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NEAR SUN AND INTERPLANETARY EVOLUTION OF SLOW AND FAST CMES

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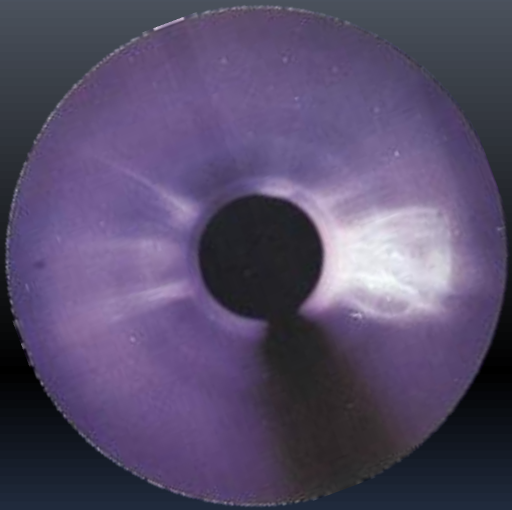
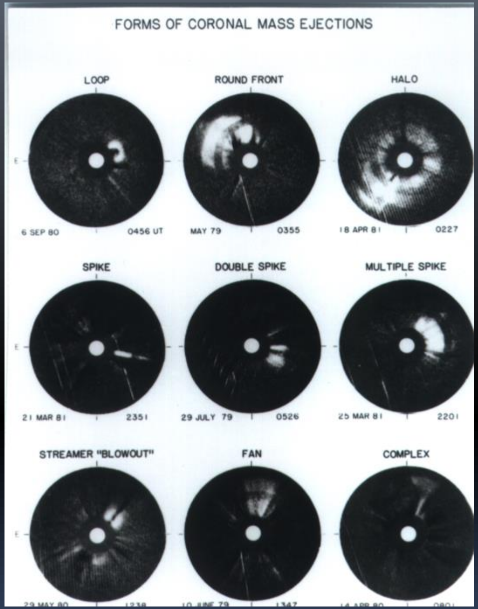
Introduction

- Remote sensing observations of CMEs have been vastly improved over the past decades.

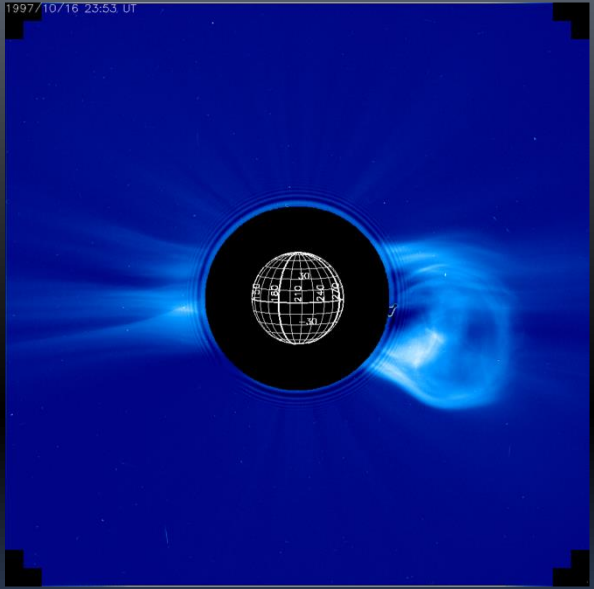
  They represent a <u>global view</u> of the phenomenon!



NASA Skylab (1973-1974); 2-6 R_S; Film detector (5“ resolution); ~100 CMEs observed

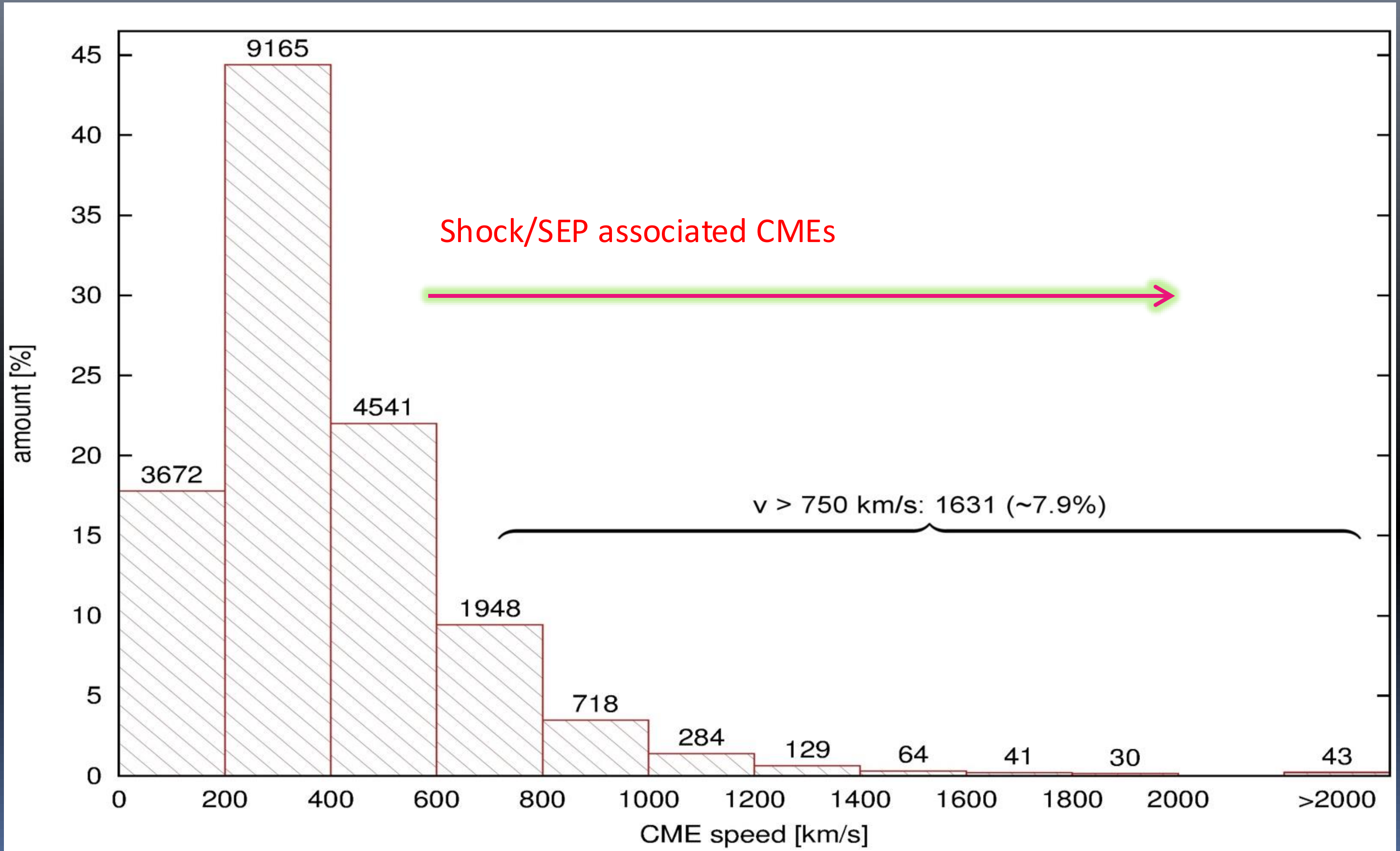


1979-1985: Solwind observations; Howard et al., 1984

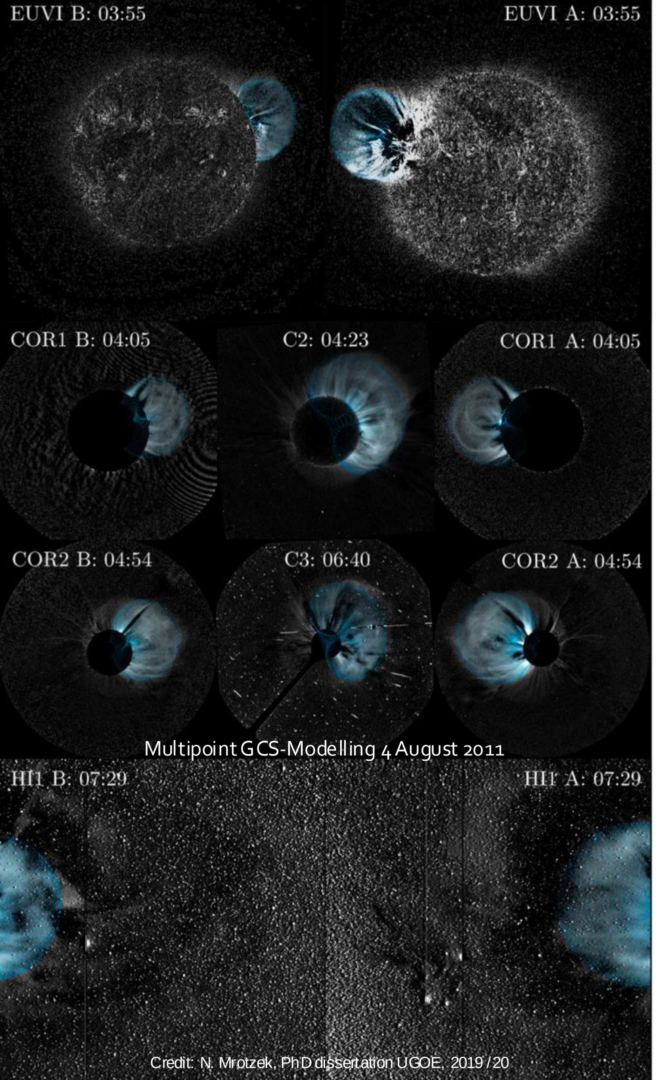


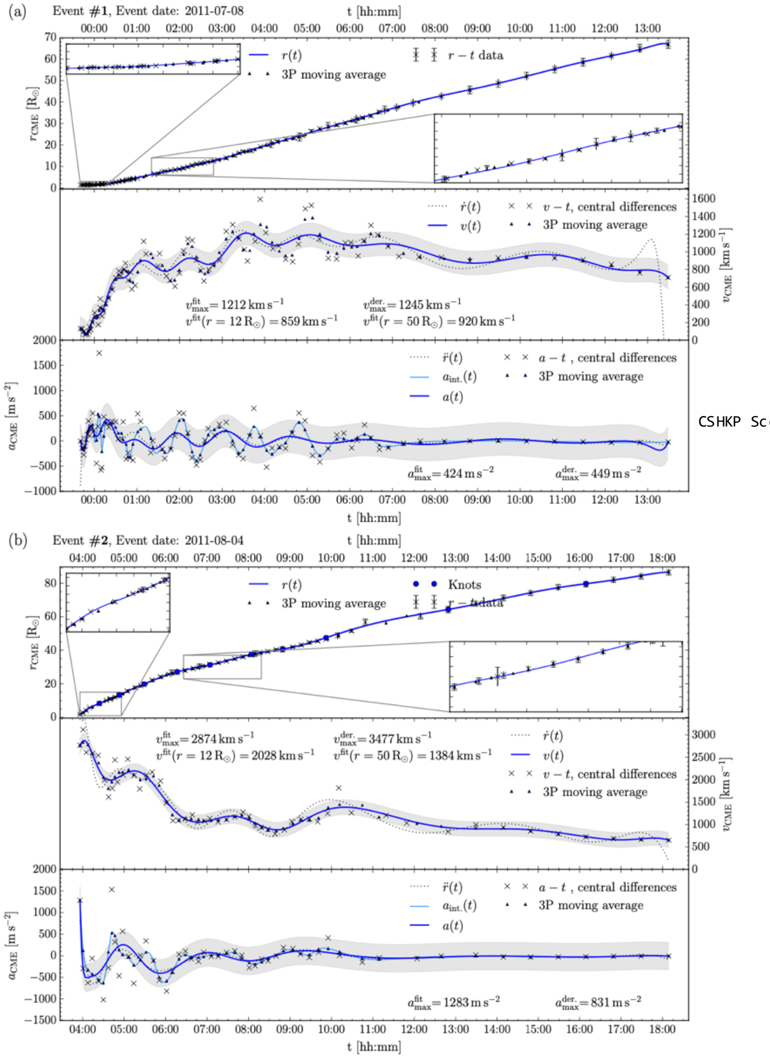
>1995: SOHO/LASCO; Cremades & Bothmer, 2004

CME (POS) speed distribution – SOHO data 1996-2011

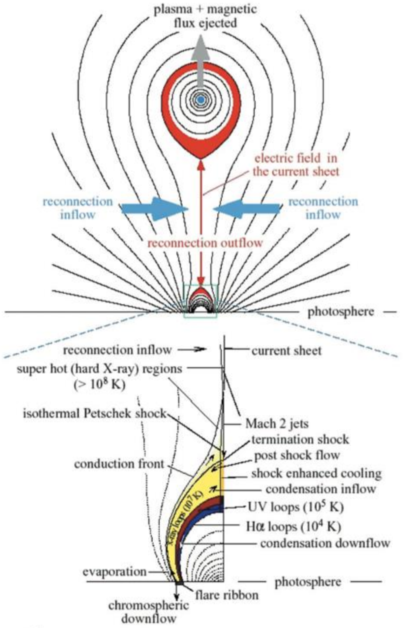


GCS-Modelling and CME-kinematics for fast CMEs – Three viewpoints with STEREO A,B and SOHO



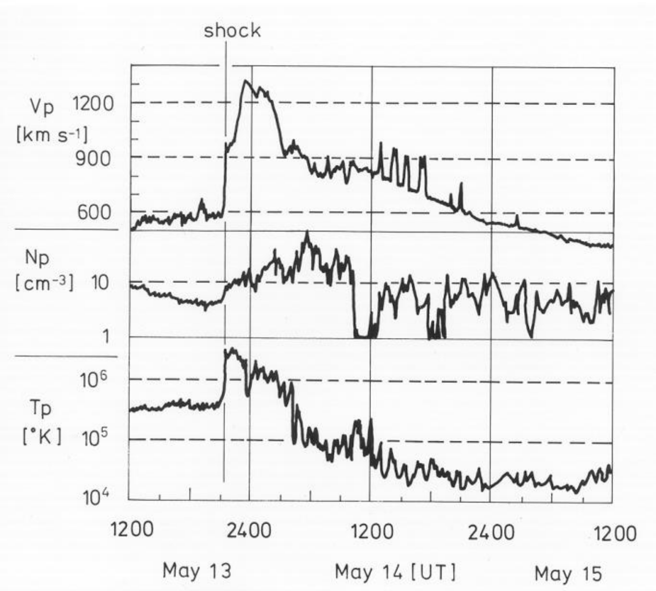


CSHKP Scenario, Chen 2017, adapted from Lin and Forbes, 2000



Shocks driven by fast CMEs

Helios 1 - 1980



Sheeley et al., JGR, 90, 1985

CME DRIVEN SHOCKS

- High CME speeds in the corona suggest that shocks can be driven at those locations
- Indirect indication of shock existence are present in radio type II burst, deflected streamers, and SEP events
- *Hildner (1975)* and *Dulk (1976)* identified "forerunners " in coronagraph images - ambiguous
- First direct detection of CME-driven shock in LASCO images (*Vourlidas, 2003*) confirmed by MHD simulations

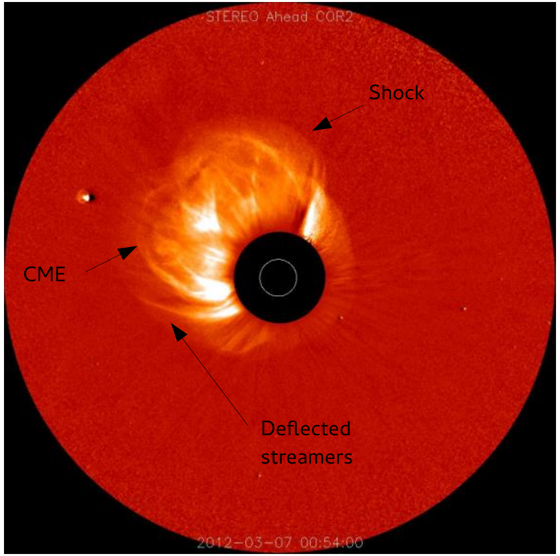
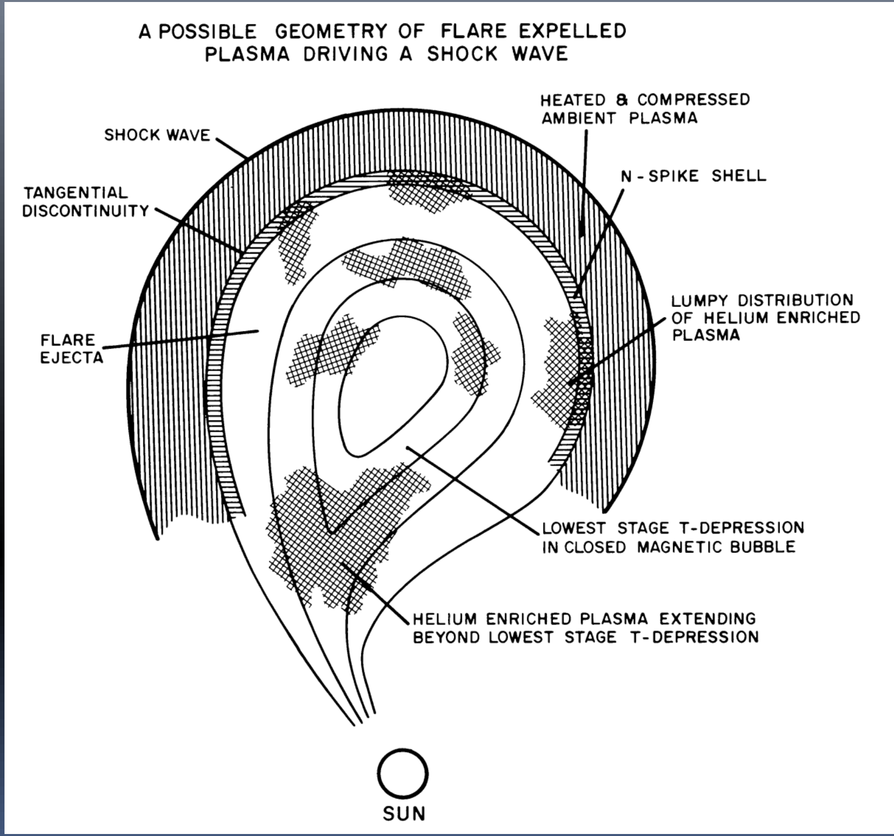


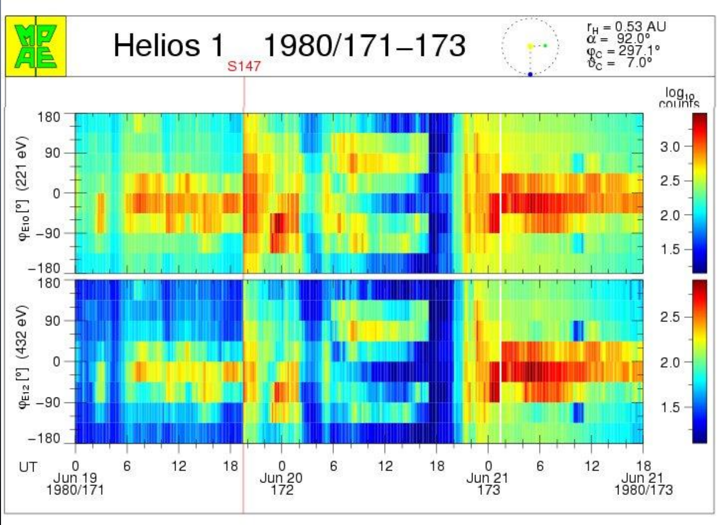
Image credit :NASA

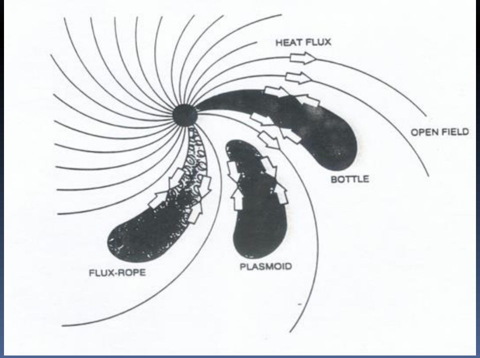
Detectability of CME driven shocks in white light images depends on the ratio between density compression and background corona (*Vourlidas,2006*)

Interpretation of ISEE 3 and Helios Measurements – single-point observations



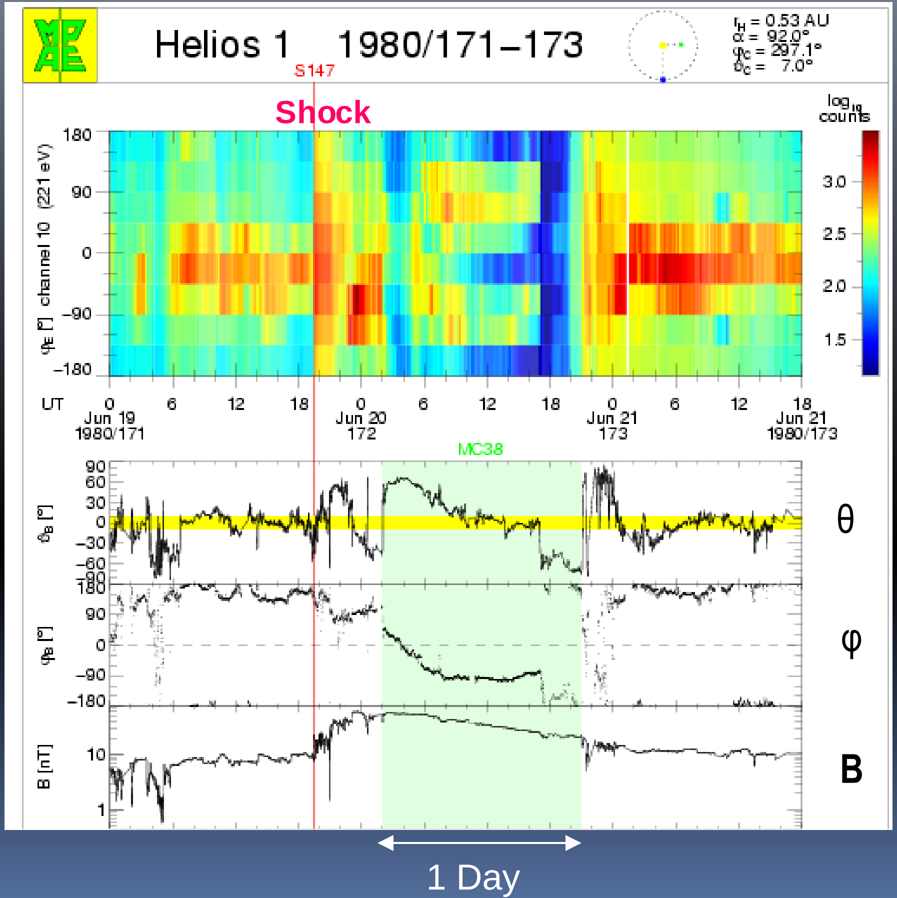
Bame et al., 1978





Phillips et al., Solar Wind 7, 1992

A magnetic cloud observed with Helios 1 directly following a CME observed with Solwind – single-point S/C observation



suprathermal electrons (E=221 keV)

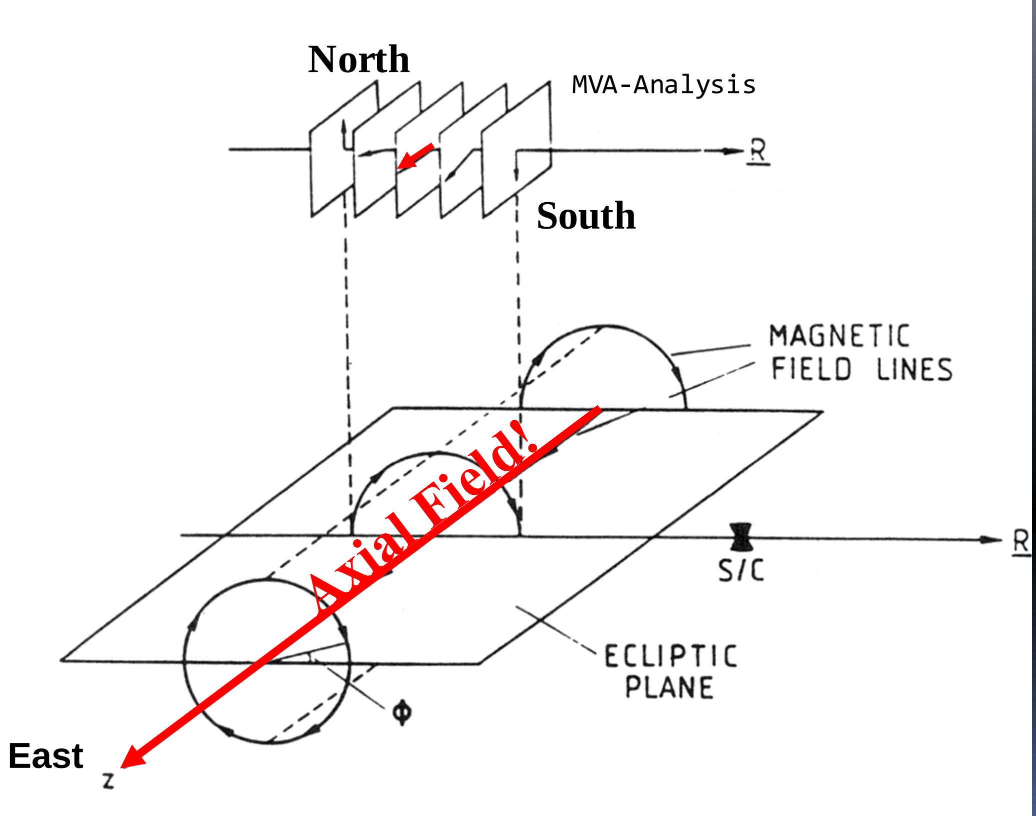
IMF-NS

IMF-EW

IMF-Strength

Bothmer, Solar Wind 9, 119-126, 1999; see also Burlaga 1990

Self-consistent MHD explanation for the magnetic structure of a MC – global vs. single-point view



Assume that the plasma is in static equilibrium, without influence of external forces, e.g., gravitation:

$$-\operatorname{div} p + \underline{j} \times \underline{B} = 0$$

p = plasma pressure

$\underline{j}$ = current density

$\underline{B}$ = magnetic field

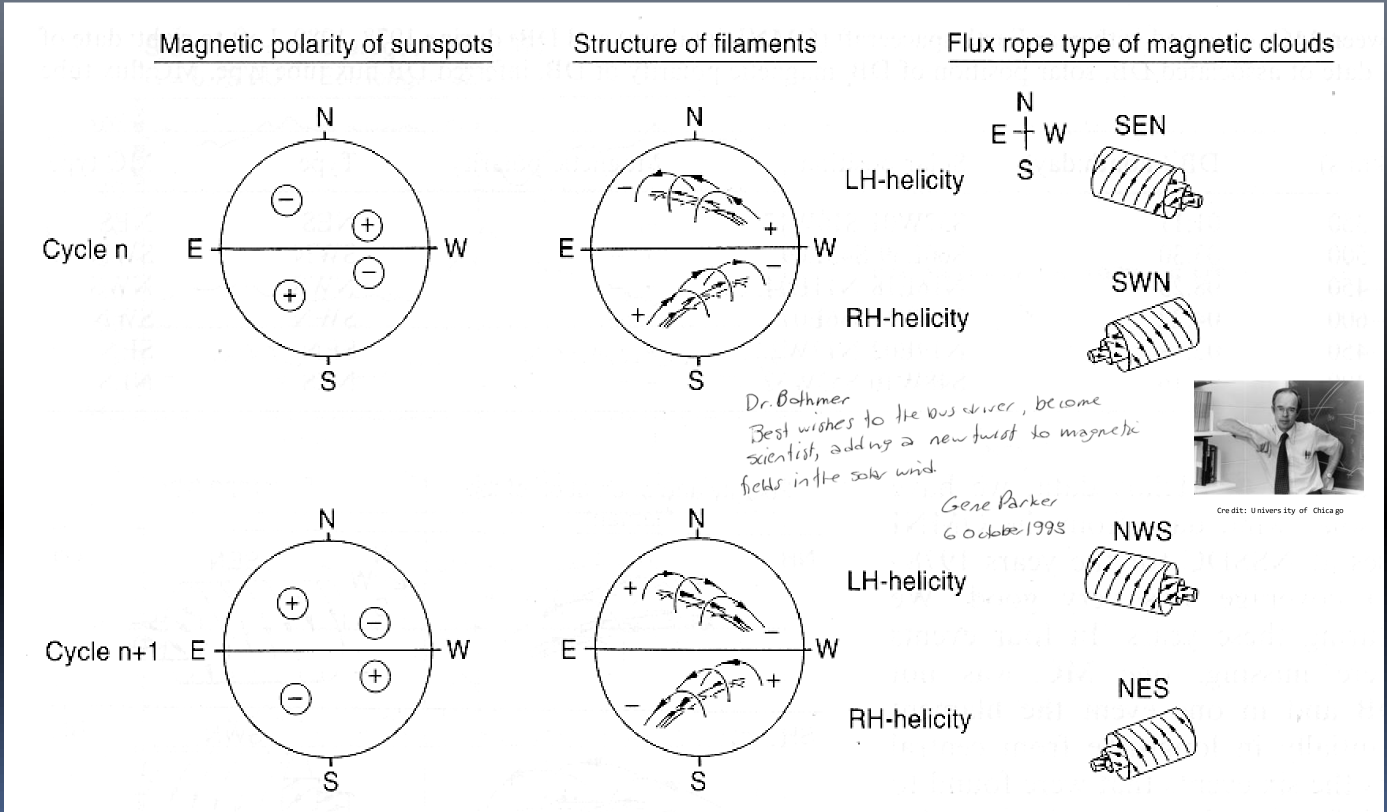
if $\beta \ll 1$, a force-free configuration can be considered:

$$\underline{j} \times \underline{B} = 0$$

the electric current is flowing everywhere parallel or antiparallel to B

Goldstein, 1983; Bothmer & Schwenn, Ann. Geophys., 16, 1998

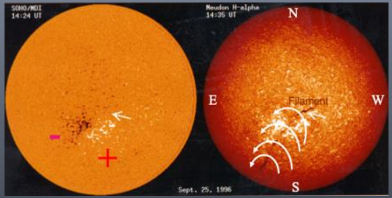
Proposed scheme for the solar cycle dependence of the observed MC types



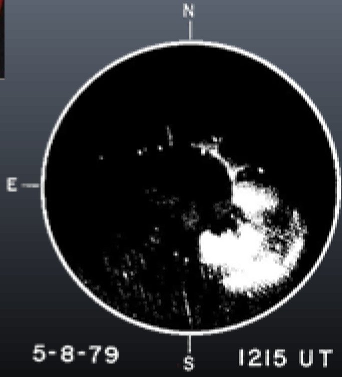
Note: no consideration of quadrupolar fields and FR distortions

Bothmer & Schwenn, 1998

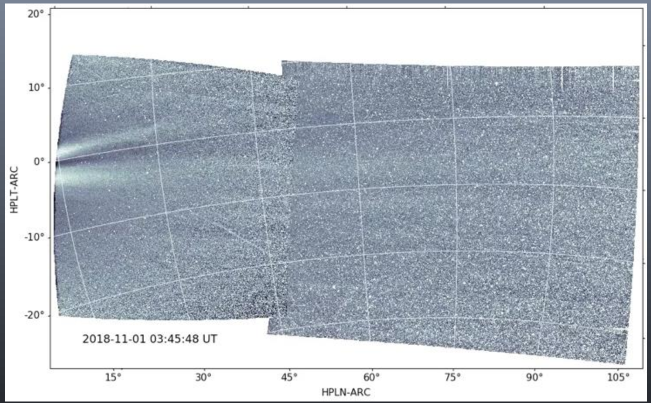
Solwind & Helios findings and WISPR-IT encounter 1 movie, inside 0.25 AU, 1-10 November 2018, varying cadence, 13,5°-108° – R.A. Howard, A. Vourlidas, V. Bothmer et al., Nature, 576, December 2019



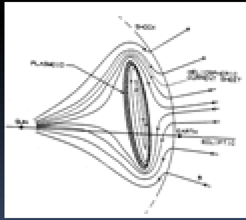
Solwind coronagraph on board P78-1 (1979-1985)



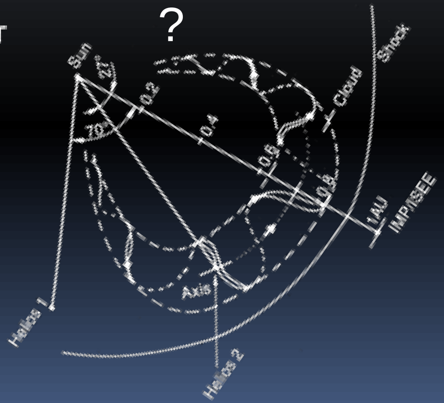
The Helios 1 & 2 spacecraft (1974-1986)

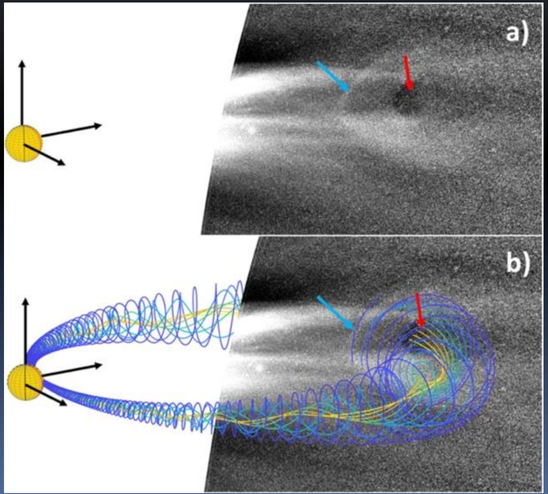


All Helios 1 directed CMEs with a speed >400 km/s (POS speed!) in the FOV of the Solwind coronagraph caused a shock at Helios 1!



Gosling, AGU Geophys. Monogr. 1990



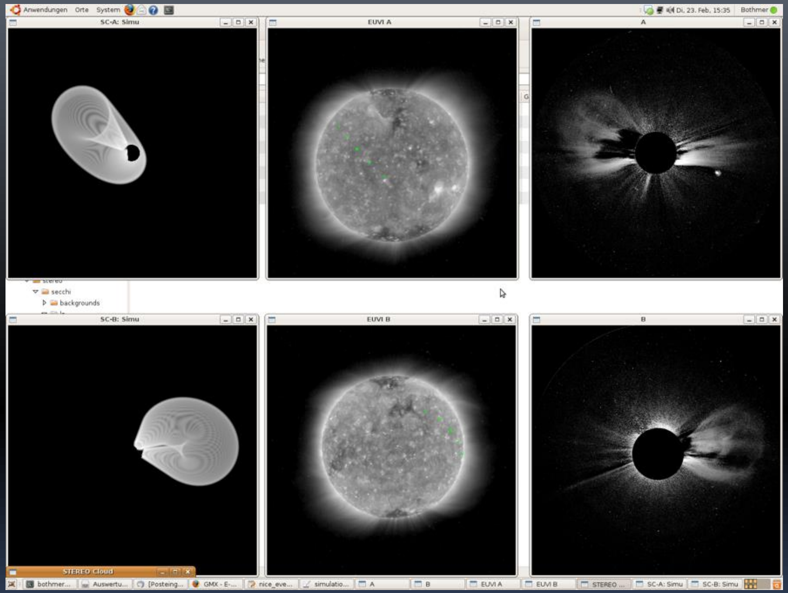


Sheeley et al., JGR, 90, 1985

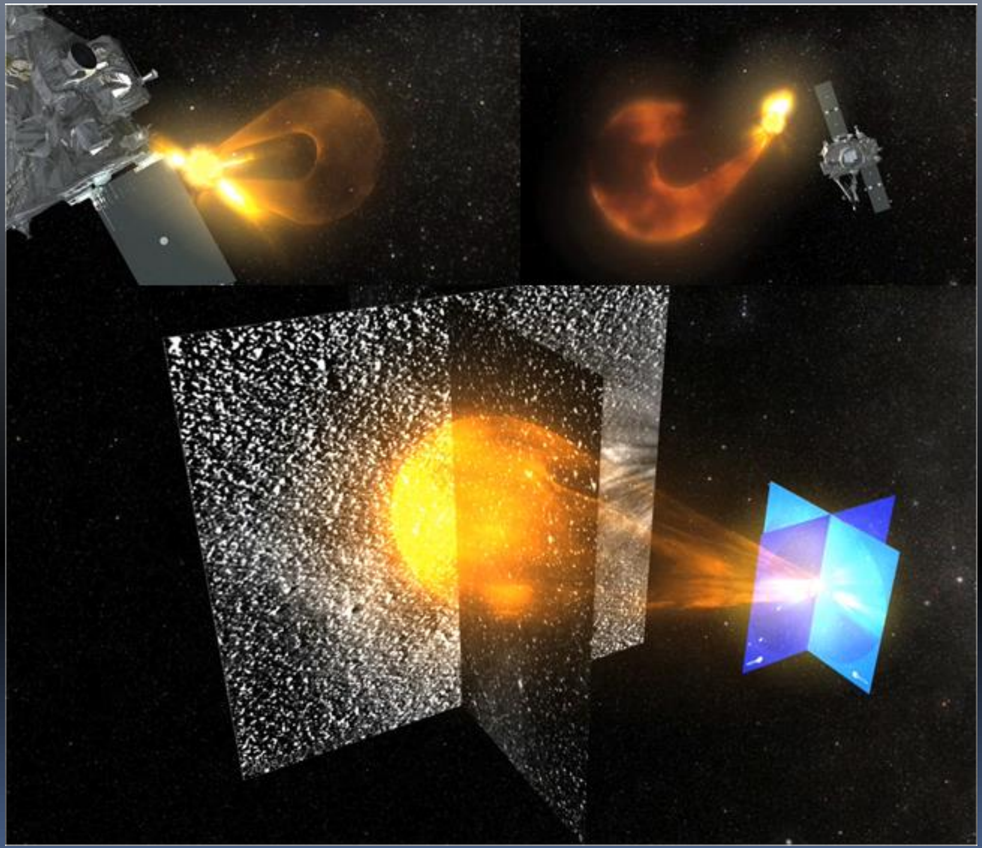
Cartoons deduced from single-point observations

Bothmer & Schwenn, Ann. Geophys., 16, 1-24, 1998

STEREO has verified the FR structure of CMEs

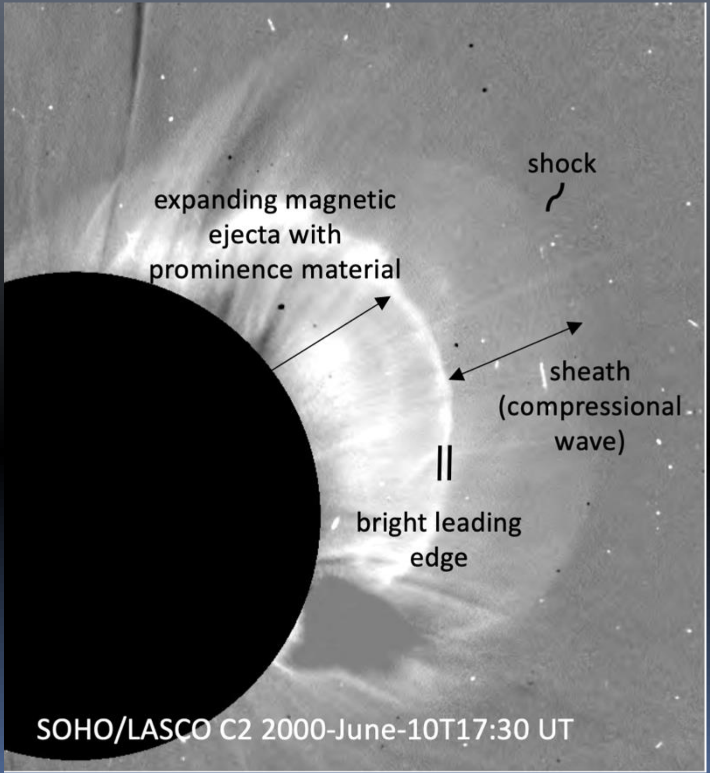


Credit: E. Bosman

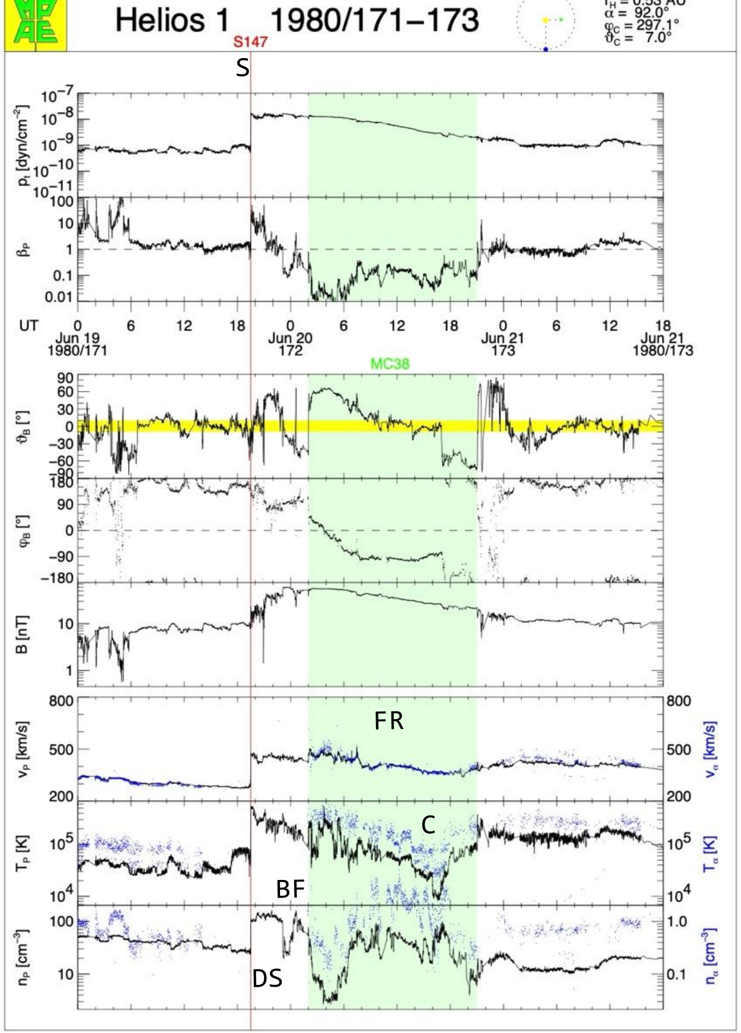


STEREO/SECCHI Consortium

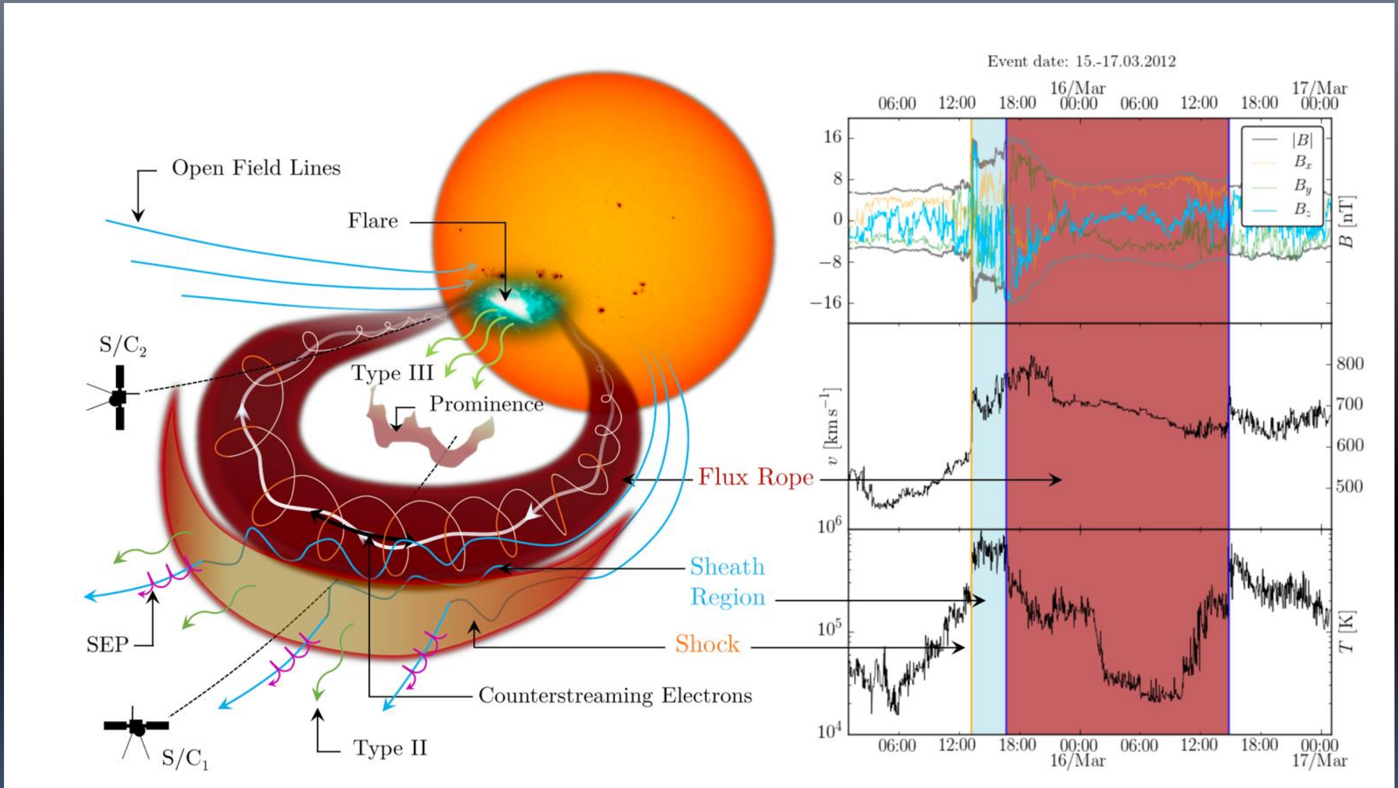
The 5 parts identified in MC events detected by the Helios S/C – global vs. single-point view (Temmer and Bothmer, 2022)



- S = Shock or compression wave
- DS = Diffuse sheath
- BF = Bright front (LE)
- FR = Flux rope (Cavity)
- C = Core



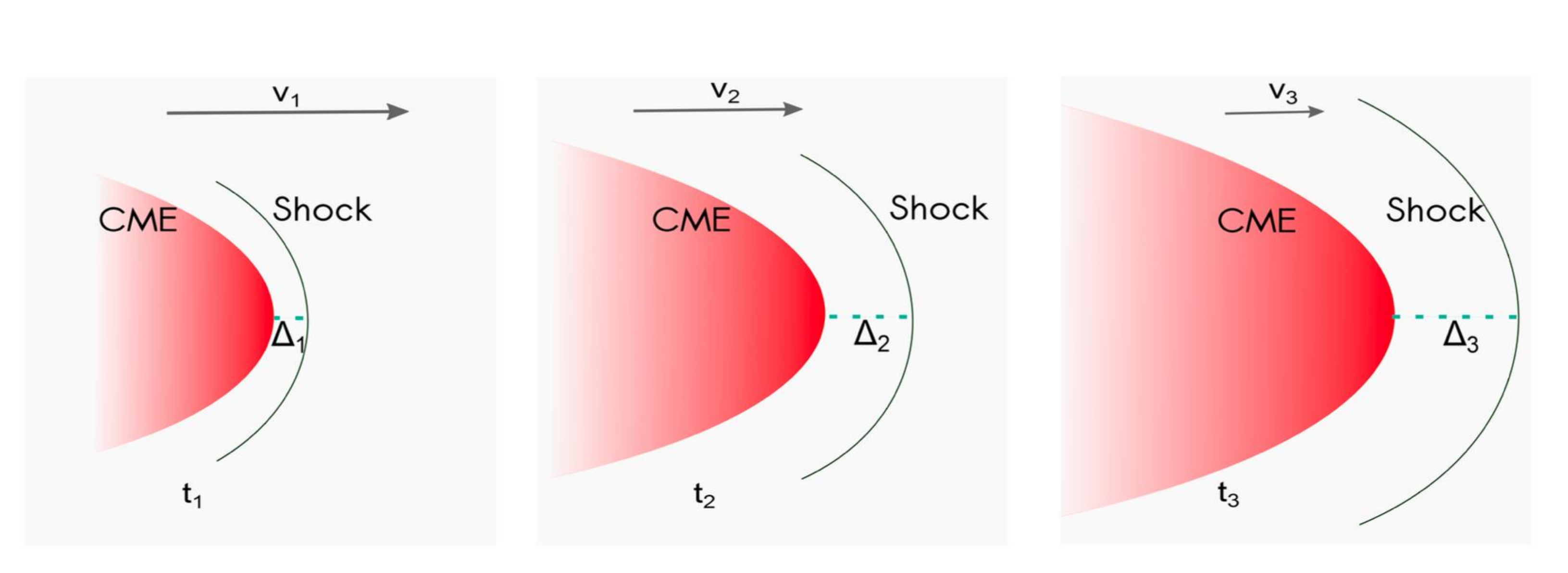
Schematic structure of a flux-rope ICME and its plasma regions – global vs. single-point view



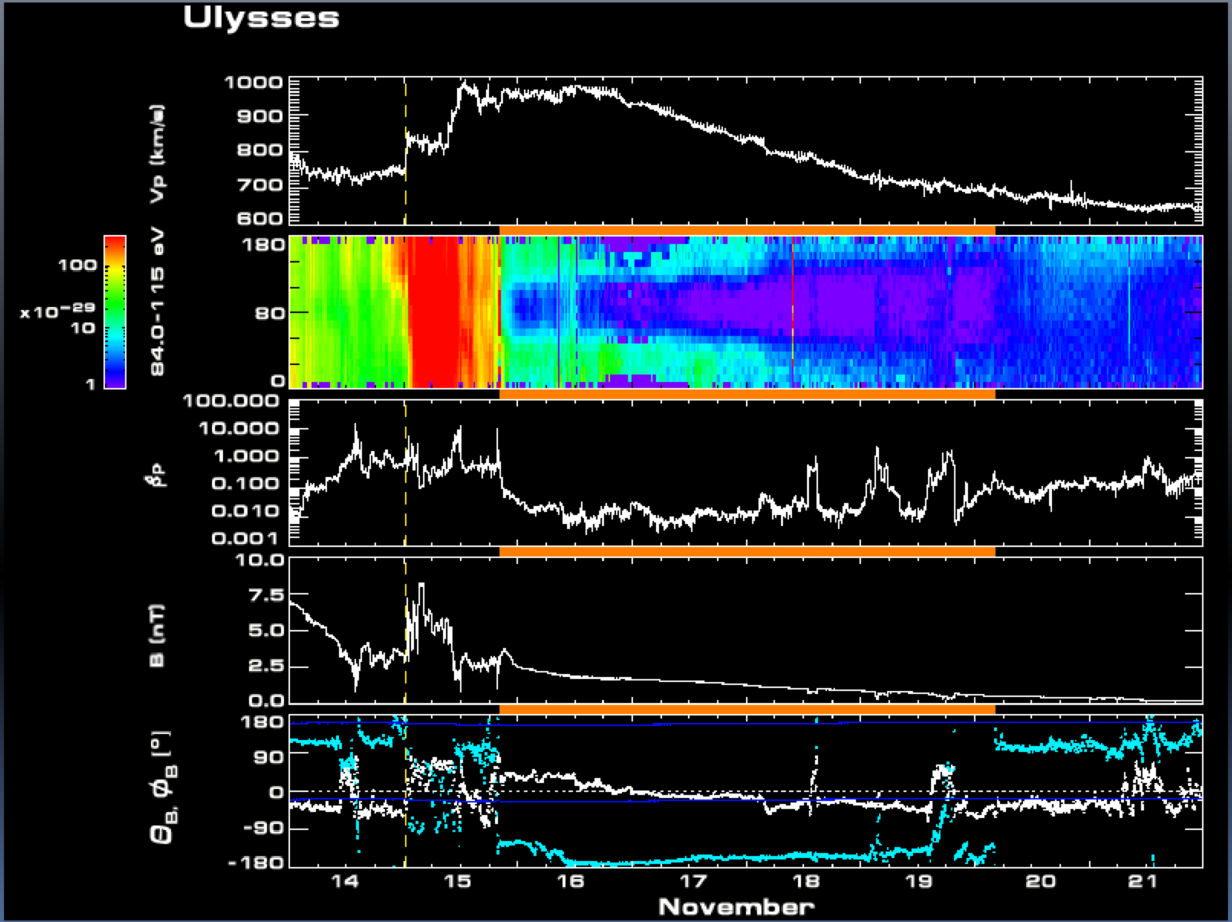
- Upstream shock/compression region (for the faster ones, quasi ∥ / quasi ⊥ shock)
- Shock (compression pile up)
- Sheath/post compression region
- Flux rope leading edge (which might be compressed)
- Flux rope body
- Trailing edge of flux rope and eventually prominence material
- Downstream region
- Reverse shock/compression signatures

Credit: N. Mrotzek, PhD dissertation UGOE, 2019/20; adapted from Zurbuchen and Richardson, 2006.

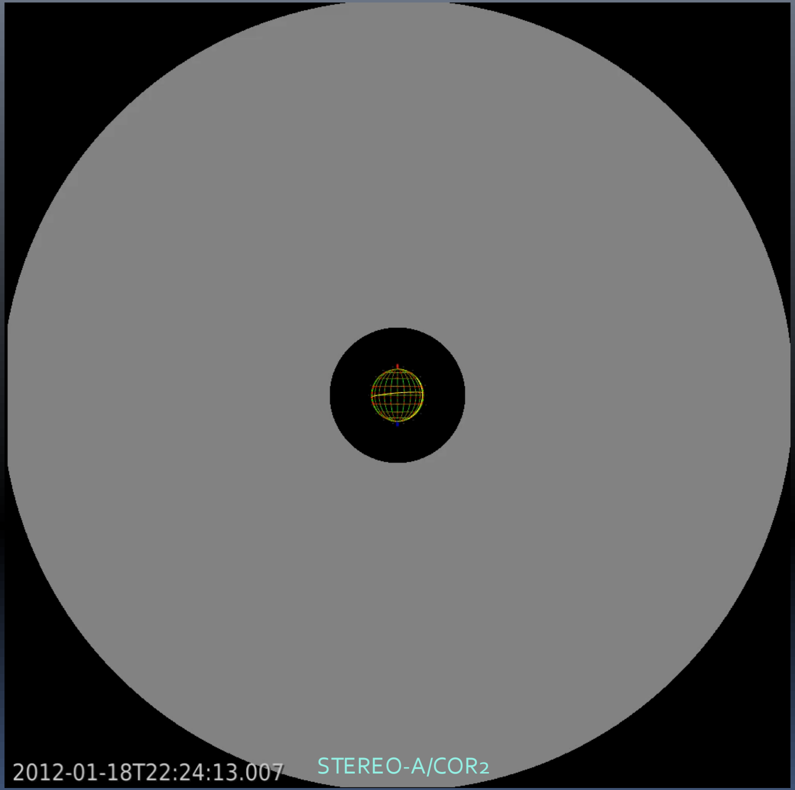
Sketch representing a CME and its driven shock in different stages of their evolution: the standoff-distance increases as the CME travels away from the Sun, and deceleration occurs during its interplanetary propagation (Volpes and Bothmer, 2015).

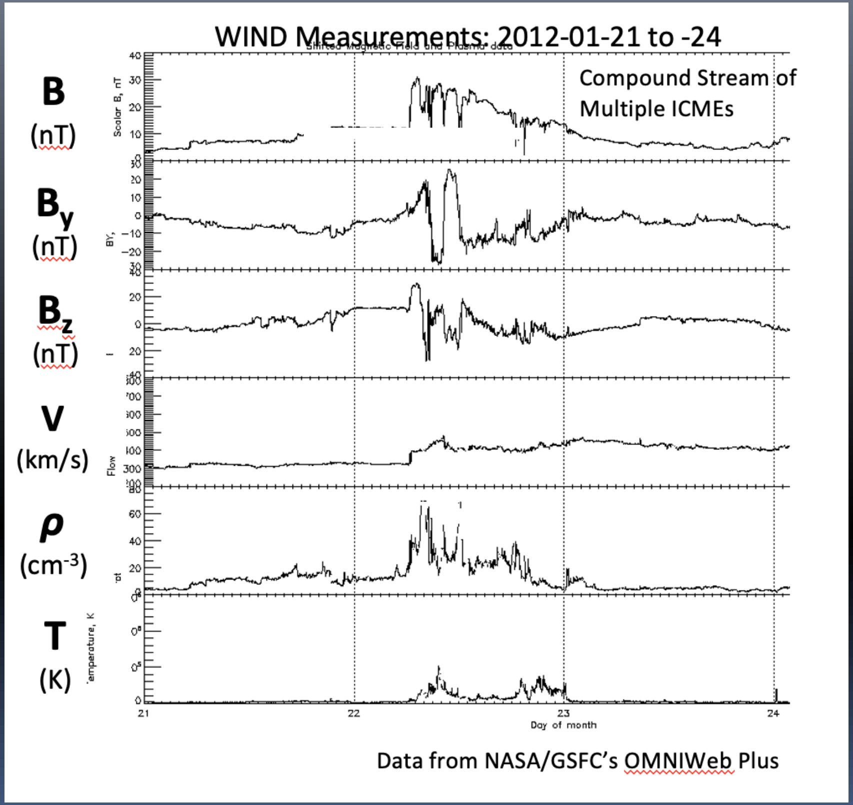


A Magnetic Cloud Observed by Ulysses at 5 AU on 15 November 2003 - de Koning et al., 2005

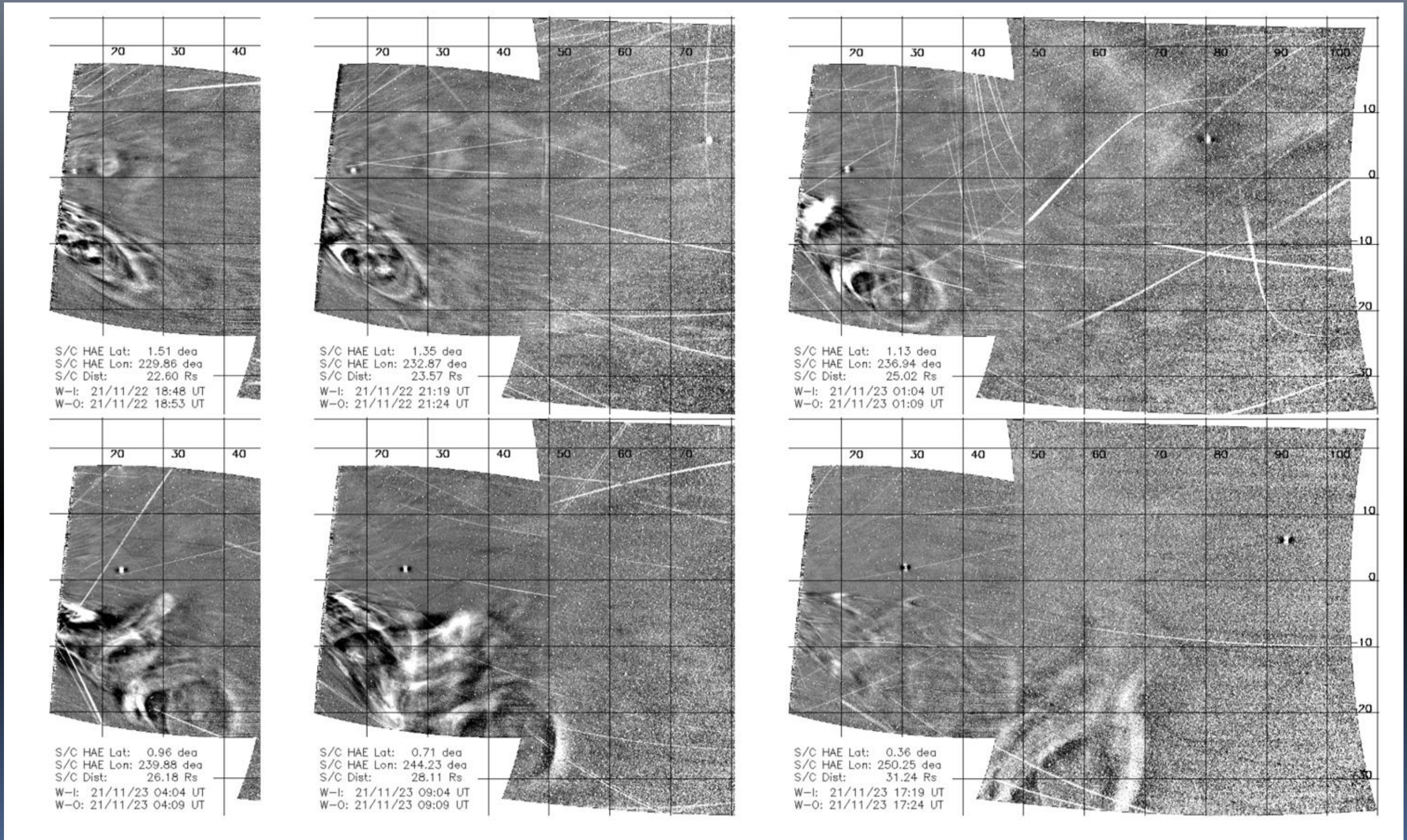


Complexity caused by multiple CMEs/ICMEs





„WISPR-Composite" Images from Encounter 10, Perihelion at 0.07 au, 16th to 26th November 2021 – CME Dynamics and Interactions close to the Sun



Credit: Howard et al., ApJ, 2022

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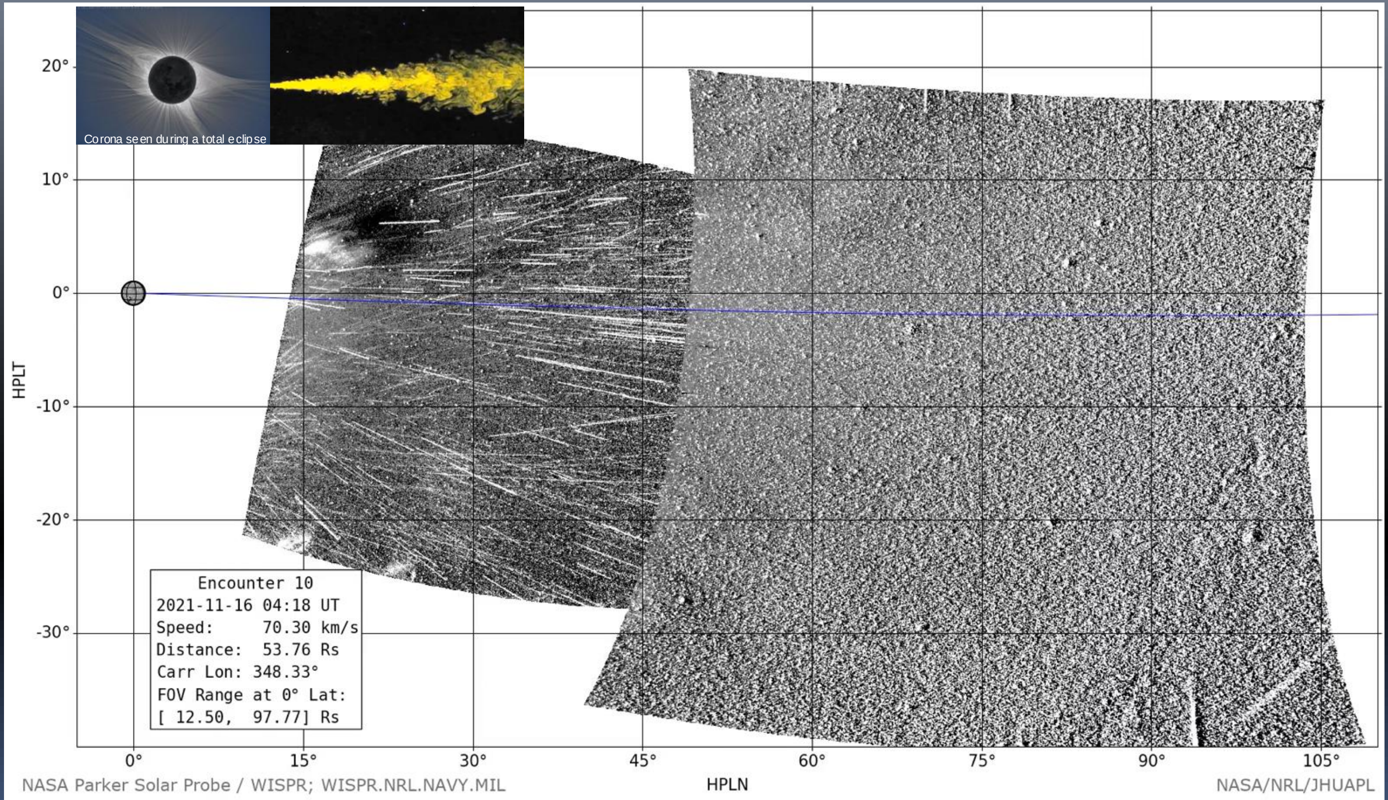
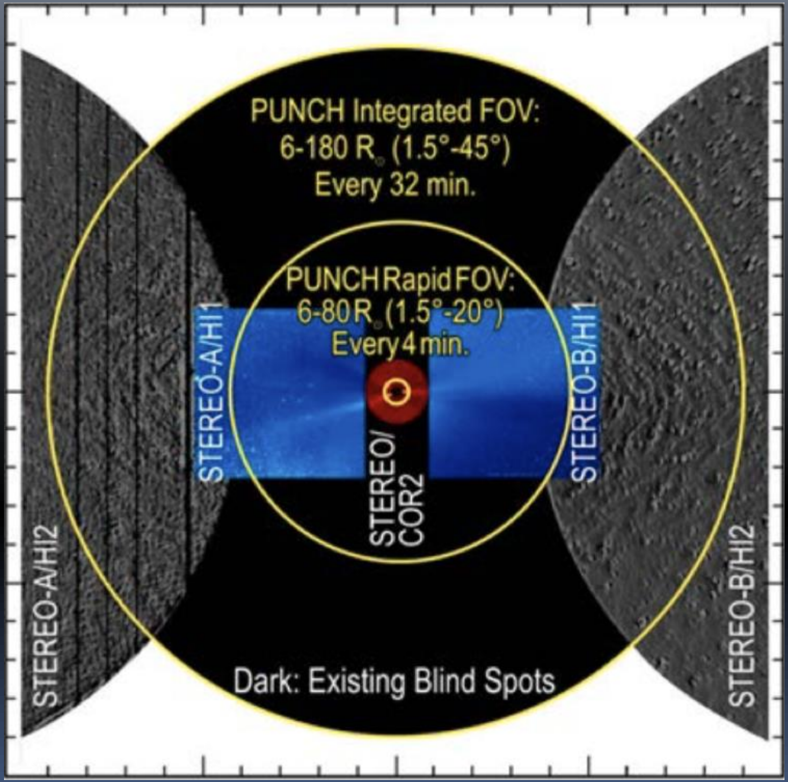


Credit: B. Gallagher/WISPR Consortium

Reliable inclusion of large-scale turbulence is fundamental to help establish more accurate SW forecasts - PSP/WISPR

Next step: Polarimeter to UNify the Corona and Heliosphere



https://punch.space.swri.edu/punch_about_mission.php

Summary and Conclusions

- The number of CMEs with speeds fast enough to drive shock waves in the IM is a few percent of the total number of CMEs during a solar cycle.
- CMEs are accelerated to about 10 R_S and then decelerate due to their interaction with the ambient solar wind.
- Remote sensing observations provide a global view of the CME whereas ICME observations represent single-point measurements – CMES/ICMEs evolve with distance from the Sun.
- The schematic structure of an ICME reveals several distinct plasma/field signatures from its upstream to its trailing regions.
- The unique observations by PSP/WISPR at the birthplace of the solar wind and of CMEs/ICMEs emphasise the importance of large-scale turbulence in their heliospheric evolution and the need to account for these processes to help establish more accurate space weather forecasts.
- The PUNCH mission will soon provide new observations on CMES/ICMEs and large-scale turbulence in the inner heliosphere.