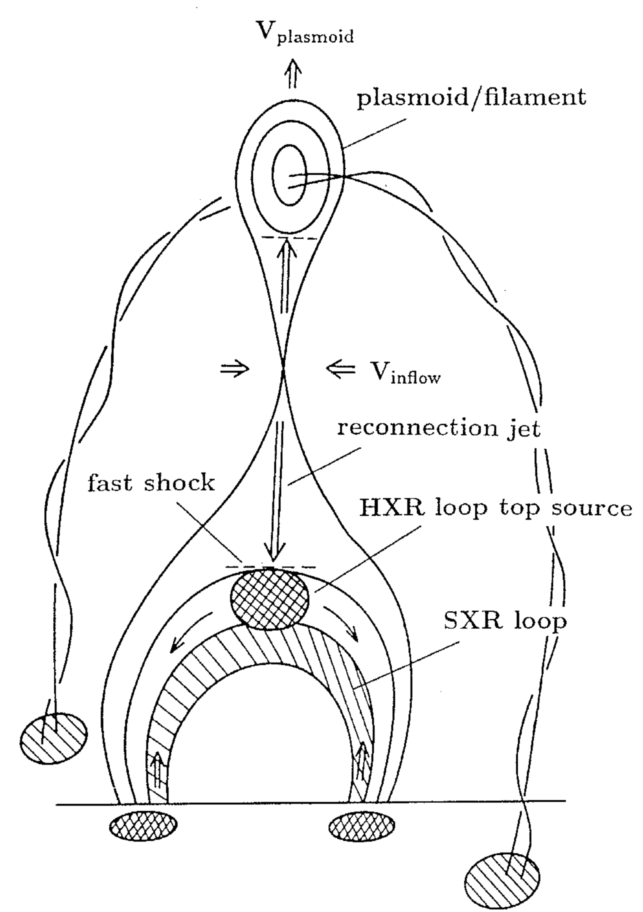

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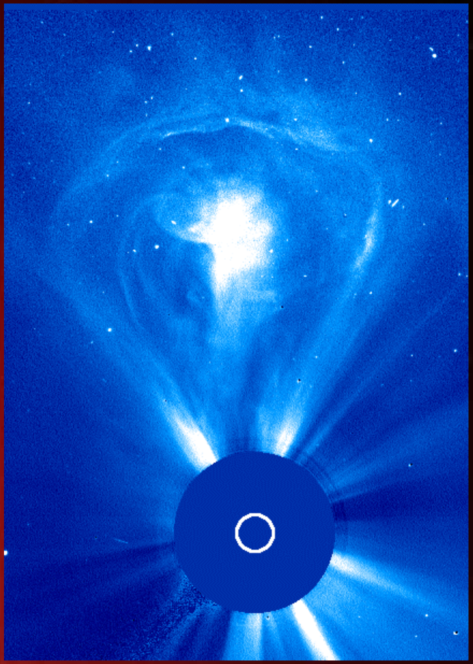

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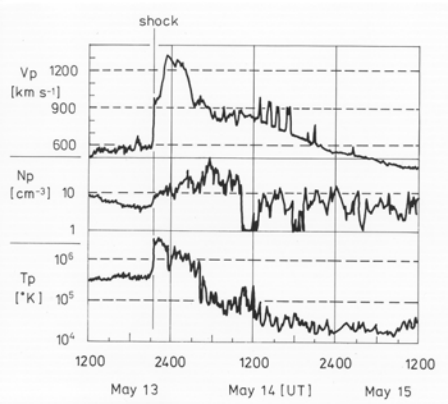

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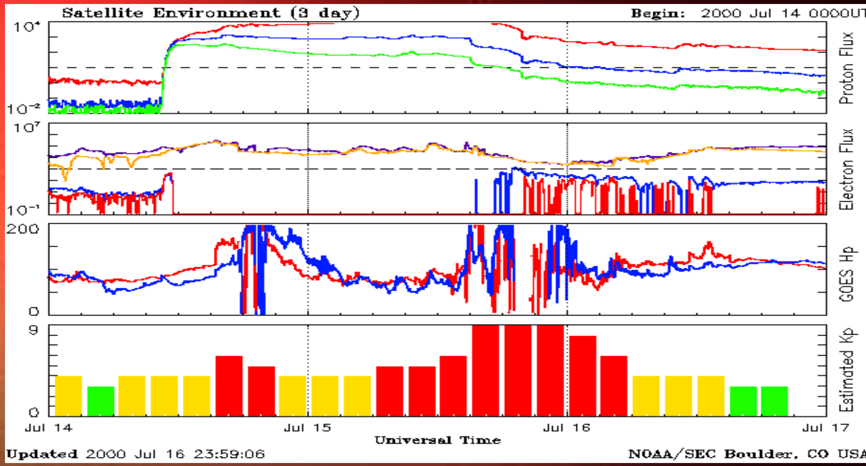
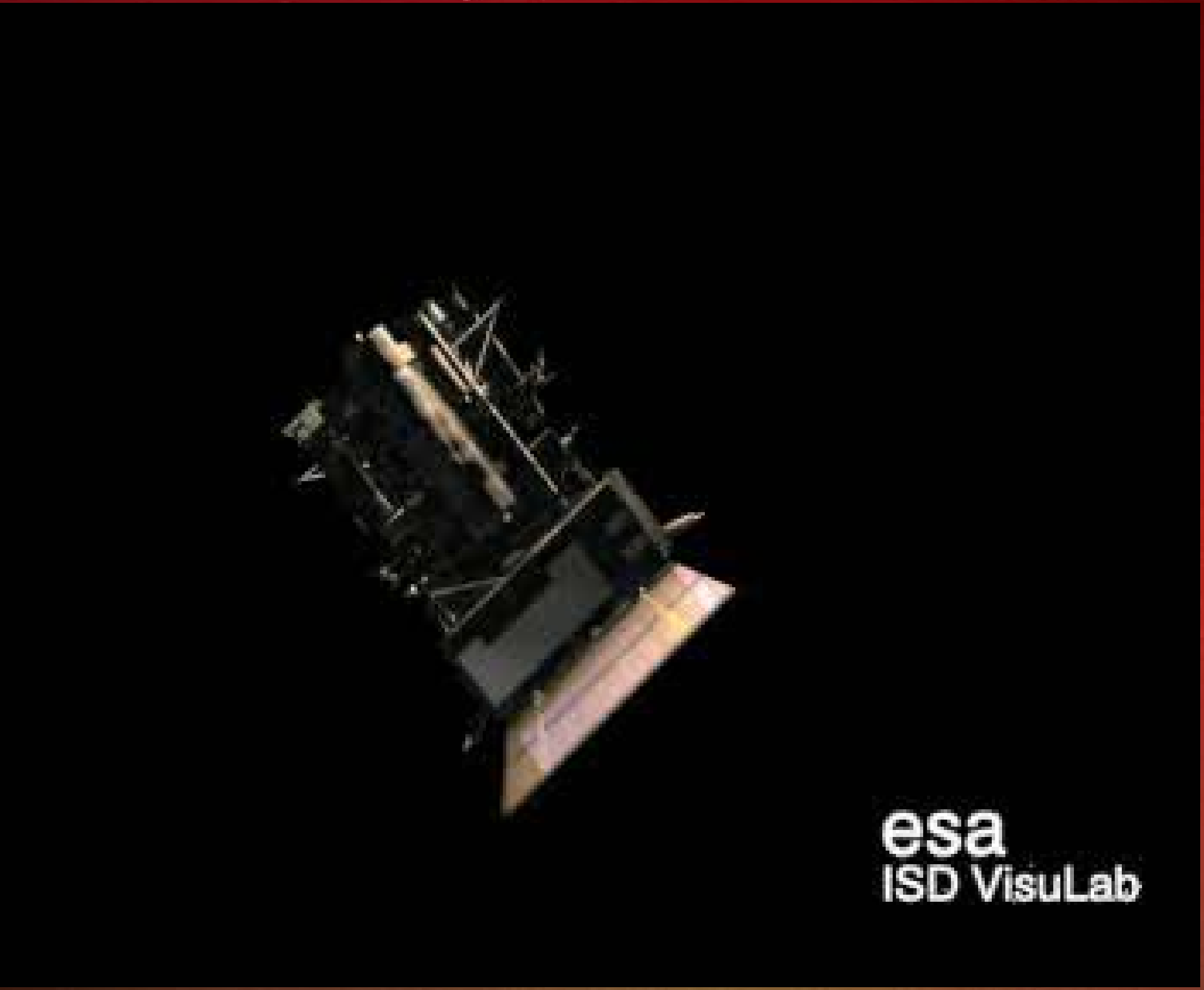
- How to predict geoeffectiveness?



SOHO - A Space Weather mission, after all...



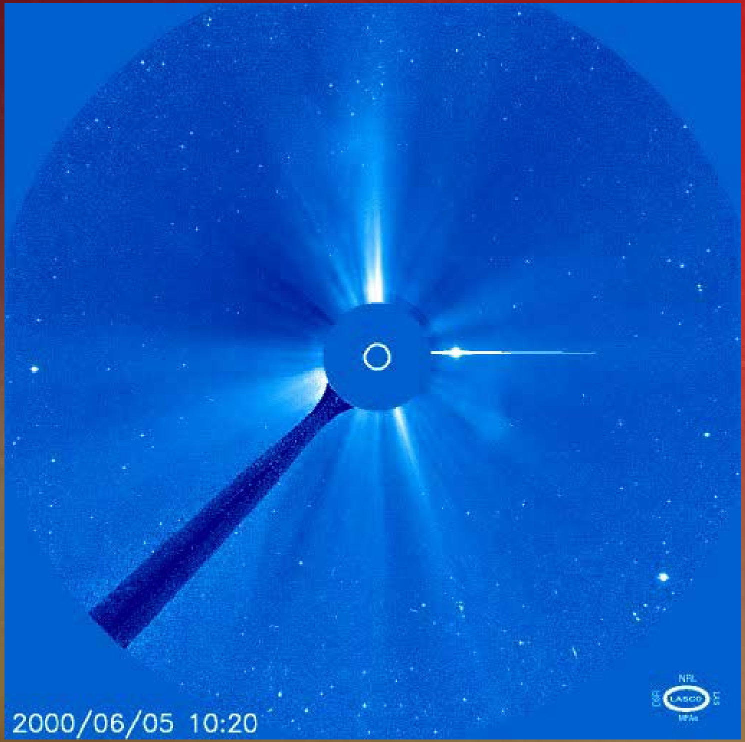
The Solar and Heliospheric Observatory (SOHO), a bilateral space project between ESA and NASA has been observing the sun continuously since early 1996.

It has enhanced our understanding substantially.

It is continuously being used by the professional forecasters.

The Solar Origins of Space Weather

STP-10/CEDAR 2001 Joint Meeting
June 17 to 22, 2001
Longmont, Colorado



For understanding Space Weather, we need new, dedicated missions, plus young researchers to disentangle the unresolved questions!