The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific
and Cultural Organization

International Atomic
Energy Agency

310/1749-13

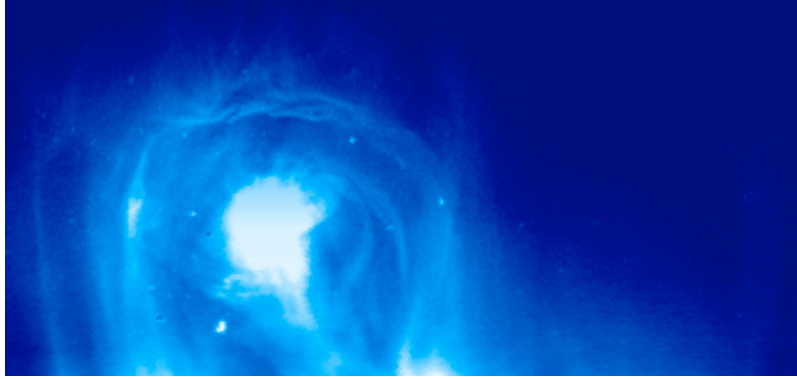
ICTP-COST-USNSWP-CAWSES-INAF-INFN
International Advanced School
on
Space Weather
2-19 May 2006

Solar Driving Modeling and Predictions

Petra VANLOMMEL
&
Andrei ZHUKOV
Solar Physics Department
Royal Observatory of Belgium
Av. Circulaire, 3
B-1180 Brussels
BELGIUM

Solar Driver modeling and Predictions

Petra Vanlommel and Andrei Zhukov



THE SIDC as RWC

SIDC: Solar Influences Data analysis Center

Hosted by the Royal Observatory of Belgium

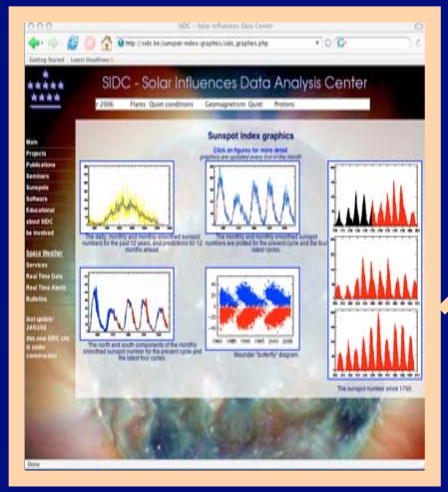
Operational Activities:

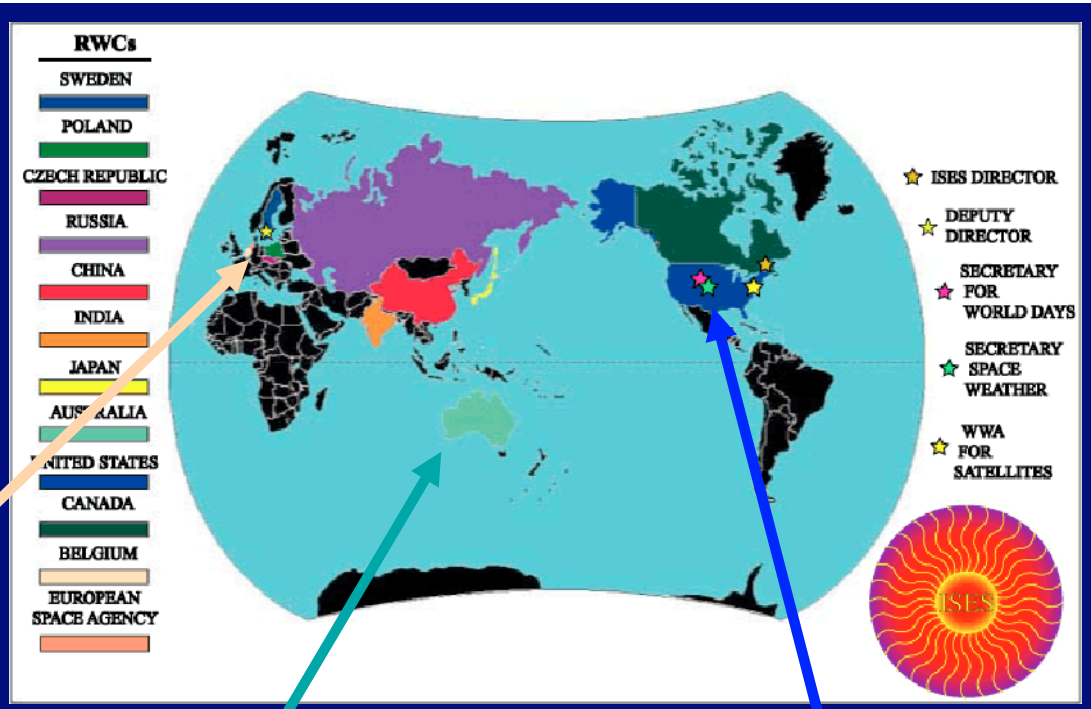
✓Regional Warning Center for Western Europe

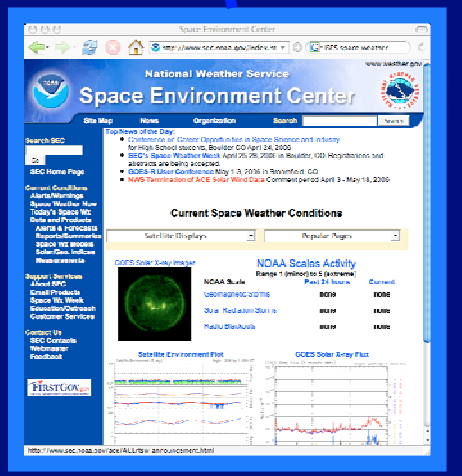
✓World Data Center for the Sunspot Index

Research group, Solar Physics

International Space Environment Service (ISES)

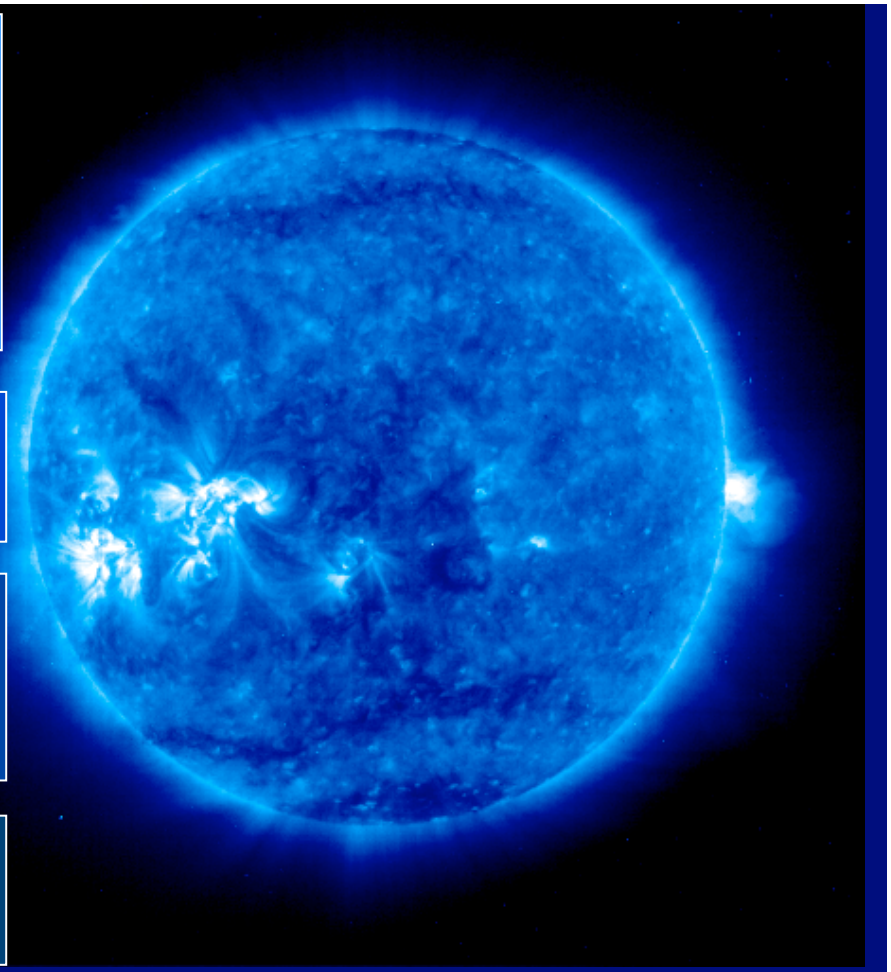






Solar driver modeling and predictions
Trieste, May 4, 2006

The SIDC Solar Influences Data analysis center



Since 1995: partners in the EIT/LASCO consortium

Since 2000: 'Regional Warning Center' of ISES

All about Space Weather

2003-2005: ESA Space Weather Applications Pilot Project

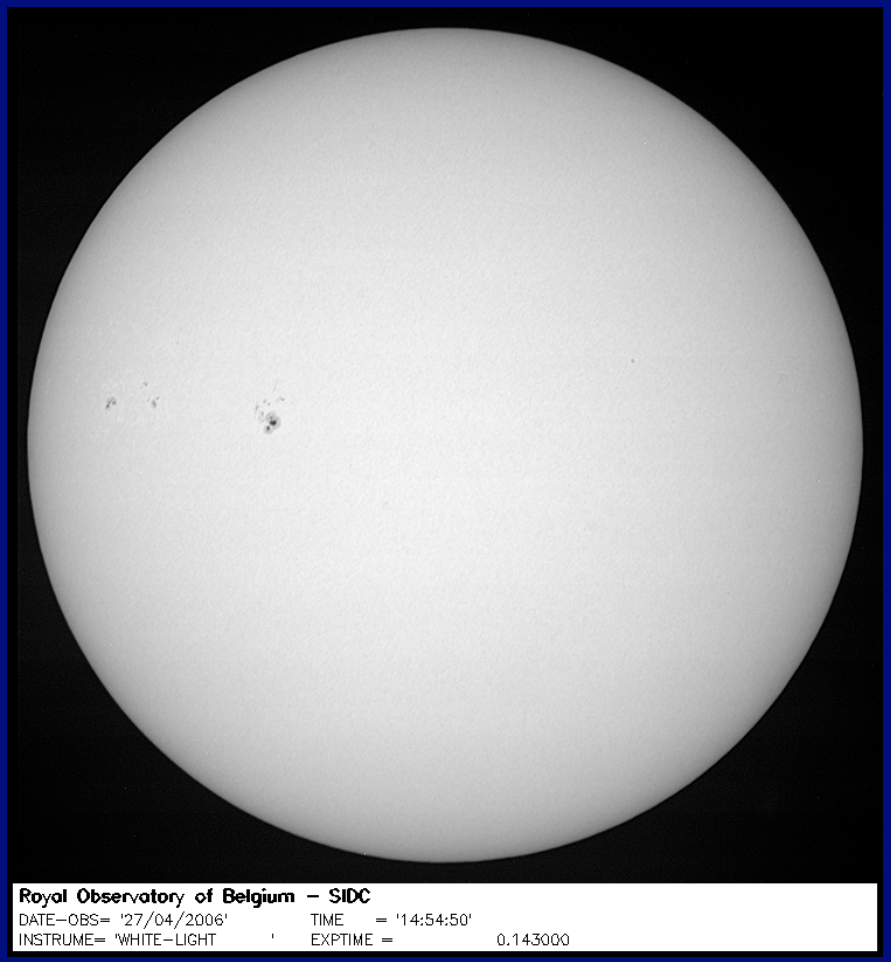
Participation in space missions

- STEREO/SECCHI (2006-?)
- PROBA2/SWAP and LYRA (2007-?)
- Solar Orbiter (2012?)

Space Weather Products

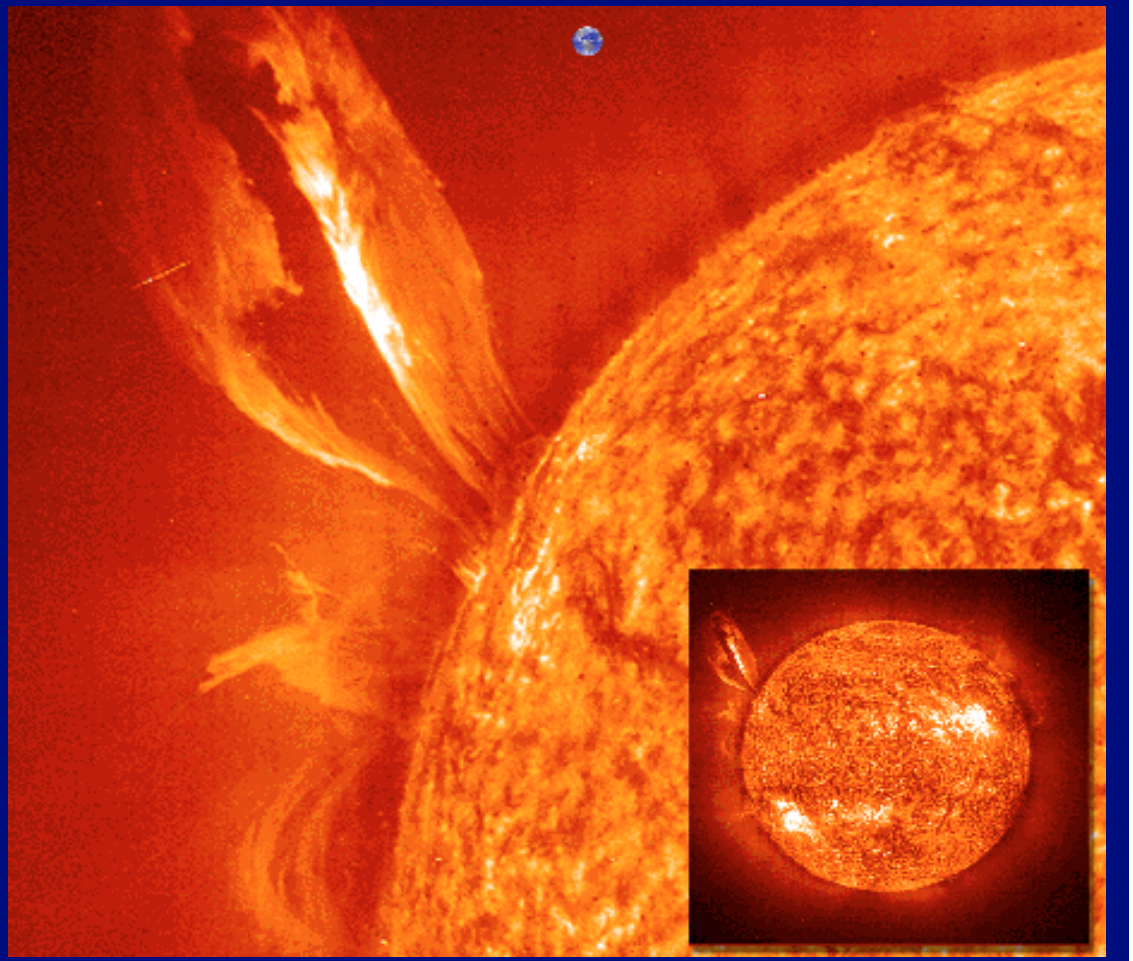
- **Solar Weather Browser**
- **Computer Aided CME Tracking**
- **Daily Solar Weather reports**
- **Real Time Alerts**

- Solar Highlights
- Weekly Bulletin
- Monthly sunspot Bulletin
- Annual SIDC CDrom
- Differential GPS and Real-Time Kinematic positioning
- ***Quality Control***
- Space Weather yellow pages

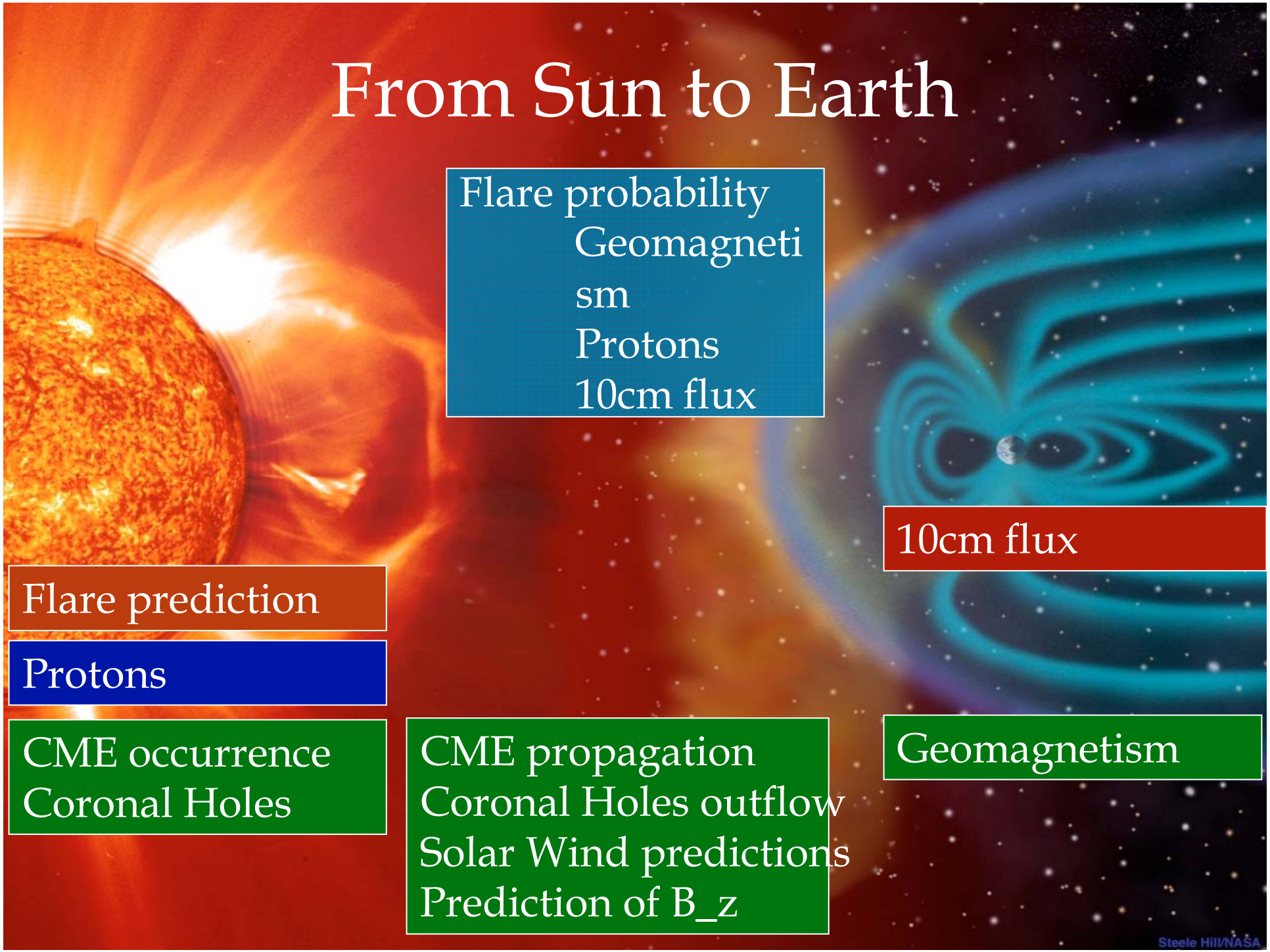


The Daily Forecast

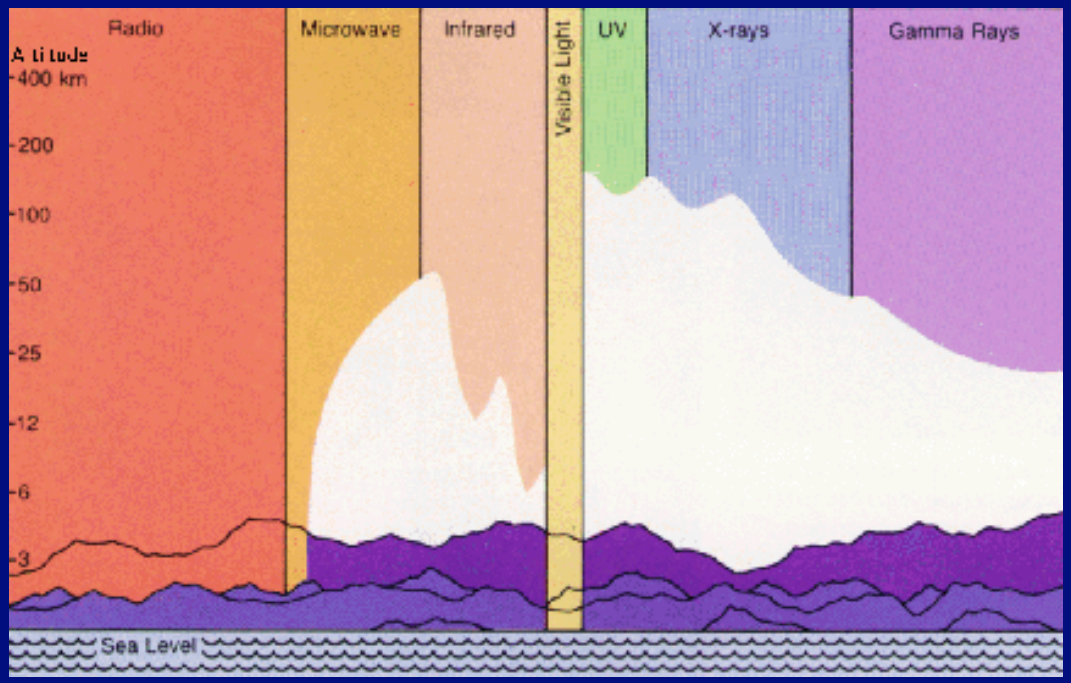
email
internet



Solar driver modeling and predictions
Trieste, May 4, 2006


From Sun to Earth
Flare probability
Geomagnetism
Protons
10cm flux
10cm flux
Flare prediction
Protons
CME occurrence
Coronal Holes
CME propagation
Coronal Holes outflow
Solar Wind predictions
Prediction of B_z
Geomagnetism
Steele Hill/NASA

Flare prediction



Large, sudden

Flare prediction

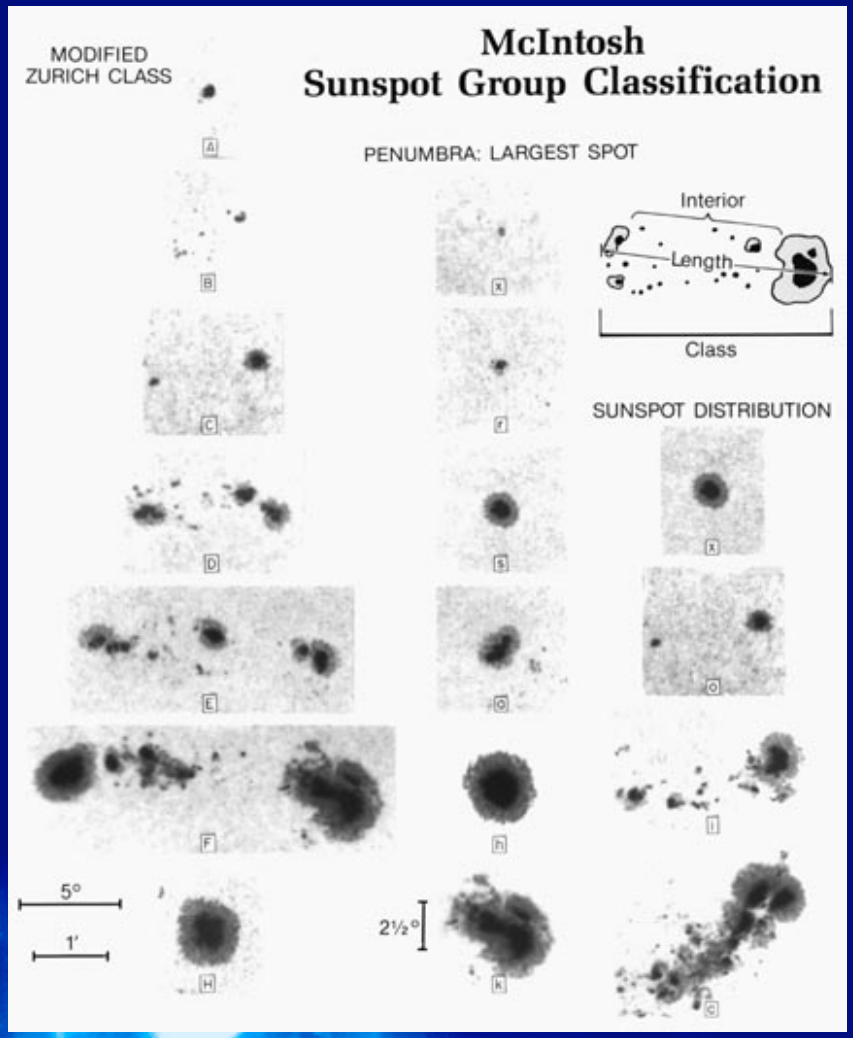
Do not read this:
Black: in
White: out

- SOHO/EIT
- SOHO/MDI, GONG+
- GOES X-rays, SXI
- Visible light

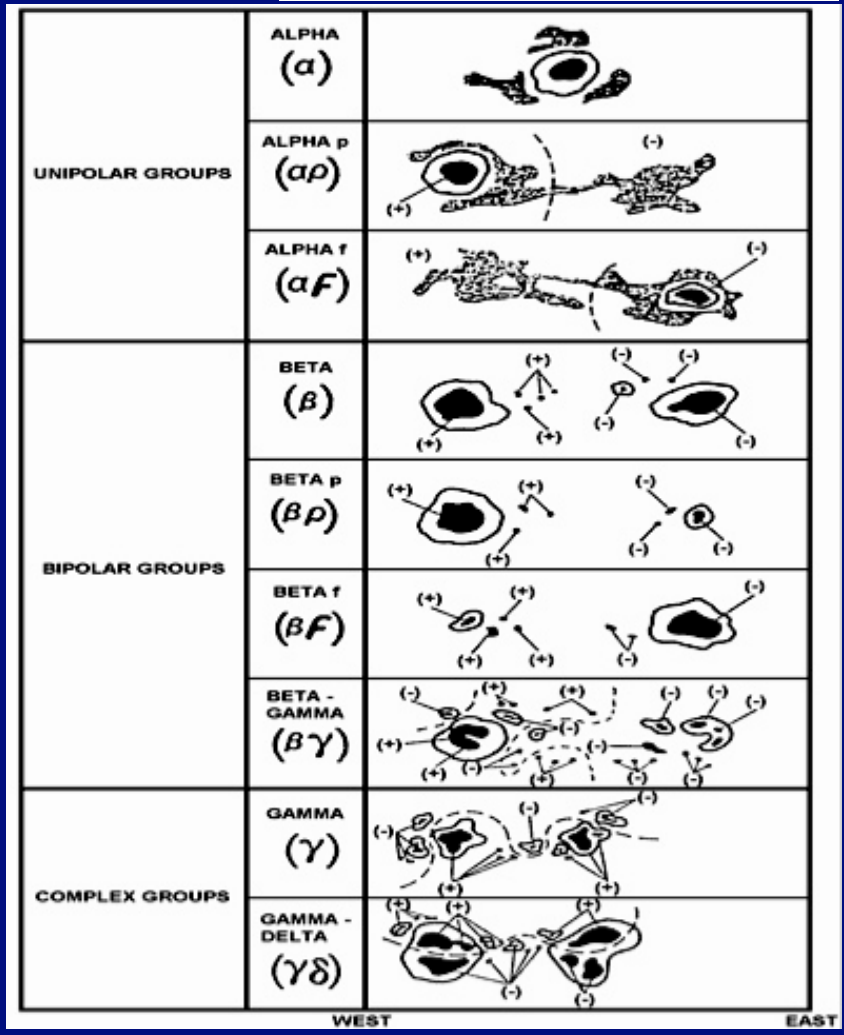
- Combi-map
- SWB
- Solar soft events
- SEC

- Persistence, Statistics
- Past rotation, recurrent groups (http://www.ips.gov.au/)
- Emerging of new active regions (solar highlight)
- Evolution of last 24 hours, dynamics or configuration change in last few hours
- Classification: McIntosh, Mount Wilson
- Other: IPS

Flare forecasts



Mount Wilson Classification



Solar driver modeling and predictions
Trieste, May 4, 2006

Bayesian approach

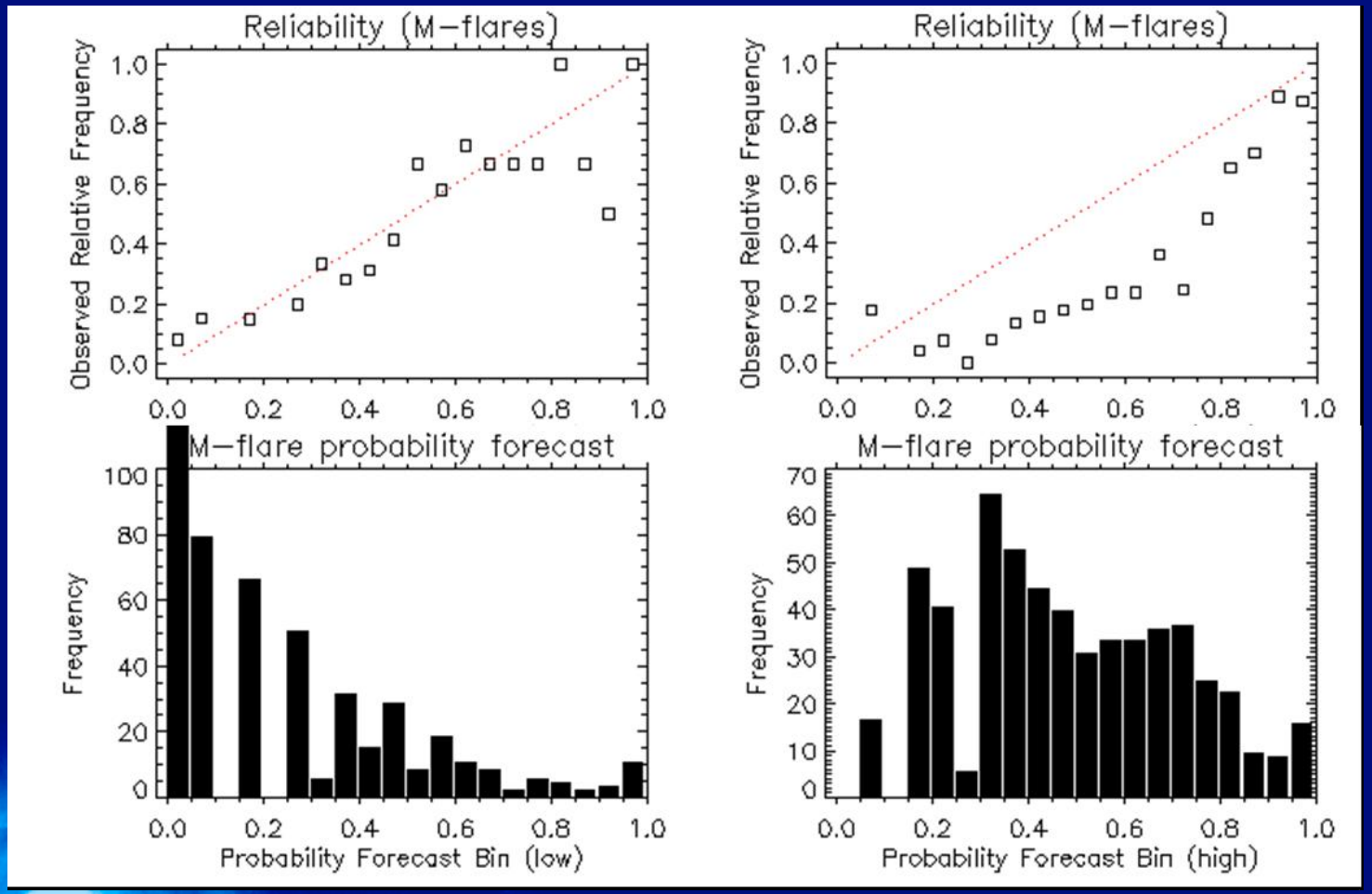
1) Existing method based on classification and historical records
2) Time history of flares of flares already observed: big AND small events. This is Persistence!

This leads to a Probability of a big event based on flare statistics and on additional information

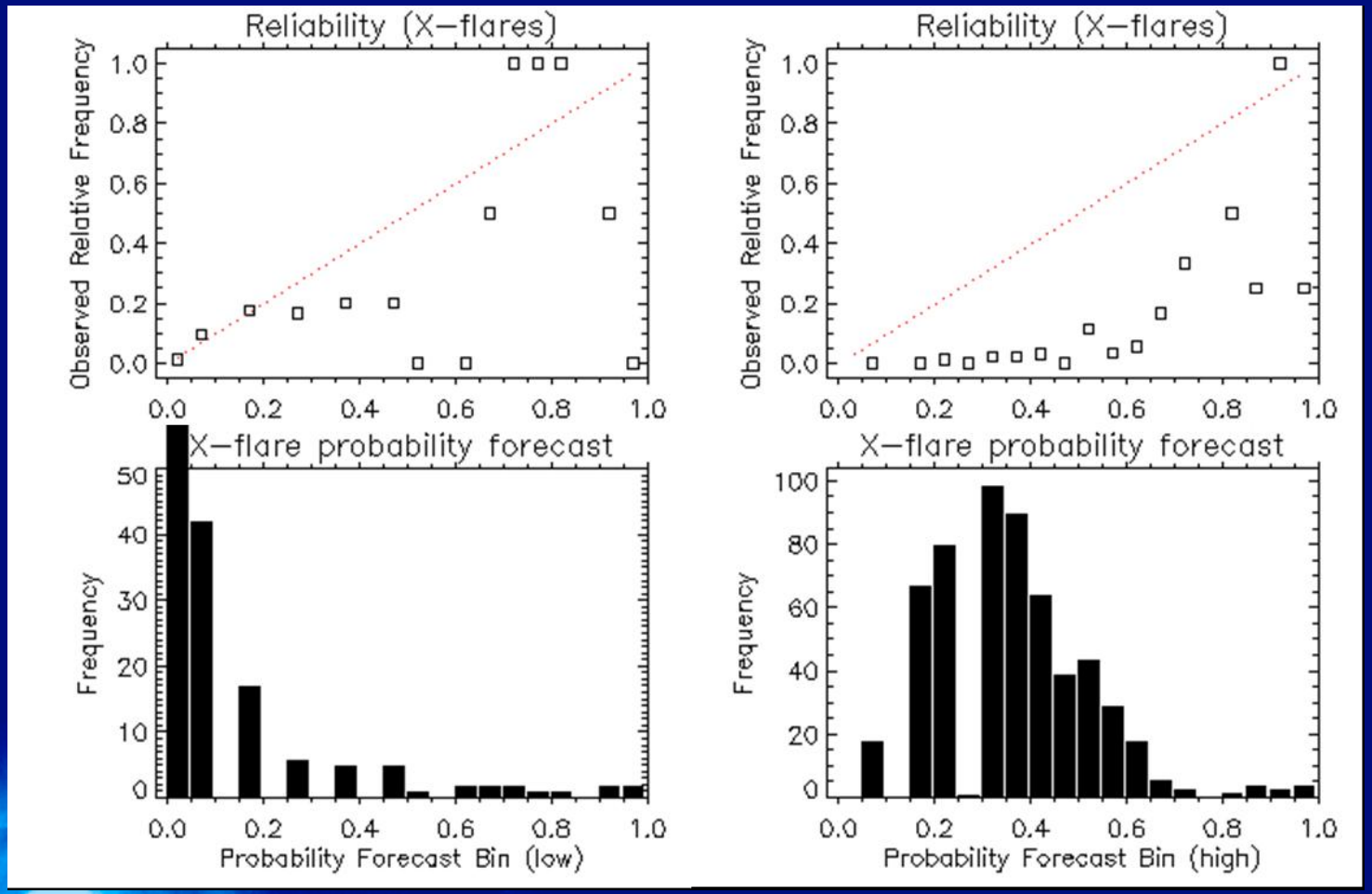
Wheatland, 2004

This is us!

Flare Probability



Flare Probability

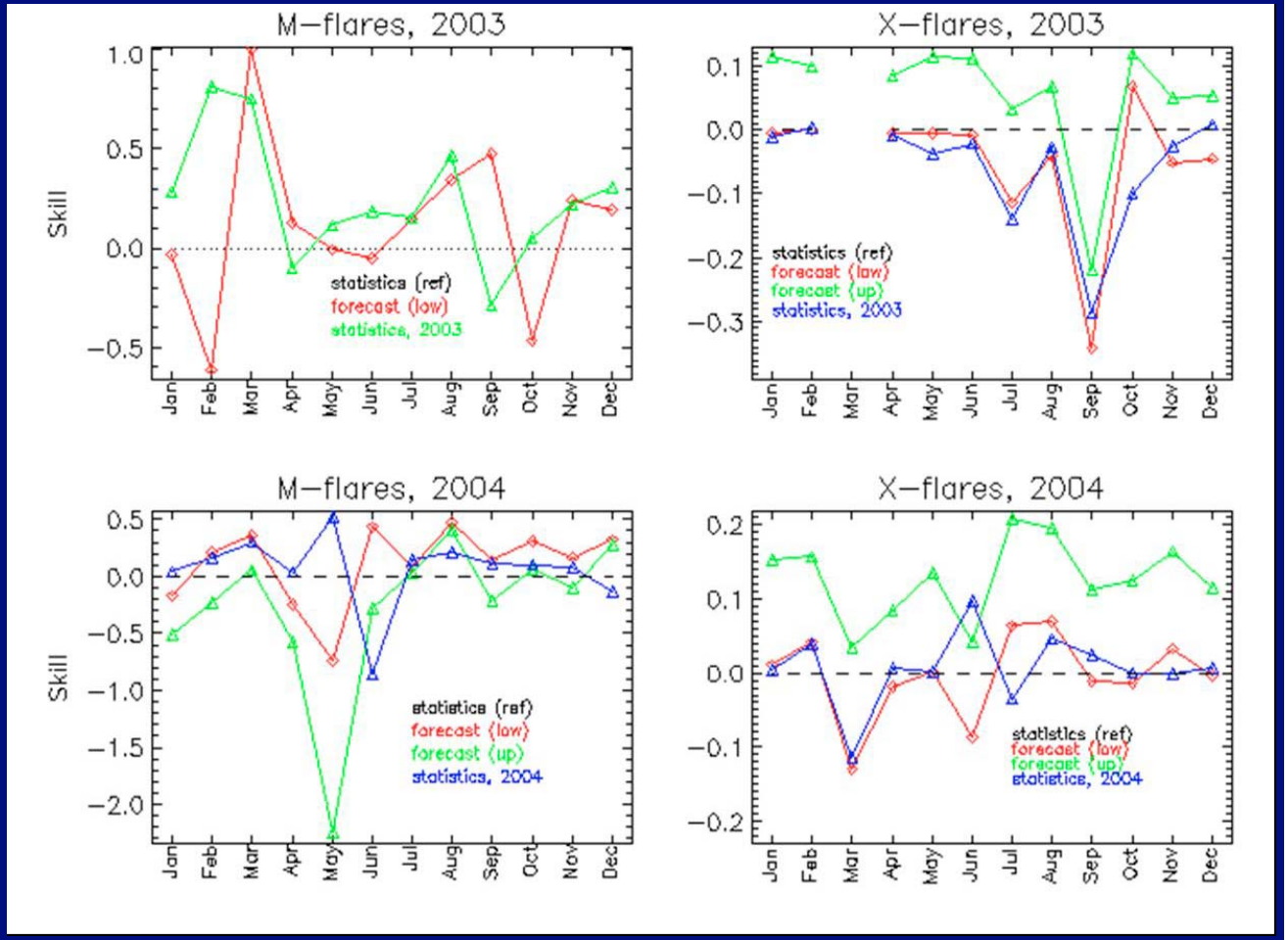


Flare forecast: Skill

Poisson statistics:
BBSO: reference
data 1988-1996
SIDC: data of year of concern

Skill=1- mse/mse_ref

Skill: compares with reference:
- Negative: worse
- 0 as good as
- Positive: better
- 1 The best



What is a CME?

A CME is

a new, discrete, bright, white light feature in the coronagraph field-of-view with a predominantly, radially outward velocity.

CORONAGRAPH definition

Physics:
Restructuring of magnetic field
Reconnection

CME occurrence prediction

- *Filament disappearance* (April 29)
- Filament
  - Width
  - Activity (April 19)
  - Curvature
  - Prominence height (at limb)

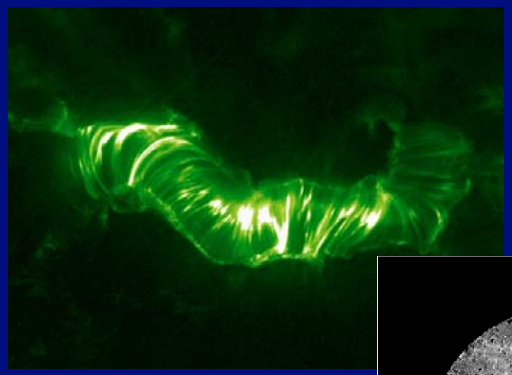
- Active regions:
  - big flares, big CME's, history
  - X-ray curve: Long duration event
- Backsided-eastlimb activity
- *Radio-outbursts type II*

Why?

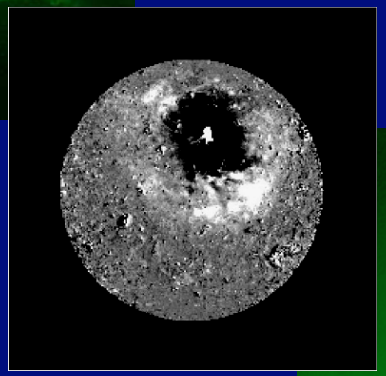
- SWB
- CACTus
- NEMO
- SEC

- SOHO/EIT
- SOHO/LASCO
- (Catania, BBSO, Uccle) H-alpha

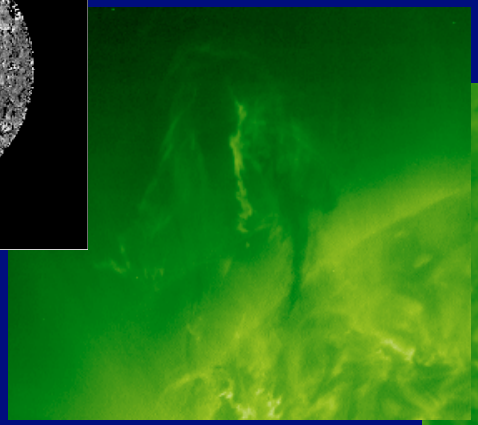
Signatures of CMEs in EUV



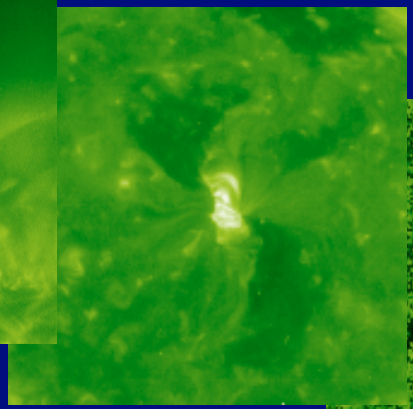
flares



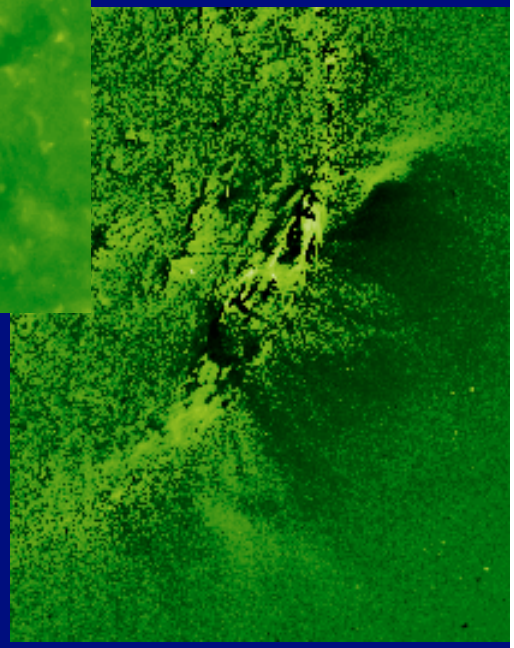
EIT waves



Prominence eruptions



dimmings

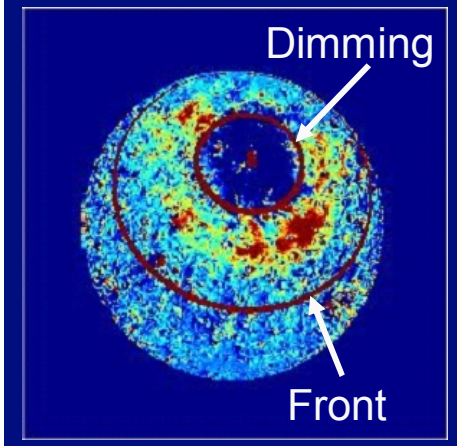


Limb signatures

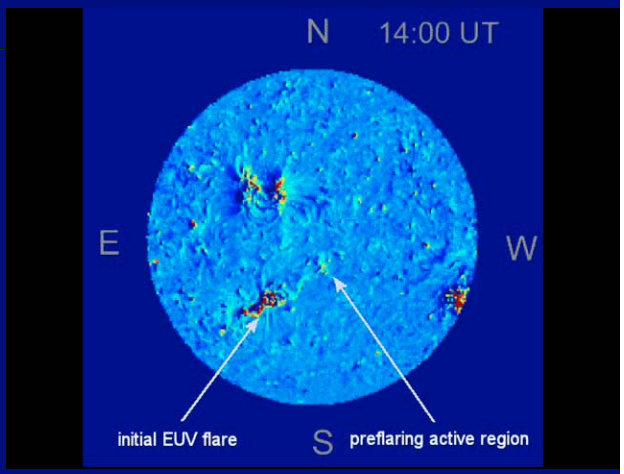
Solar image processing Why?

Solar driver modeling and predictions
Trieste, May 4, 2006

NEMO: Novel EIT wave Machine Observing



filament eruption;
C1.3 flare;
EIT wave;
dimming.



Automated data analysis

Other example: Jan 15, 2005

Proton events

http://www.sec.noaa.gov/ace/

if increase fits solar flaring activity (magnetic connectivity),

if big next event,

then warning

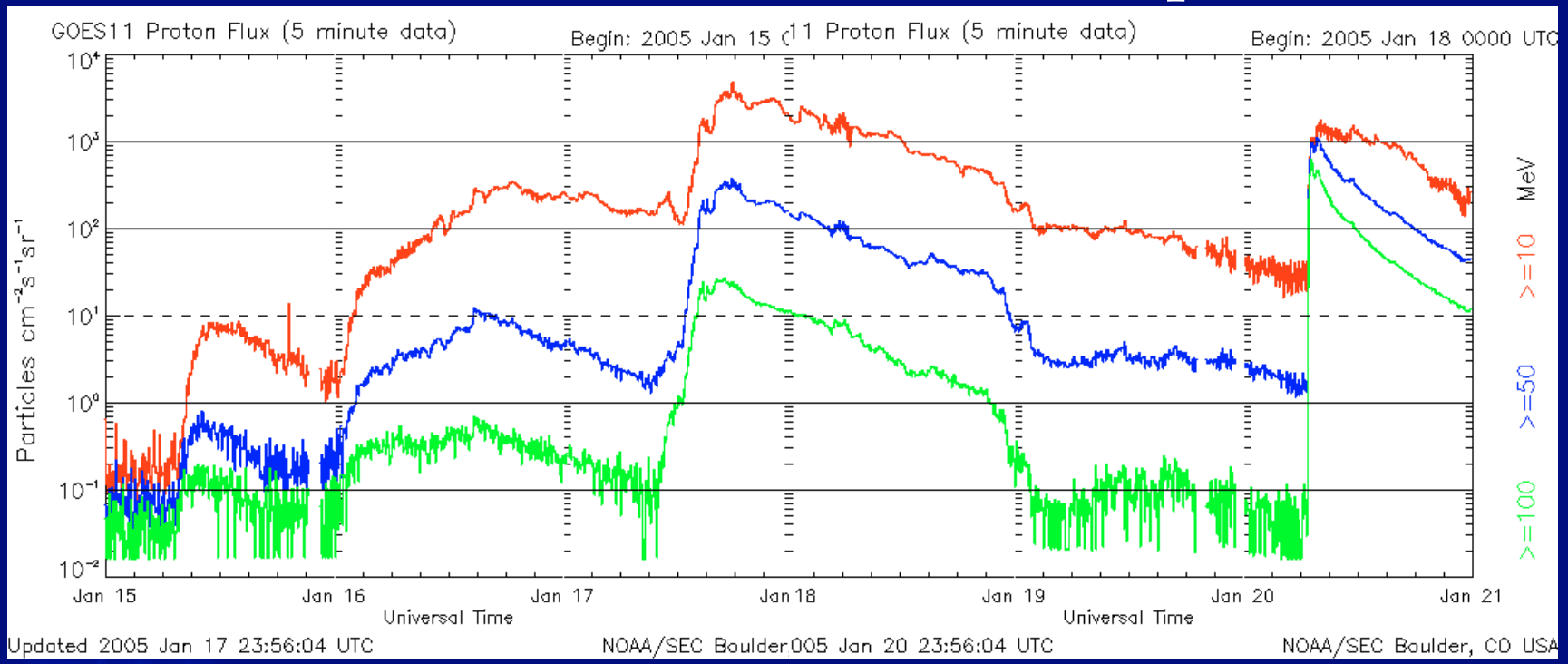
GOES real-time particle flux data

Event defined as flux of 10 p cm-2 s-1 ster-1 (PFU) at > 10 MeV

CME/flare driven Proton event

Gradual event

Impulsive event

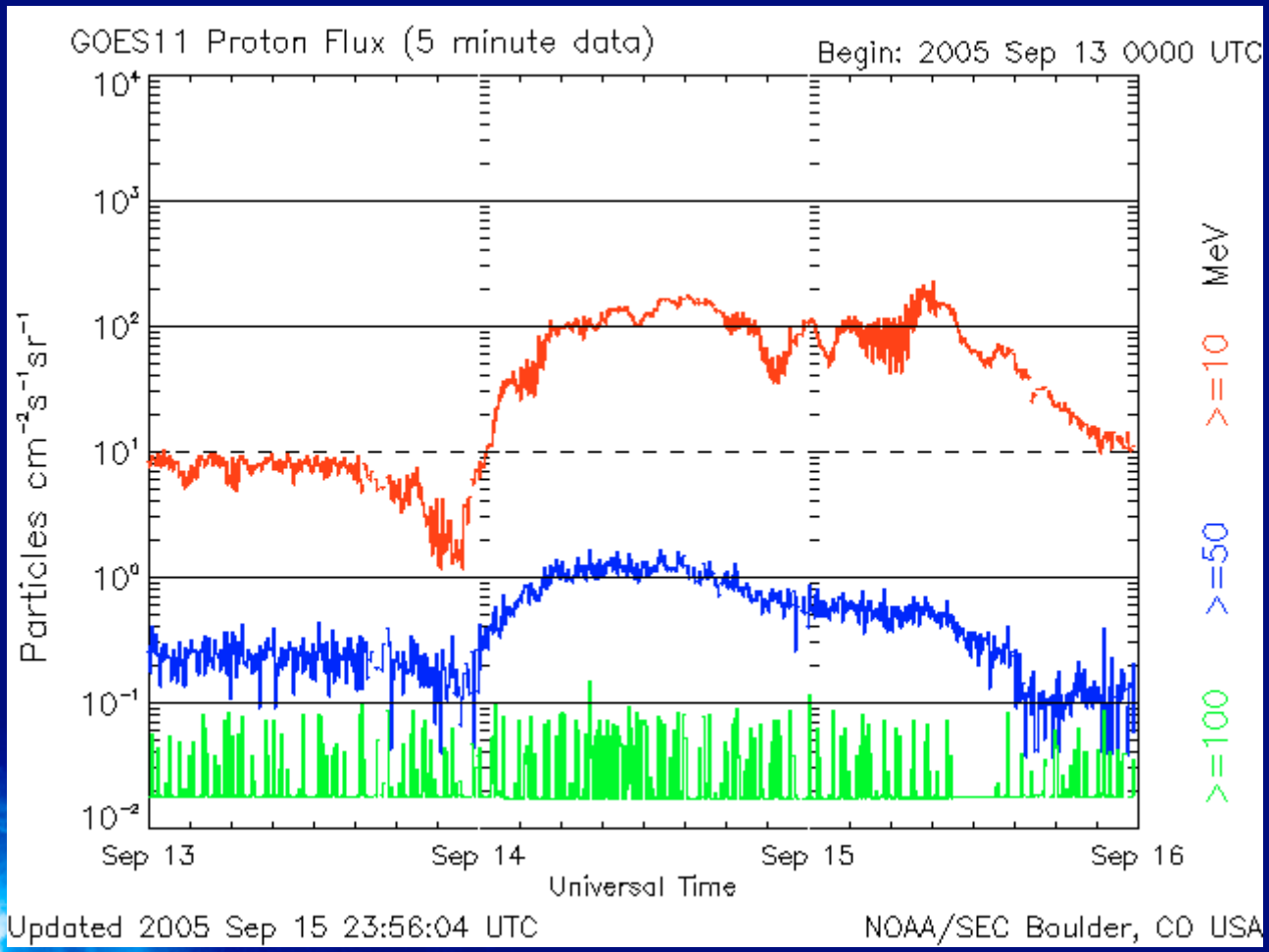


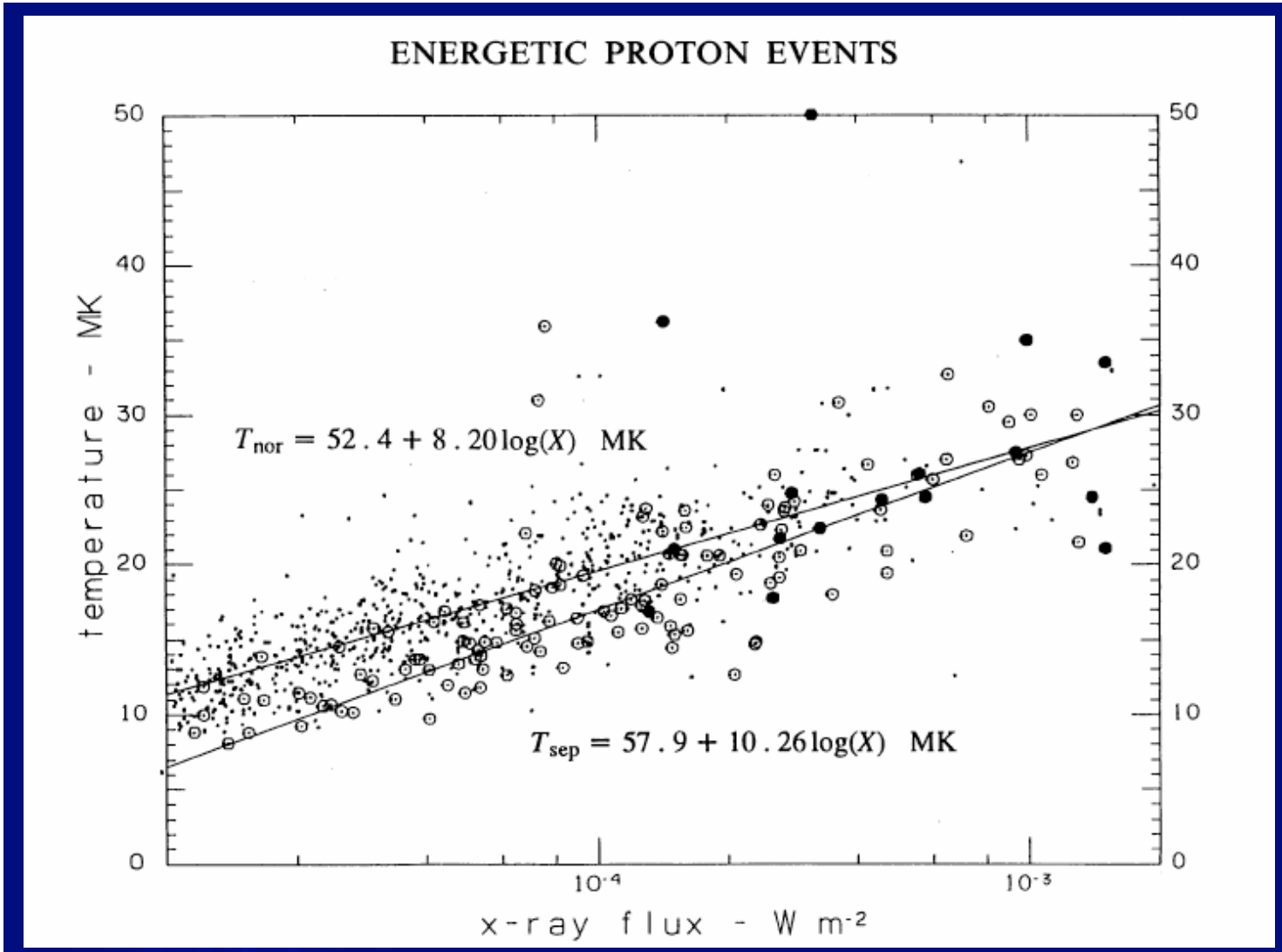
http://www.sec.noaa.gov/ftpmenu/indices/2005_events.html

http://www.sec.noaa.gov/ftpmenu/warehouse.html

Arrival of ICME

- some SEP events have <u>two</u> peaks- a prompt one arriving 10s of minutes after the solar activity, and a second, arriving with the ICME shock



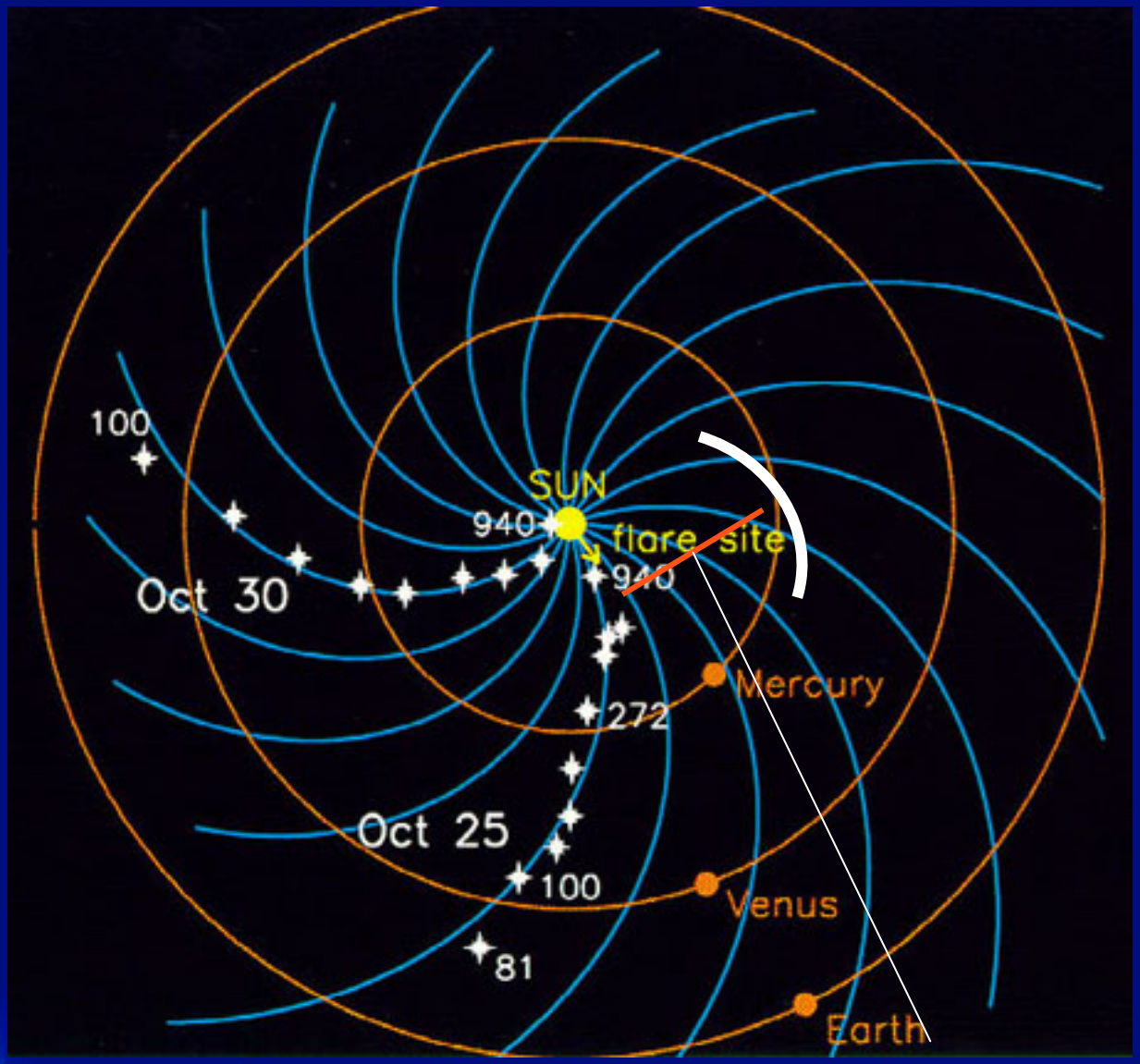


Temperature determination with aid of flare peak: short advance warning Garcia, 1994

Magnetic connectivity

CME: shock front has large extension and can intercept with some magnetic field line connected with earth
→even backsided CME can give rise to protons arriving at earth (UNCERTAIN)

Flares on the Westlimb: source on a magnetic field line going to earth



Solar driver modeling and predictions
Trieste, May 4, 2006

Coronal holes

- SOHO/EIT
- SOHO/MDI, GONG+

- SWB
- Niemegh

- Location
- Recurrence (Solar Highlight)
- Polarity

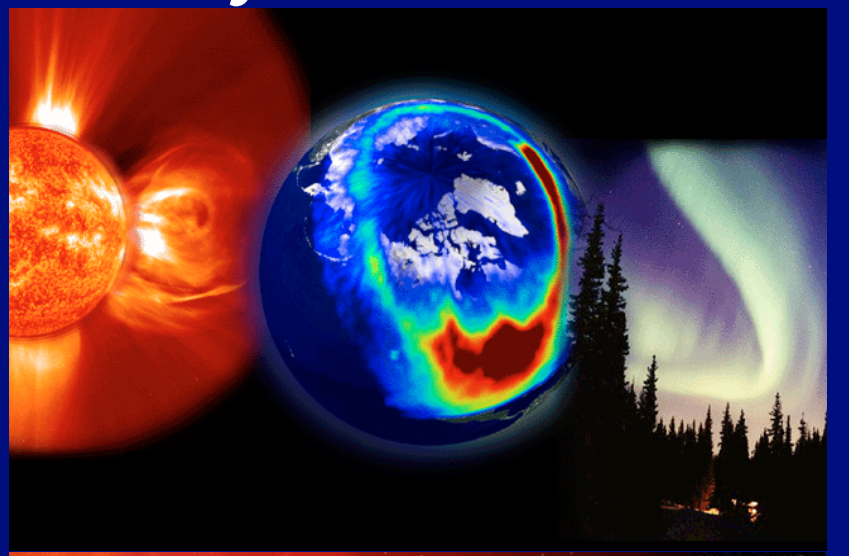
Solar minimum

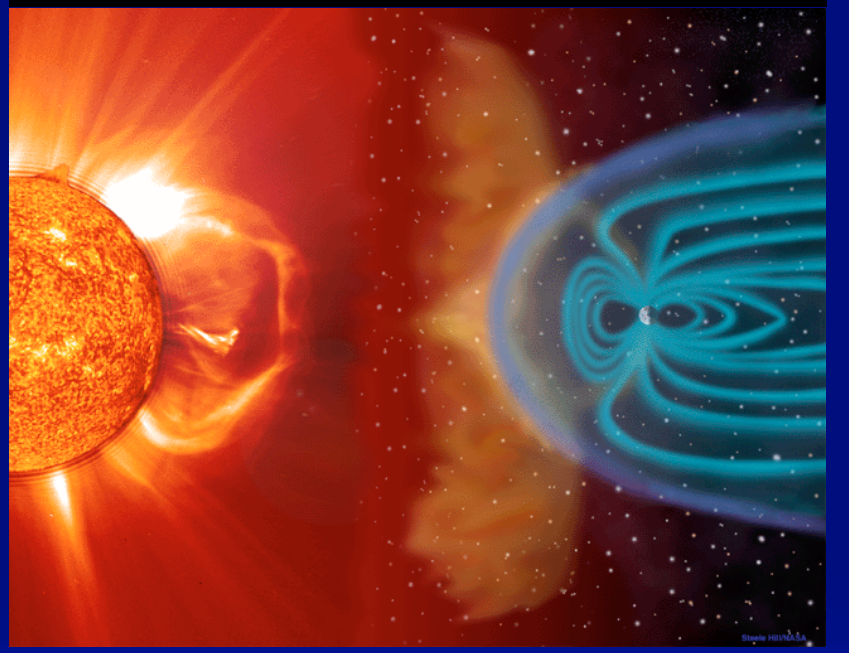
All the strongest geomagnetic storms are produced by CMEs!

To be geoeffective, the CME-associated disturbance should:

1) arrive to the Earth;

2) have a suitable magnetic field configuration: IMF ***Bz*** component should be negative (**southward**), **strong** enough and **long-lasting**.

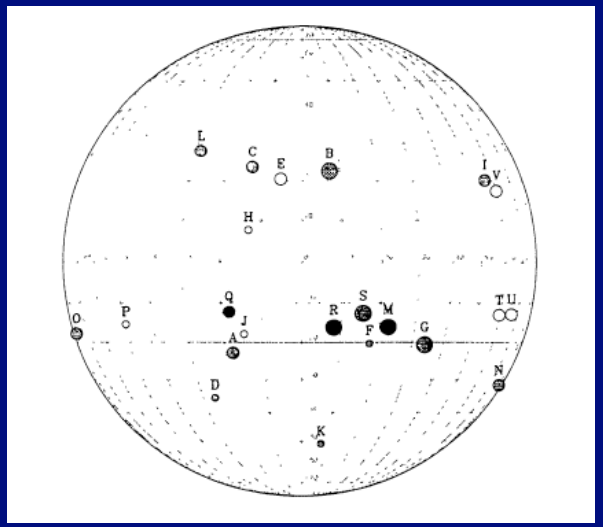




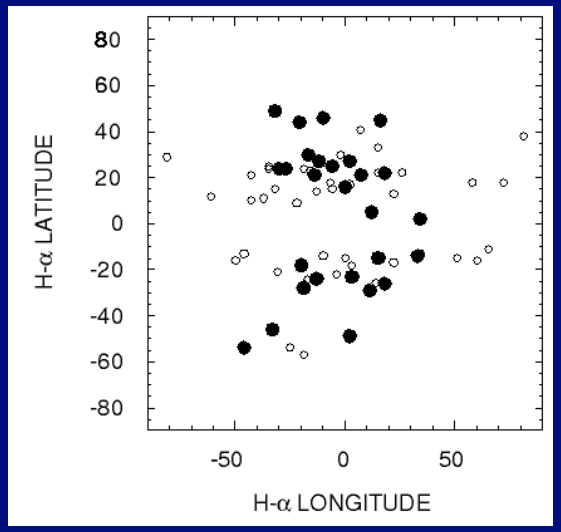
To be geoeffective, the CME-associated disturbance should arrive to the Earth!

- A CME should be frontside – importance of solar disc observations
- A CME should be wide enough – importance of partial and full halo CMEs
- Source regions of geoeffective CMEs are concentrated around the central meridian.

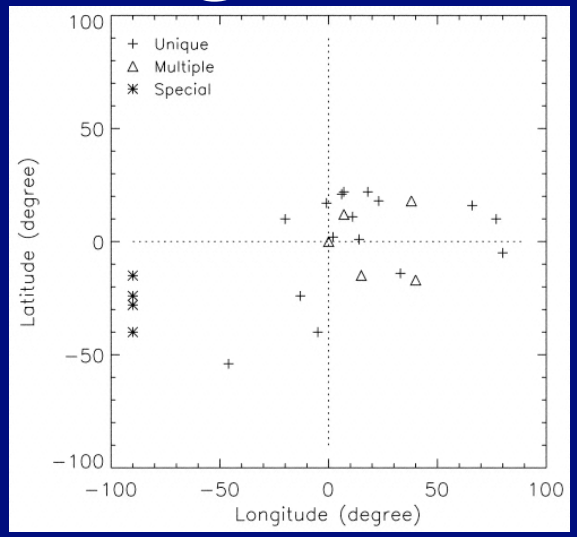
Location of ICME source regions



(Lyons et al. 1999)

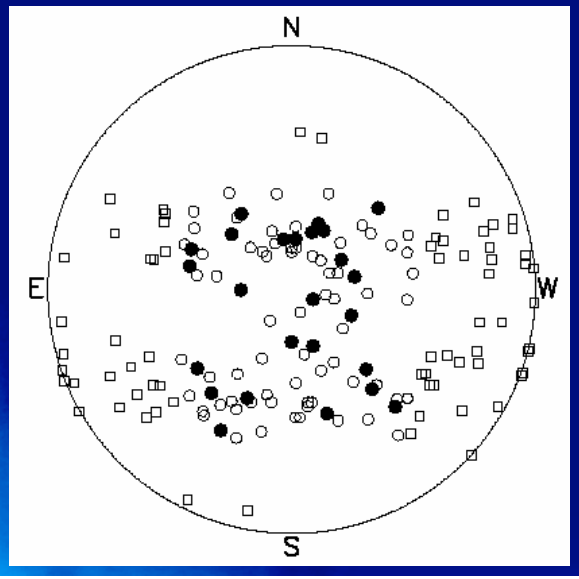


(Cane et al. 2000)

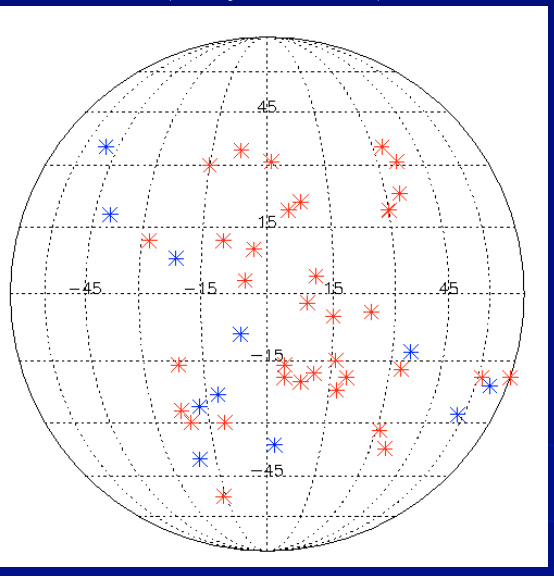


(Zhang et al. 2003)

(Manoharan et al. 2004)

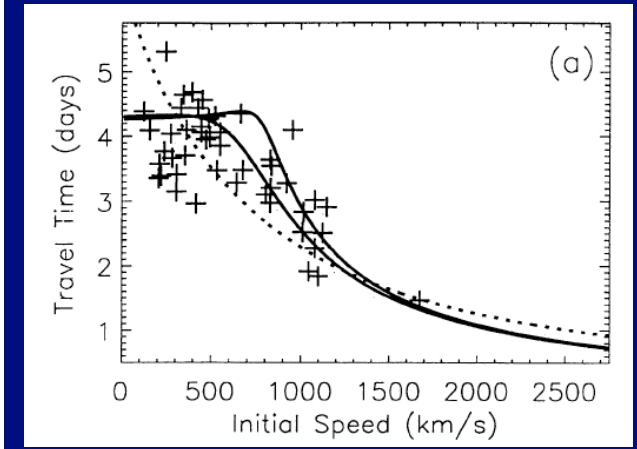


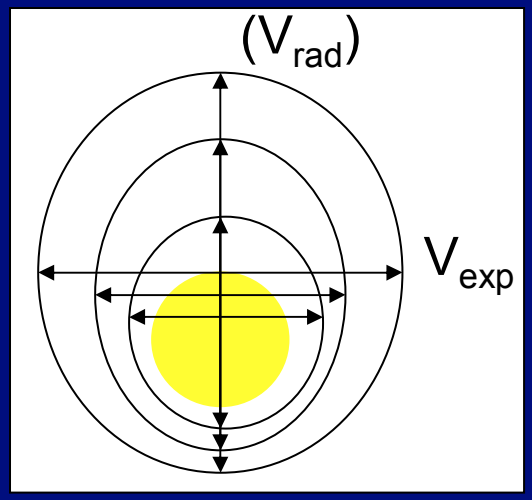
(My own)

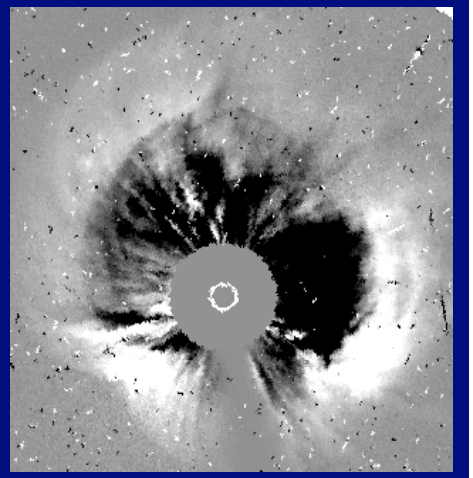


Predicting the CME arrival time

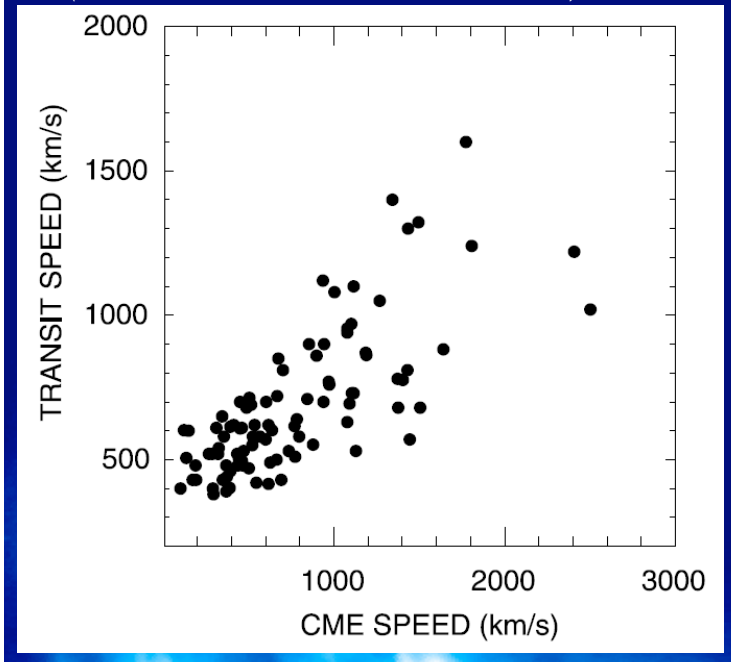
(Gopalswamy et al. 2001)



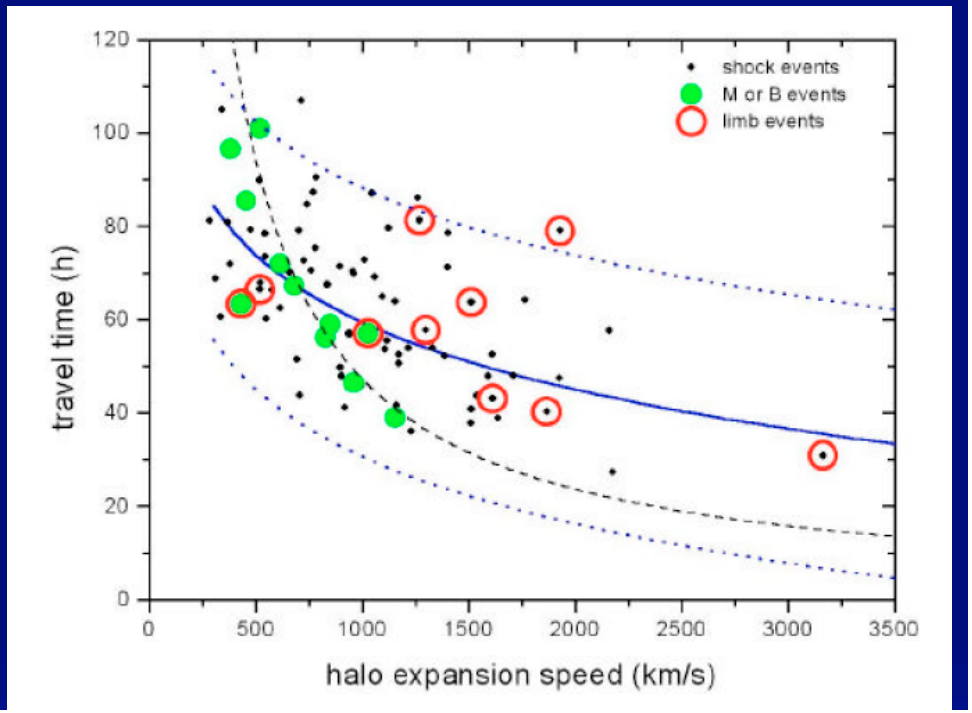




(Cane & Richardson 2003)

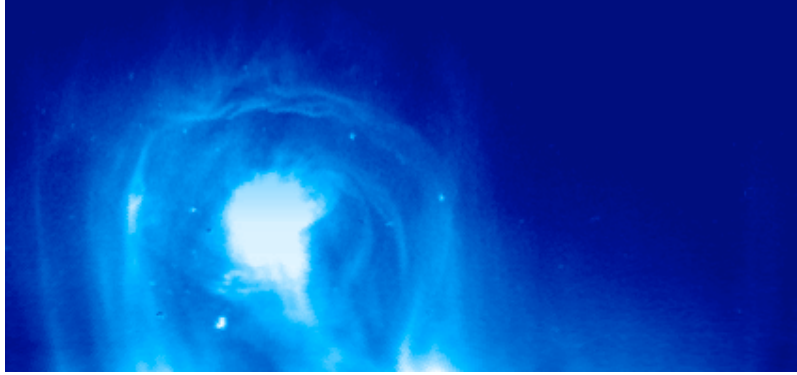


(Schwenn et al. 2005)

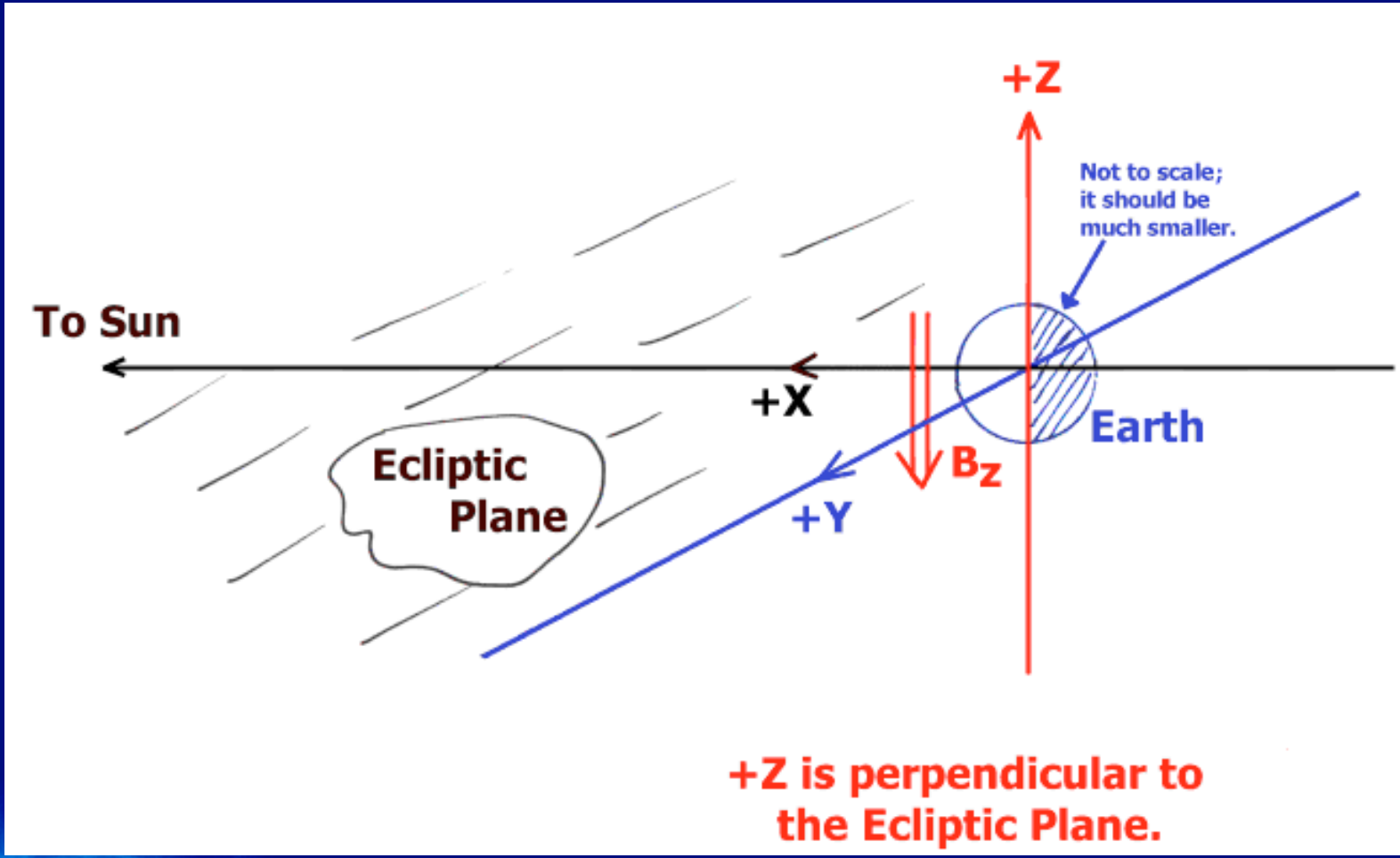


To be geoeffective, the CME-associated disturbance should have suitable magnetic field configuration!

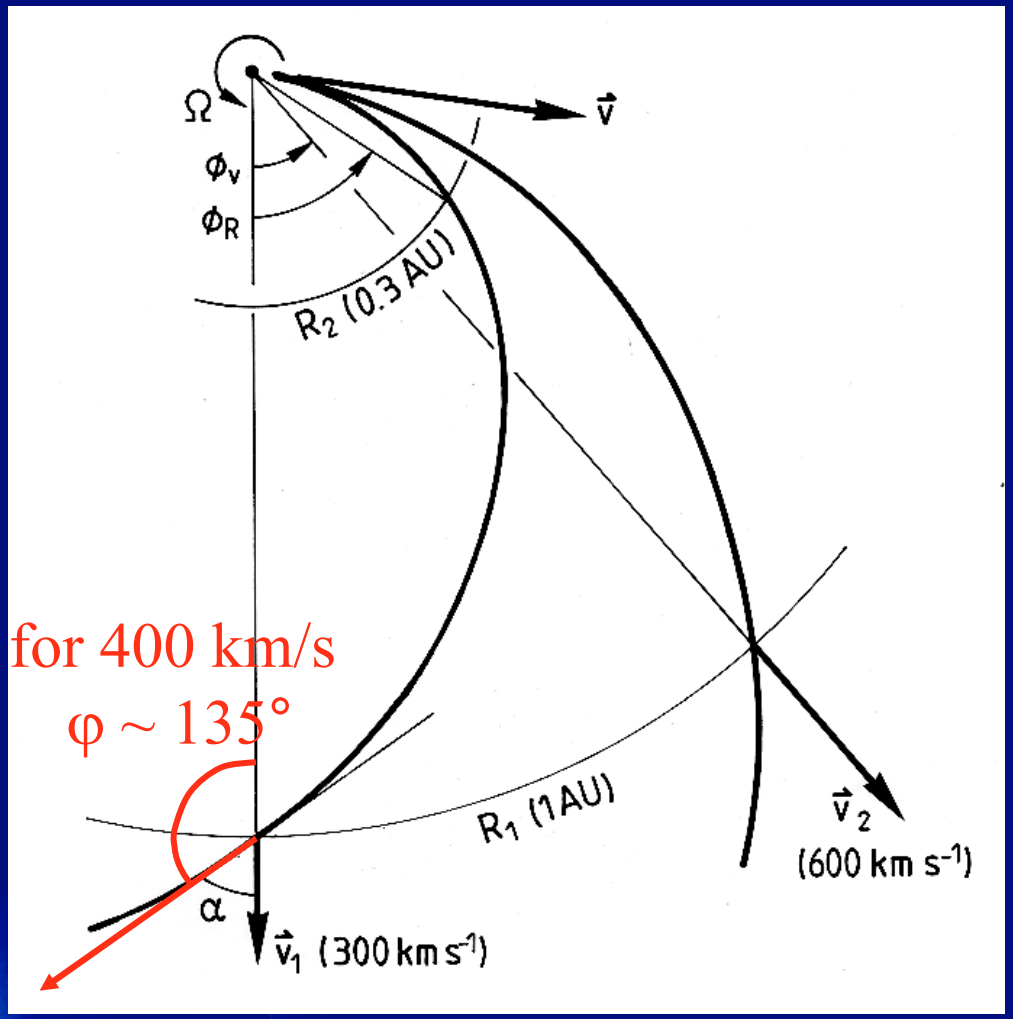
- The interplanetary magnetic field (IMF) component Bz should be negative (southward), strong enough and long-lasting



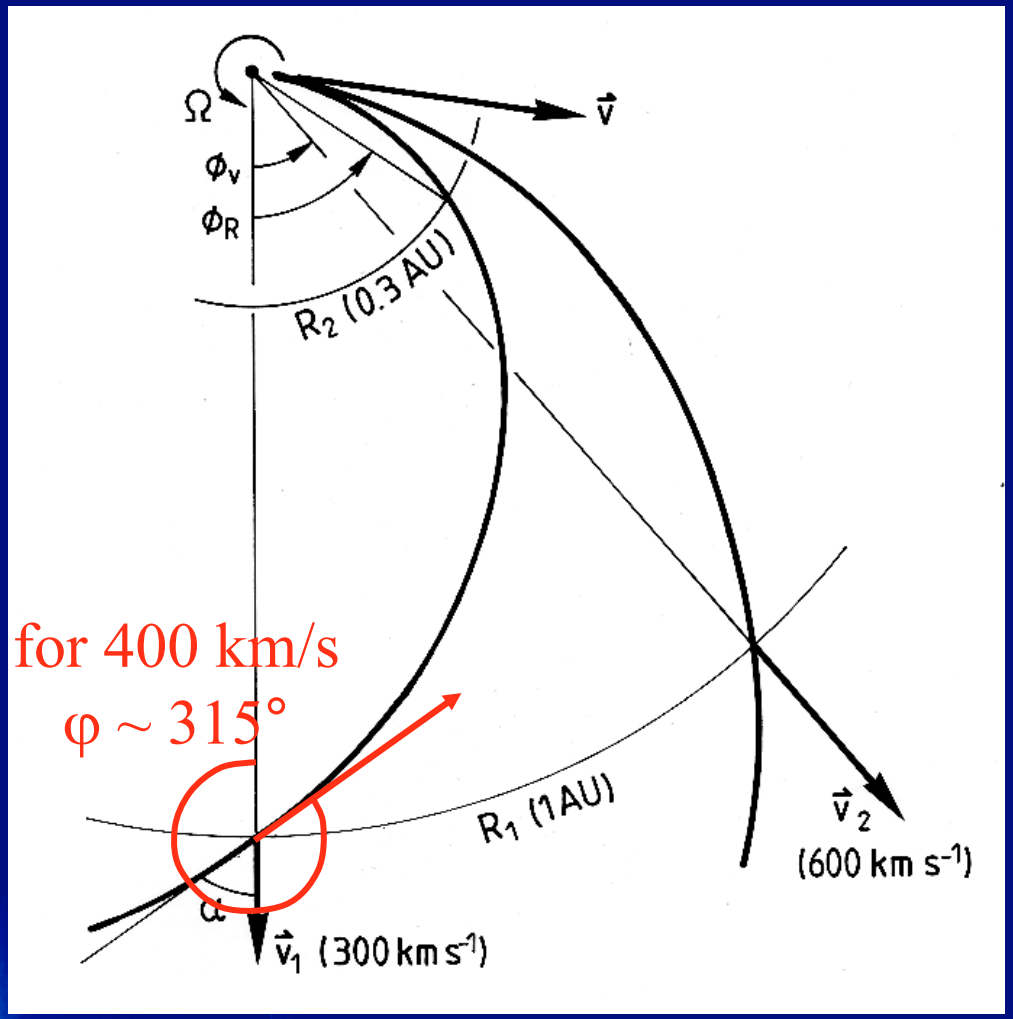
Coordinate system



IMF polarity



IMF polarity



Solar driver modeling and predictions
Trieste, May 4, 2006

Fast solar wind

- High speed: 400 – 800 km/s
- Low density: ~ 3 cm^{-3}
- High temperature: ~ 10^5 K ~ 10 eV
- Stationary for long times
- Strong Alfvénic fluctuations

By the way: 1 eV = 1.6 10^4 K

Slow solar wind

- Low speed: 250 – 400 km/s
- High density: ~ 10 cm^{-3}
- Low temperature: ~ 10^4 K ~ 1 eV
- Very variable

By the way: 1 eV = 1.6 10^4 K

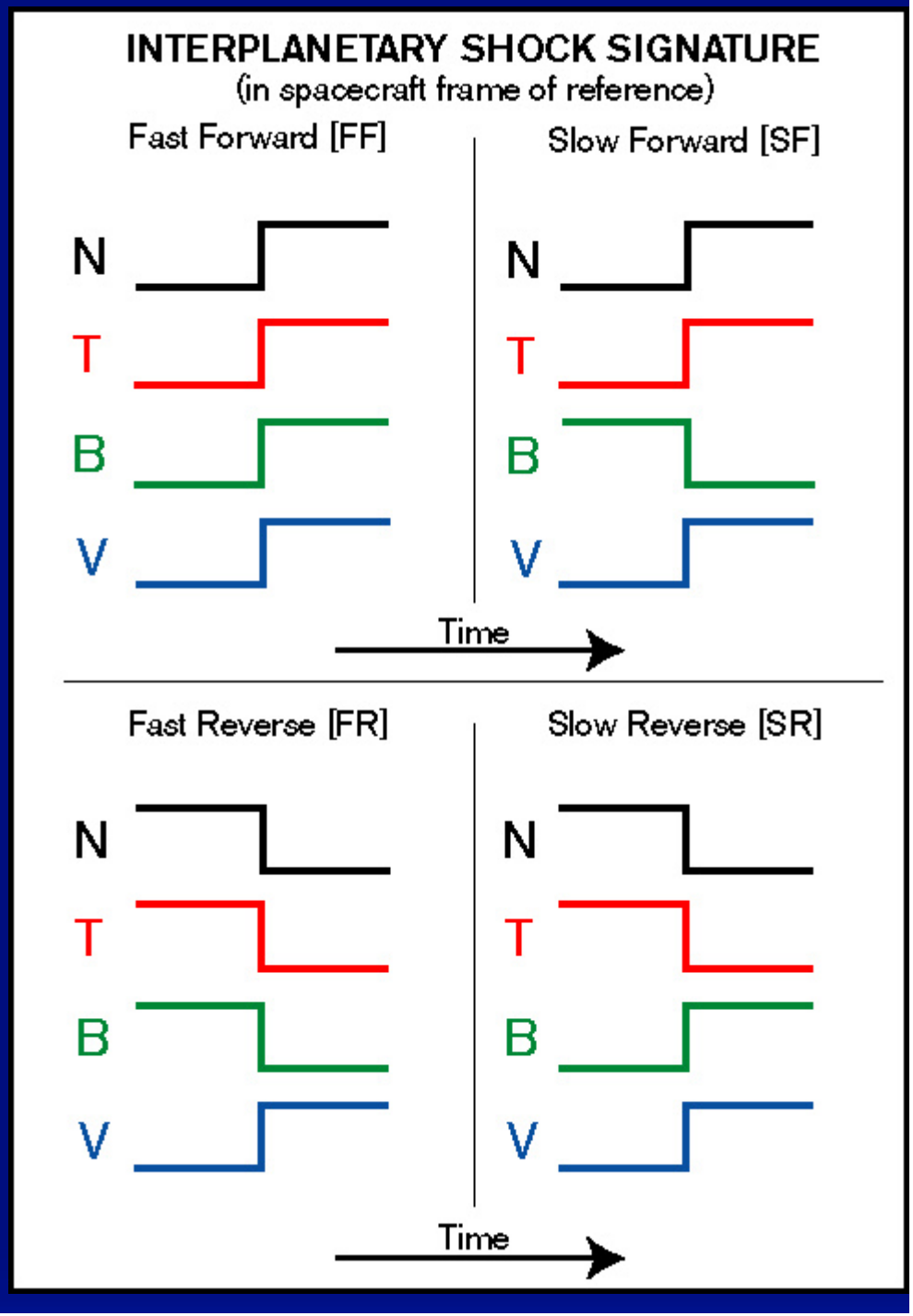
ICME signatures

- Shock (if the ICME is fast enough)
- …followed by shocked sheath plasma (compressed and heated, with oscillating magnetic field)
- …followed often by the driver gas (ICME itself):
  - Strong magnetic field
  - Temperature depression: typically < ~ 105 K ~ 10 eV
  - Low variance of the magnetic field
  - Large-scale smooth field rotation (magnetic cloud): in about 30% of cases
  - Composition signatures (increased a/p and O/O ratios etc.)
  - Bi-directional electrons

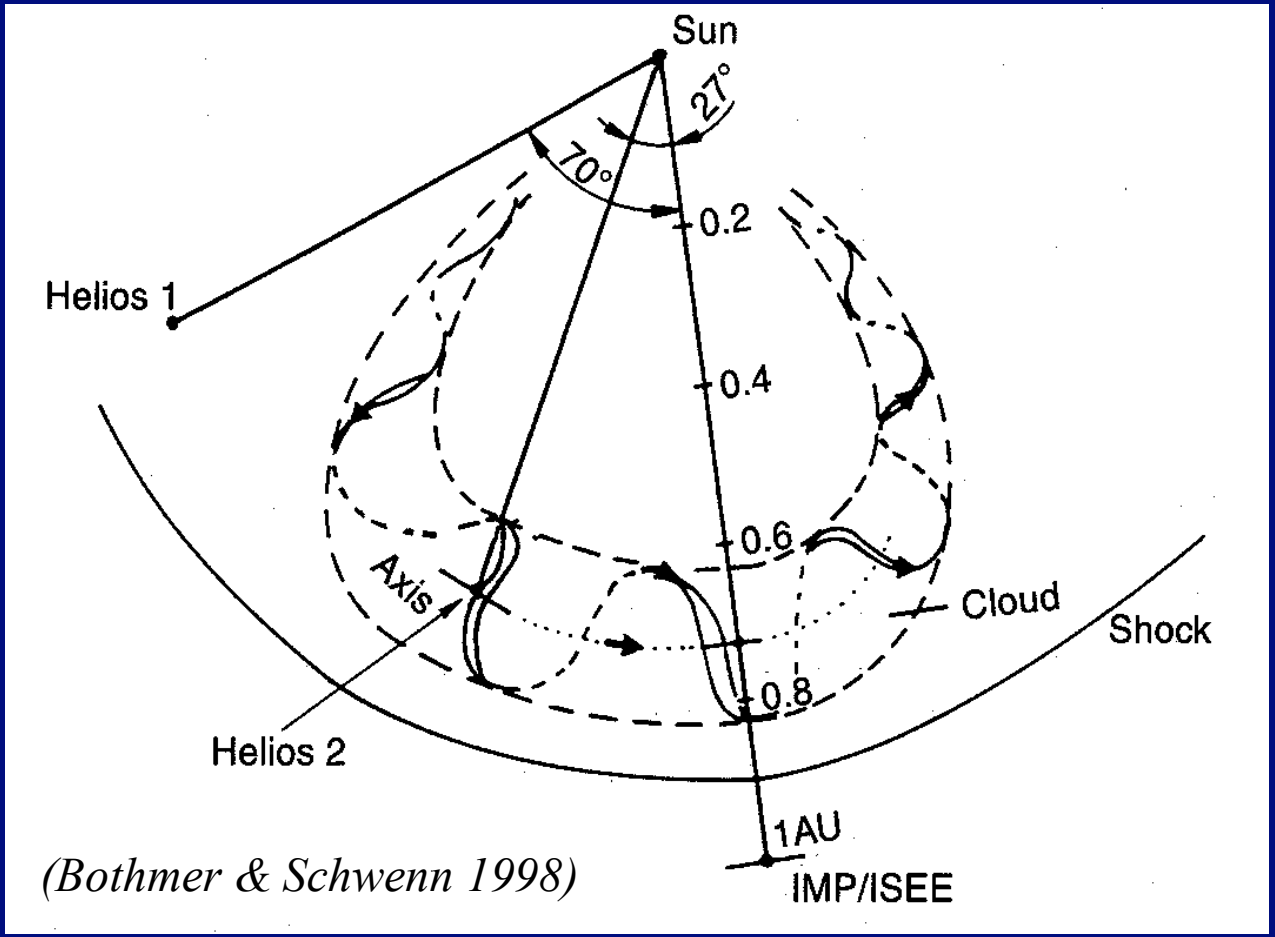
Low $\beta = \frac{8\pi p}{B^2}$

Usually only a subset of these signatures is observed.

Interplanetary shocks

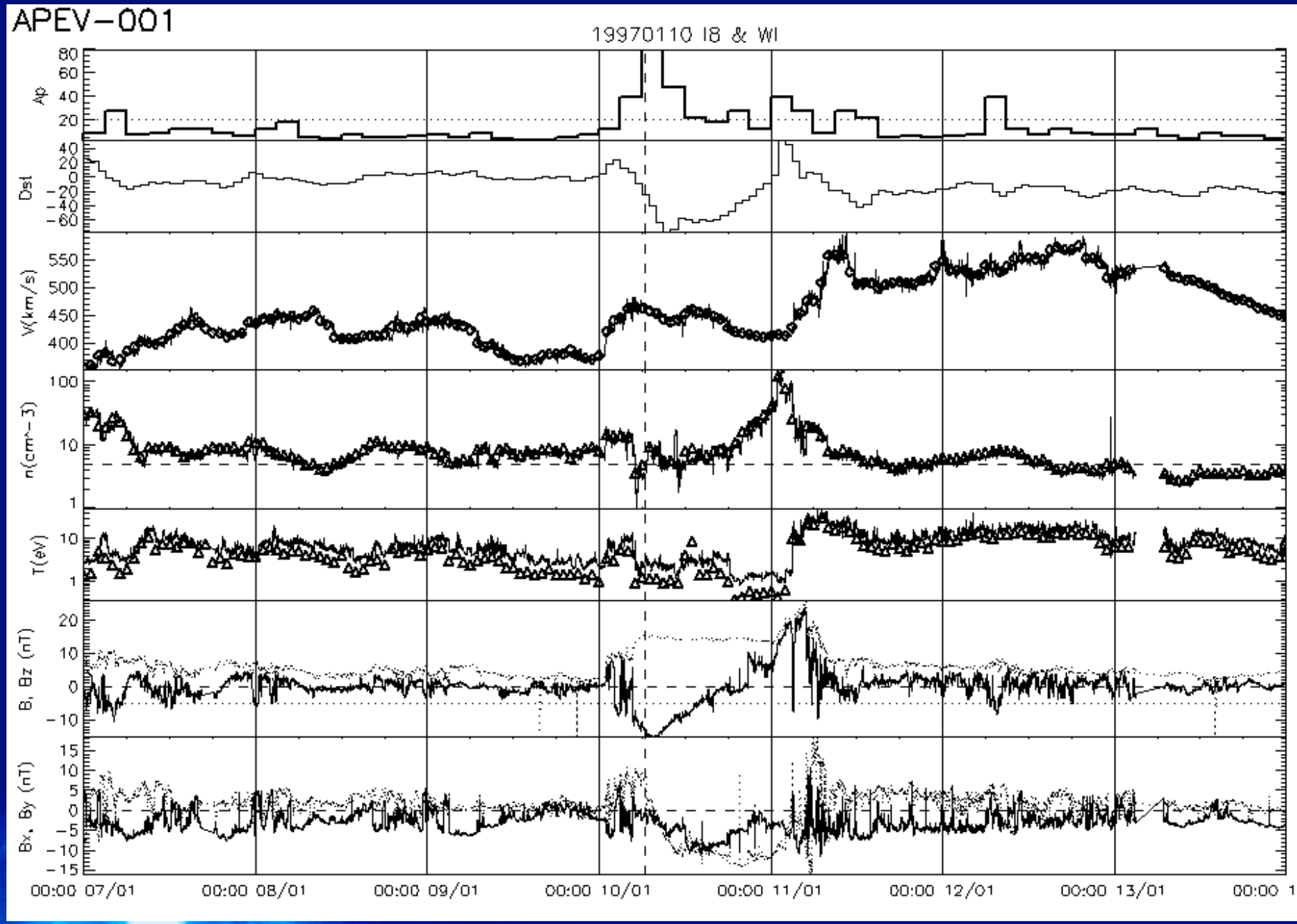


CME-driven shock waves



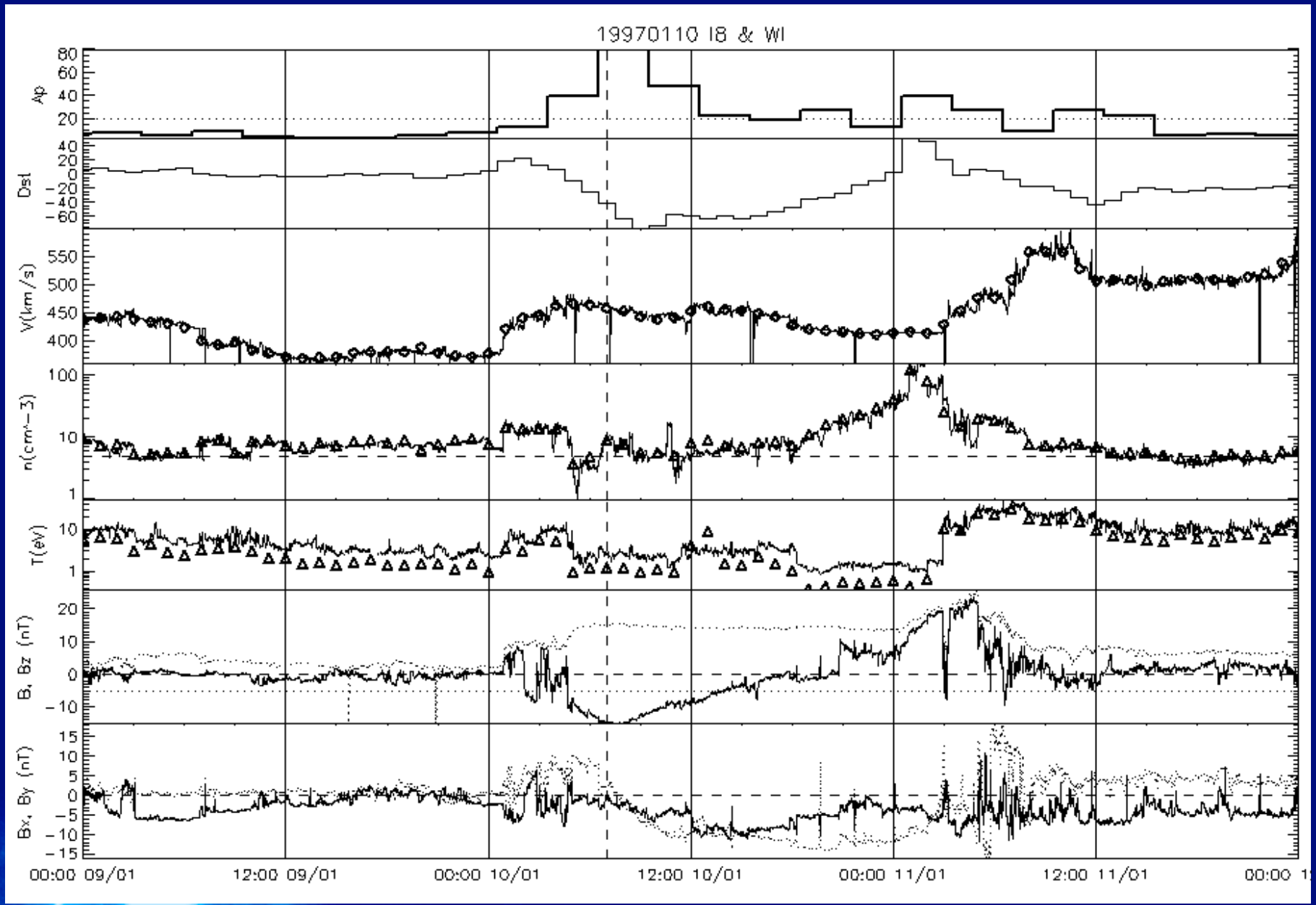
(Bothmer & Schwenn 1998)

A CME-driven shock has larger angular extent than the CME itself!



ICME

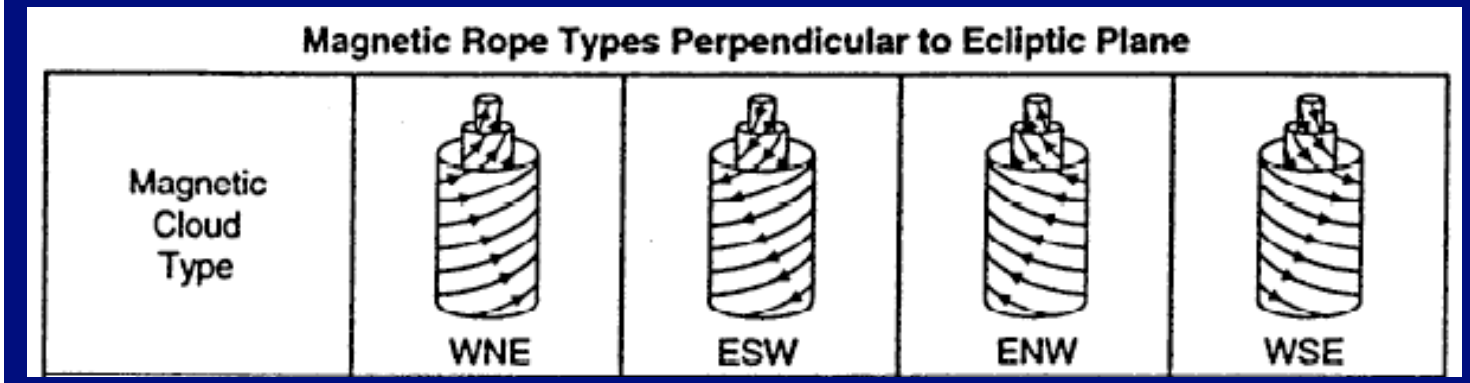
Solar driver modeling and predictions
Trieste, May 4, 2006



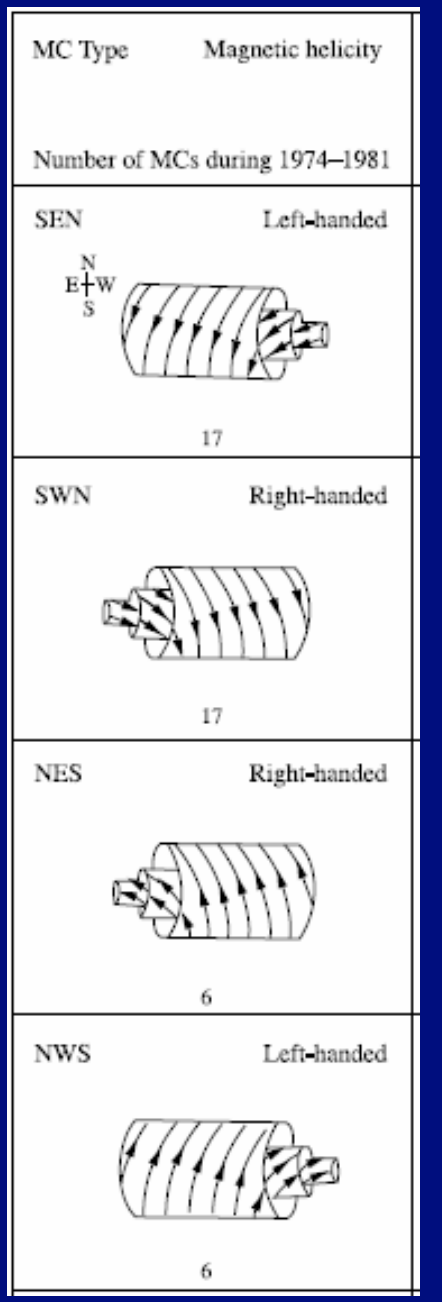
ICME

Solar driver modeling and predictions
Trieste, May 4, 2006

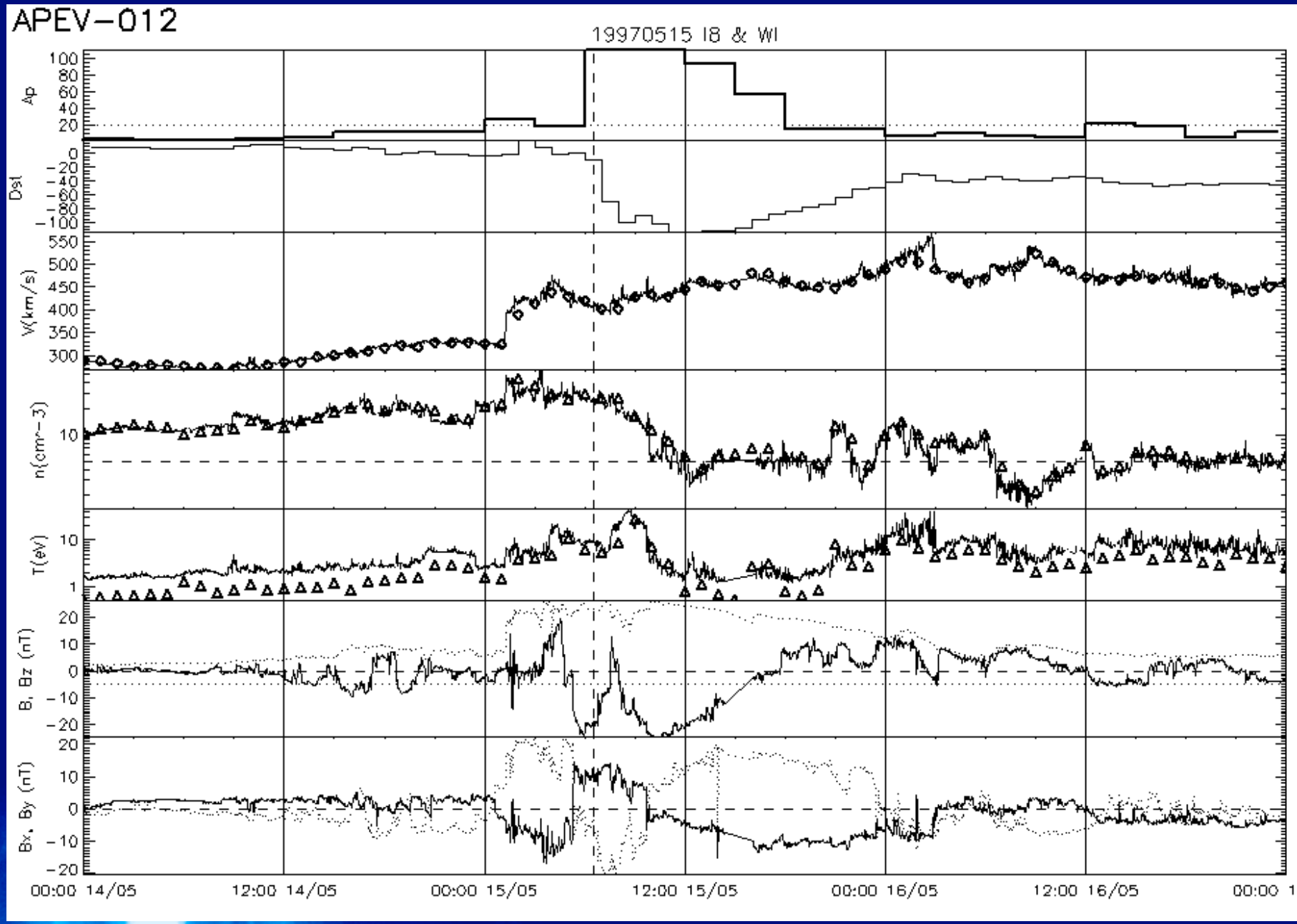
Magnetic cloud (MC) types



(Mulligan et al. 1998)

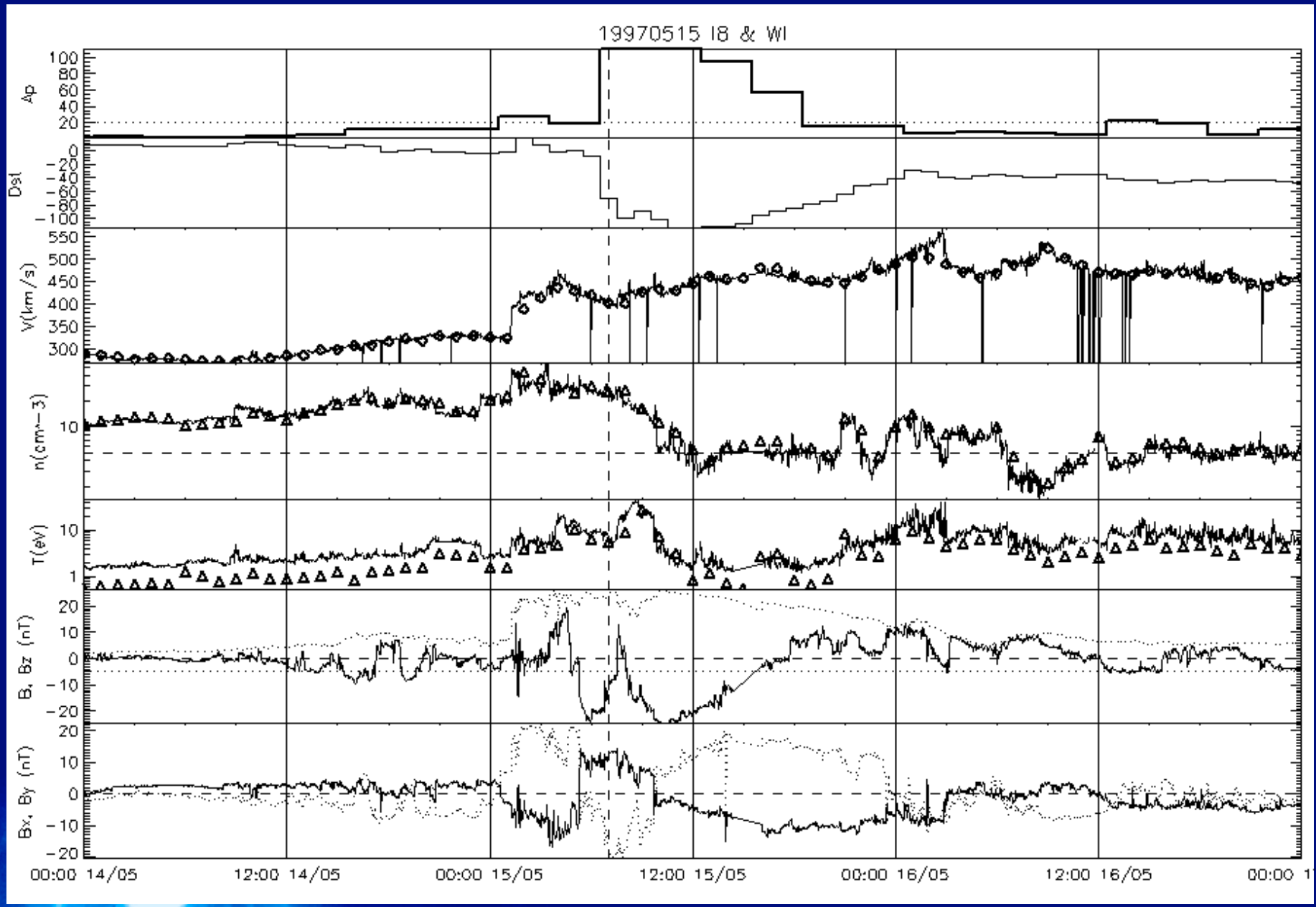


(Bothmer & Schwenn 1998)



ICME

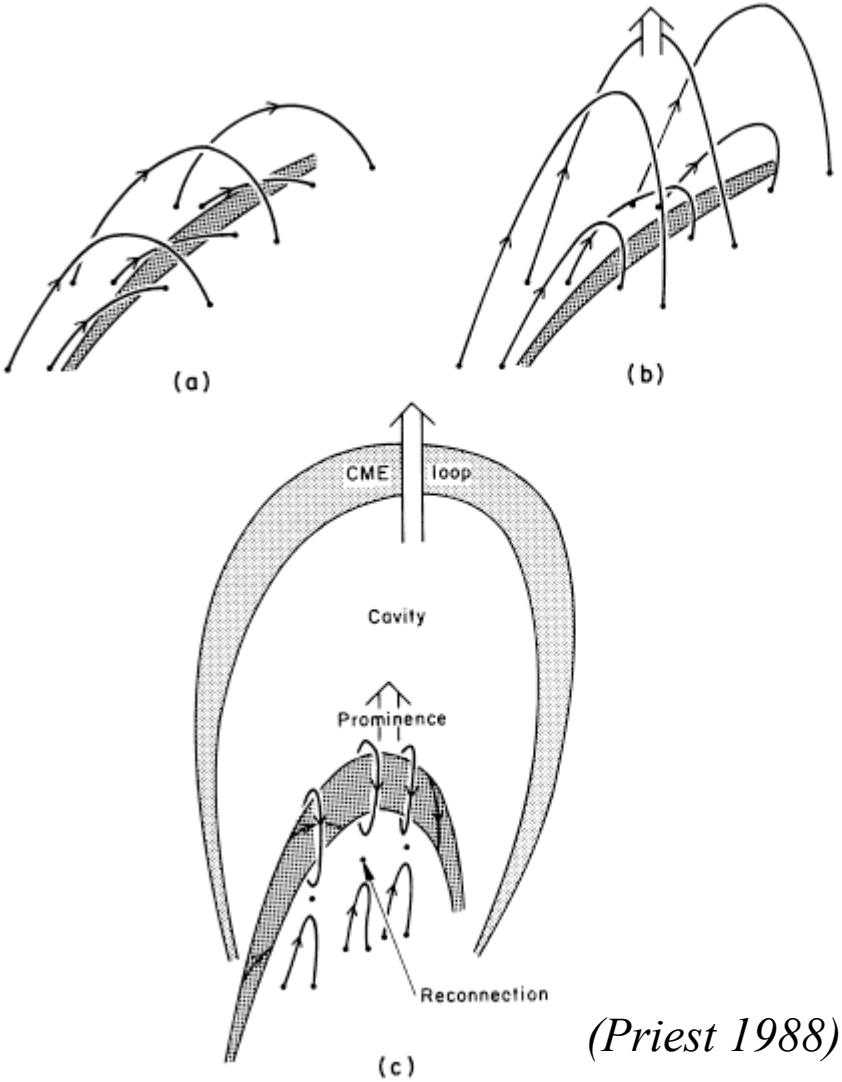
Solar driver modeling and predictions
Trieste, May 4, 2006



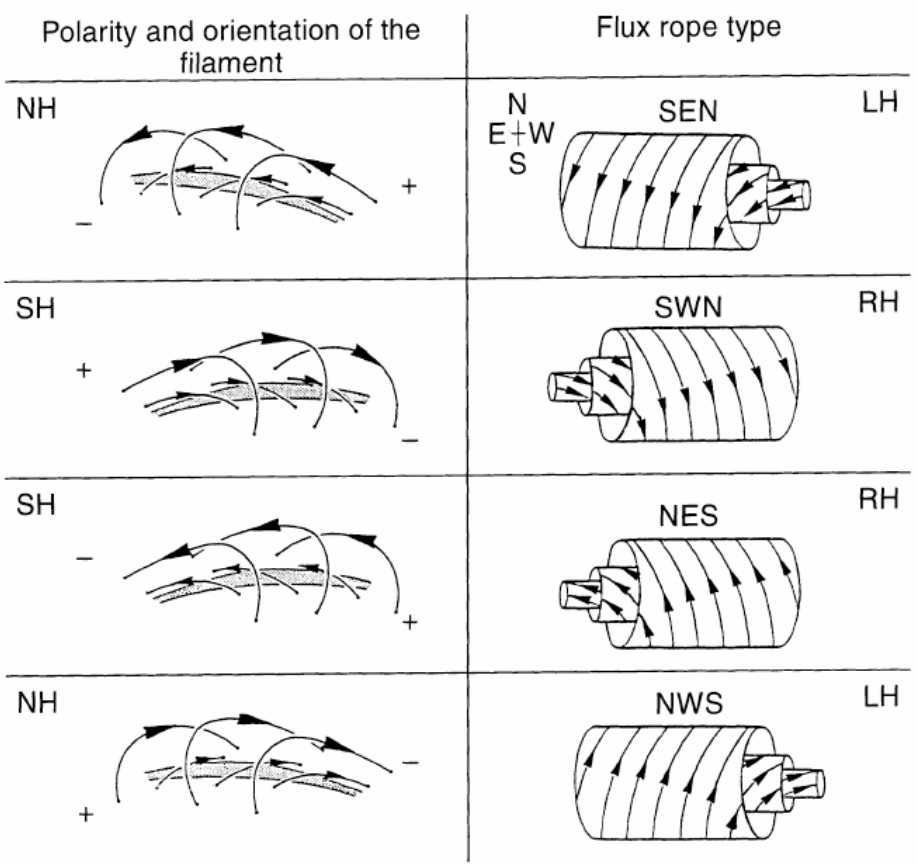
ICME

Solar driver modeling and predictions
Trieste, May 4, 2006

Inferring the orientation of erupting flux ropes from solar observations

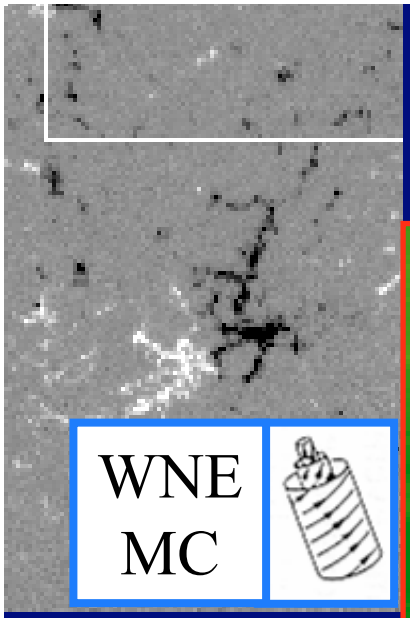


(Priest 1988)

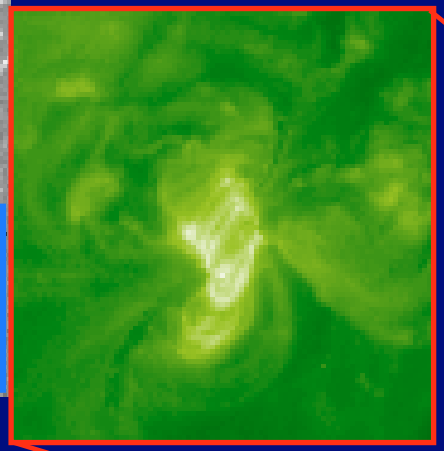


(Bothmer & Schwenn 1998)

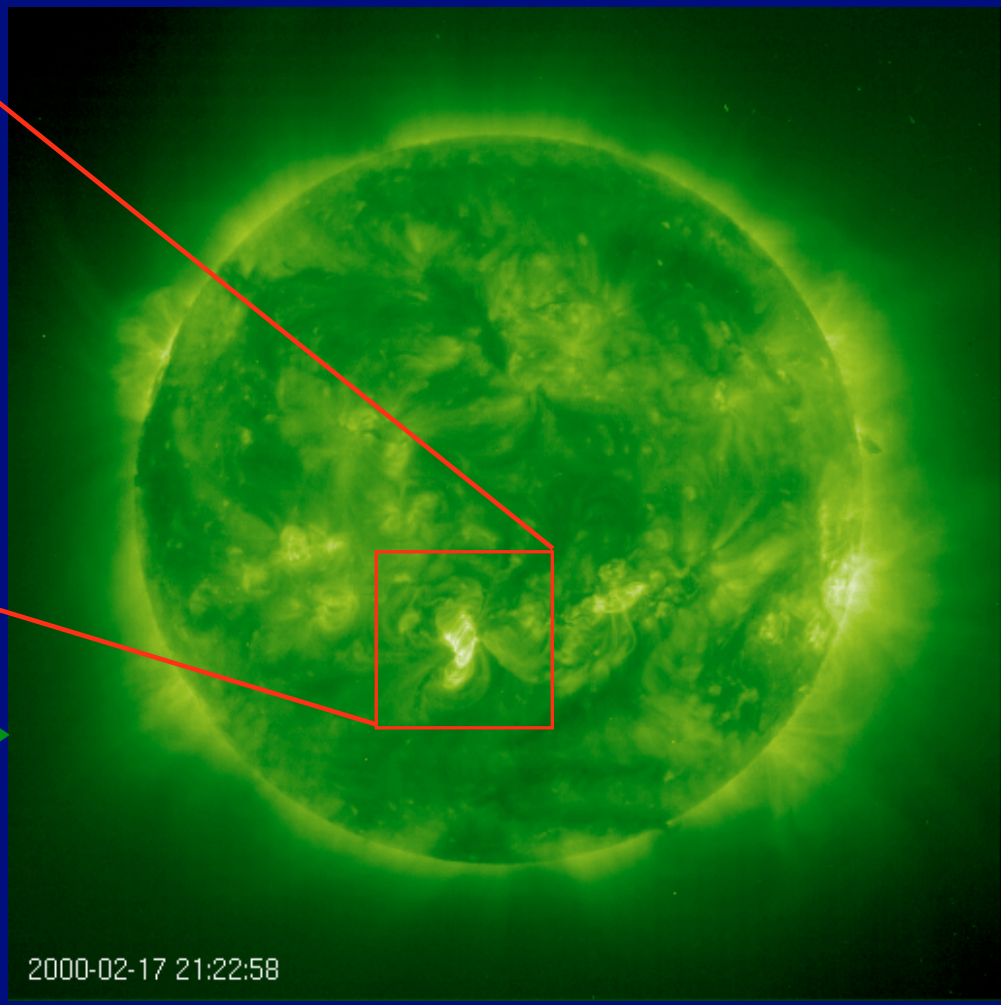
Flux rope orientation!



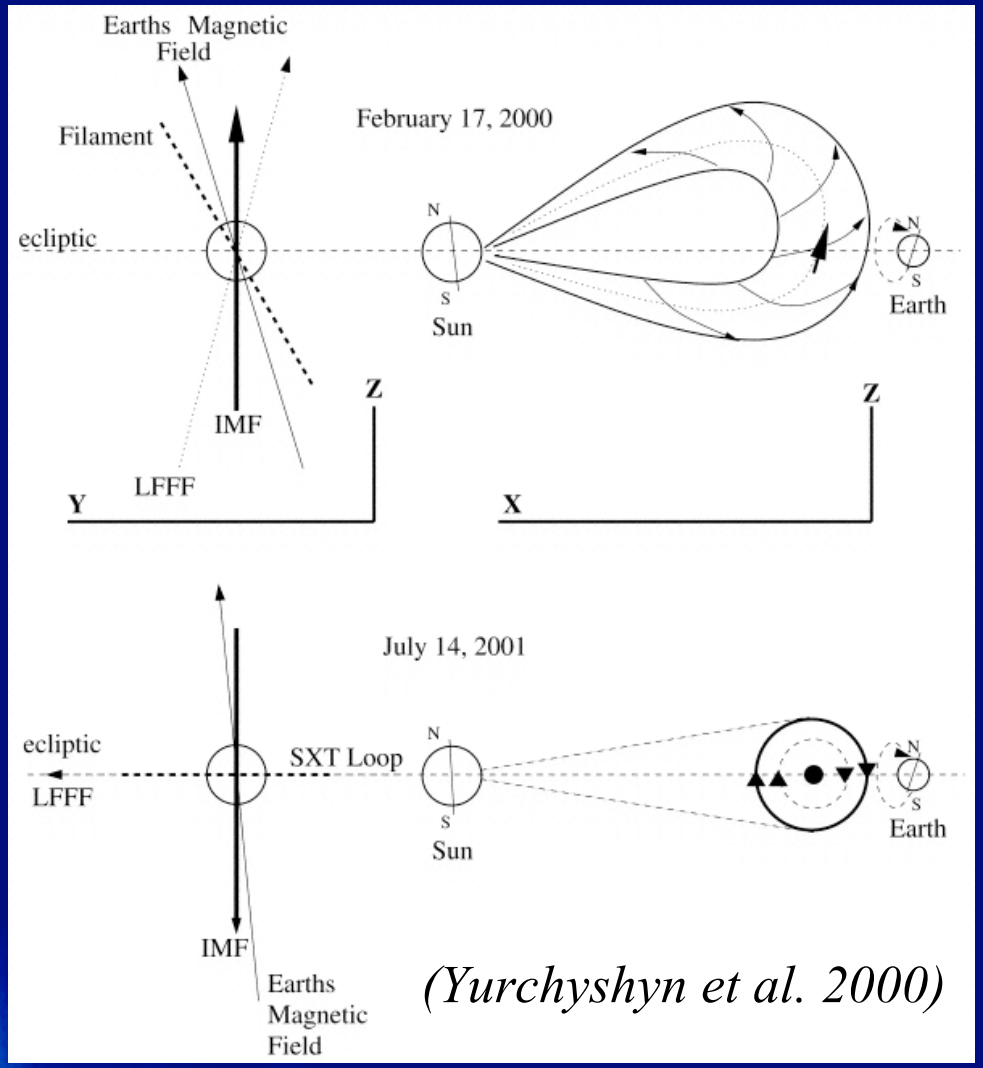
SOHO/MDI



SOHO/EIT
Fe XII bandpass
(195 Å)

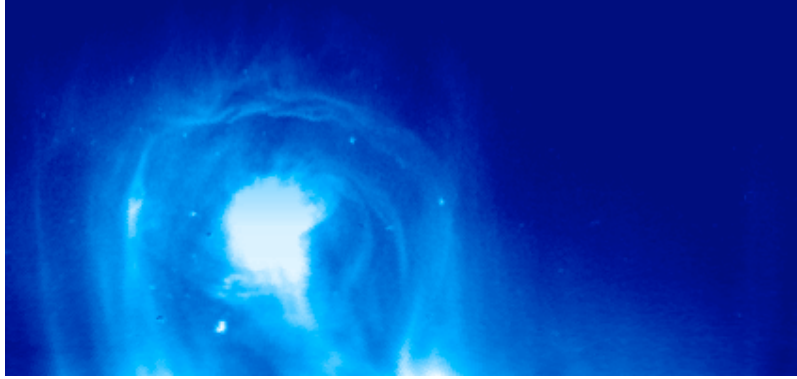


A way to predict the orientation of the magnetic field in MCs on the base of solar observations
(Marubashi 1986,
Bothmer & Schwenn 1994,
Rust 1994,
Yurchyshyn et al. 2001,
McAllister et al. 2001)



(Yurchyshyn et al. 2000)

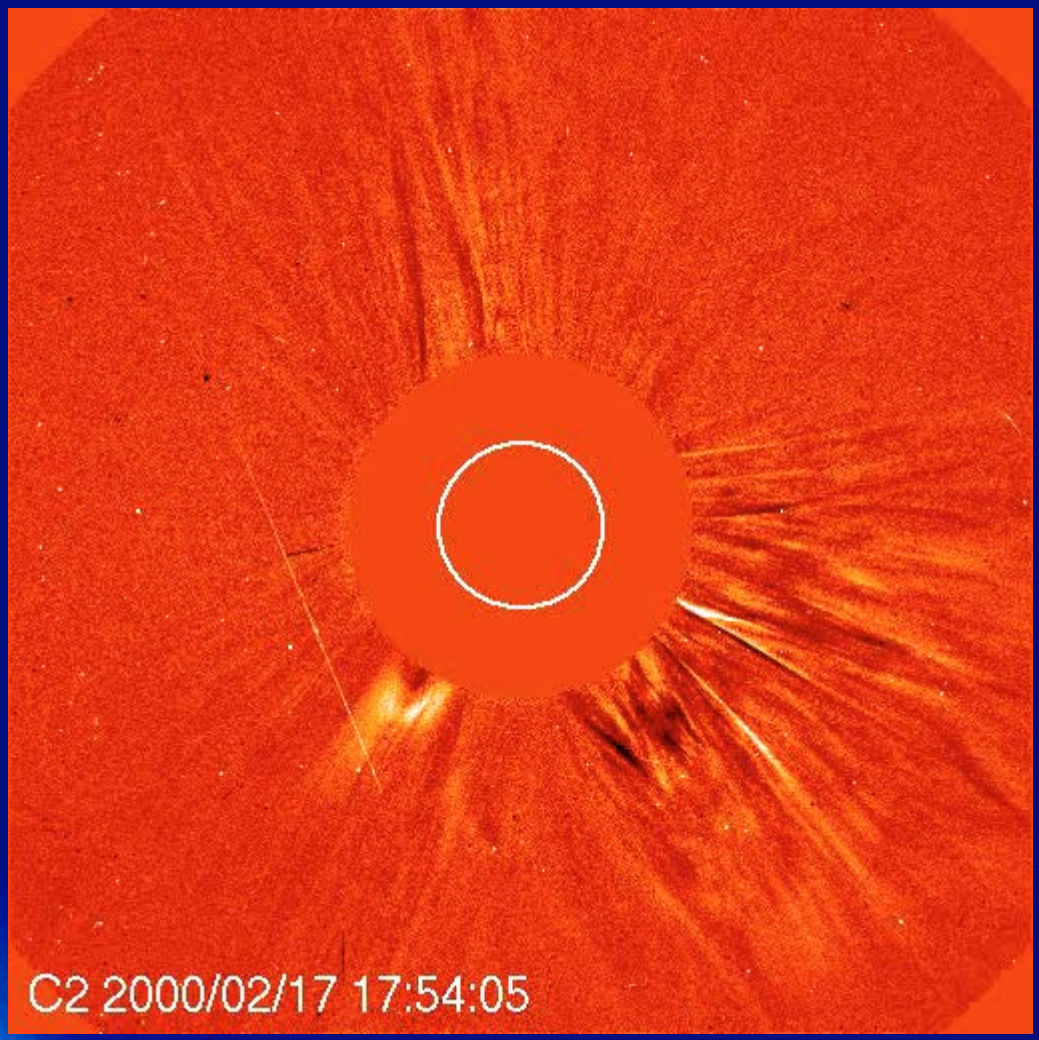
An example: halo CME on February 17, 2000



Solar driver modeling and predictions
Trieste, May 4, 2006

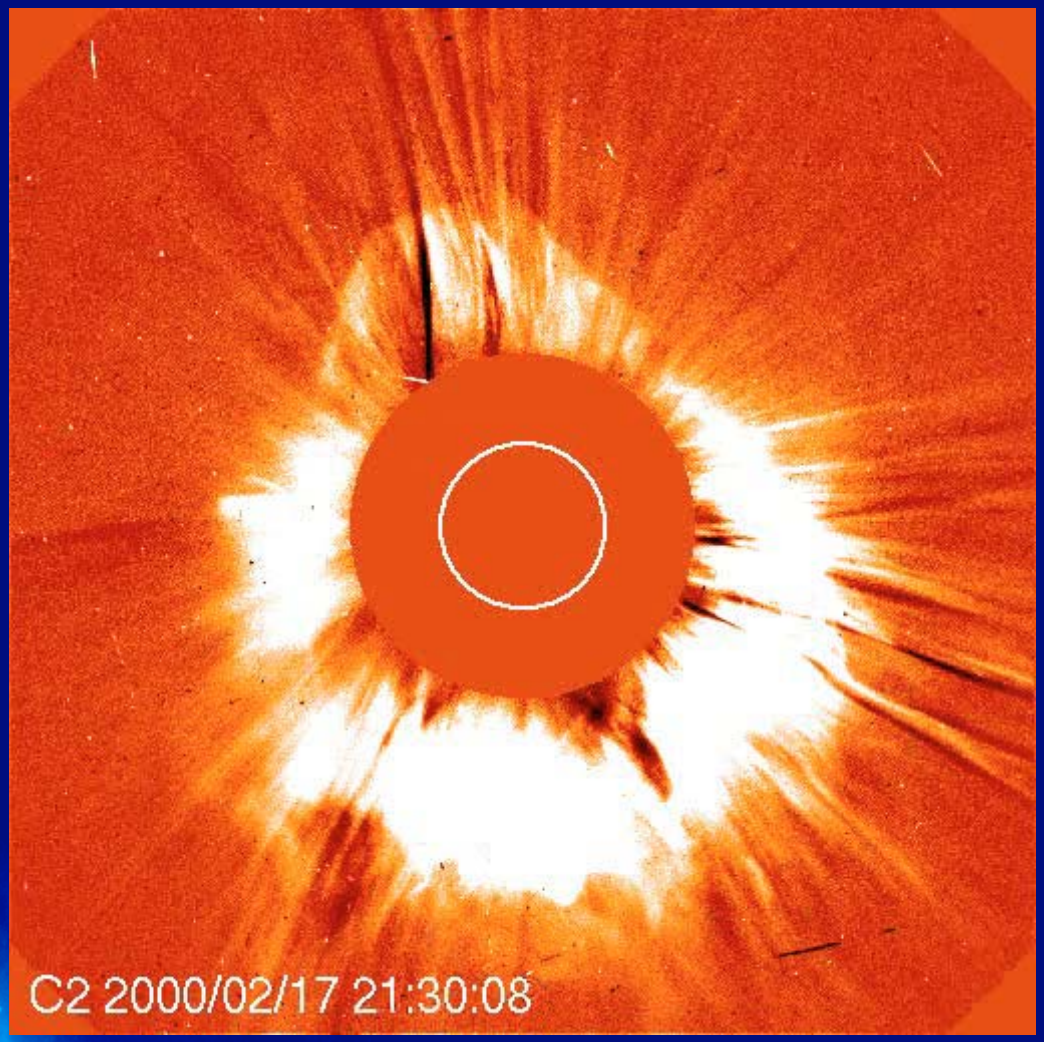
Full halo CME on February 17, 2000

SOHO/LASCO C2



Full halo CME on February 17, 2000

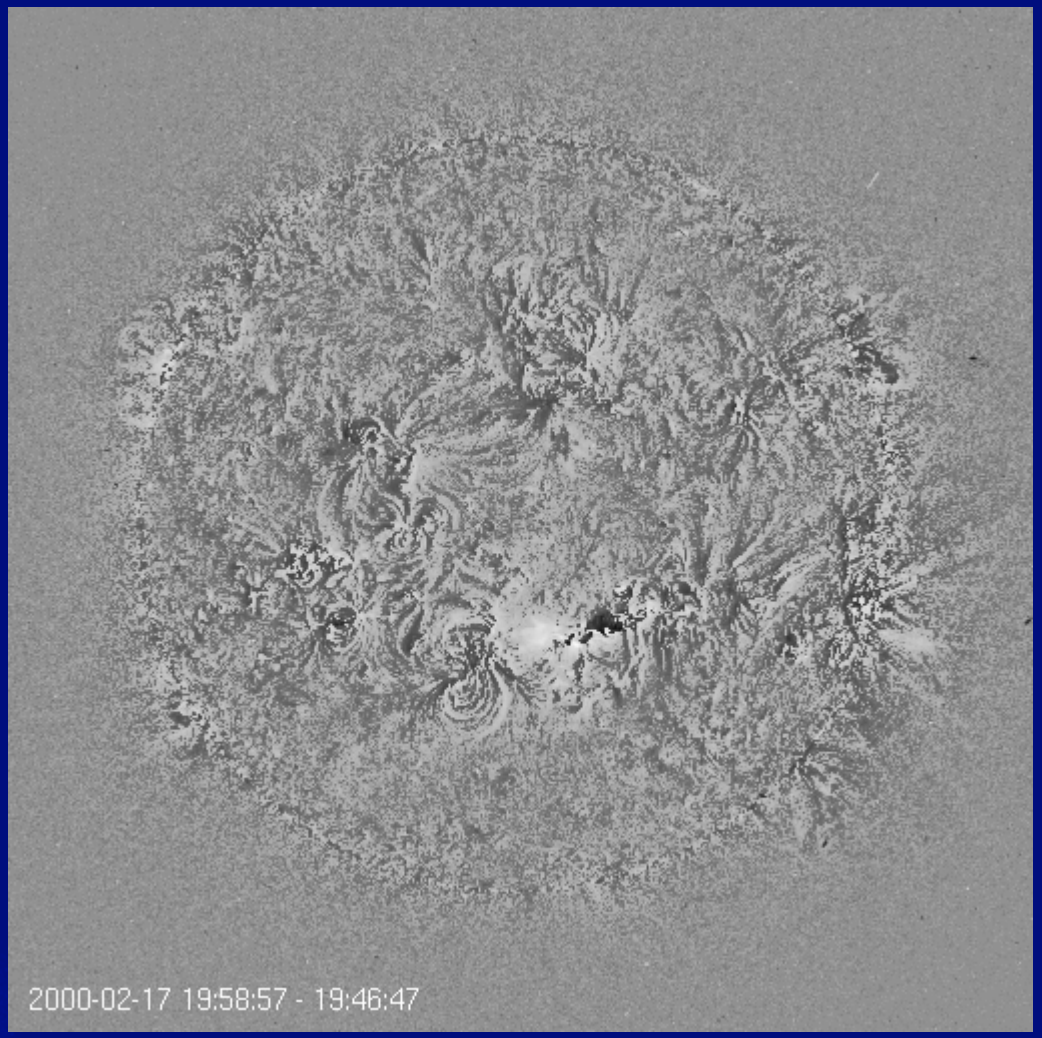
SOHO/LASCO C2



Full halo CME on February 17, 2000: frontside!

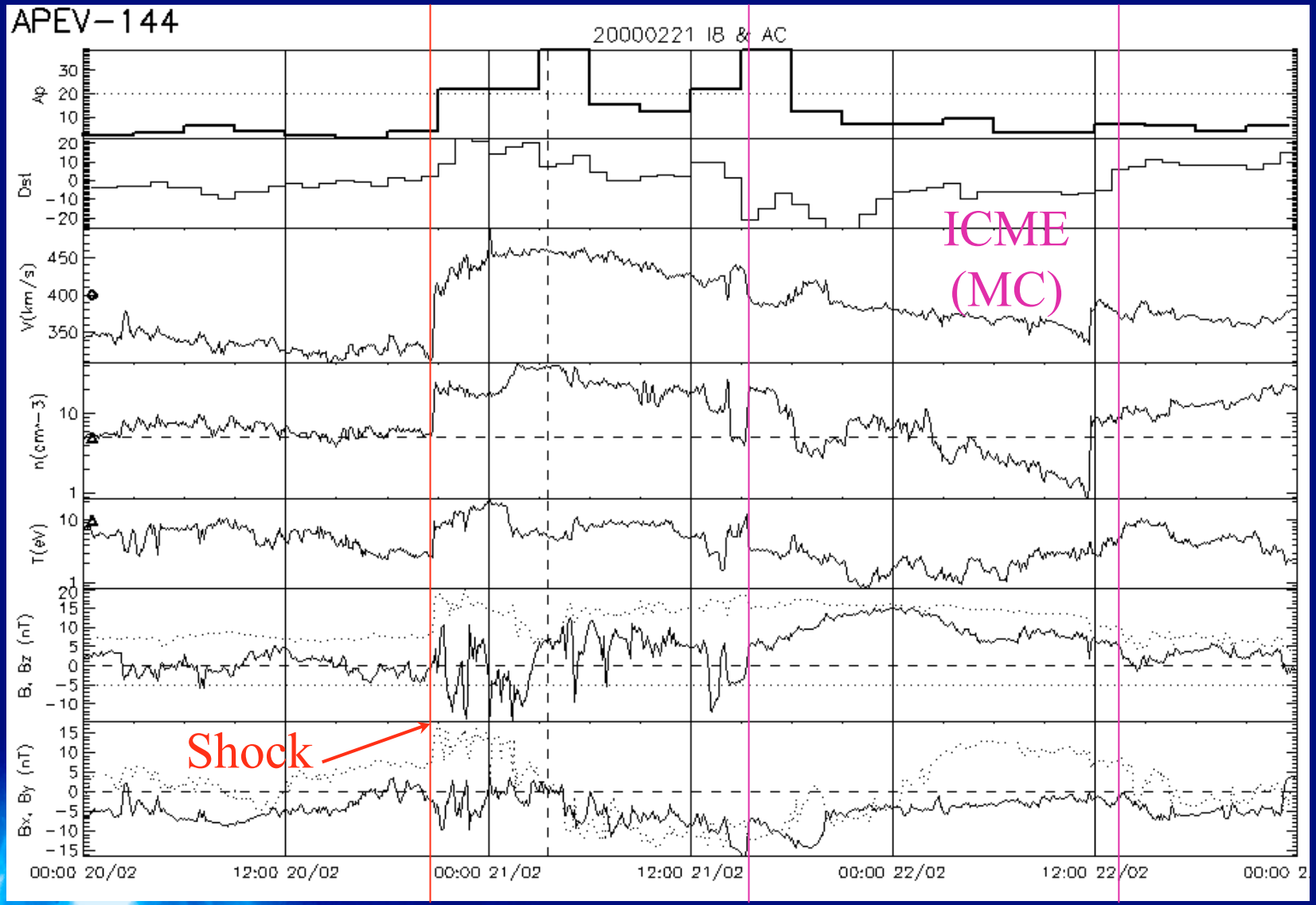
SOHO/EIT
Fe XII bandpass
(195 Å)
~1.5 MK plasma

Running difference movie

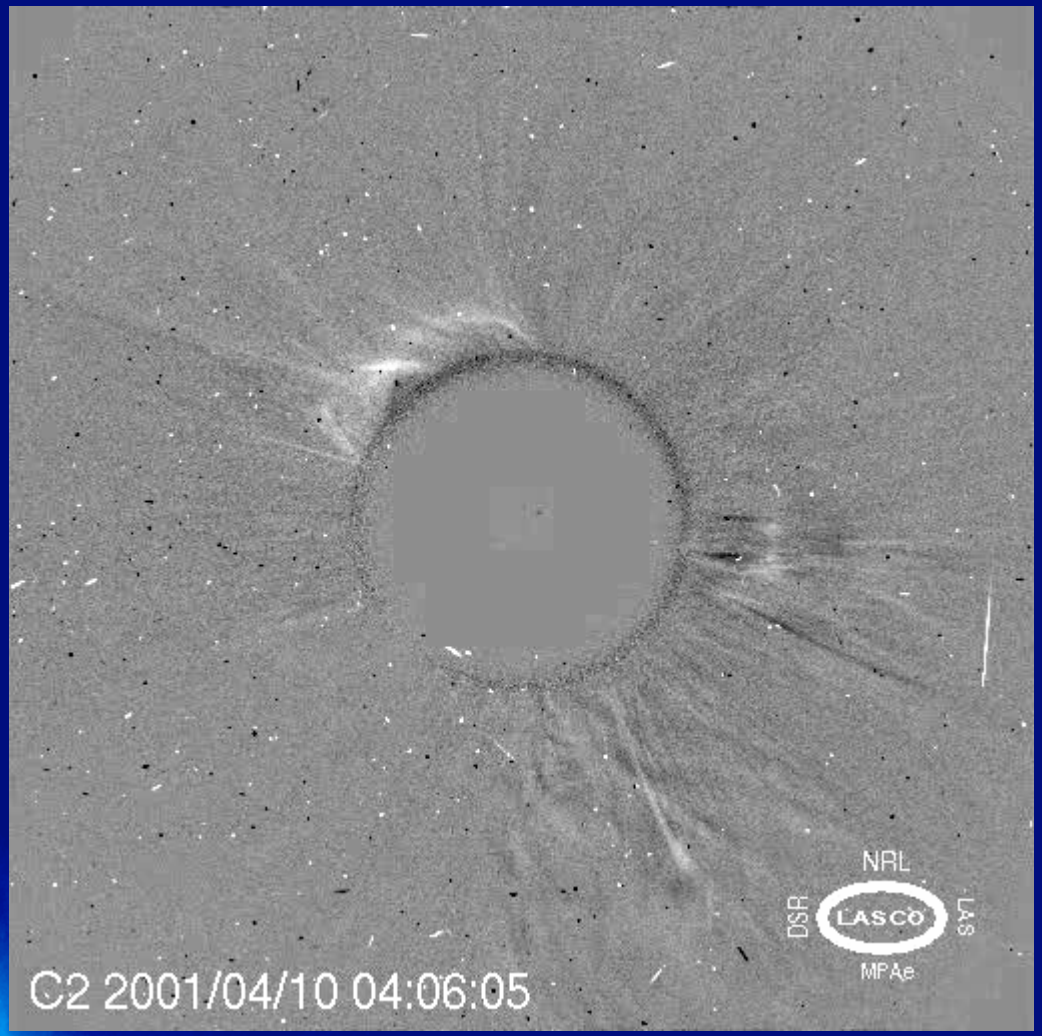


Flux rope orientation: WNE!

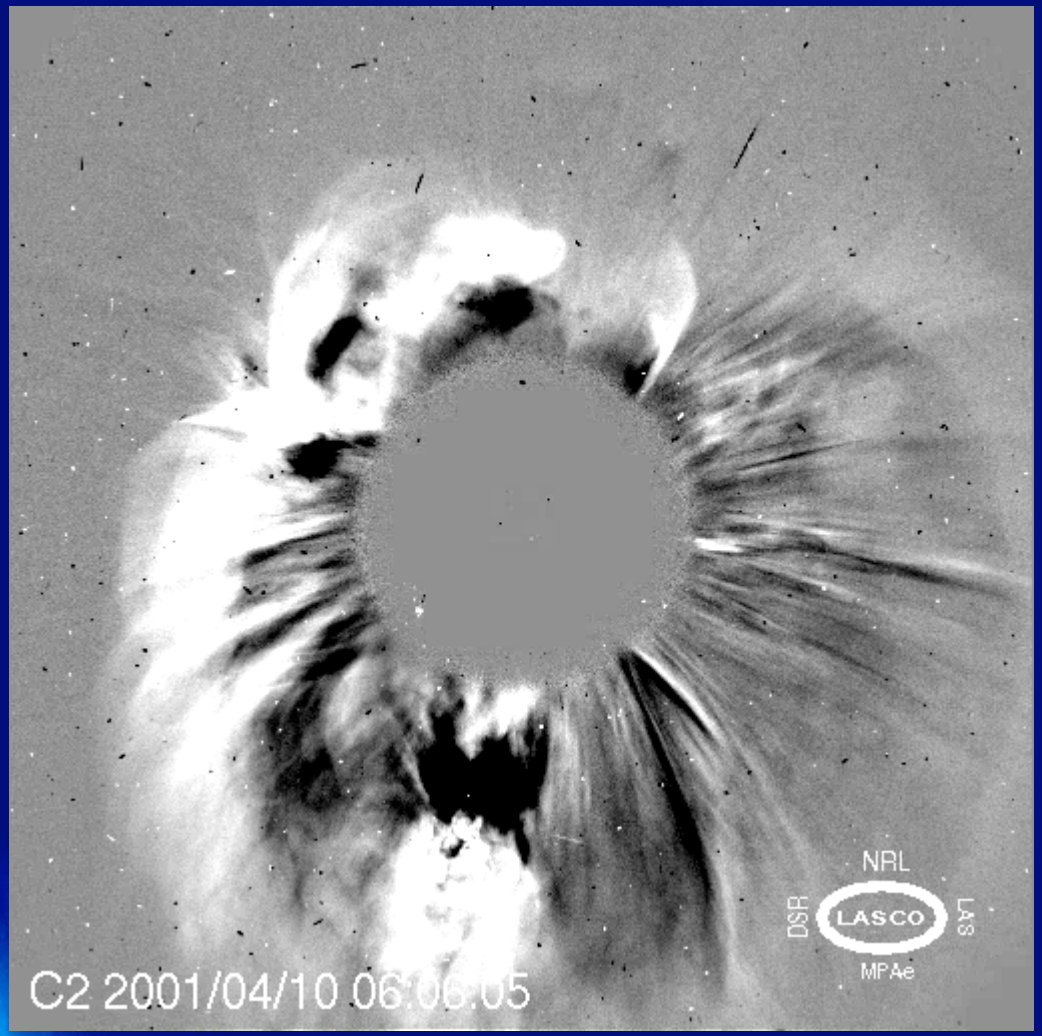
ACE



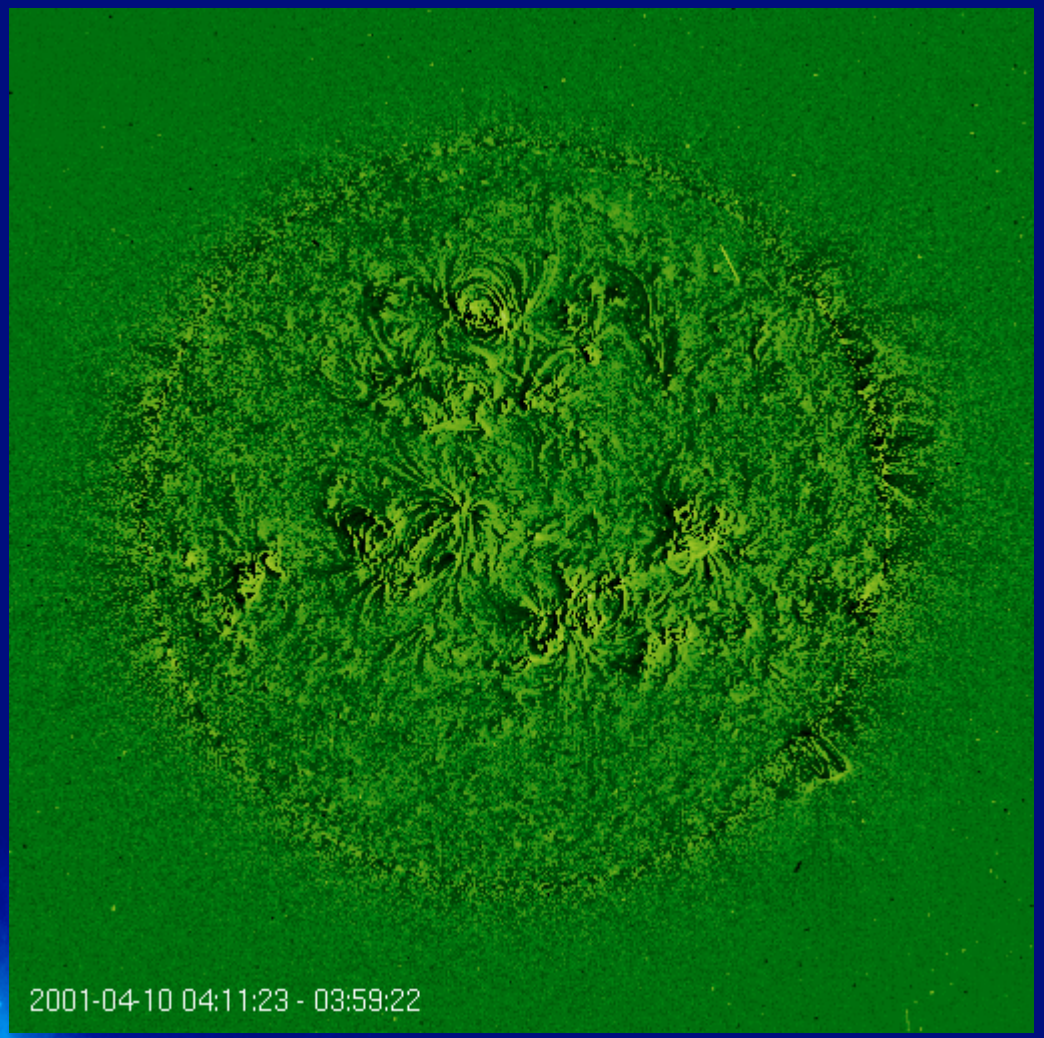
An example: halo CME on April 10, 2001



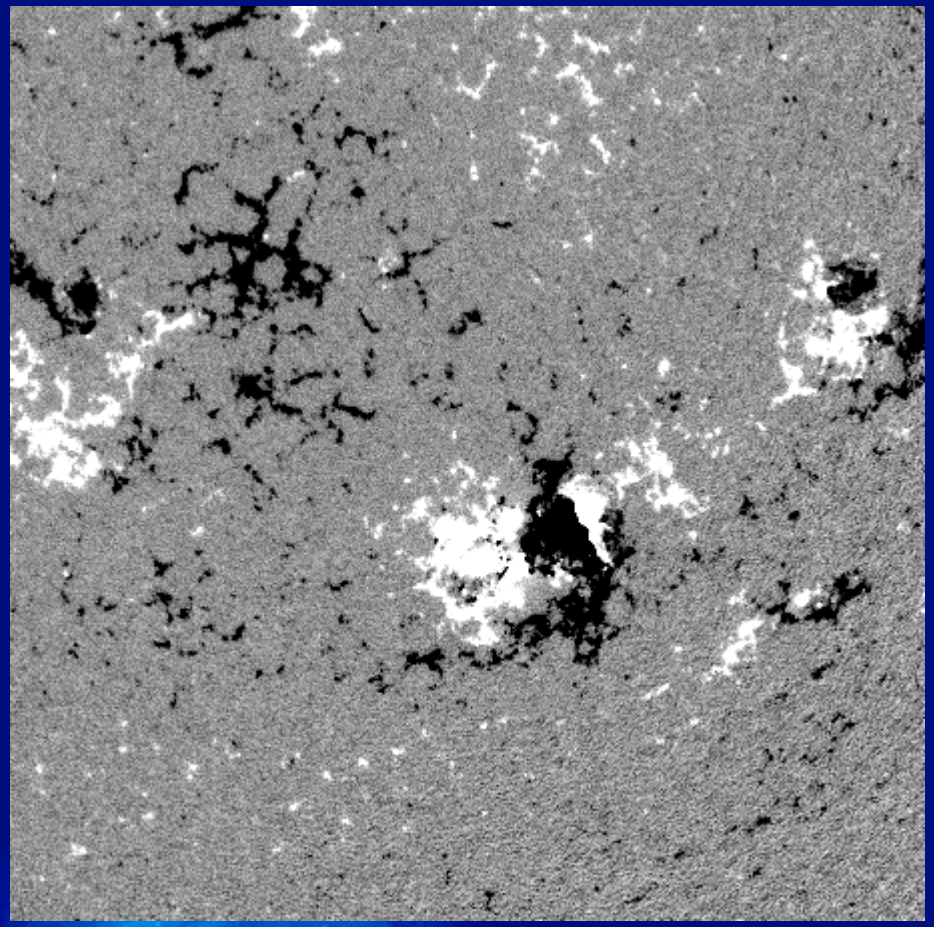
An example: halo CME on April 10, 2001

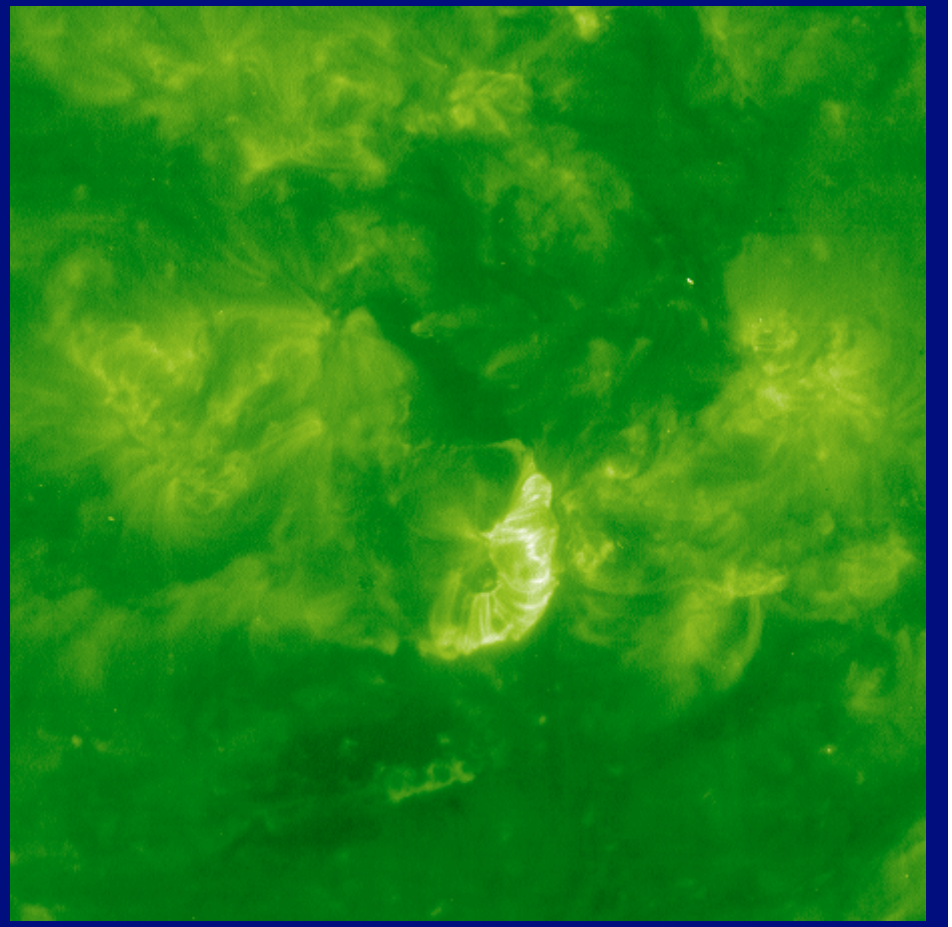


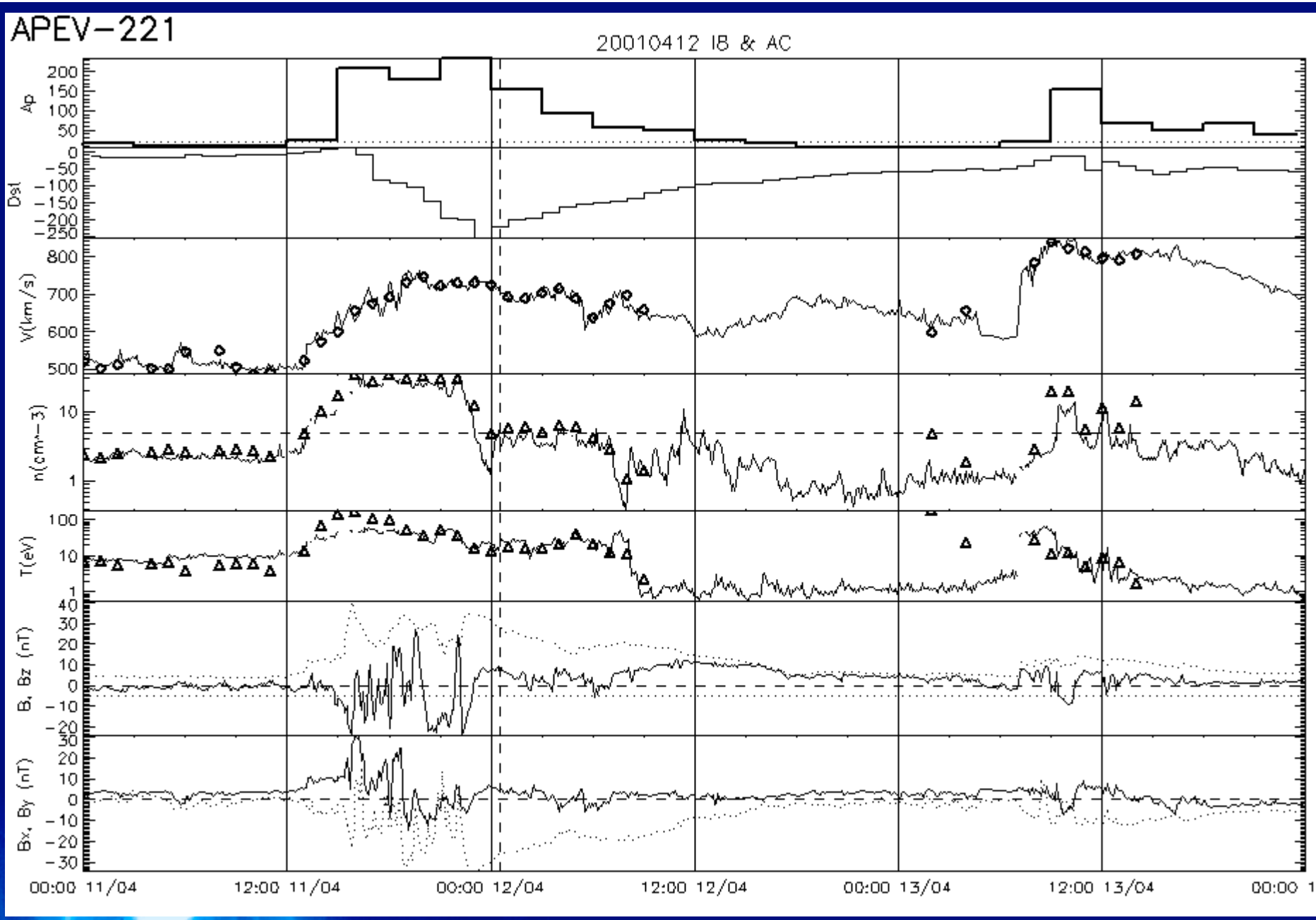
An example: halo CME on April 10, 2001



An example: halo CME on April 10, 2001



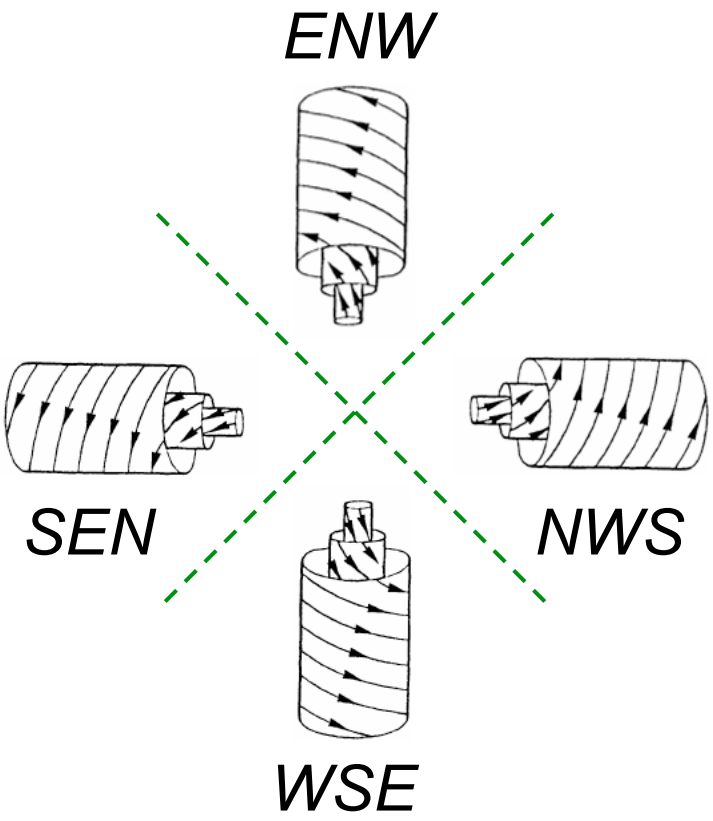




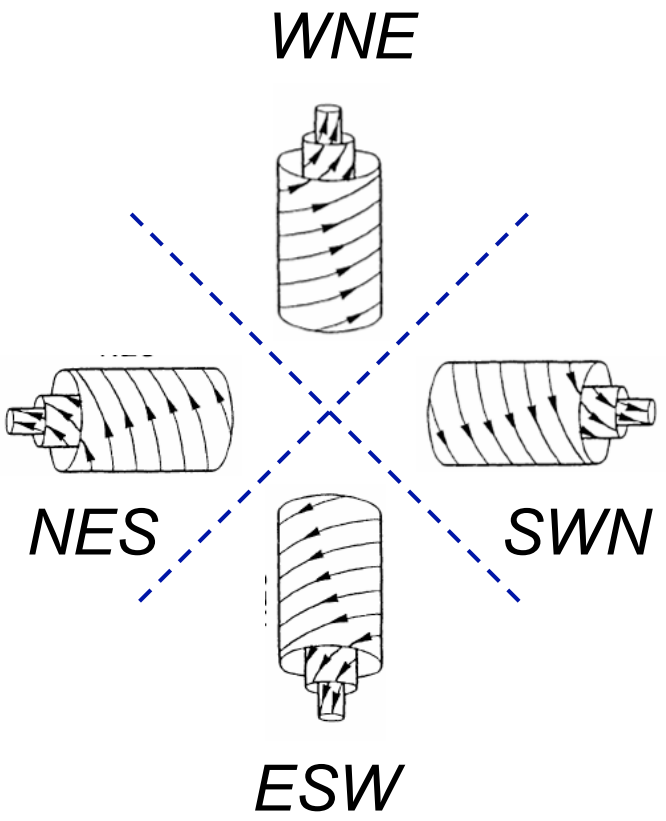
Solar driver modeling and predictions
Trieste, May 4, 2006

What predictions can be made?

Left-handed flux ropes



Right-handed flux ropes



6 out of 8 flux rope types contain southward Bz!
Additionally, one should not forget the sheath plasma!

Some useful references (1)

- http://sidc.be SIDC Web site
- http://www.sec.noaa.gov/ace/ real-time ACE data
- http://www.srl.caltech.edu/ACE/ ACE data
- http://dbserv.sinp.msu.ru/apev/ solar wind plots together with geomagnetic indices
- http://cdaw.gsfc.nasa.gov/CME_list/index.html SOHO/LASCO CME catalog
- http://lasco-www.nrl.navy.mil/cmelist.html preliminary LASCO CME List
- http://sohowww.nascom.nasa.gov/ SOHO data
- http://lasco-www.nrl.navy.mil/daily_mpg/ LASCO/EIT daily MPEG movies (plain and running difference)

Some useful references (2)

- http://gse.gi.alaska.edu/index.html "Fearless Forecasts"
- http://www.sec.noaa.gov/ws/ Wang-Sheeley-Arge model for the "quiet" solar wind (real-time)
- http://www.sec.noaa.gov/ftpmenu/index.html SEC FTP server of solar and geomagnetic data
- http://gpsatm.oma.be/ K index prediction on the base of MAK model
- http://lasp.colorado.edu/space_weather/ real-time Dst index forecast
- http://lepmfi.gsfc.nasa.gov/mfi/mag_cloud_S1.html Lepping's list of MCs