# Transients on the Sun
# and solar-terrestrial relations

International Max-Planck Research School
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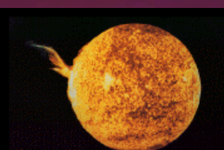
## Effects from Solar Storms



**ELECTROMAGNETIC RADIATION**
*ARRIVAL: IMMEDIATELY*
*DURATION: 1-2 HOURS*

X-RAYS, EUV, RADIO BURSTS

SATCOM INTERFERENCE
RADAR INTERFERENCE
SHORTWAVE RADIO FADES

**HIGH ENERGY PARTICLES**
*ARRIVAL: 15 MIN TO FEW HOURS*
*DURATION: DAYS*

PROTON EVENTS

SATELLITE DISORIENTATION
FALSE SENSOR READINGS
SPACECRAFT DAMAGE
LAUNCH PAYLOAD FAILURE
HIGH ALTITUDE AIRCRAFT RADIATION
SHORTWAVE RADIO FADES

**LOW-MEDIUM ENERGY PARTICLES**
*ARRIVAL: 2-4 DAYS*
*DURATION: DAYS*

GEOMAGNETIC STORMS

SPACECRAFT CHARGING & DRAG
SPACETRACK ERRORS
LAUNCH TRAJECTORY ERRORS
RADAR INTERFERENCE
RADIO PROPAGATION ANOMALIES
POWER BLACKOUTS

Source: Flares | CMEs/Flares | CMEs/Coronal Holes

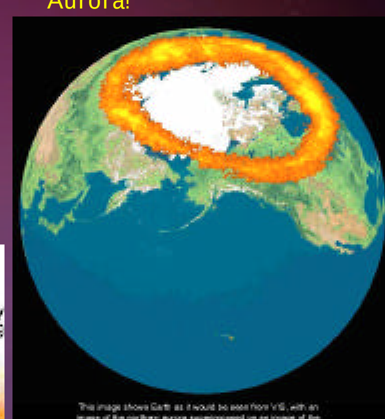
# The Sun as the driver of Space Weather

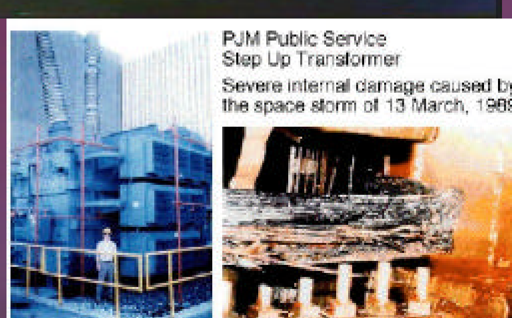
Major geomagnetic storms may cause

- 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

# Space Weather!

Northern lights,
Aurora!

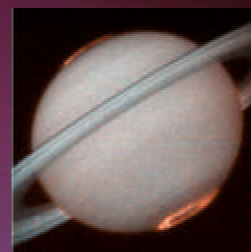


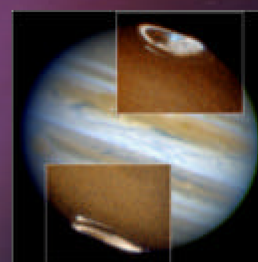



Space "storms" may cause severe damage to, e.g., power systems on earth!

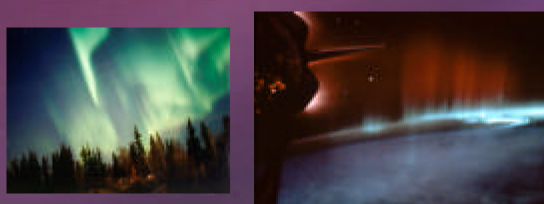
# The cause of space storms

On Saturn



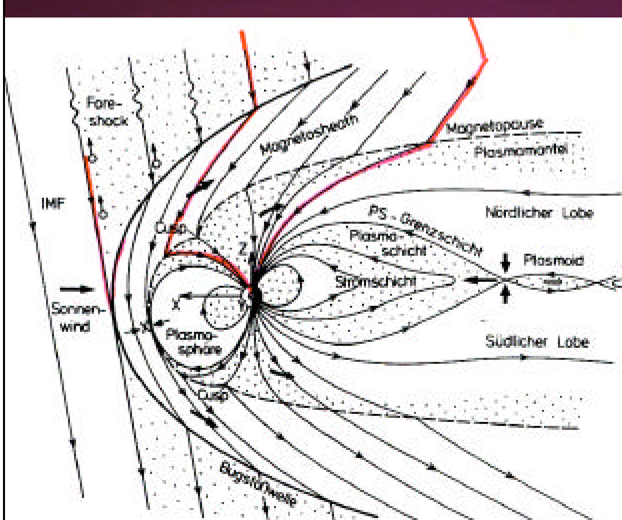


On Jupiter



On Earth

# What makes geospace vulnerable? $B_z$ south!

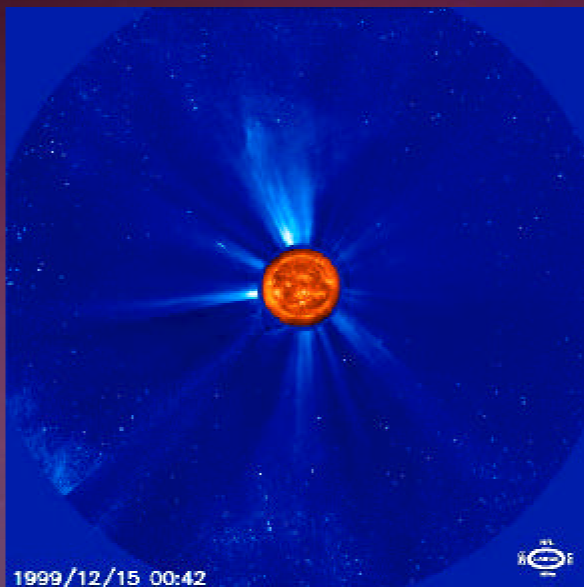



Magnetic reconnection at the front side of the magnetosphere occurs, when the interplanetary $B_z$ turns south, i.e. anti-parallel to the Earth's intrinsic field.

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

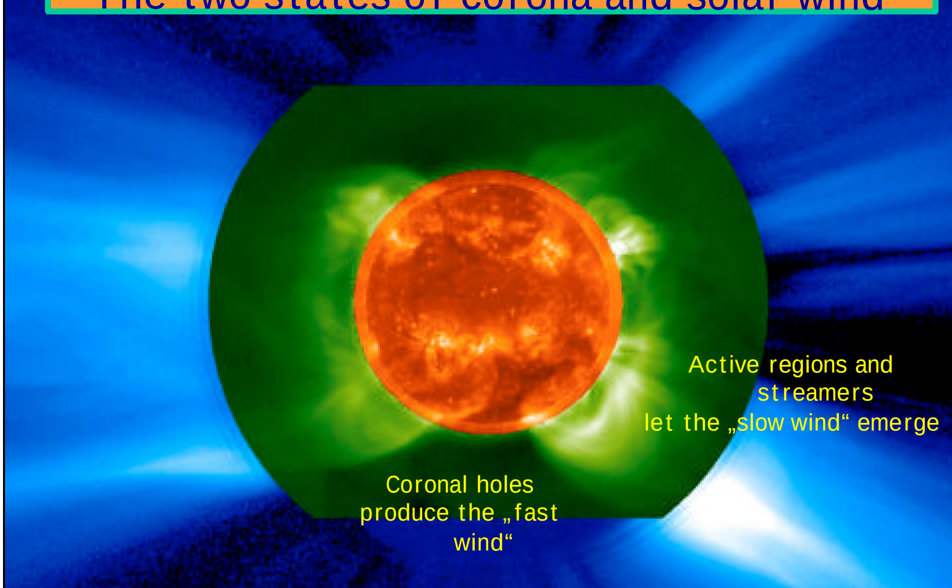
Reconection in the tail causes ejection of plasmoids away from the Earth and injection of lobe plasma into the polar caps.

# What makes the interplanetary $B_z$ turn southward?



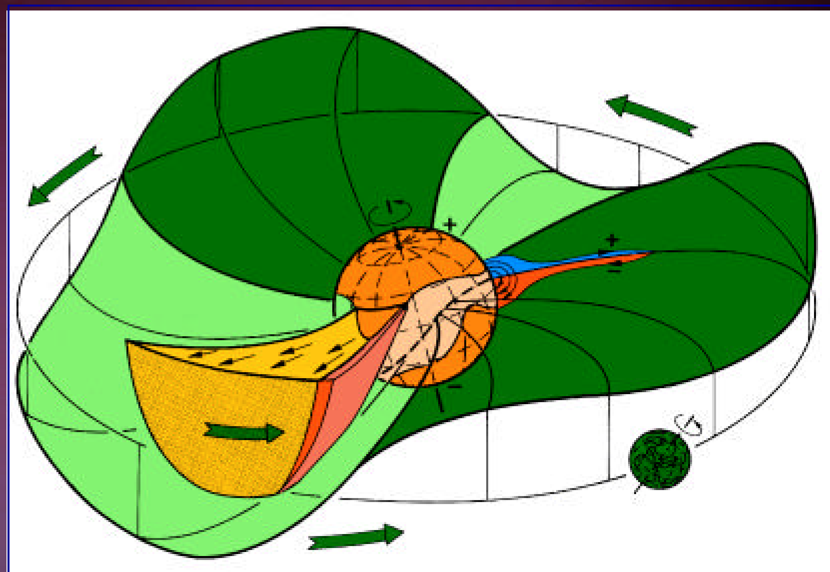

- Fluctuations (Alfvénic) in fast streams from the **quiet sun**
- Deflections in front of and inside ejecta from transient events on the **active sun**

# The two states of corona and solar wind

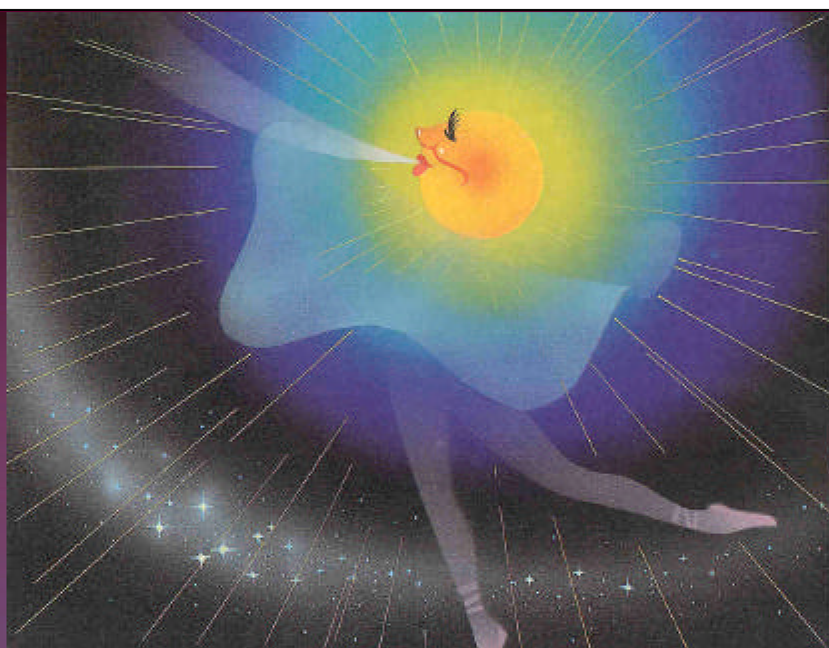



The corona of sun at beginning activity (1998), viewed by **EIT** and **LASCO-C1/C2**

## The two states of corona and solar wind

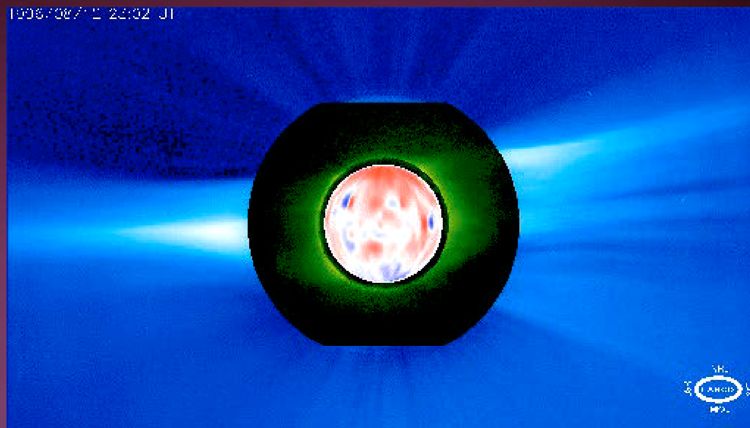


The Sun as a "ballerina", according to *Alfvén, 1977*.



The Sun as a "ballerina"

## See the ballerina dance!

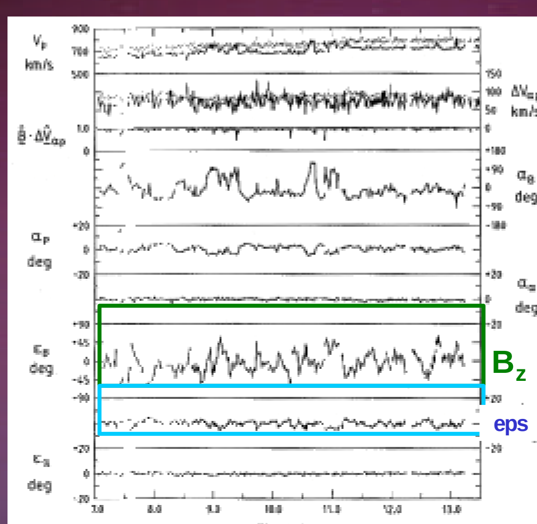


The Sun and its corona at solar activity minimum during the Whole Sun Month (WSM) in 1996, seen by the **LASCO C1/C2** coronagraphs on **SOHO** and the **WSO** magnetograph.

At times, coronal holes and high speed streams emerging from there reach down to the ecliptic plane.

## How to obtain $B_z$ south?

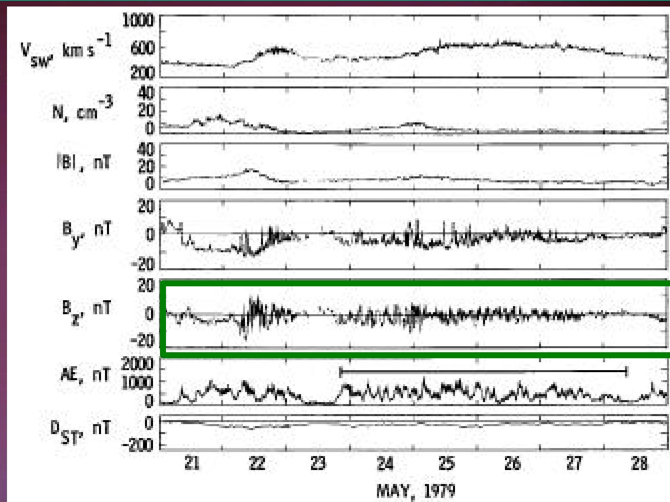
## 1. By Alfvén waves in high speed streams



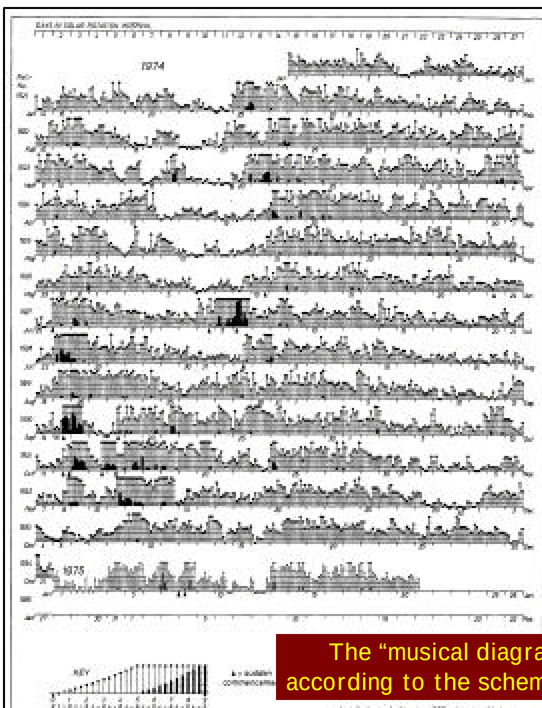

Alfvén waves cause substantial deflections in both: flow direction and magnetic field.

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

# High speed streams: M-regions!

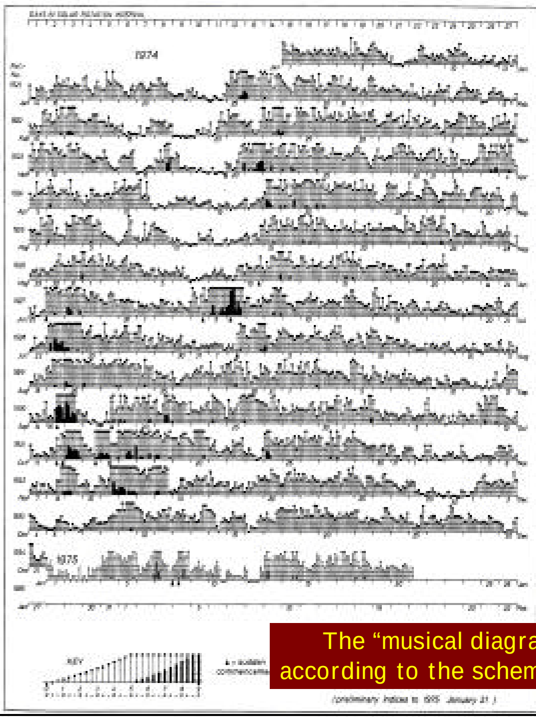



Alfvén waves occur usually in high speed streams. Their magnetic excursions include $B_z$-components that cause mild geomagnetic effects. Conclusion: the high speed streams are the "M-regions", as they were termed by Bartels in the 1930s.




M-regions often persist for many solar rotations, in particular at low solar activity. So do high speed streams from coronal holes (i.e. the inactive" sun).

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

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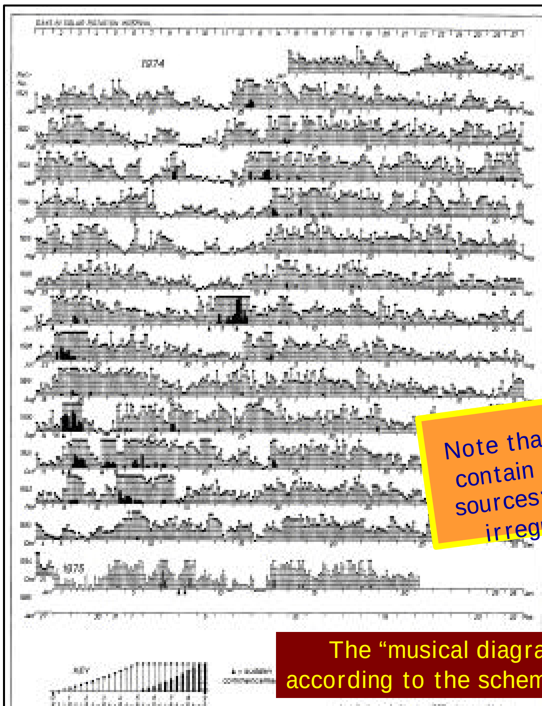
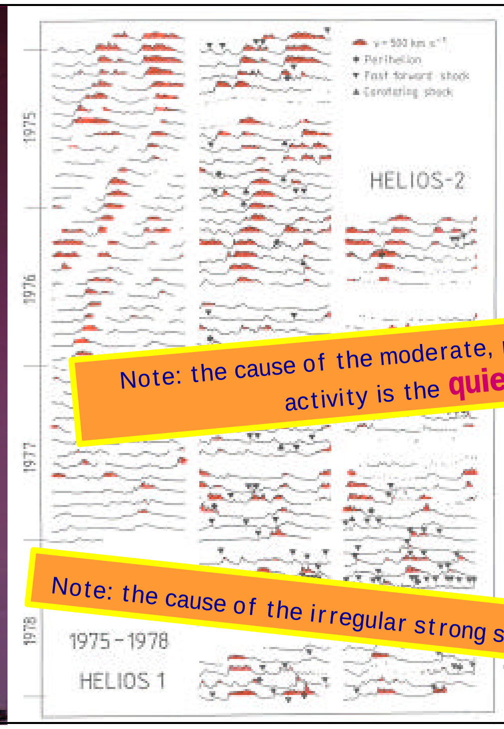



M-regions often persist for many solar rotations, in particular at low solar activity. So do high speed streams from coronal holes (i.e. the inactive" sun).

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)



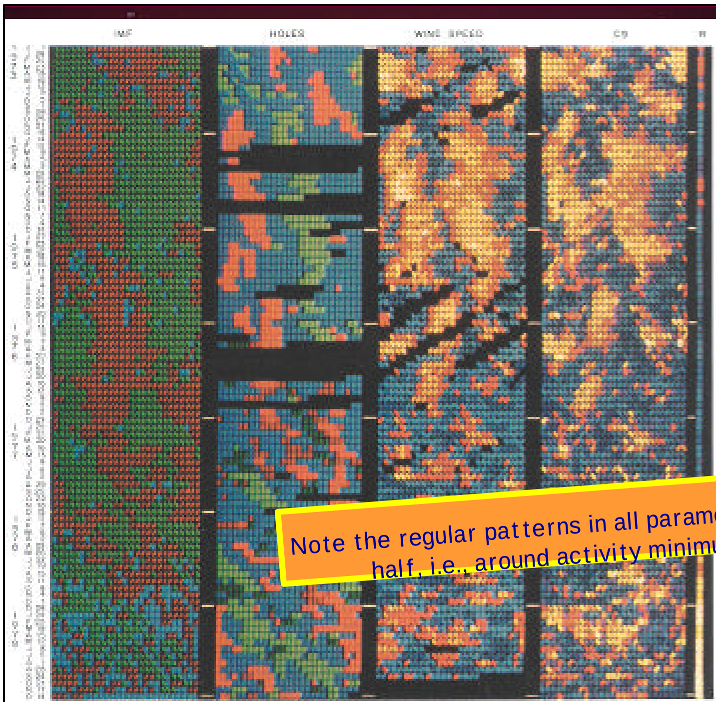

The solar wind stream structure, observed by the Helios and IMP spacecraft around the activity minimum in 1976

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

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

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

Note: the cause of the irregular strong storms is the **active Sun**



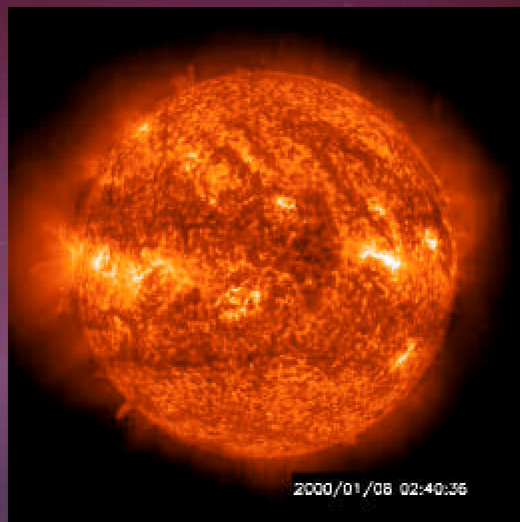

7 years of data, arranged by solar rotations:

- IP Magnetic field,
- Coronal holes,
- Solar wind speed,
- Geomagnetic index

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

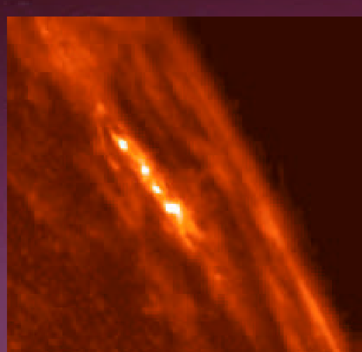
## How to obtain $B_z$ south?

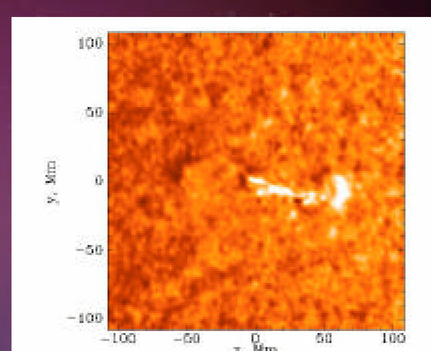
## 2. Here comes the the **active Sun**!



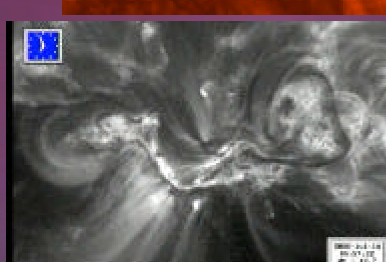

The „active“ sun, seen in EUV by EIT on SOHO

## Flares



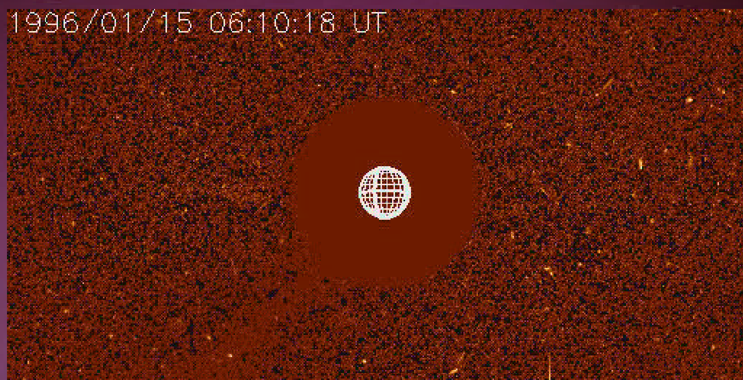



A „sun quake“, triggered by a strong flare, observed by MDI on SOHO on July 9, 1996



The „Bastille“ flare, on July 14, 2000

# Coronal mass ejections (CMEs)



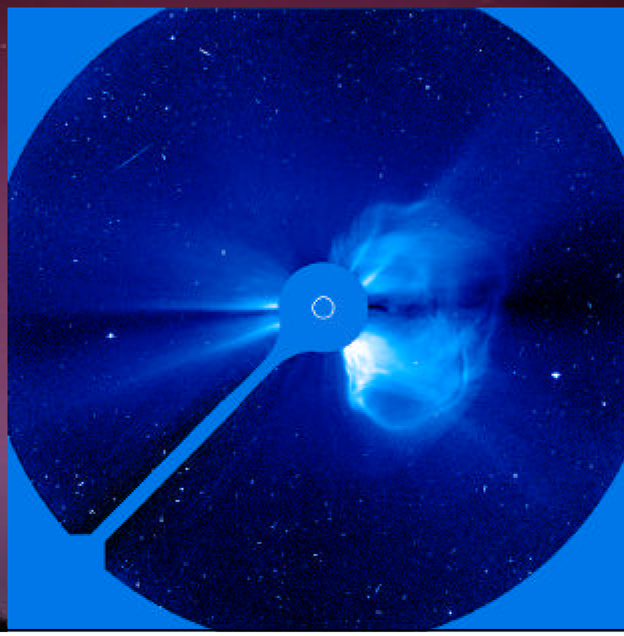

The CME of Jan 15, 1996, as seen by LASCO **- C3** on **SOHO**

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

Skylab people claimed to have discovered CMEs. They are not right...

This CME observation at the eclipse of 1860 was not taken seriously. Bad luck for a discoverer!

## Some CMEs are really spectacular!



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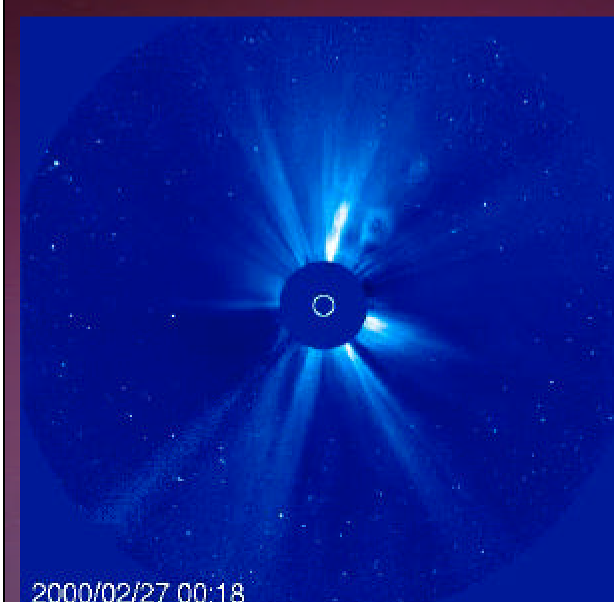
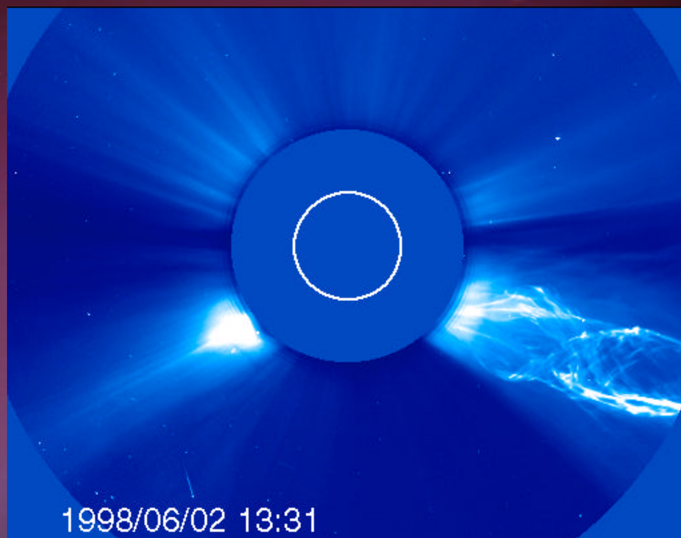


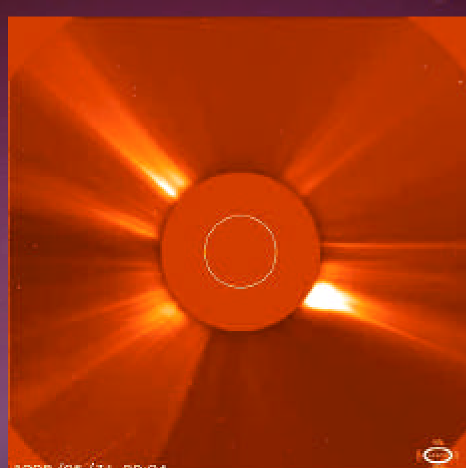

The „lightbulb“ CME, observed in February 2000 by LASCO C3 on SOHO

## Some CMEs are really spectacular!




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

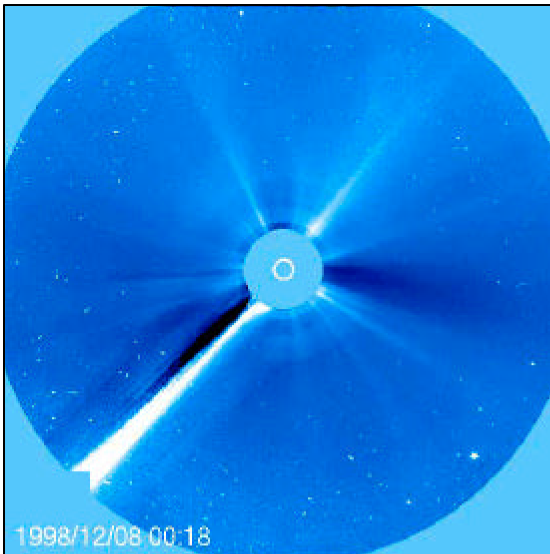
## Some CMEs are really spectacular!

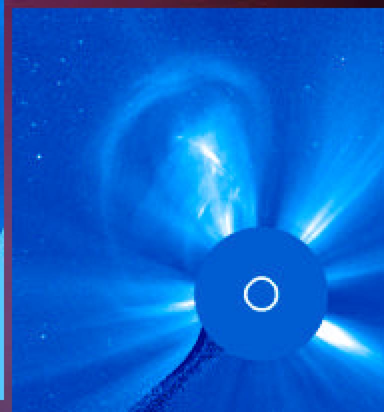



The same CME, seen as a quick-motion movie

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!

## Some CMEs are spectacular!

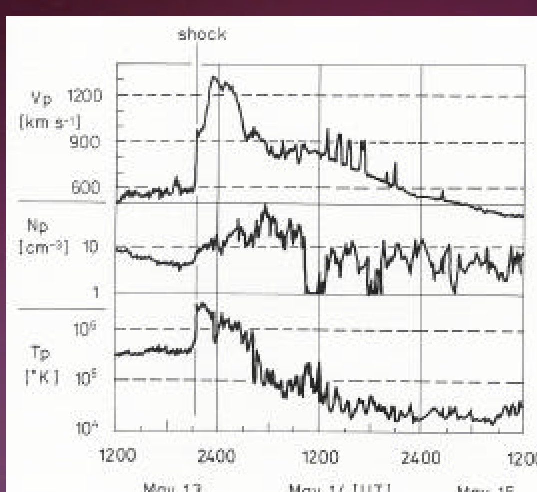


Most big CMEs show a characteristic 3-part structure:

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

## Fast CMEs drive interplanetary shock waves



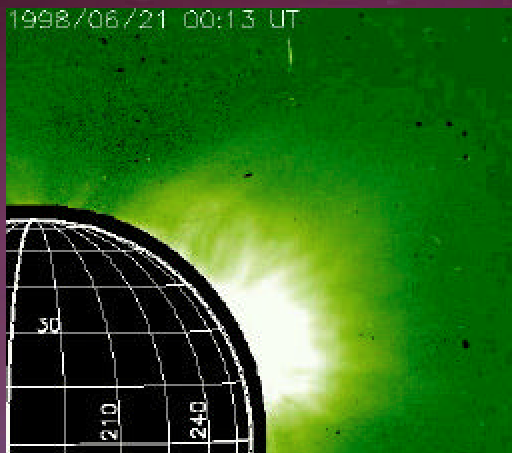

A very fast interplanetary shock wave, as seen by **Helios** in 1978

Such shock waves literally shake up the whole heliosphere!

These are typical CME products in the interplanetary medium:

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

## There is a huge variety of CMEs, including soft ones!



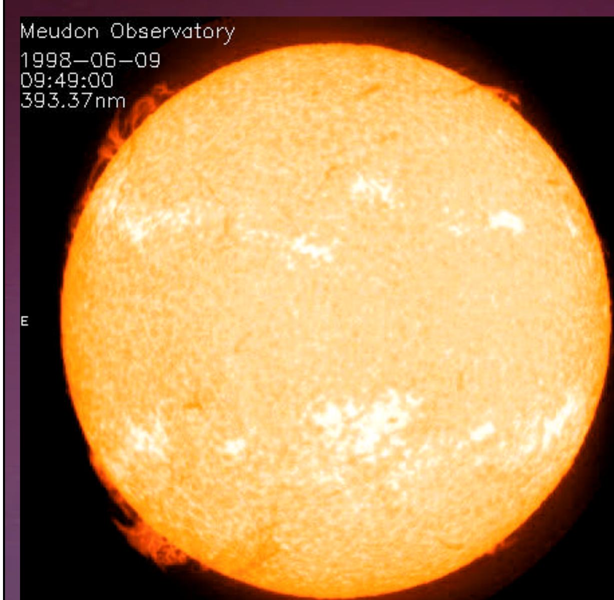

Here comes a "balloon-type" CME, observed by **LASCO-C1,** on June 21, 1998.

It also shows the characteristic 3-part structure:

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

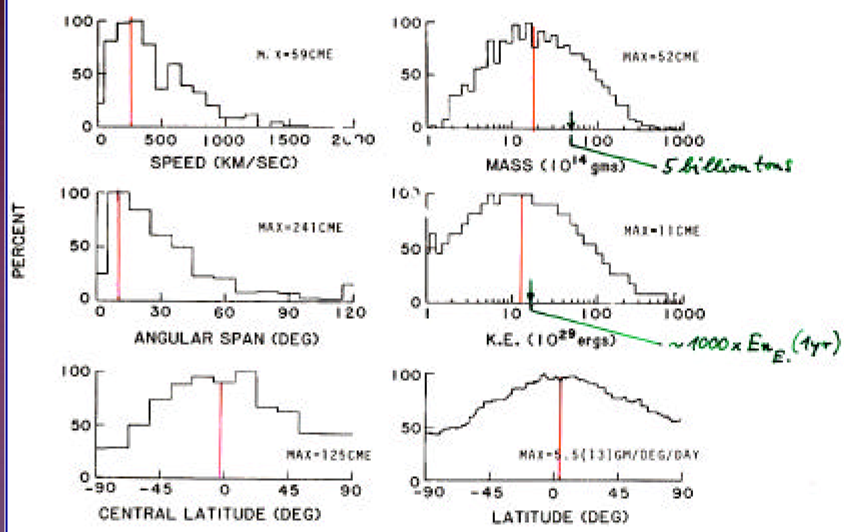
This balloon took some 30 hours to finally take off!
It ran away at the slow wind speed, probably no shock was associated with it.
It was the offspring of an eruptive prominence.

## There is a huge variety of CMEs



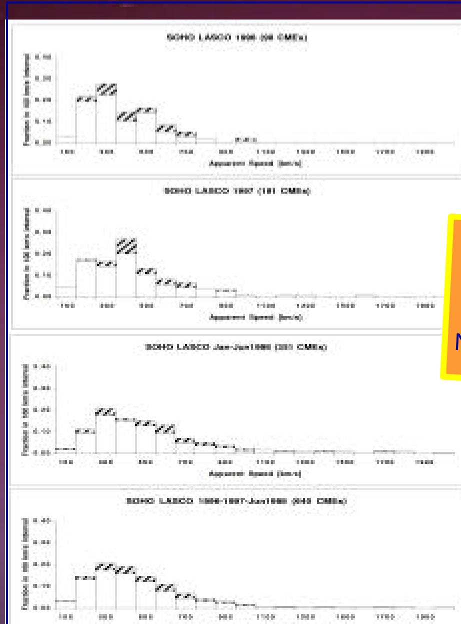

The balloon type CME on June 21, 1998 was due to a filament that had been observed in H-alpha and the K-line during its complete journey across the disk, before it finally erupted.

# Properties of CMEs, 1979 to 1981



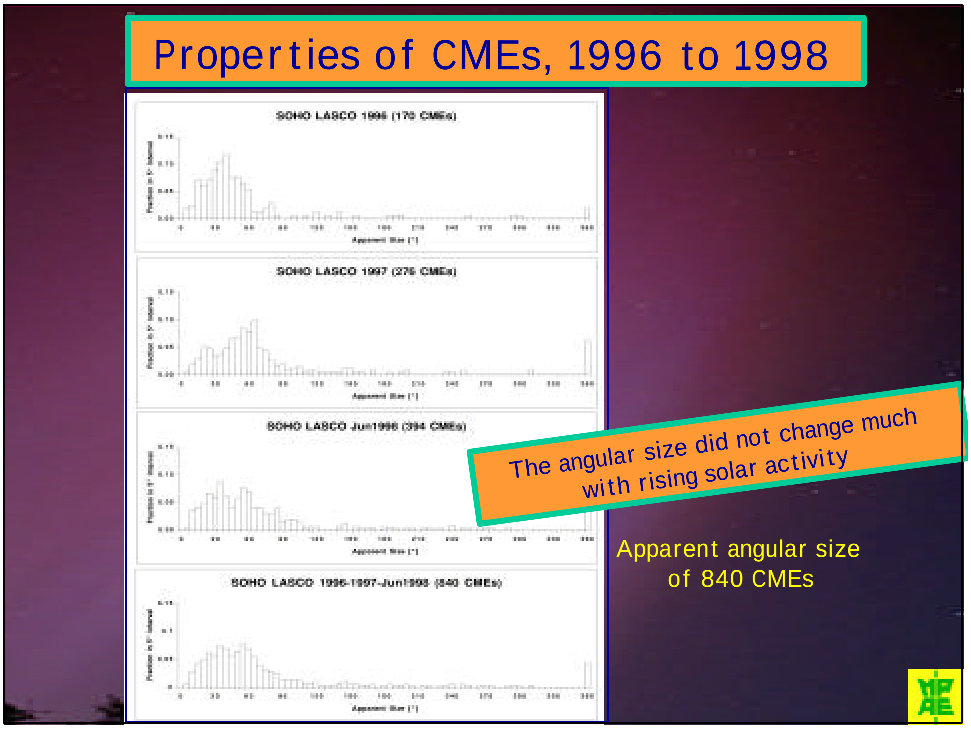

Statistical analysis of about 1000 CMEs observed by **SOLWIND**

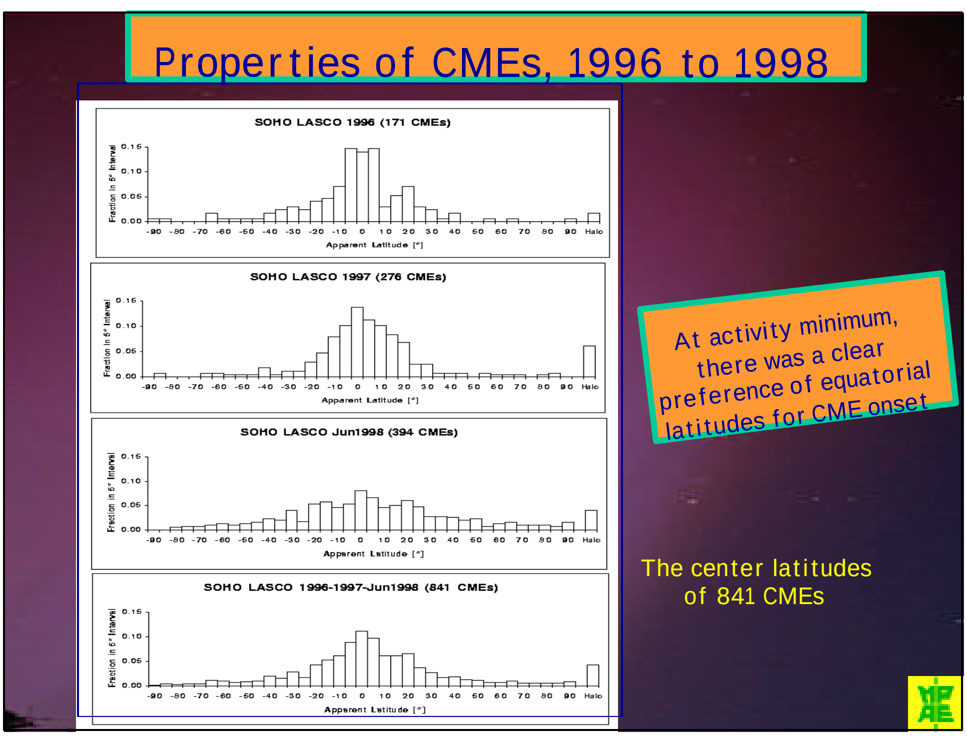
# Properties of CMEs, 1996 to 1998



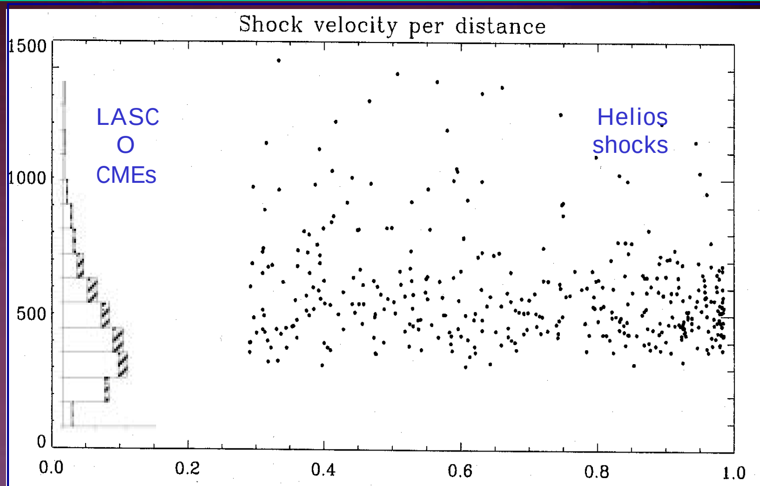
Note the small number of slow CMEs! The increased sensitivity of the modern instrumentation has NOT increased the number of slow, faint CMEs.

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


Properties of CMEs, 1996 to 1998
SOHO LASCO 1996 (170 CMEs)
SOHO LASCO 1997 (276 CMEs)
SOHO LASCO Jun1998 (394 CMEs)
SOHO LASCO 1996-1997-Jun1998 (840 CMEs)
The angular size did not change much with rising solar activity
Apparent angular size of 840 CMEs


Properties of CMEs, 1996 to 1998
SOHO LASCO 1996 (171 CMEs)
SOHO LASCO 1997 (276 CMEs)
SOHO LASCO Jun1998 (394 CMEs)
SOHO LASCO 1996-1997-Jun1998 (841 CMEs)
Fraction in 5° Interval
Apparent Latitude [°]
At activity minimum, there was a clear preference of equatorial latitudes for CME onset
The center latitudes of 841 CMEs

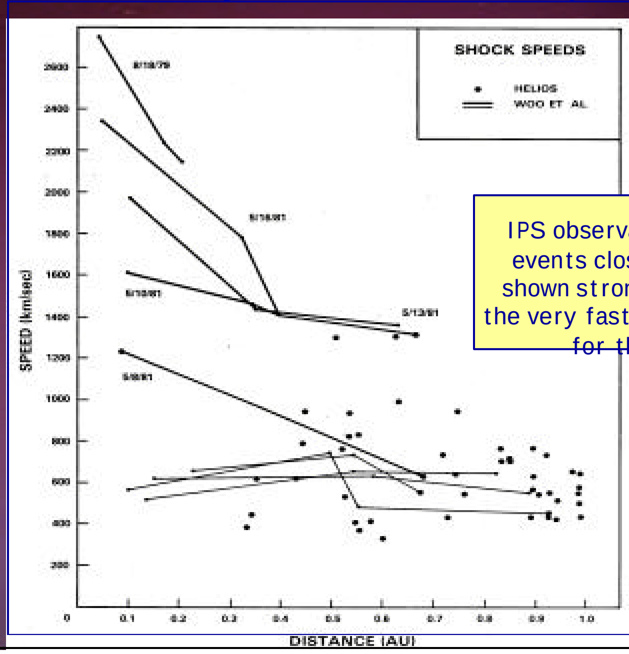
# How do ejecta and shocks propagate?




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

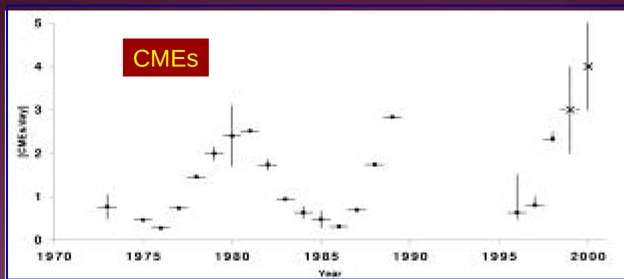
Apparently, there is no significant deceleration beyond 0.3 AU. It must occur closer to the sun!

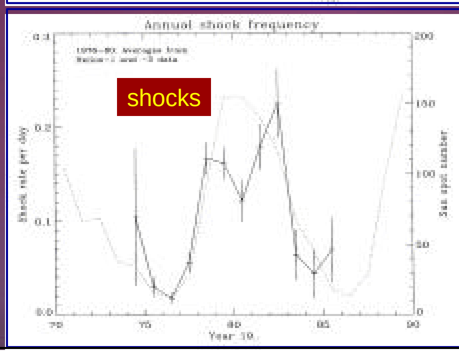
# How do ejecta and shocks propagate?




IPS observations of transient events close to the sun have shown strong deceleration for the very fast events, not so much for the slow ones.

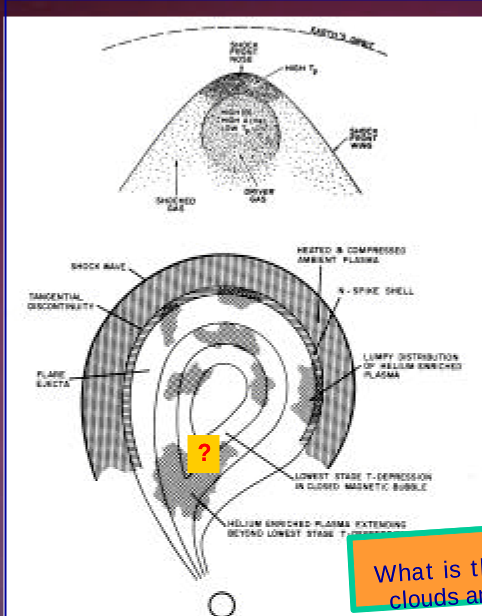
# CMEs and shocks during 2 solar cycles



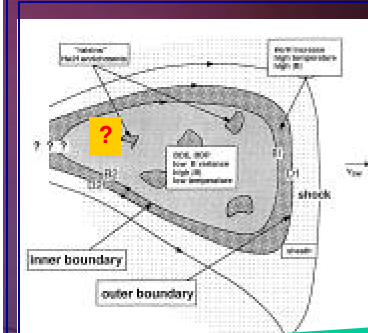




- That means: only one out of 10 CME shock hits the earth!
- That, in turn, means: the average cone angle of shock fronts amounts to about $100^0$,
- Note that the average cone angle of CMEs is only $50^0$.
- In other words: the shock fronts extend much further than the ejecta!

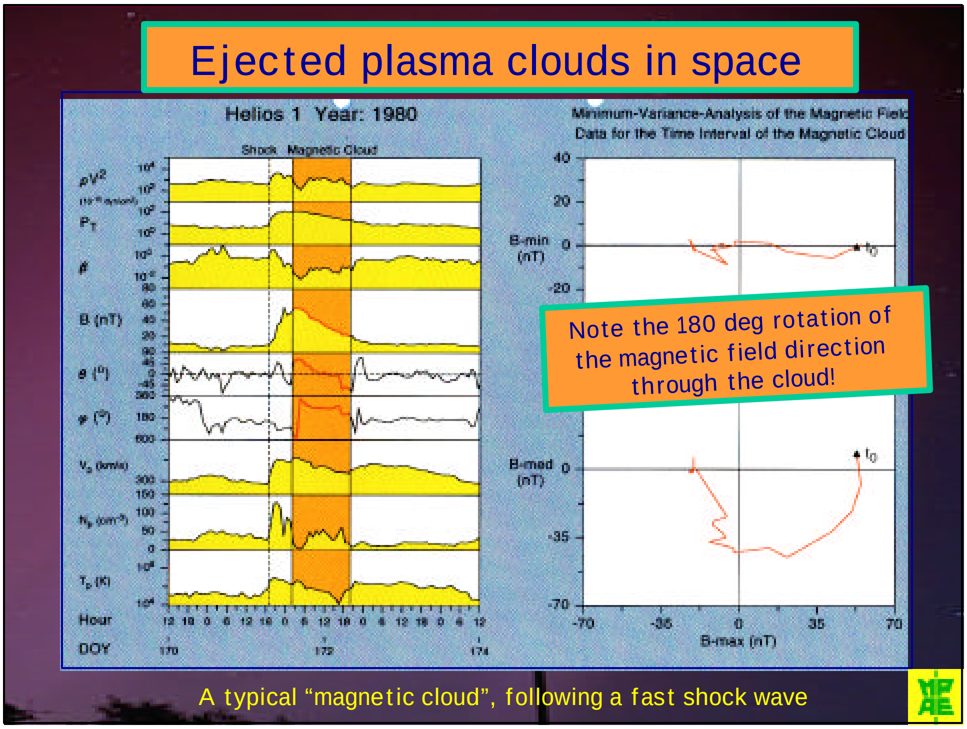
# Ejected plasma clouds and shocks in space

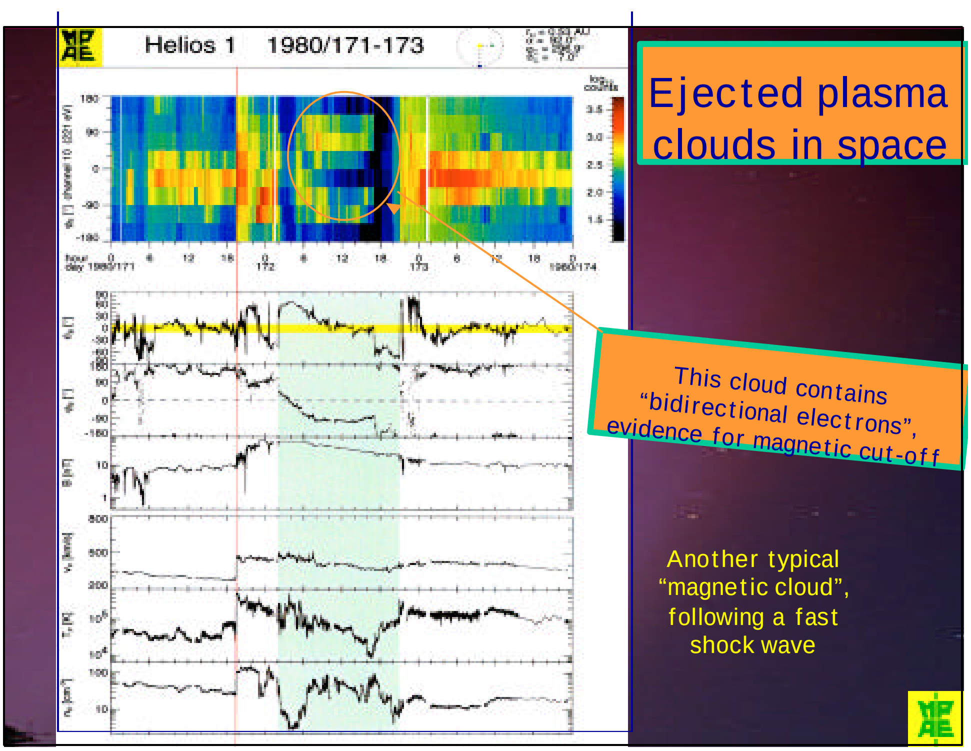



These are old sketches from the 1970s. We have now new evidence for the shock fronts to be much larger than their associated ejecta!




What is the shape of the ejected plasma clouds and the associated shock wave?

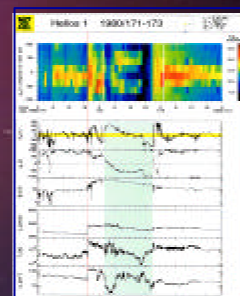

Ejected plasma clouds in space
Helios 1 Year: 1980
Shock Magnetic Cloud
Minimum-Variance-Analysis of the Magnetic Field
Data for the Time Interval of the Magnetic Cloud
B (nT)
Hour
DOY
B-min (nT)
B-med (nT)
B-max (nT)
Note the 180 deg rotation of the magnetic field direction through the cloud!
A typical "magnetic cloud", following a fast shock wave


Helios 1 1980/171-173
Ejected plasma clouds in space
This cloud contains "bidirectional electrons", evidence for magnetic cut-off
Another typical "magnetic cloud", following a fast shock wave

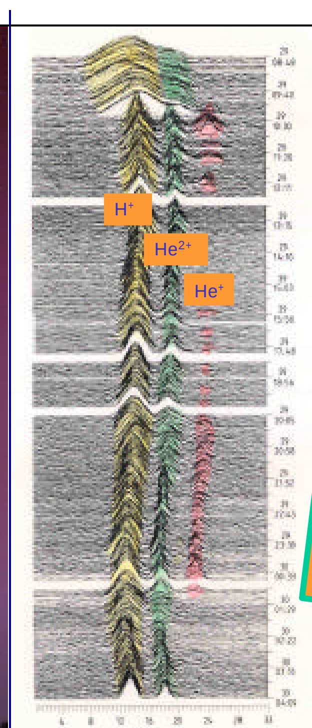
# Ejected plasma clouds in space

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.**



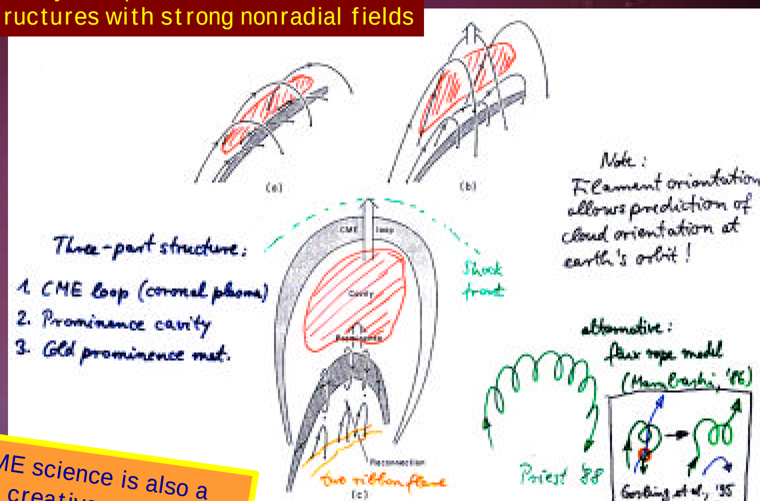

# Ejected plasma clouds in space

Discovery of singly ionized Helium ions in the driver gas following an interplanetary shock wave by **Helios 1** in January 1977: remnants of cold prominence material.

There was only one more such event in July 1977. The next one occurred not earlier than in January 1997, following the halo event on Jan. 6th.

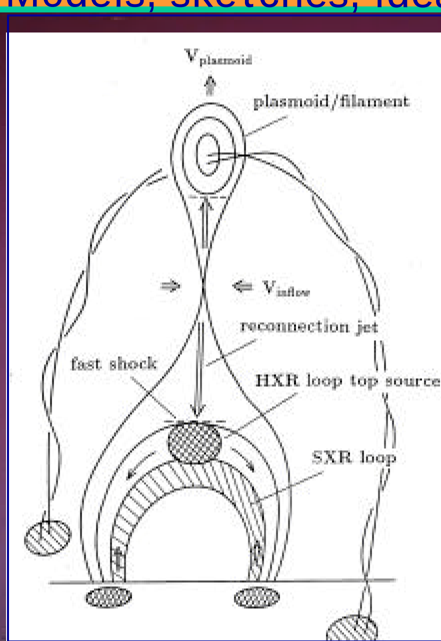
## Why does $B_z$ turn south following CMEs?

It is generally accepted that CMEs involve fluxrope structures with strong nonradial fields

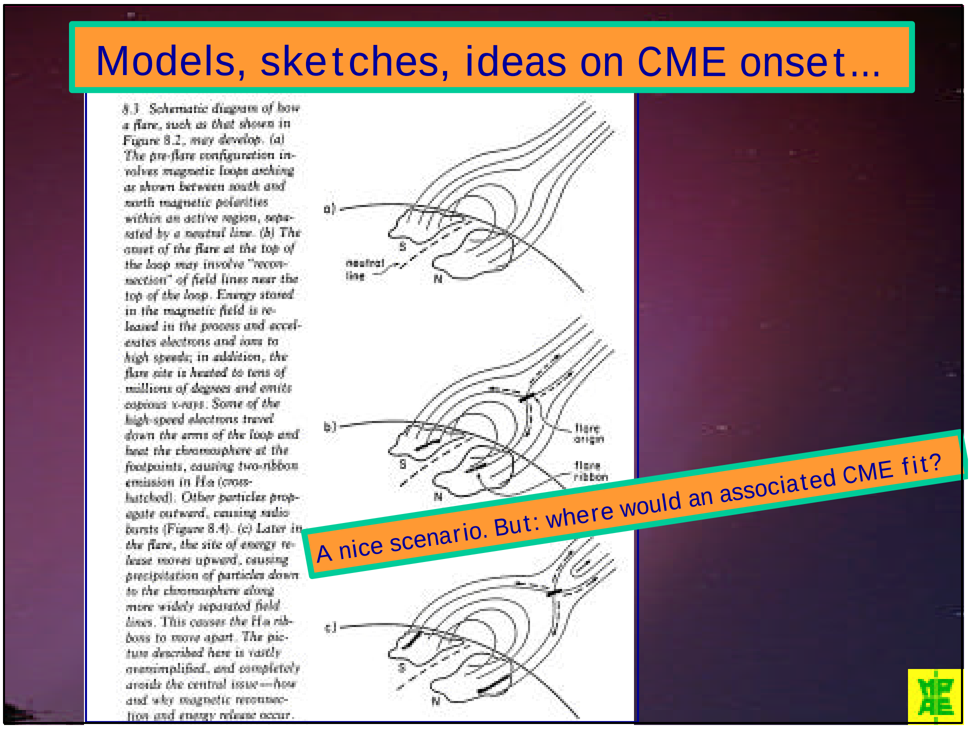



Note: CME science is also a field for creative artists...

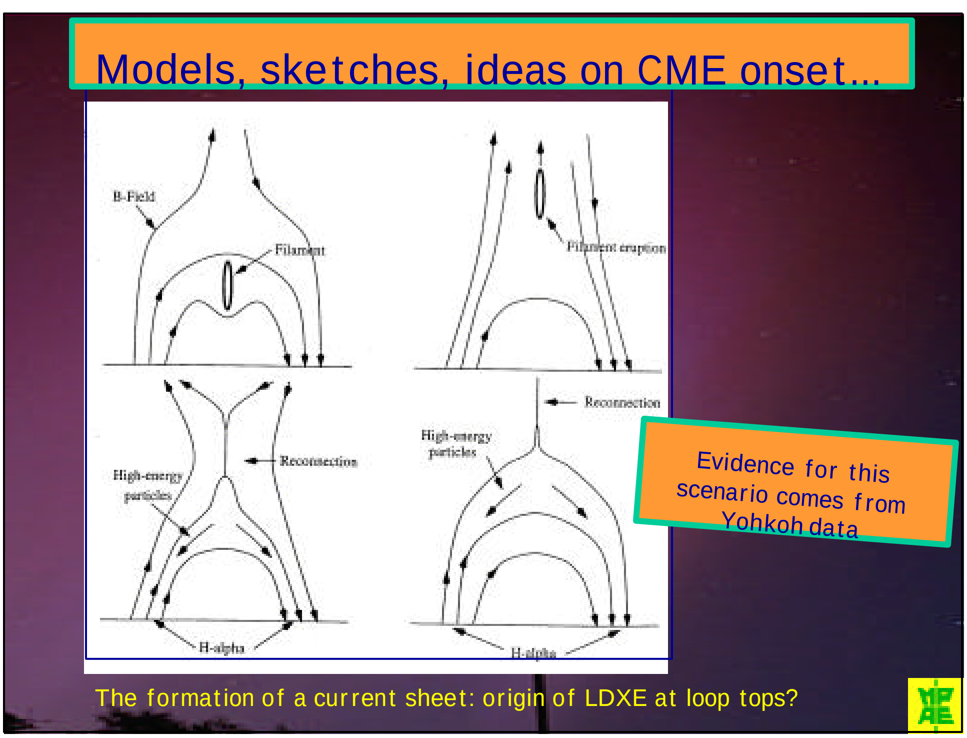
## Models, sketches, ideas on CME onset...




There are a whole bunch of scenarios being sketched. In order to decide which one applies, we need precisely timed multi-wavelength (interdisciplinary?) observations!

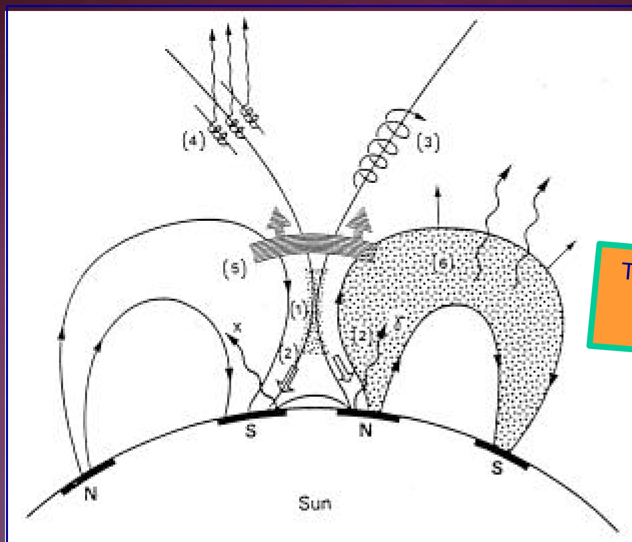


Models, sketches, ideas on CME onset...
8.3 Schematic diagram of how a flare, such as that shown in Figure 8.2, may develop. (a) The pre-flare configuration involves magnetic loops arching as shown between south and north magnetic polarities within an active region, separated by a neutral line. (b) The onset of the flare at the top of the loop may involve "reconnection" of field lines near the top of the loop. Energy stored in the magnetic field is released in the process and accelerates electrons and ions to high speeds; in addition, the flare site is heated to tens of millions of degrees and emits copious x-rays. Some of the high-speed electrons travel down the arms of the loop and heat the chromosphere at the footpoints, causing two-ribbon emission in Hα (cross-hatched). Other particles propagate outward, causing radio bursts (Figure 8.4). (c) Later in the flare, the site of energy release moves upward, causing precipitation of particles down to the chromosphere along more widely separated field lines. This causes the Hα ribbons to move apart. The picture described here is vastly oversimplified, and completely avoids the central issue—how and why magnetic reconnection and energy release occur.
a)
neutral line
S
N
b)
flare origin
flare ribbon
c)
A nice scenario. But: where would an associated CME fit?

Models, sketches, ideas on CME onset...
B-Field
Filament
Filament eruption
Reconnection
High-energy particles
Reconnection
High-energy particles
H-alpha
H-alpha
Evidence for this scenario comes from Yohkoh data
The formation of a current sheet: origin of LDXE at loop tops?

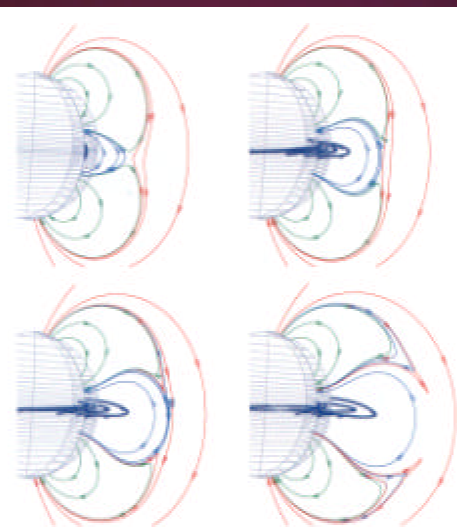
# Models, sketches, ideas on CME onset...




There are some more scenarios on the market...

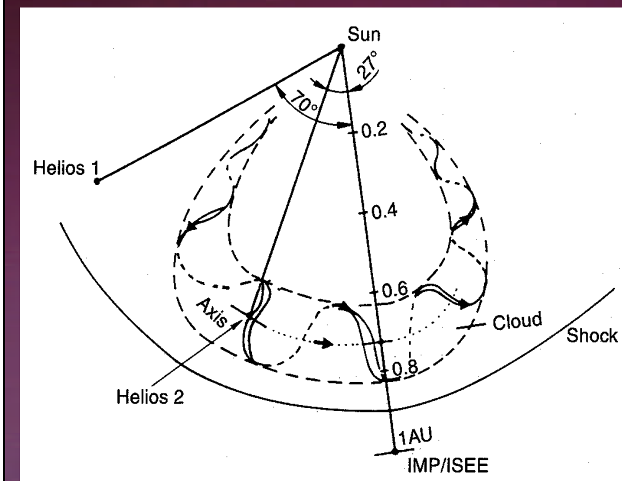
A scenario with reconnection between neighboring loops

# Models, sketches, ideas on CME onset...



The „breakout model“ for CMEs, by Antiochos et al.,

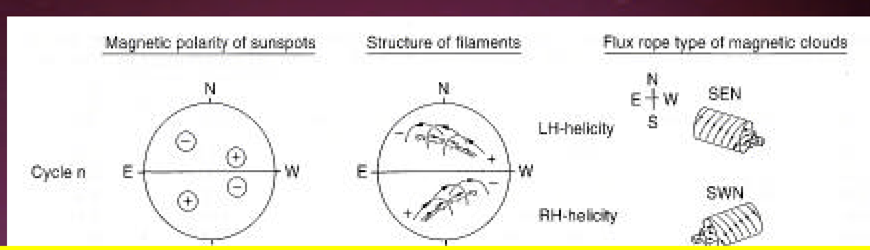
# Why does $B_z$ turn south following CMEs?



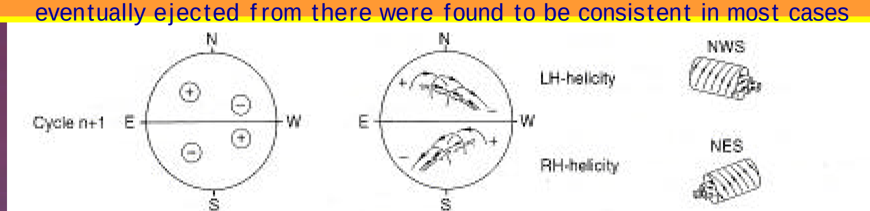

The flux rope topology of a magnetic cloud in interplanetary space.

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

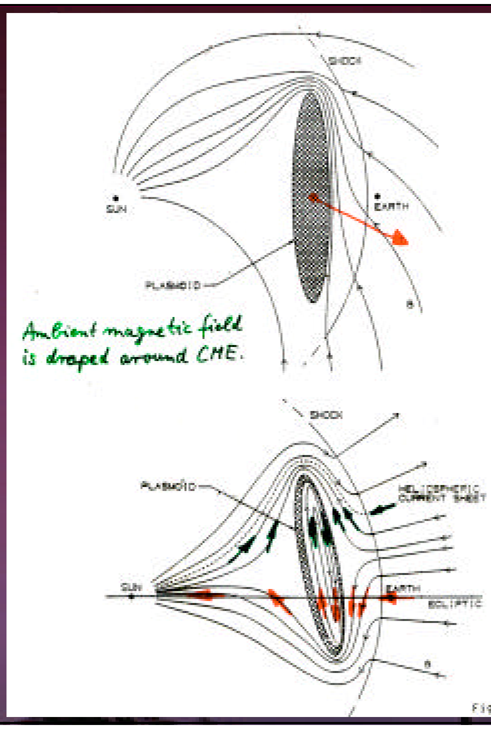
# Why does $B_z$ turn south following CMEs?




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



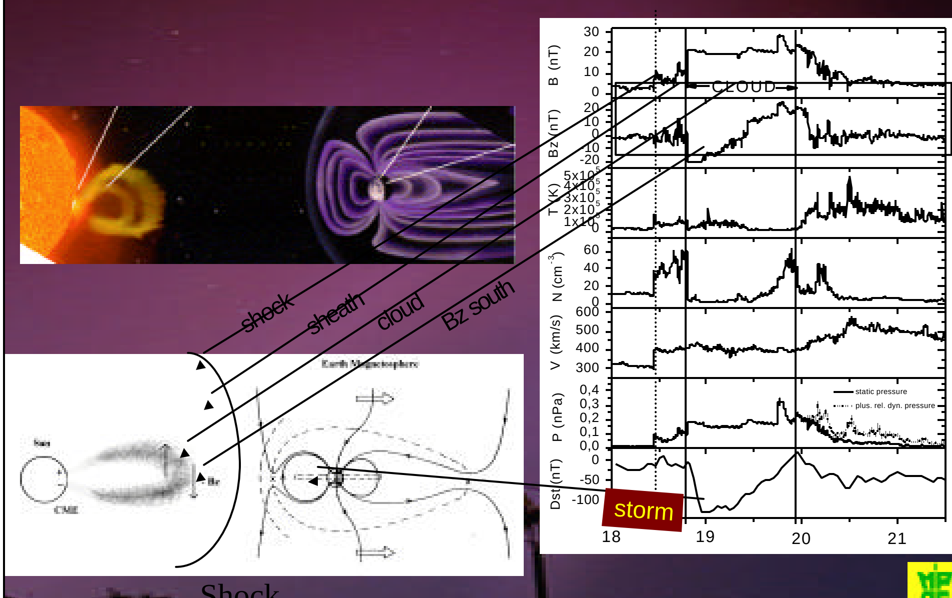

The flux rope topologies of magnetic clouds in interplanetary space.
All 4 types are observed and correspond well to their filament sources.
But their geoefficiency differs dramatically!

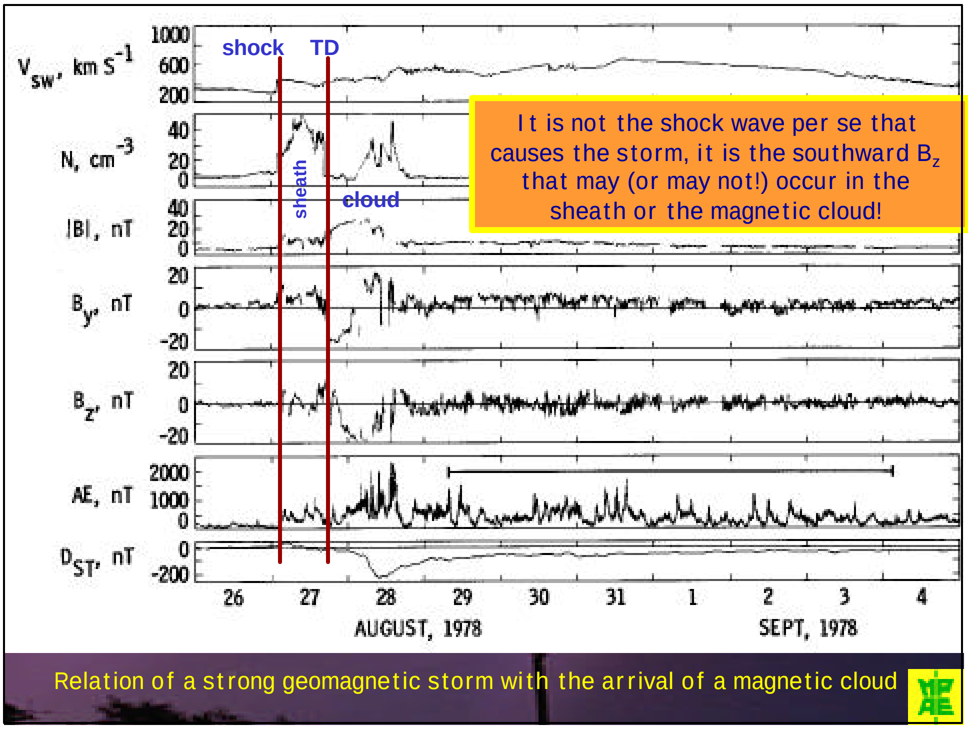



Field line "draping" imposed by a magnetic cloud plowing through the ambient solar wind plasma

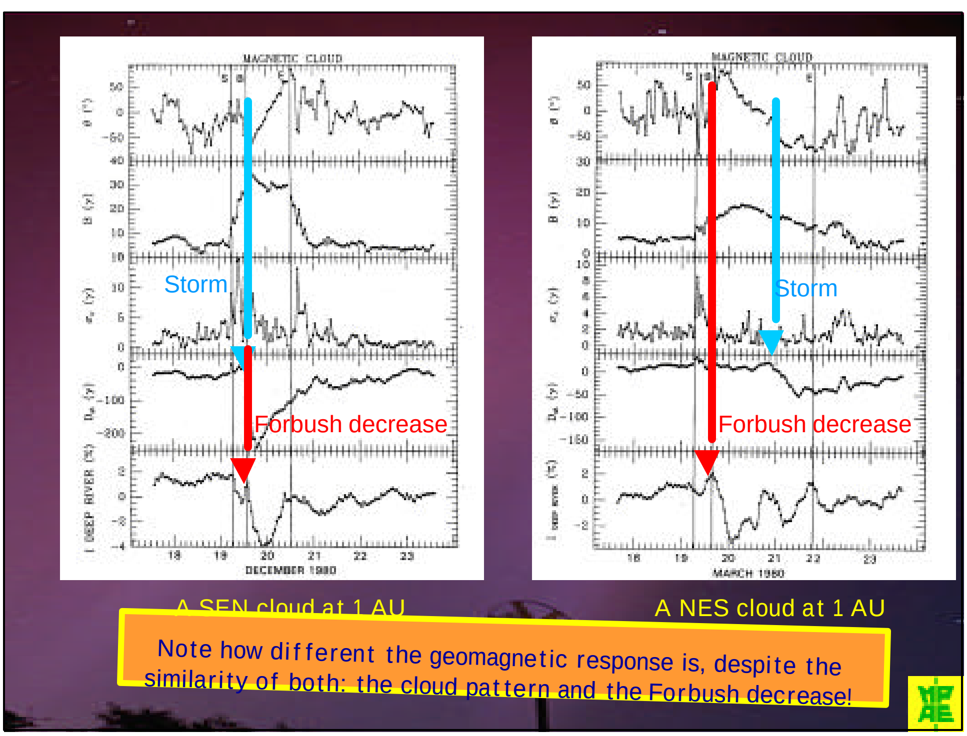
Note the field deflections during the sheath and cloud passage. The details depend strongly on both: the cloud topology and the relative position to the HCS

# What happens at Earth when ejecta arrive?





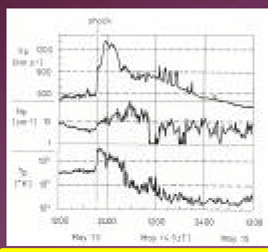
$V_{sw}$, km $s^{-1}$
N, $cm^{-3}$
|B|, nT
$B_y$, nT
$B_z$, nT
AE, nT
$D_{ST}$, nT
shock
TD
sheath
cloud
It is not the shock wave per se that causes the storm, it is the southward $B_z$ that may (or may not!) occur in the sheath or the magnetic cloud!
26 27 28 29 30 31 1 2 3 4
AUGUST, 1978
SEPT, 1978
Relation of a strong geomagnetic storm with the arrival of a magnetic cloud

MAGNETIC CLOUD
Storm
Forbush decrease
DECEMBER 1980
MARCH 1980
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!

# What progress have we made in understanding space weather and predicting it?

1. 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:

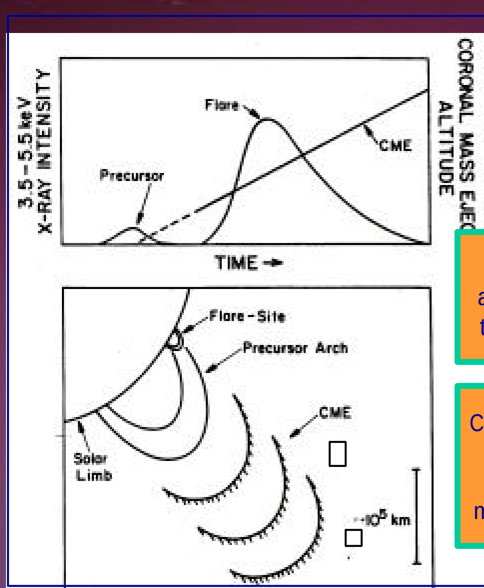
- an observer within the angular span of a fast >400 km/s) CME has a 100% chance to be hit by a fast shock wave,
- vice versa: every shock (except at CIRs) can be traced back to a fast CME.

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

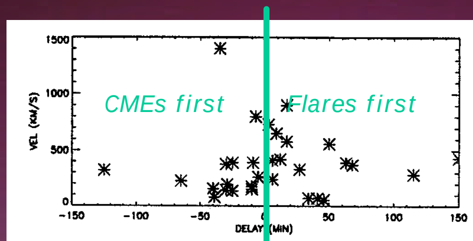
# CME-flare relation, a hen-and-egg situation?




The soft X-rays precursors are associated with the CME rather than the ensuing hard X-ray flare which in many cases occurs later.

CMEs are large-scale processes, often associated with a soft X-ray precursor, while an associated flare may (or may not!) start at one foot of the CME arch

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




Time separation between flares and correlated CMEs

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

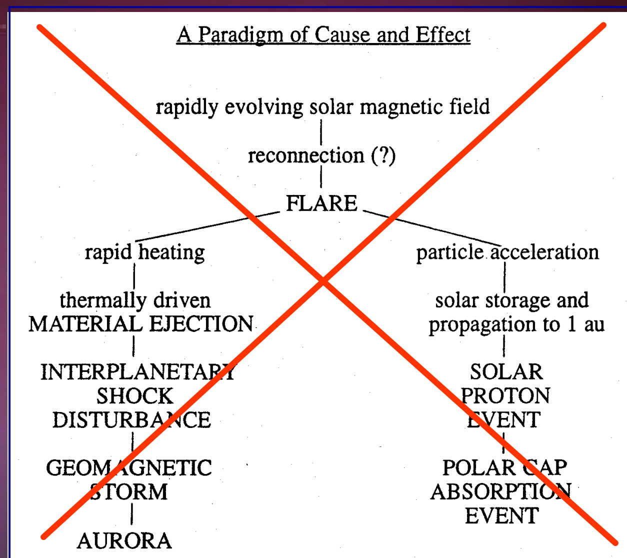
**Flares and CMEs are probably symptoms of a more basic "magnetic disease" of the sun.**

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!"**

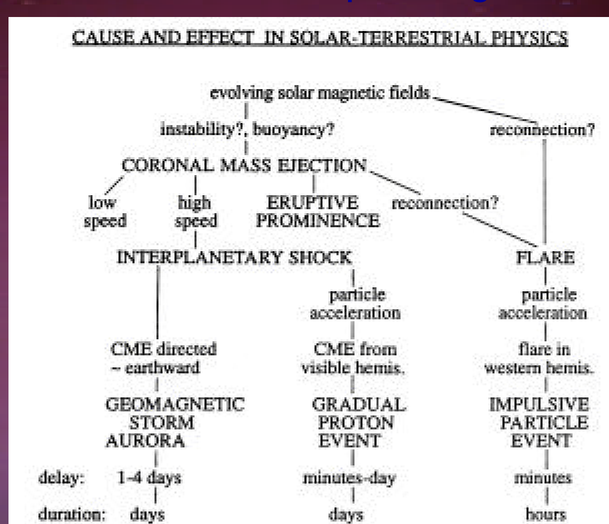
# Remember the fundamental law for data evaluation in natural sciences:

**There are lies,**
**damned lies,**
**and statistics!**

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



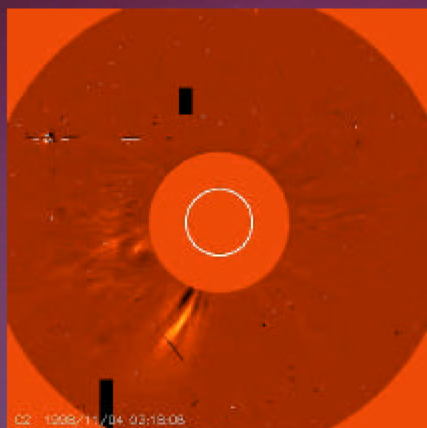

## The modern paradigm




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...

# What progress have we made in understanding space weather and predicting it?

2. We can now watch earthward pointed CMEs early on




## 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

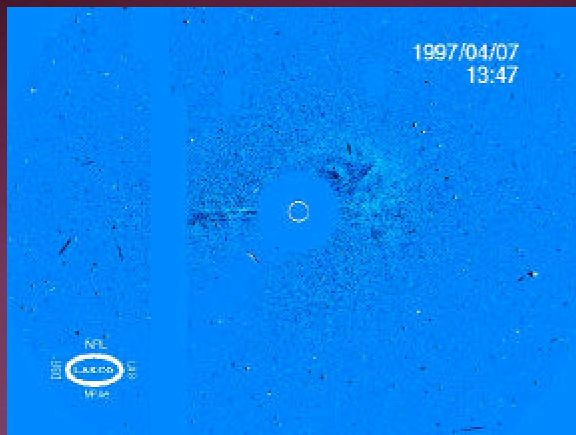
# Front or backside: a new quality from SOHO


The EIT instrument on SOHO provides continuoues surveillance of the sun's disk

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!

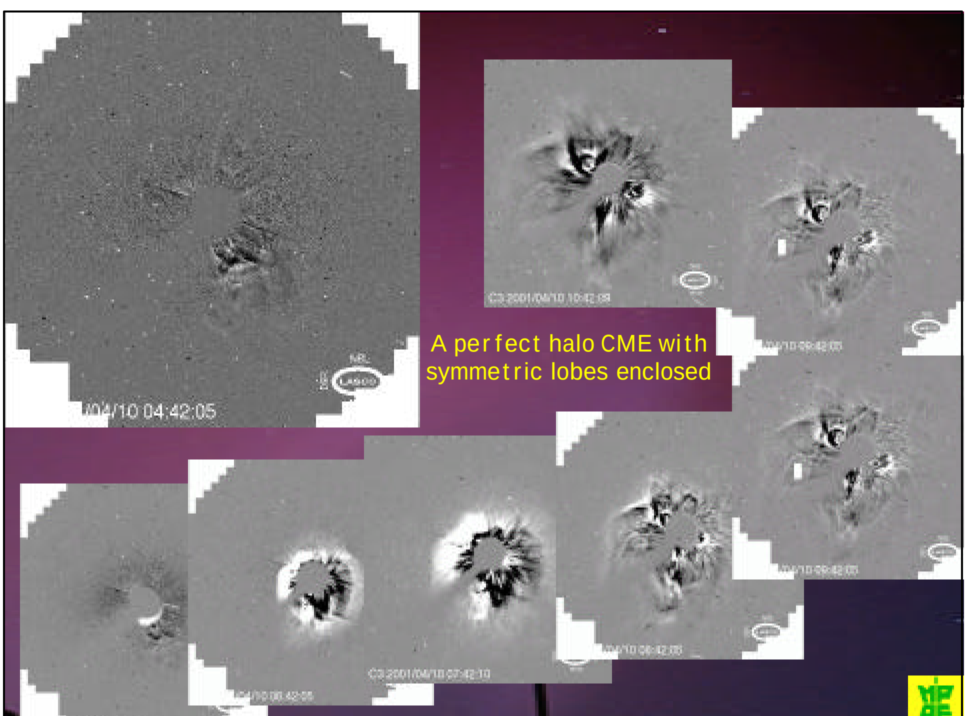
# Halo CMEs: a new quality from SOHO



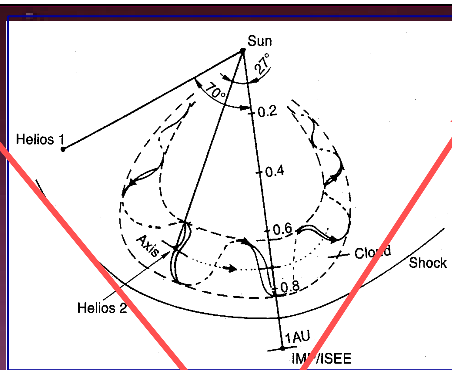

The Halo CME of April 7, 1997, observed by **LASCO-C3**

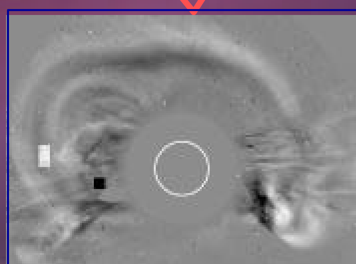
This event caused:

- 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
- fortunately enough, a strong geomagnetic storm on April 10, 1997...




A perfect halo CME with symmetric lobes enclosed

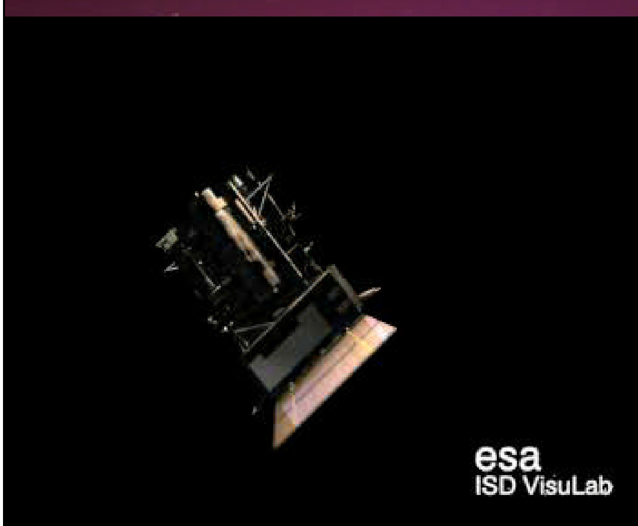


An extended flux rope CME seen from the front or back side.
Note the 2D rope structure and the engulfing 3D halo CME structure.

The lobes are due to a projection effect!

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

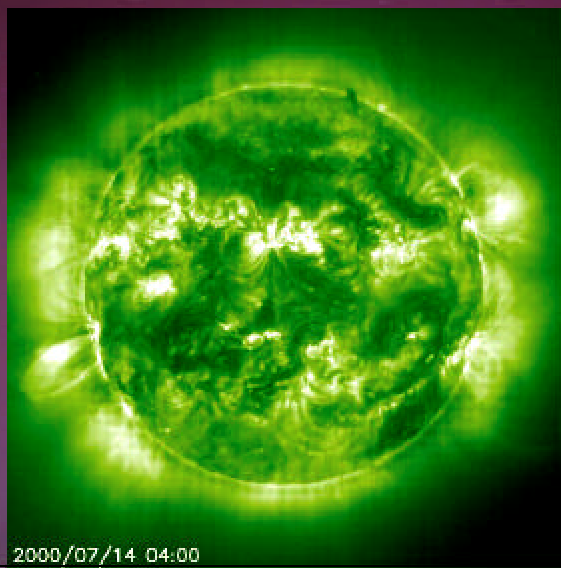



The Solar and Heliospheric Observatory (SOHO), a bilateral space project between ESA and NASA has been observing the sun continuously since early 1996.

It has enhanced our understanding substantially.

It is continuously being used by the professional forecasters.

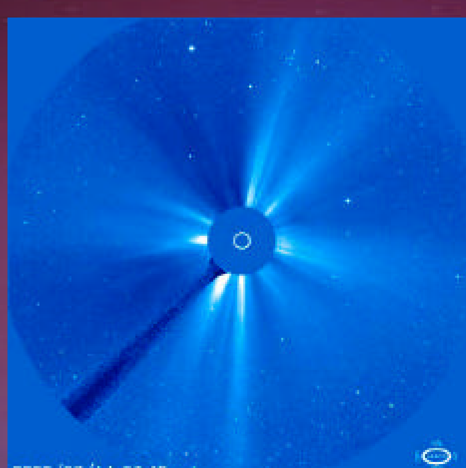
## The “Bastille event”, with all blows and whistles: July 14, 2000.




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

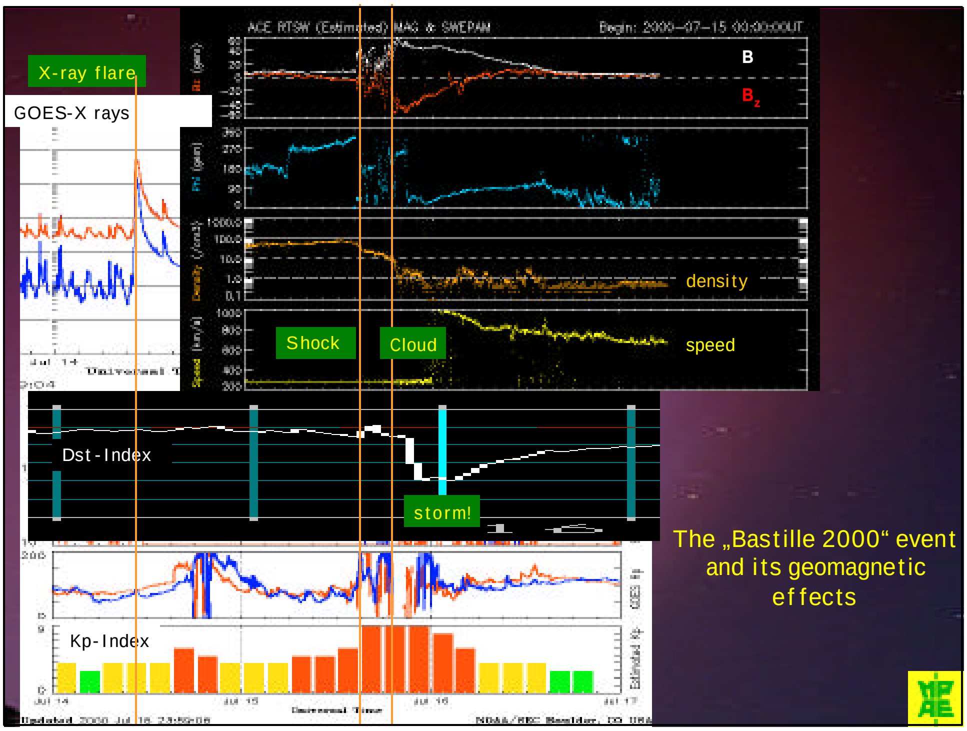
## The “Bastille event”, with all blows and whistles: July 14, 2000.

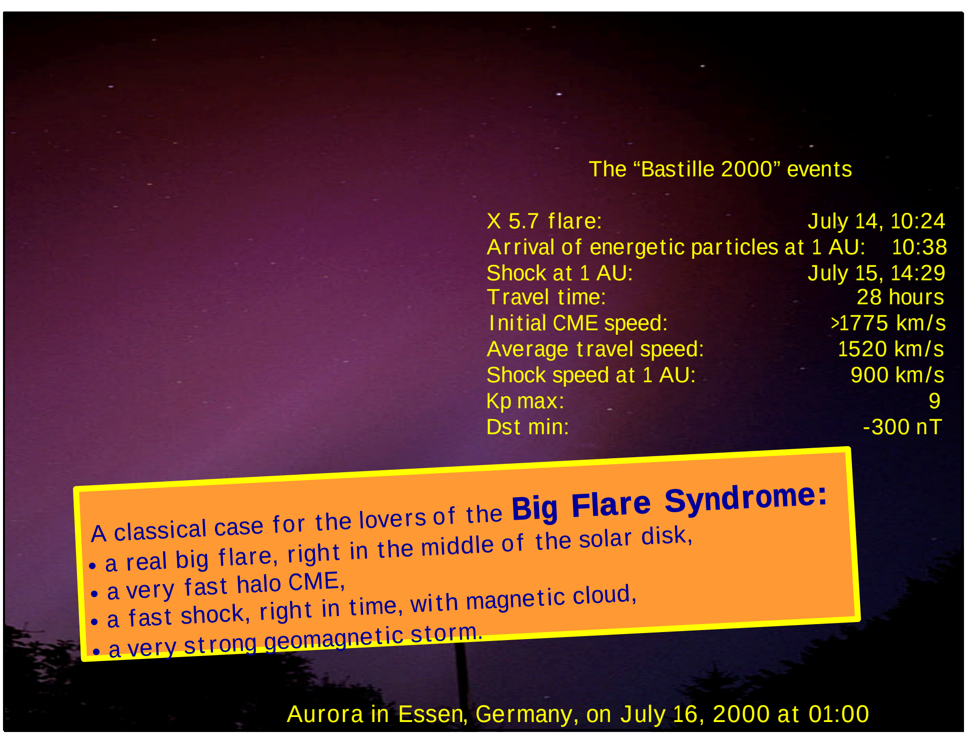
An optical telescope as a Cosmic Ray detector...!



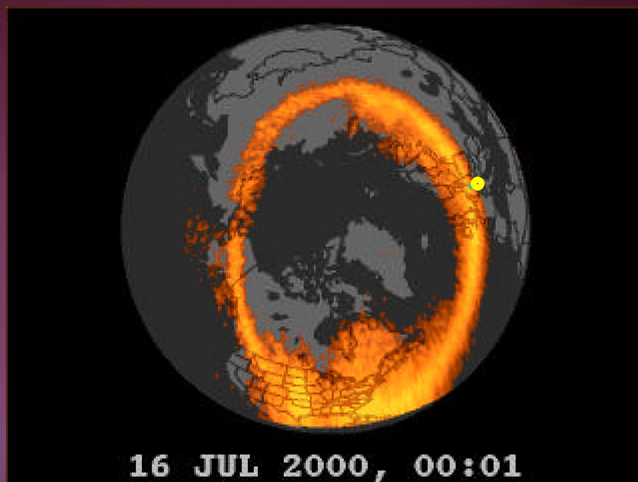

The huge solar mass ejection on July 14, 2000, observed by **LASCO-C3**.

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.


X-ray flare
GOES-X rays
ACE RTSW (Estimated) MAG & SWEPAM
Begin: 2000-07-15 00:00:00UT
B
$B_z$
density
Shock
Cloud
speed
Dst-Index
storm!
Kp-Index
Universal Time
NOAA/SEC Boulder, CO USA
The „Bastille 2000“ event and its geomagnetic effects


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
Average travel speed: 1520 km/s
Shock speed at 1 AU: 900 km/s
Kp max: 9
Dst min: -300 nT
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 01:00

# The “Bastille event”: its effects at Earth

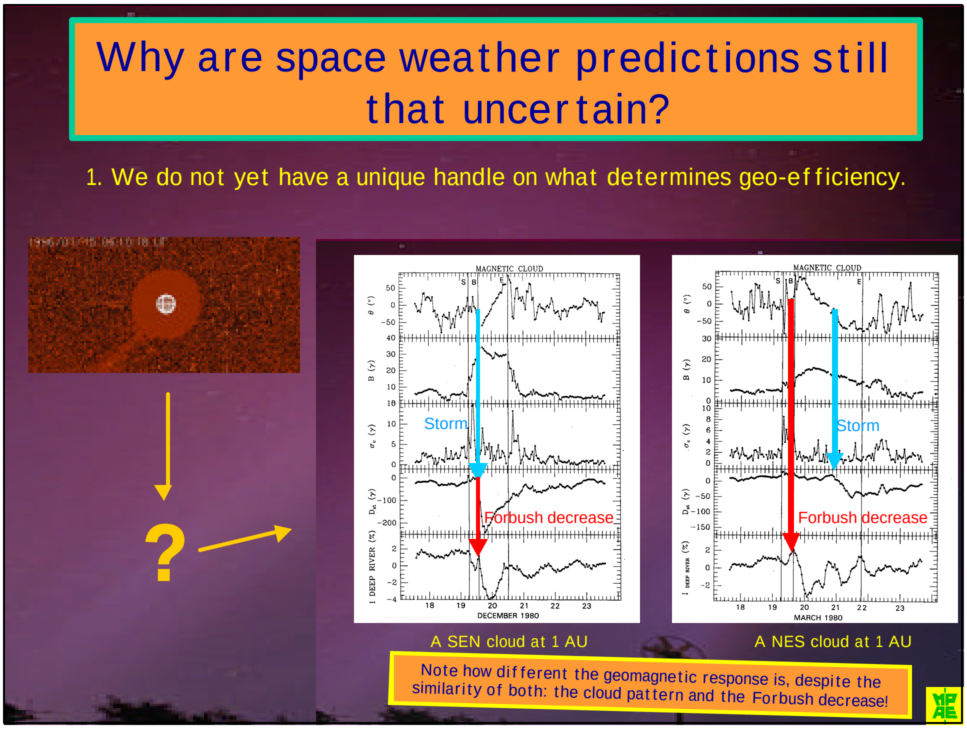


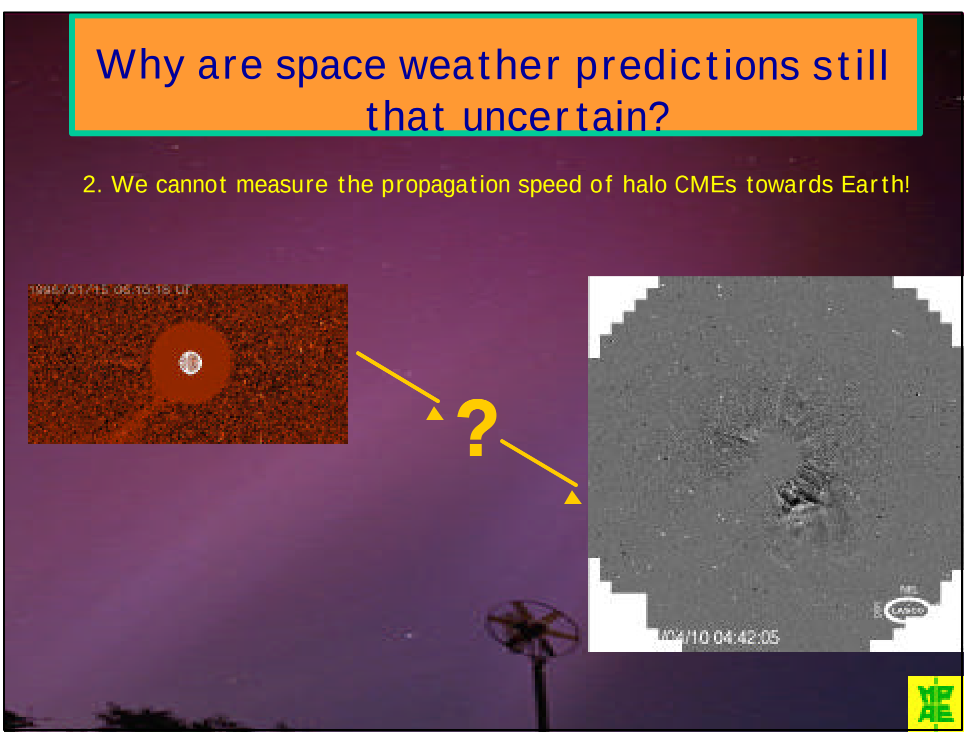

That was the auroral oval on July 16, 2000:
aurorae all over the USA and even middle Europe!

# The “Bastille event”: its effects on satellites

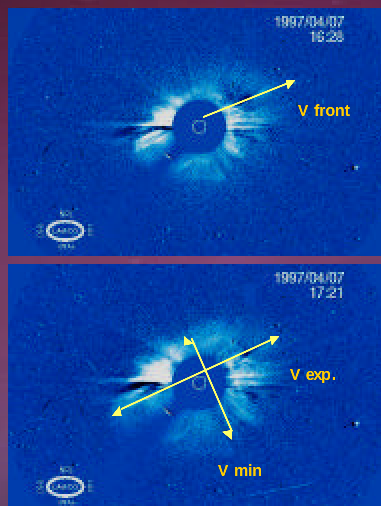
14-16 July 2000: proton event & geomagnetic storm, Ap*=192, Dst min = -300 nT

- **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
- **GEO** Satellites lost ~0.1 amp output from solar arrays


Why are space weather predictions still that uncertain?
1. We do not yet have a unique handle on what determines geo-efficiency.
?
MAGNETIC CLOUD
Storm
Forbush decrease
DECEMBER 1980
MAGNETIC CLOUD
Storm
Forbush decrease
MARCH 1980
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!


Why are space weather predictions still that uncertain?
2. We cannot measure the propagation speed of halo CMEs towards Earth!
?

# How to predict travel times of halo CMEs?



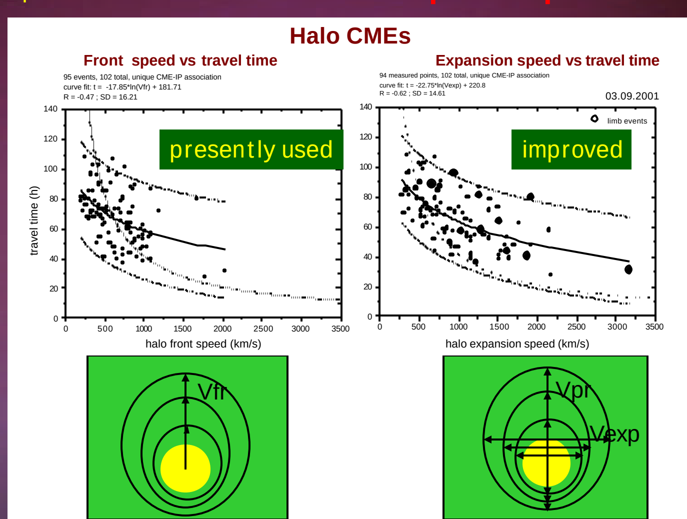

The apparent „front speed“ $v_{front}$ depends on the ejection direction.

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

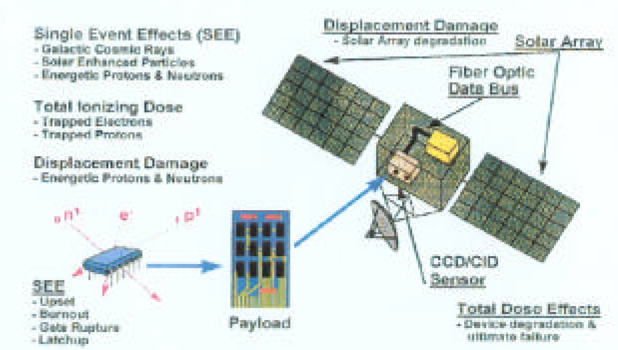
An empirical function was derived: **an improved prediction tool!**

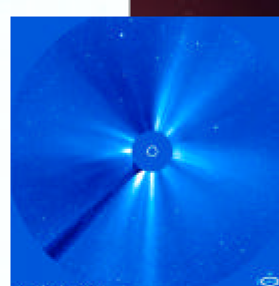


## Solar storms and their effects on geospace

- **Electromagnetic radiation**: Flare X-rays and UV affect ionosphere/communications.
- **Energetic particles (ions and electrons)** from flares penetrate spacecraft skins and endanger astronauts.
- **CMEs** initiate shock waves, move magnetosphere inside GEO, enhance radiation belts, and cause geomagnetic storms & substorms.
- **Geomagnetic storms** disturb ionospheric fields & current systems, cause surface charging on satellites.
- **Disturbed current systems** heat the upper atmosphere, cause additional drag on satellites.
- **Auroral substorm** current systems and fields affect satellites directly.
- **Killer electrons**: increase at GEO after low level magnetic storm, last for weeks.

## Effects from solar storms: energetic particles

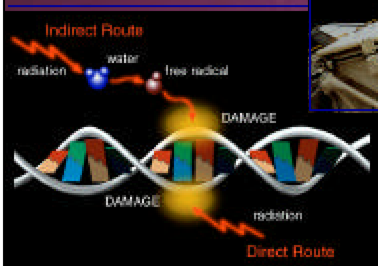


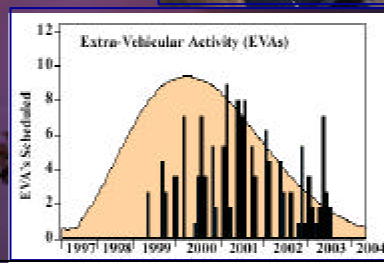



- Radiation
- Surface charging
- Deep dielectric charging
- Single Events
- Damage

Commercial interests often do not allow anomaly reporting...

# High Energy Particles: Hazards to Humans

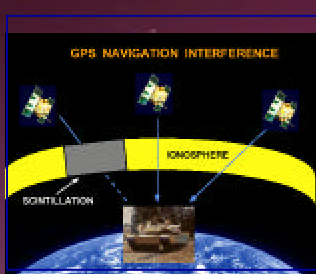



Humans in space
- Space Shuttle, International Space Station, missions to Mars

Crew/passengers in high-flying jets
- Concorde carries radiation detectors
- Passengers may receive radiation doses equivalent to several chest X rays.

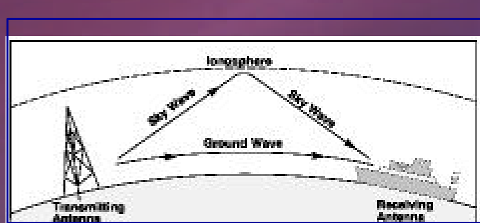
# Navigation systems (GPS, LORAN C)

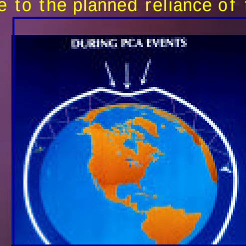



When the ionosphere between the satellites and the user becomes turbulent and irregular, the signal may "scintillate" and prove difficult to track
- loss of signal lock on one or several satellites
- Both single and dual frequency systems may be affected

The Total Electron Content (TEC) along the path of a GPS signal can introduce a positioning error ( up to 100 m)

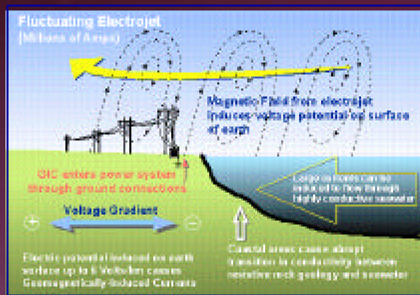
The effects on GPS could be one of the most significant space weather effects due to the planned reliance of this system in the future.

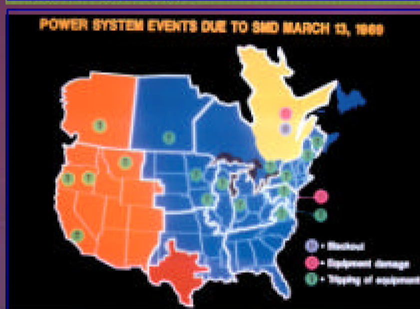



A 7-10 km height change of the lower ionosphere can give position errors of 1-12 km

# Geomagnetic Induced Currents

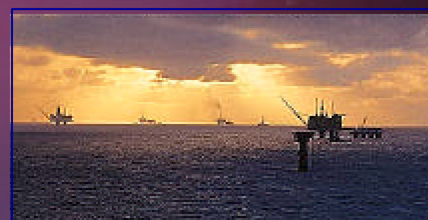



These currents will leak into all long conductors:

- power grids,
- oil and gas pipelines (increased corrosion)

Train light signals can be affected (two documented events in Sweden)




# Space weather: why should we care?

Our society is much more dependant on technology today compared to in 1989

The most rapidly growing sector of the communication market is satellite based

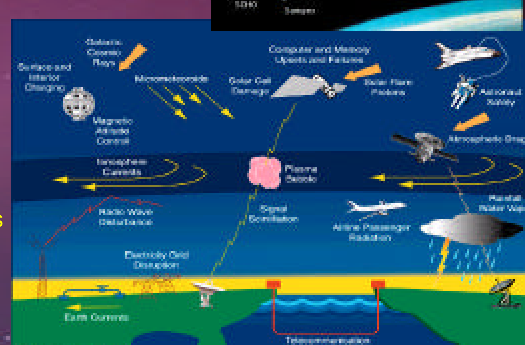
- Broadcast TV/Radio,
- Long-distance telephone service, cell phones, pagers
- Internet, finance transactions

Change in technology

- more sensitive payloads
- high performance components
- lightweight and low cost

Humans in Space

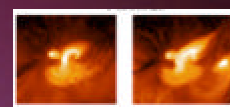
- More and longer manned missions

Space Weather warning will be very important for our society in the future.

# Research topics for the future:

- How to predict CMEs/flares before they occur?



Sigmoids?

# Research topics for the future:

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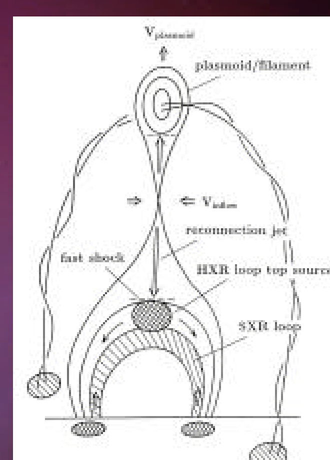

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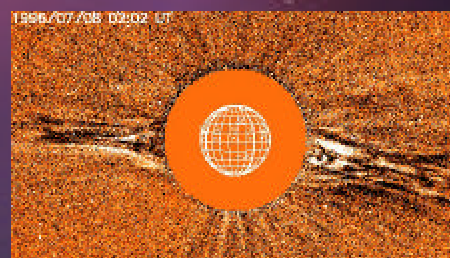


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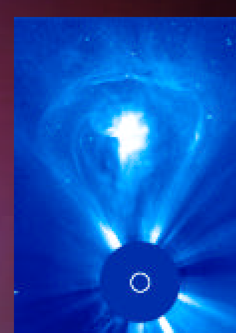

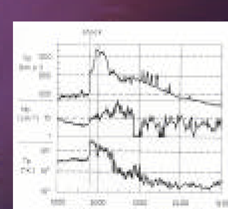

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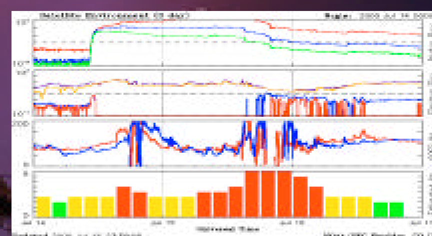

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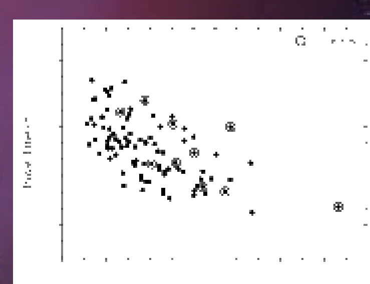
- Better models and observations of CME propagation towards Earth is needed



# Transients on the Sun and solar-terrestrial relations

International Max-Planck Research School
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