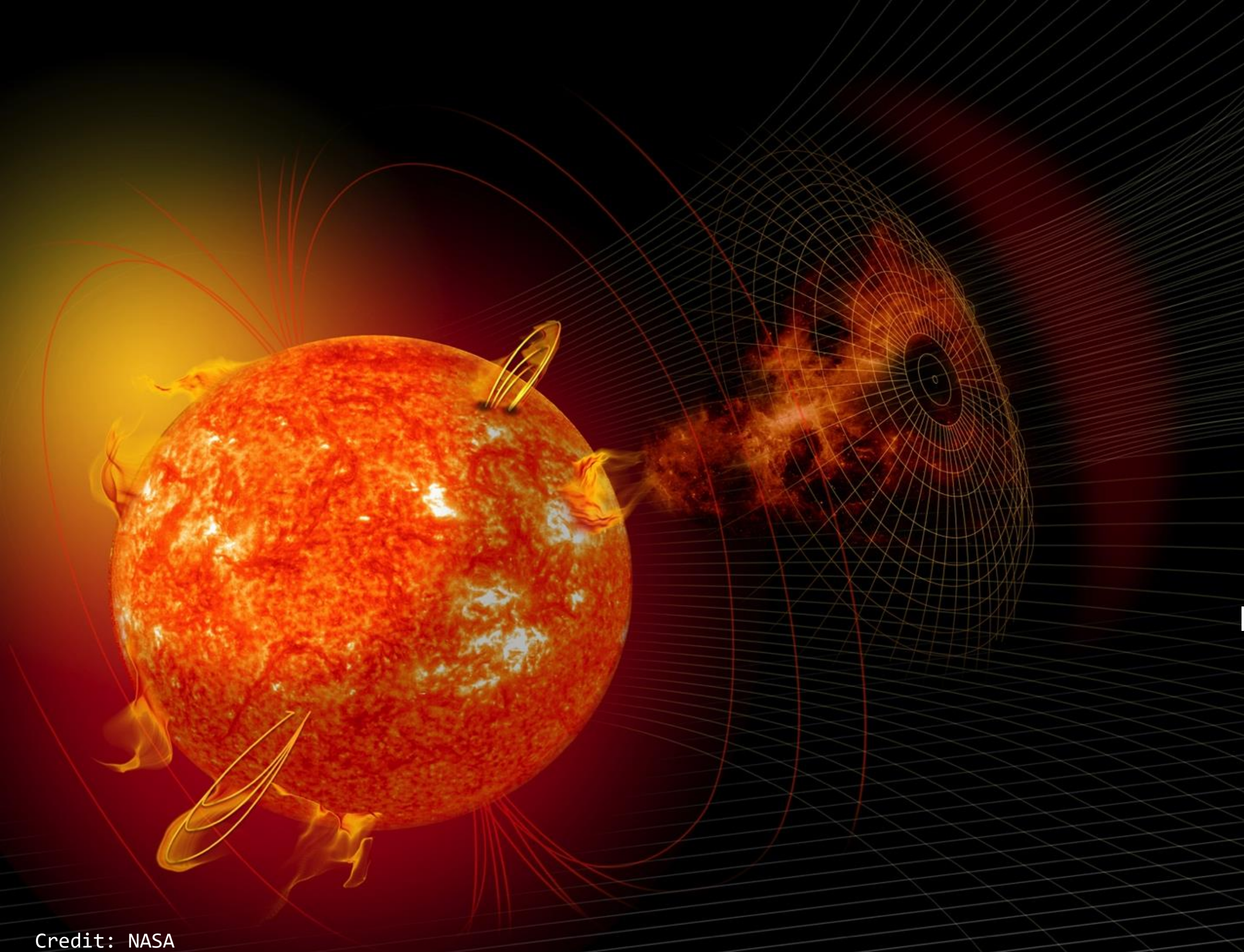
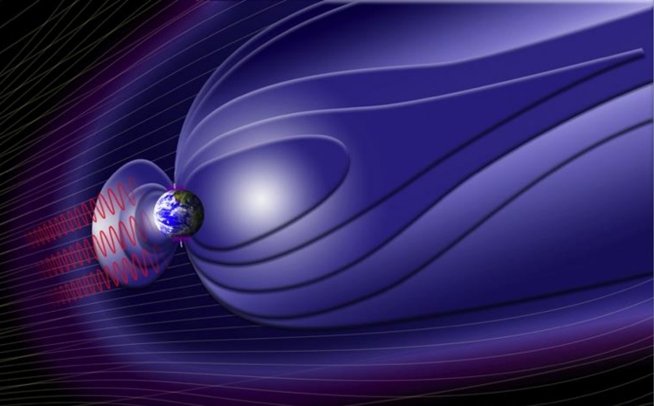




Credit: NASA

Volker Bothmer

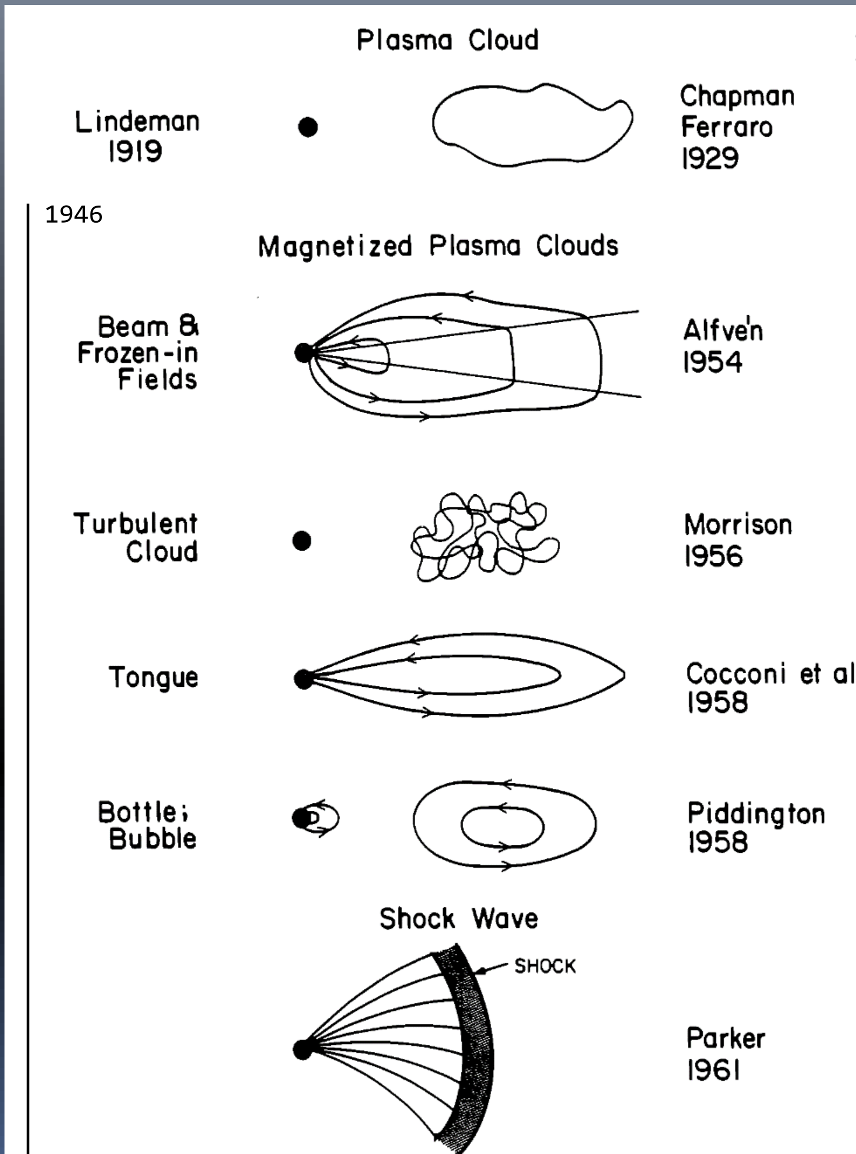
University of Göttingen
Institute for Astrophysics and Geophysics
Göttingen, Germany

10 June 2024

United Nations/Germany Workshop on
the International Space Weather Initiative:
Preparing for the Solar Maximum

CORONAL MASS EJECTIONS OBSERVATIONS, FLUX ROPES AND SPACE WEATHER

Early ideas of space storms caused by the Sun



No magnetic flux rope had been proposed!

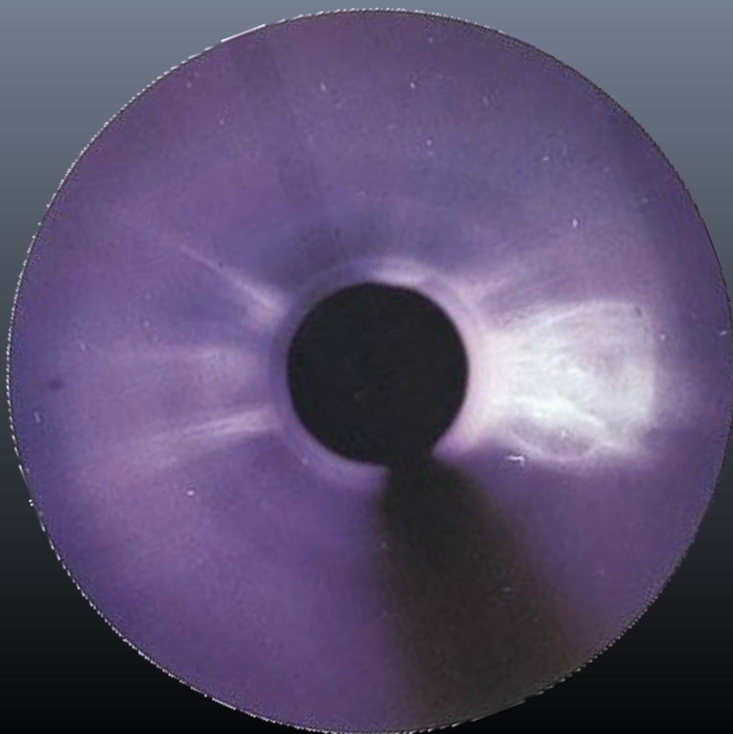
1852: Edward Sabine claimed that the sunspot periodicity is evident also in geomagnetic activity records and that there might be a physical impact of the Sun's activity on the Earth.

Nobody had ever recognized a direct link between solar and terrestrial phenomena, but on September 1, 1859, Richard Carrington observed together with Robert Hodgson an outstandingly intense "white-light flare" – a sporadic electromagnetic emission (EM) on the Sun's visible surface, lasting for some minutes. The flare observed by Carrington and Hodgson was followed by a geomagnetic storm about 18 hours later and Carrington claimed that the solar flare might have been the indicator of solar processes that subsequently led to the geomagnetic storm.

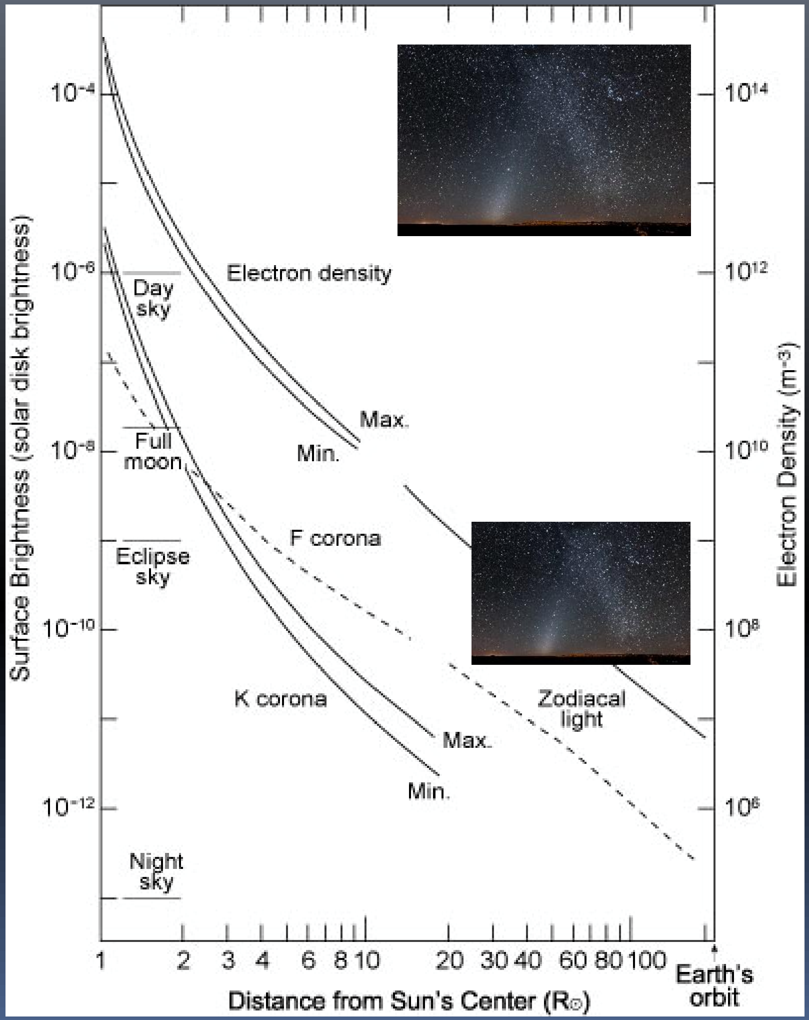
Burlaga, L.F., Magnetic clouds, in Physics of the Inner Heliosphere Vol.II, ed. by R. Schwenn and E. Marsch, *Springer*, Berlin/Heidelberg, 1991.

Coronal mass ejections (CMEs) have been discovered in the 1970s

- The solar corona and CMEs are very faint: B<10^{-6} MSB
- Thomson-scattering of solar photons at free electrons
- At distances >3 R_S F-corona is brighter!



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

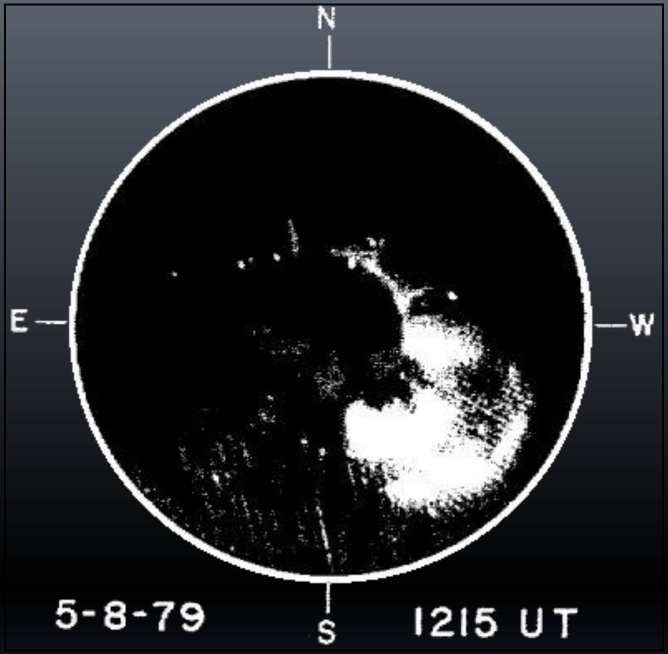


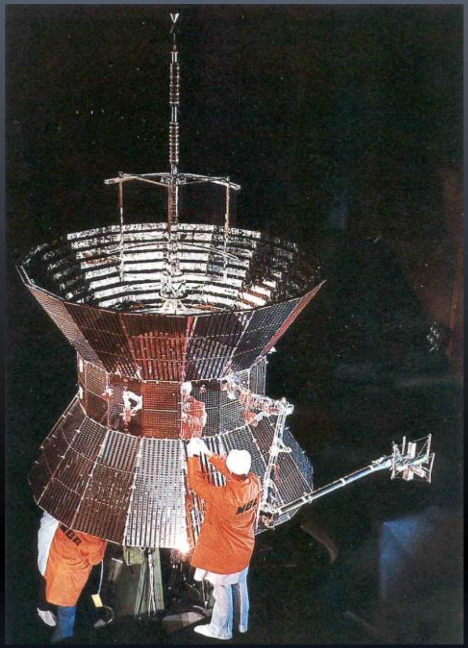
What is a CME?
A new, discrete, bright feature appearing in the field of view of the coronagraph and moving outwards over a period of minutes to hours

(Munro, R.H., J.T. Gosling, E. Hildner, R.M. MacQueen, A.I. Poland, C.L. Ross, The Association Of Coronal Mass Ejection Transients With Other Forms Of Solar Activity, *Solar Physics* **61**, 201-215, 1979).

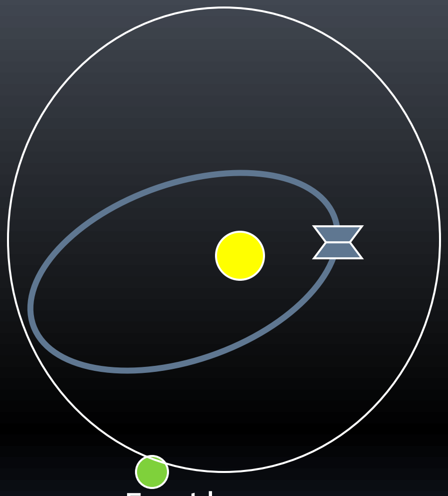
Credits: A. Vourlidas, K. Lang, NASA

Correlated analysis of remote sensing and in situ observations





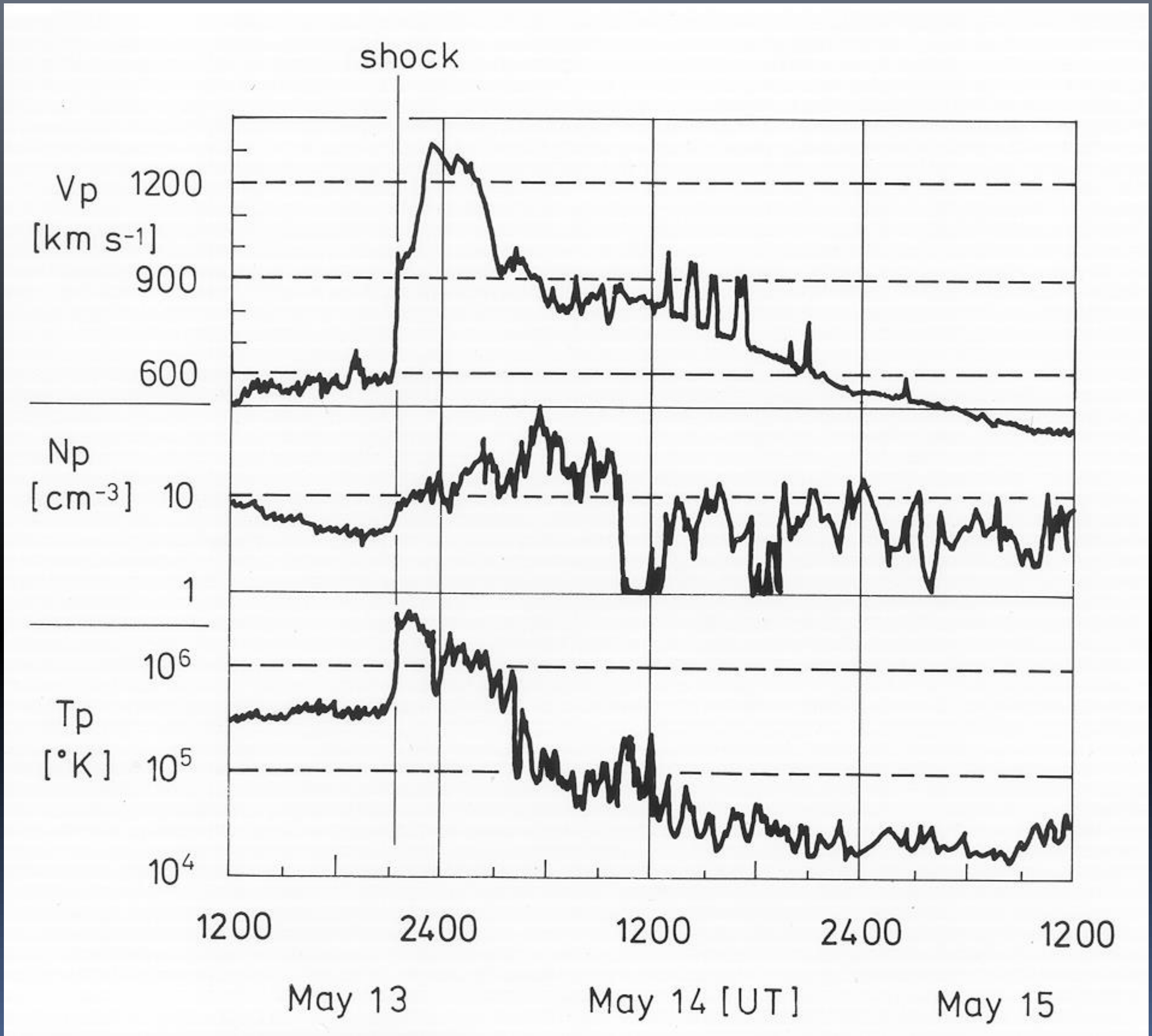
Orbit: 0.29 – 1 au



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

The Helios 1 & 2 spacecraft
(1974-1986)

Fast interplanetary shock measured by Helios 1 in 1978



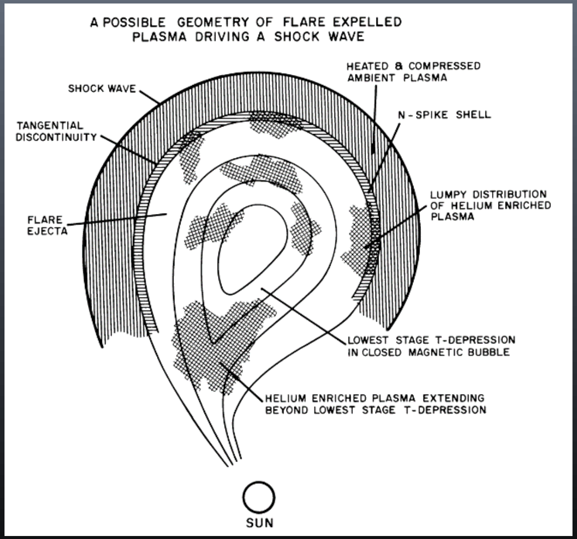
All Helios 1 directed CMEs with a speed >400 km/s in the FOV of the Solwind coronagraph caused a shock at Helios 1!

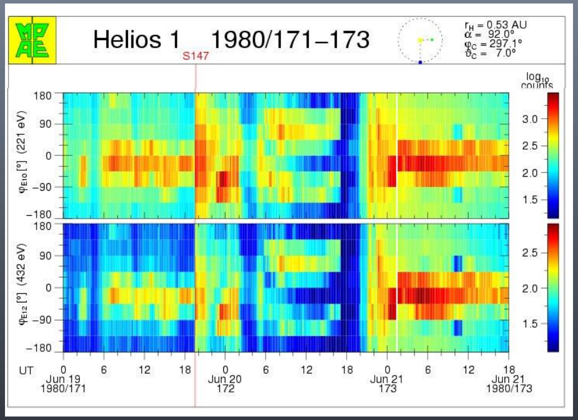
Sheeley, N.R. Jr., R.A. Howard, M.J. Koomen, D.J. Michles, R. Schwenn, K.-H. Mühlhäuser, and H. Rosenbauer, Coronal mass ejections and interplanetary shocks, J. Geophys. Res., 90, 1985.

Gosling, J.T., J.R. Asbridge, S.J. Bame, W.C. Feldman, R.D. Zwickl, Observations of large fluxes of He+ in the solar wind following an interplanetary shock, J. Geophys. Res. 85, 3431-3434, 1980.

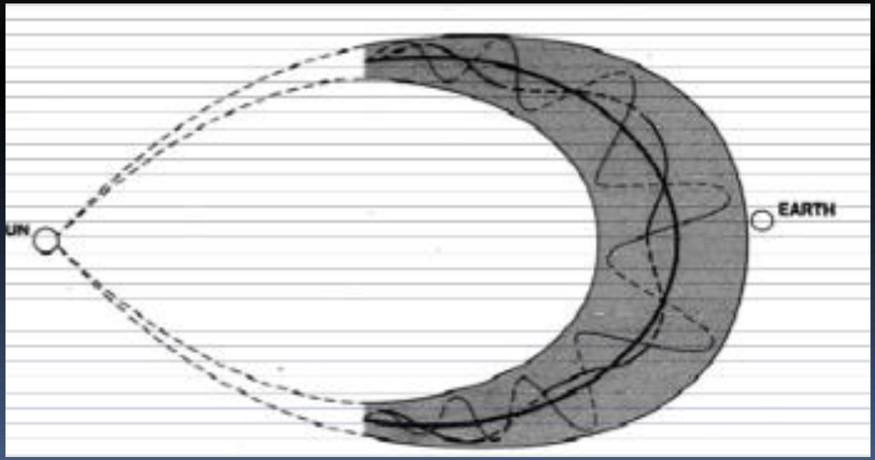
Interpretation of ISEE 3 and Helios Measurements

Bame, S.J., J.R. Asbridge, W.C. Feldman, J.T. Gosling, R.D. Zwickl, Bi-directional streaming of solar wind electrons > 80 eV: ISEE evidence for a closed-field structure within the driver gas of an interplanetary shock, *Geophys. Res. Lett.* **8**, 173-176, 1981.

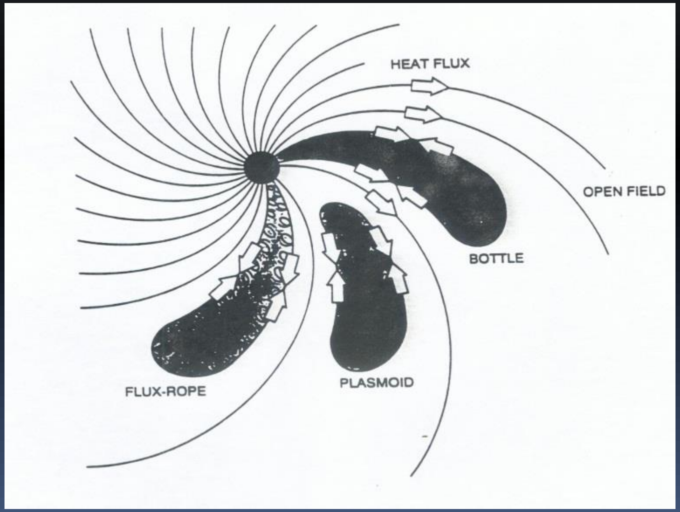




Credit: K. Ivory, MPAE; Phillips L.J., J.T. Gosling, D.J. McComas, S.J. Bame, W.C. Feldman, Quantitative Analysis of Bidirectional Electron Fluxes within Coronal Mass Ejections at 1 AU, in Solar Wind Seven, ed. E. Marsch and R. Schwenn, *Pergamon*, Oxford, 1992 .

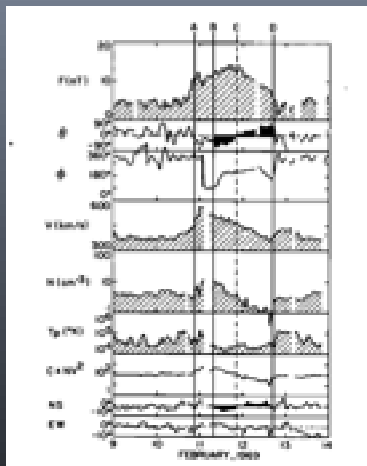


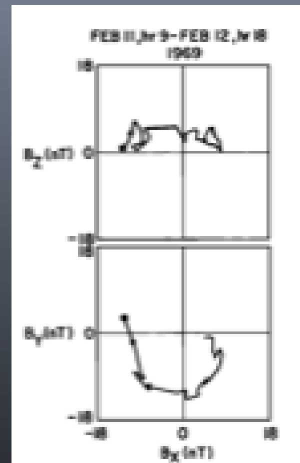
Burlaga, L.F., R.P. Lepping, J.A. Jones, Global configuration of a magnetic cloud, in Physics of Magnetic Flux Ropes, ed. by E.R. Priest, L.C. Lee, C.T. Russell, AGU Geophysical Monograph 58, 373-377, 1990.

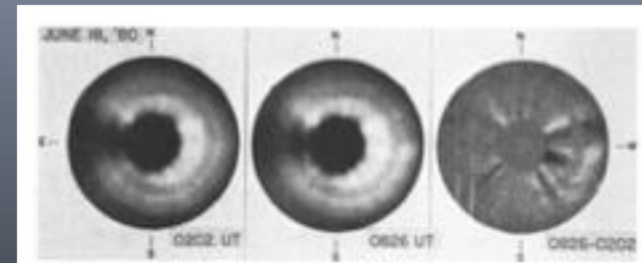


Gosling, J.T., Coronal mass ejections and magnetic flux ropes in interplanetary space, in Physics of Magnetic Flux Ropes, ed. by E.R. Priest, L.C. Lee, C.T. Russell, *AGU Geophysical Monograph* **58**, 343-364, 1990.

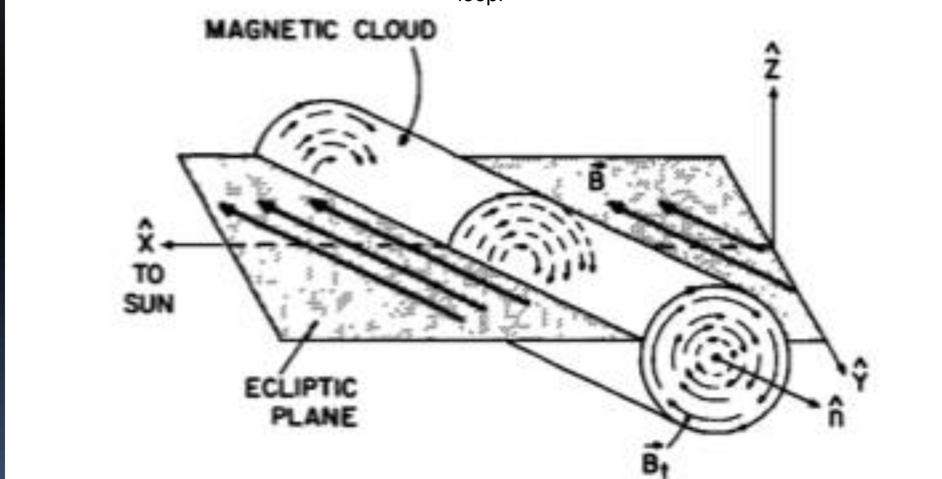
Interpretation of ISEE 3 and Helios Measurements

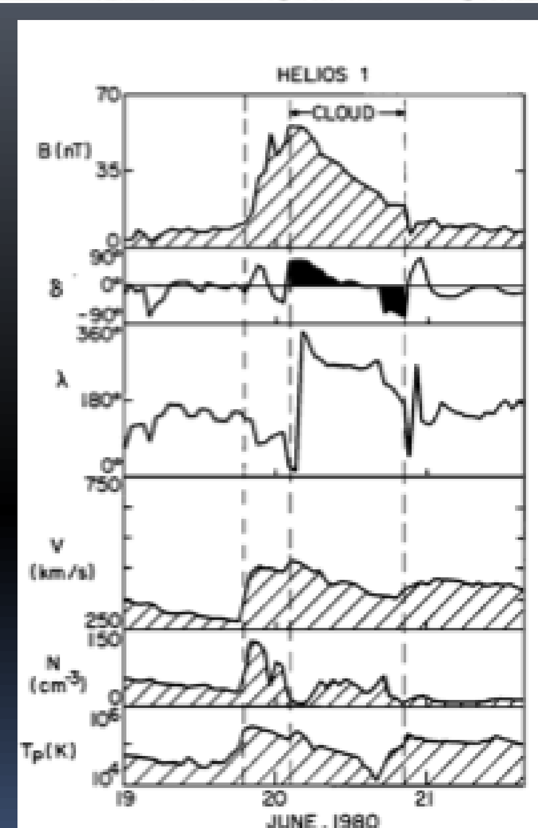






The magnetic field has the form of a cylindrical helix rather than the form of a closed circular loop.

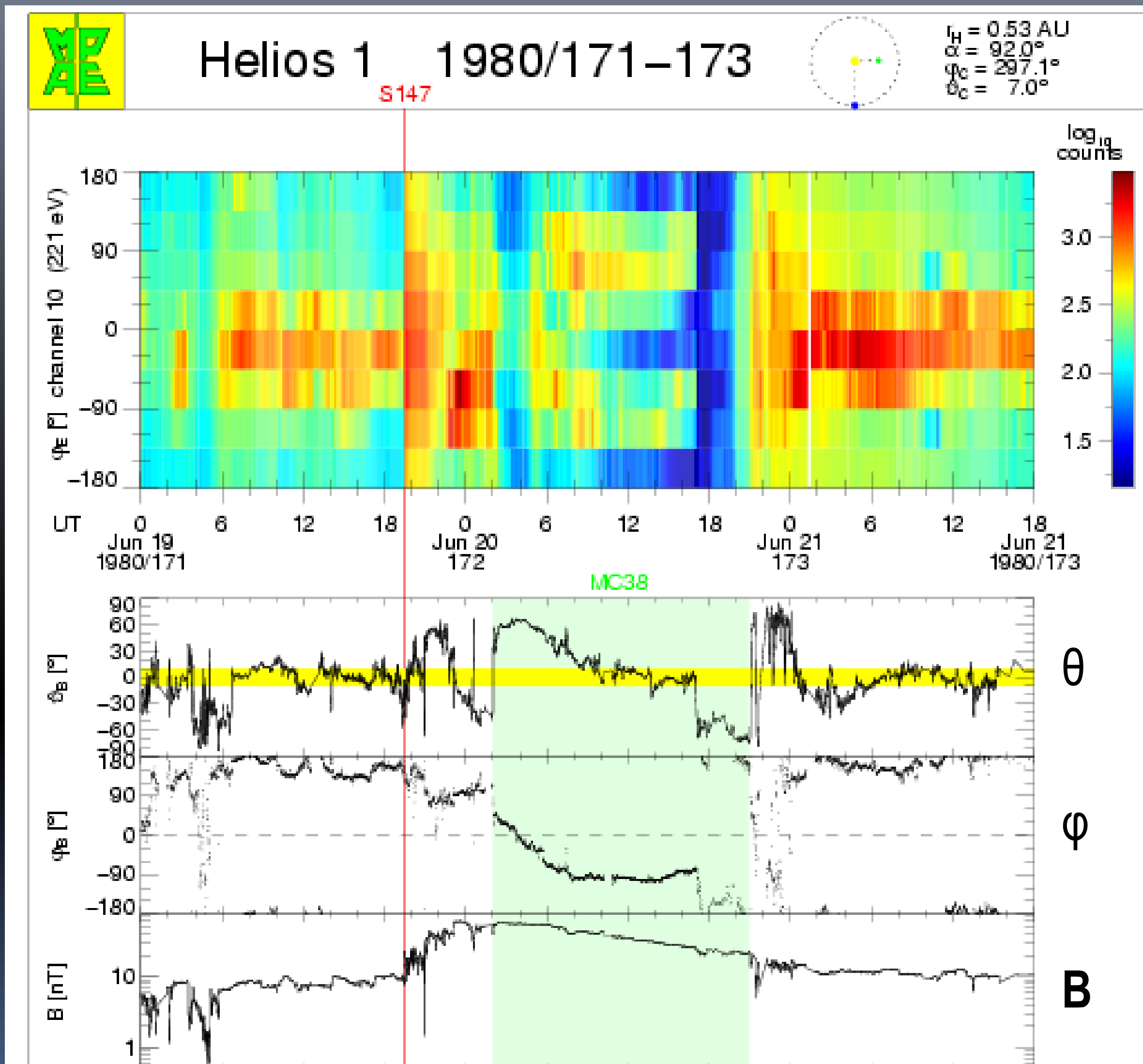




Klein, L.W., L.F. Burlaga, Interplanetary Magnetic Clouds At 1 AU, *J. Geophys. Res.* **87**, 613-624, 1982.

Burlaga, L.F., L. Klein, N.R. Sheeley Jr., D.J. Michels, R.A. Howard, M.J. Koomen, R. Schwenn, H. Rosenbauer, A magnetic cloud and a coronal mass ejection, Geophys. Res. Lett. 9, 1317-1320, 1982.

A magnetic cloud detected by Helios 1 following a CME observed with Solwind



Suprathermal electrons
(E=221 keV)

IMF NS-direction

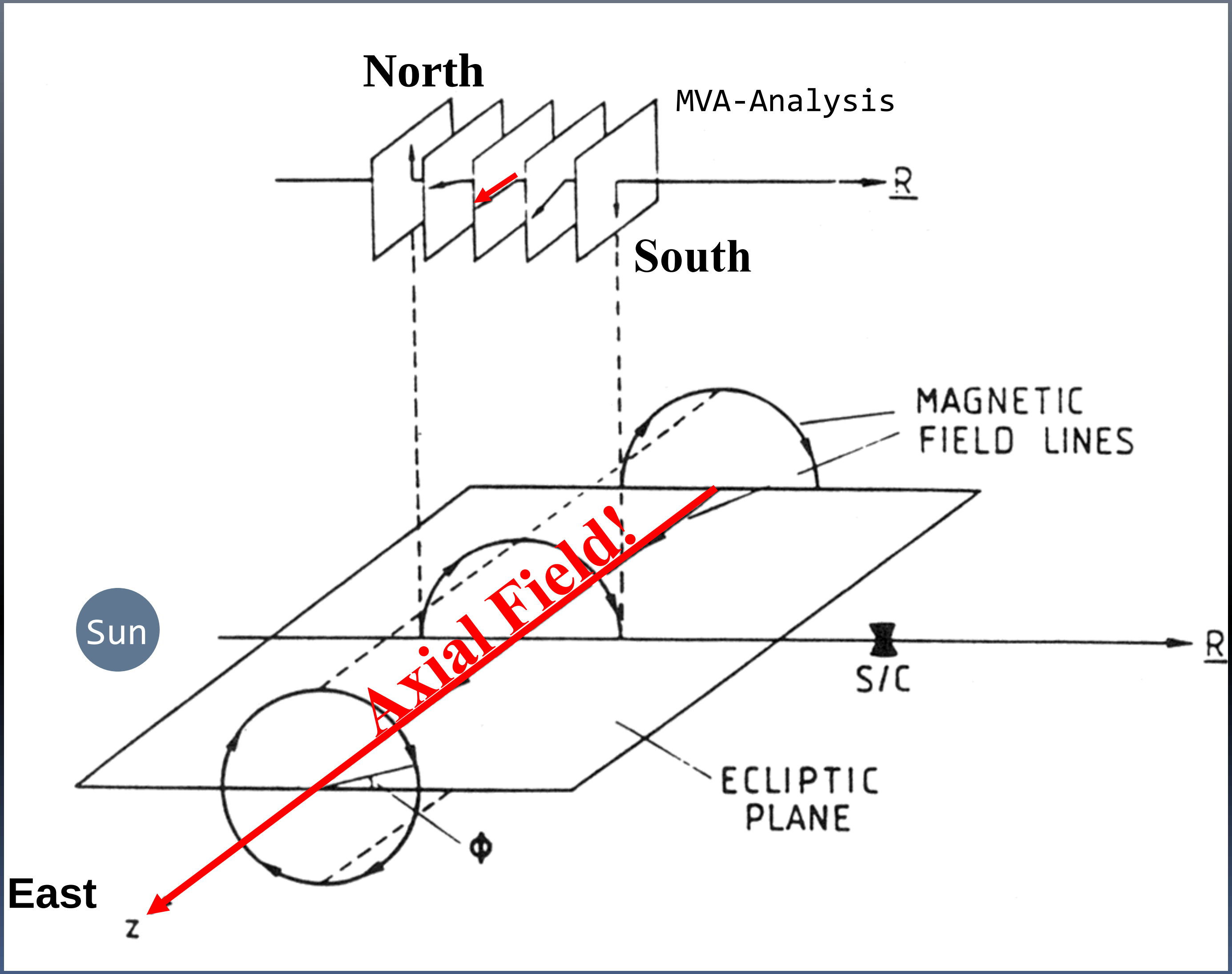
IMF EW-direction

IMF strength

Shock 1 Day

Bothmer, V., Magnetic Field Structure and Topology Within CMEs in the Solar Wind, Solar Wind 9 Conference Proc., published by American Institute of Physics (AIP), 119-126, 1999.

Possible explanation for the magnetic structure of a MC



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

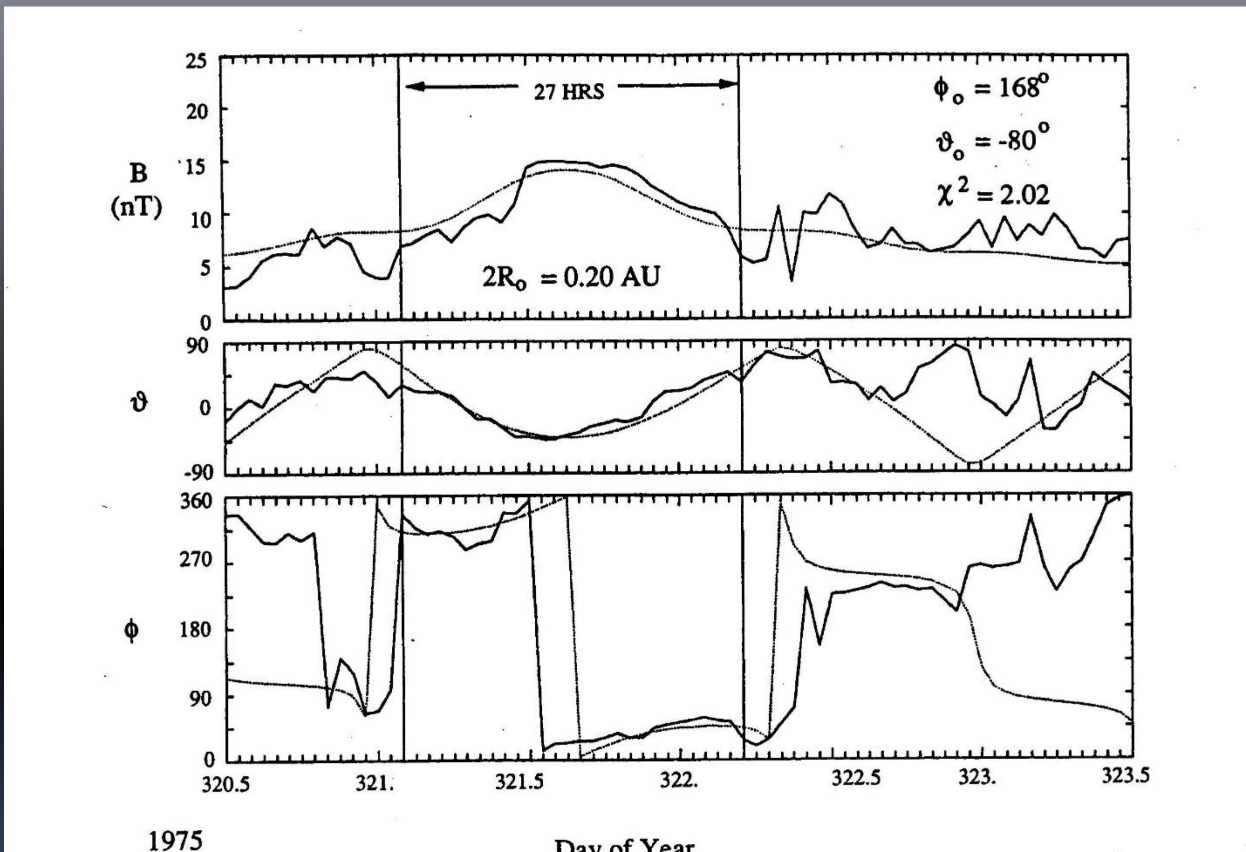
if $\beta \ll 1$, a force-free configuration can be considered:

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

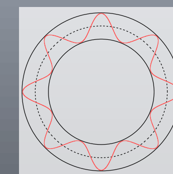
The electric current is flowing everywhere parallel or antiparallel to B

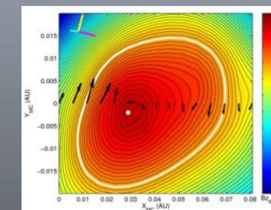
Goldstein, H., On the field configuration in magnetic clouds, in Solar Wind Five, *NASA Conf. Publ.* **2280**, 731, 1983; Bothmer, V., and R. Schwenn, The Structure and Origin of Magnetic Clouds in the Solar Wind, Annales Geophysicae, 16, 1-24, 1998.

MC measured by ISEE 3 and IMP 8 fit based on Lundquist-equations (see also various other modelling techniques)



Lepping et al., 1990





Other modelling approaches:

A circular-cylindrical flux rope analytical model for magnetic clouds, T. Nieves-Chinchilla , M. G. Linton , M. A. Hidalgo , A. Vourlidas , N. P. Savani , A. Szabo, The Astrophysical Journal, 823:27 (13pp), 2016.

Grad-Shafranov reconstruction of magnetic clouds: overview and improvements, A. Isavnin , E.K.J. Kilpua H.E.J. Koskinen, Solar Physicsv 2011, Volume 273, Issue 1 , pp 205-219.

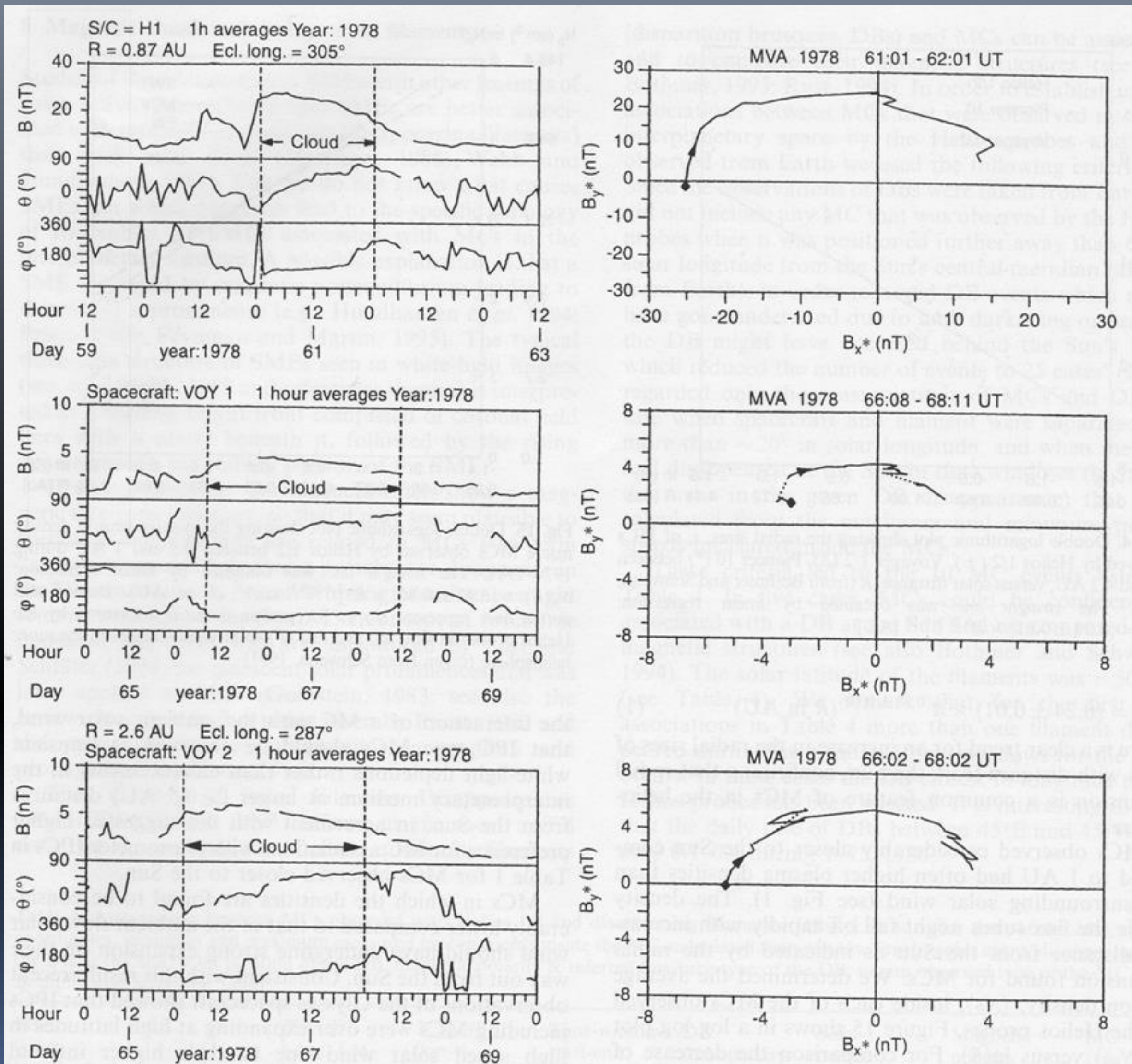
Reconstruction of magnetic clouds in the solar wind: Orientations and configurations ,Qiang Hu and Bengt U.O¨. Sonnerup, JGR, Vol. 107, A7, 1142, 10.1029/2001JA000293, 2002.

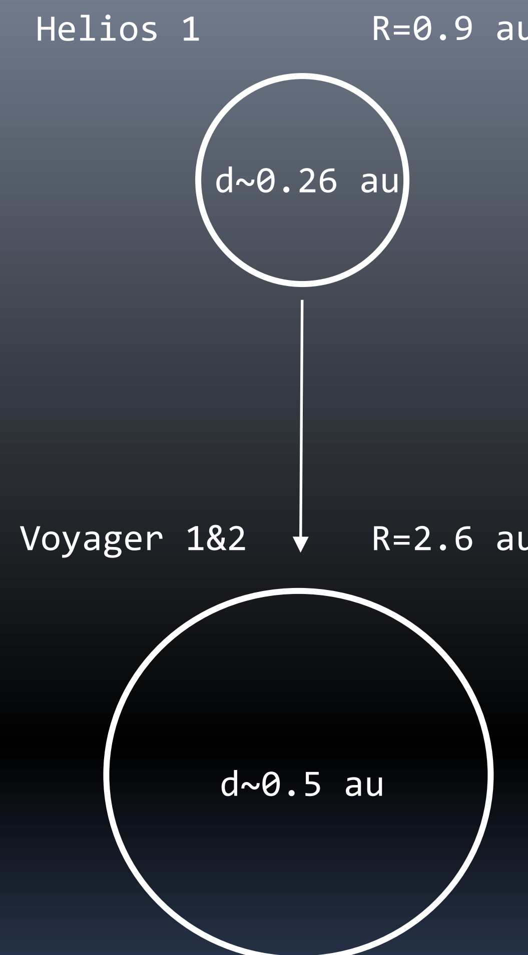
Magnetic cloud fit by uniform-twist toroidal flux ropes M. Vandas and E. Romashets, A&A 608, A118 (2017).

Writhed Magnetic Flux Rope Model, J. Weiss, T. Nieves-Chinchilla, C. Möstl, Martin A. Reiss, Tanja Amerstorfer, and Rachel L. Bailey, Astronomy & Astrophysics, ©ESO 2022 July 25, 2022.

On the Quasi-Three-Dimensional Configuration of Magnetic Clouds, Qiang Hu, Wen He, Jiong Qiu, Angelos Vourlidas, and Chunming Zhu,Geophys AGU, Volume48, Issue2, 2021.

MC observed by Helios 1 and Voyager 1&2 in 1978 – field rotation not just a local phenomenon, evidence for expansion



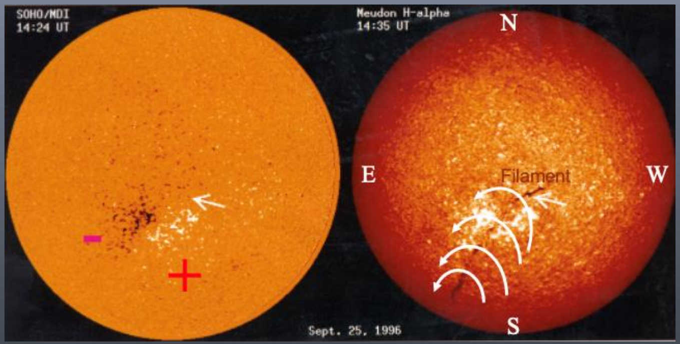


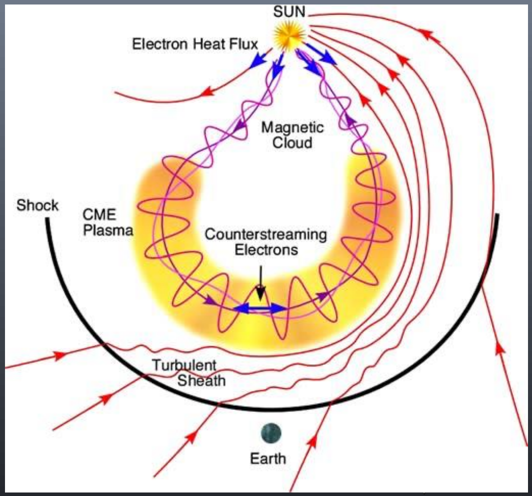
Bothmer, V., and R. Schwenn, The Structure and Origin of Magnetic Clouds in the Solar Wind, Annales Geophysicae, 16, 1-24, 1998.

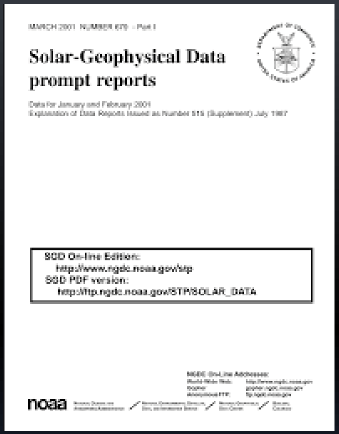
See also recent studies of radial alignments, e.g., Self-Similarity of ICME Flux Ropes: Observations by Radially Aligned Spacecraft in the Inner Heliosphere, S. W. Good, E.K.J. Kilpua, A. T. LaMoury, ,R. J. Forsyth, J. P. Eastwood,and C. Möstl.

Possible solar origin of MCs as magnetic flux ropes

T. H. Zurbuchen and I. G. Richardson, In-Situ Solar Wind and Magnetic Field Signatures of Interplanetary Coronal Mass Ejections,Space Science Reviews, 123:31–43, March 2006.






Solar-Geophysical Data prompt reports

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http://www.ngdc.noaa.gov/stp
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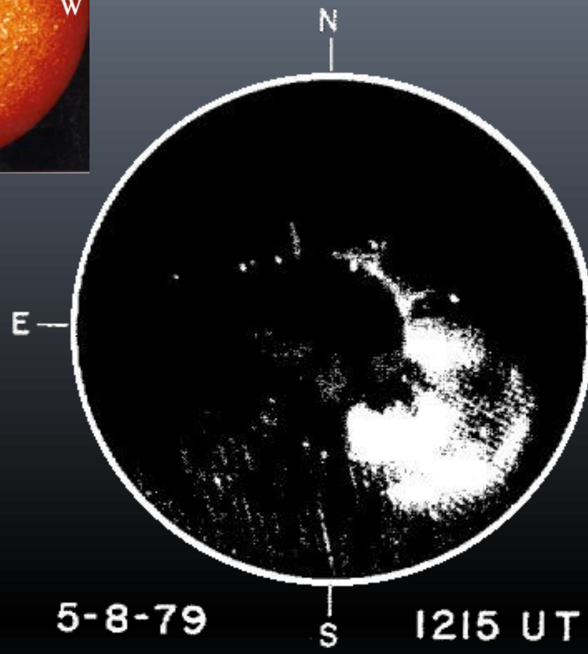
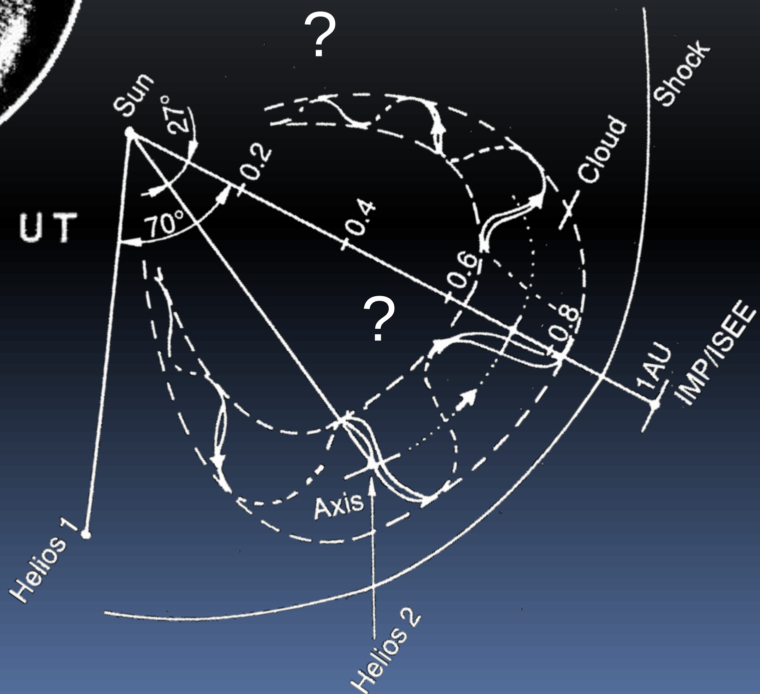
http://ftp.ngdc.noaa.gov/STP/SOLAR_DATA

noaa

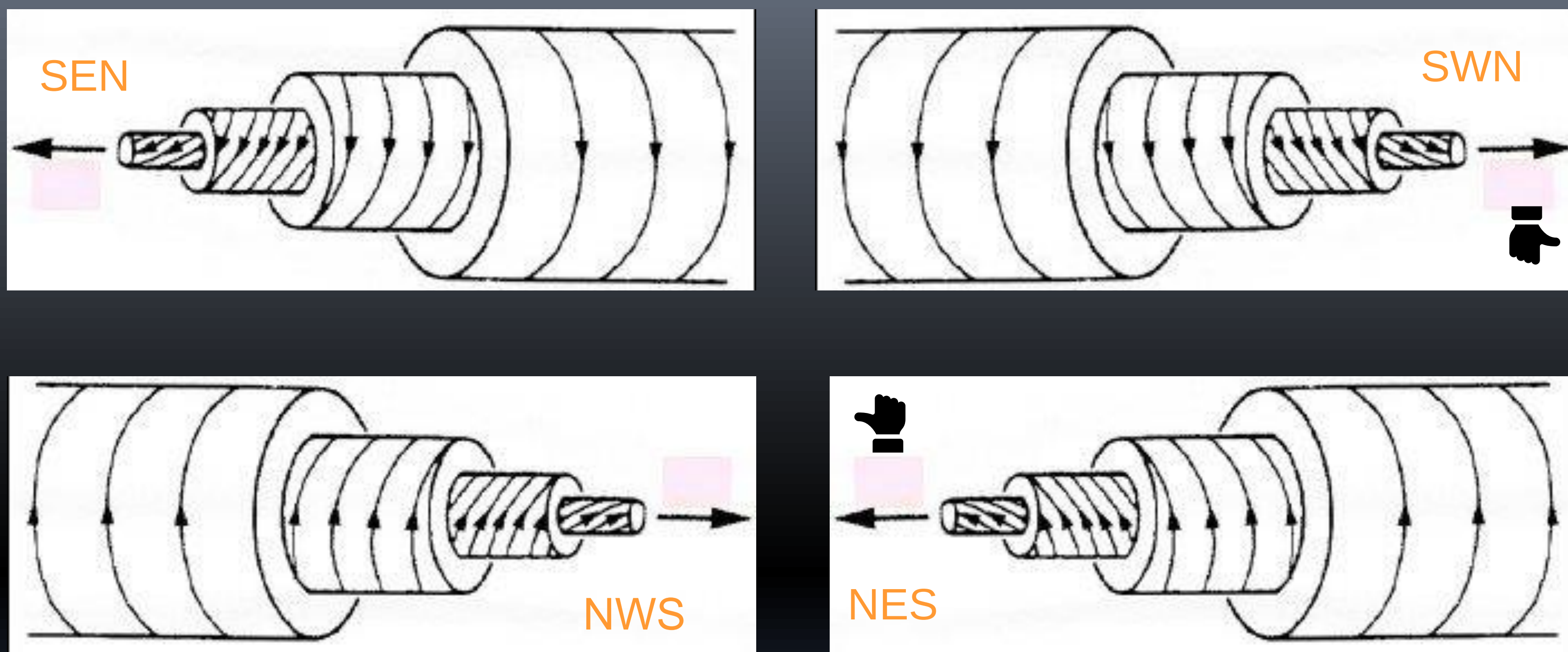




Adapted from Marubashi, K., Structure of the interplanetary magnetic clouds and their solar origins, Adv. Space Res. 6, 335, 1986; Bothmer, V., and R. Schwenn, The Structure and Origin of Magnetic Clouds in the Solar Wind, Annales Geophysicae, 16, 1-24, 1998.

The four different types of MCs as magnetic FRs oriented parallel to the ecliptic plane

LH RH

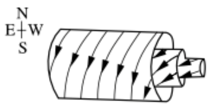
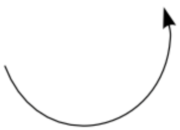
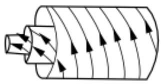
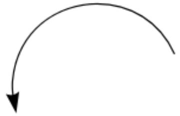


Based on Helios observations during 1974-1981

46 unique clouds: 23 LH, 23 RH

Bothmer, V., and R. Schwenn, The Structure and Origin of Magnetic Clouds in the Solar Wind, Annales Geophysicae, 16, 1-24, 1998.

The different rotations observed in MCs by the Helios s/c

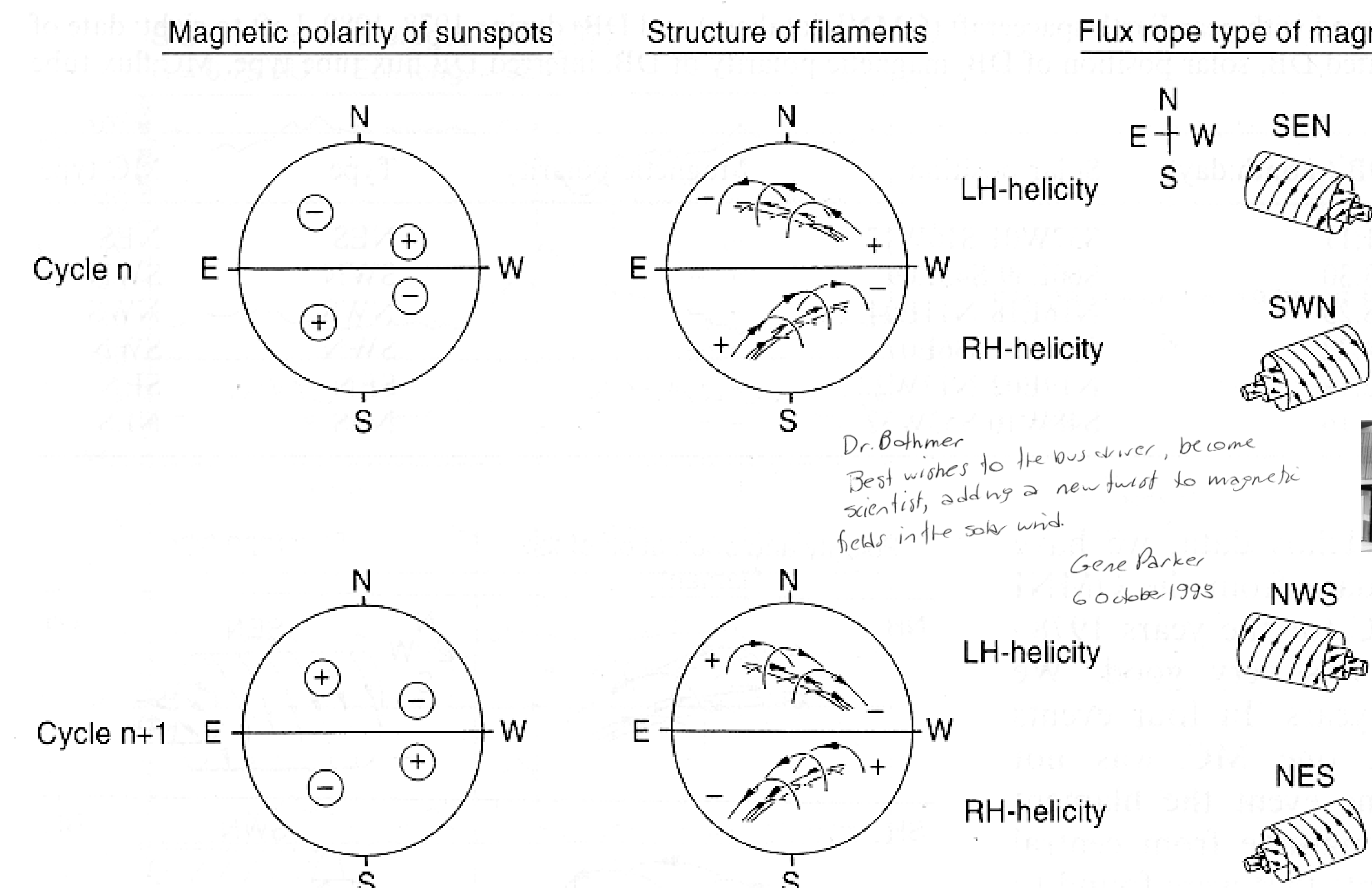
MC Type / Magnetic helicity / Number of MCs during 1974–1981	Variation of magnetic field vector	Direction of magnetic field on flux tube axis	Rotation of magnetic field vector in *Bz*-*By*-plane (*Bx**-*By**-plane)
SEN — Left-handed  17	South (–*Bz*)→north (+*Bz*)	East (+*By*)	
SWN — Right-handed  17	South (–*Bz*)→north (+*Bz*)	West (–*By*)	
NES — Right-handed  6	North (+*Bz*)→south (–*Bz*)	East (+*By*)	
NWS — Left-handed  6	North (+*Bz*)→south (–*Bz*)	West (–*By*)	
Orientations for high inclinations to the ecliptic SEN, NWS, SWN, NES	East (+*By*)→west (–*By*) West(–*By*)→east(+*By*)	North (+*Bz*)→south (–*Bz*) South (–*Bz*)→north (+*Bz*)	Rotations in *By*-*Bz*-(*By**-*Bx**-) plane

Sketch showing the different magnetic configurations of MCs and their magnetic helicity (left-handed (LH), right-handed (RH)) based on the magnetic flux-tube concept and the field rotation that a s/c would observe during the cloud's passage. The number at the bottom indicates how often each MC-type was observed by Helios 1/2 between 0.3-1 AU during 1974-1981.

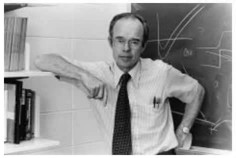
Note: perpendicular cases had also been included.

Bothmer, V., and R. Schwenn, The Structure and Origin of Magnetic Clouds in the Solar Wind, Annales Geophysicae, 16, 1-24, 1998.

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



Dr. Bothmer
Best wishes to the bus driver, become scientist, adding a new twist to magnetic fields in the solar wind.
Gene Parker
6 October 1998

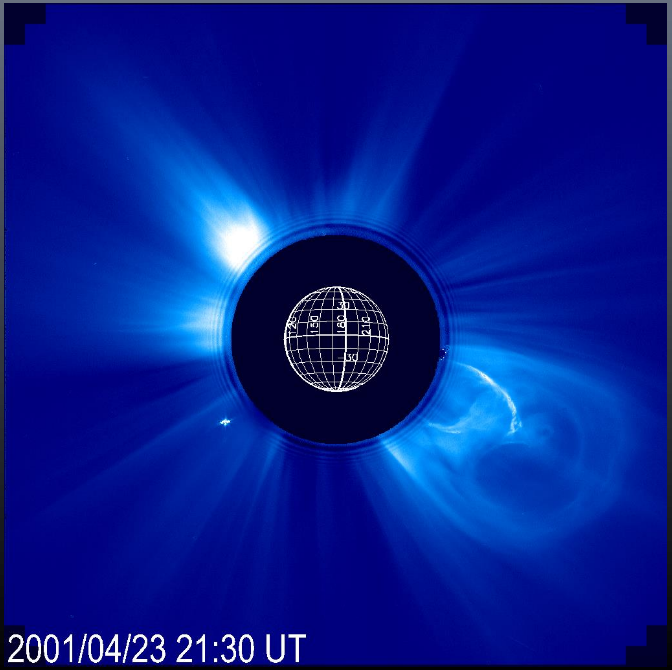


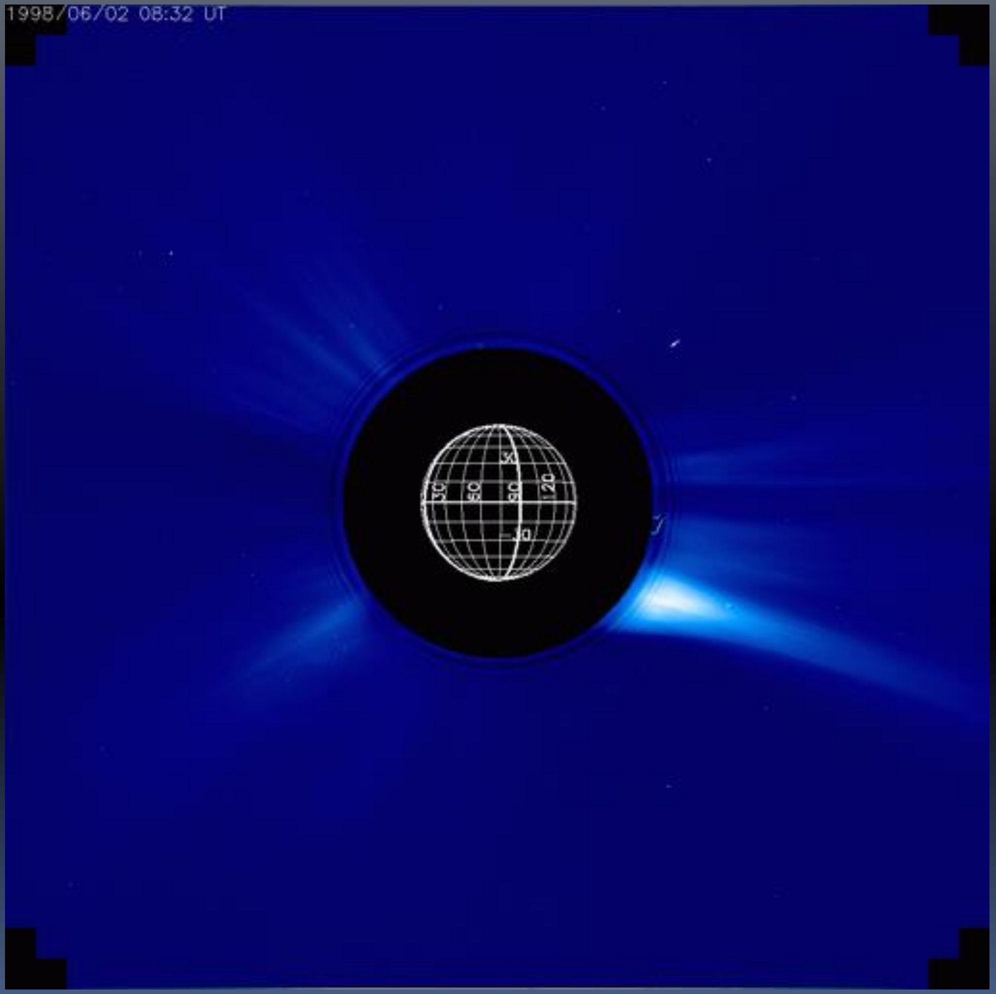
Credit: University of Chicago

Note: no consideration of quadrupolar fields

Bothmer, V., and R. Schwenn, The Structure and Origin of Magnetic Clouds in the Solar Wind, Annales Geophysicae, 16, 1-24, 1998.

The flux rope structure of CMEs could be revealed with SOHO/LASCO observations – the ESA/NASA SOHO mission launched in December 1995 set a milestone in solar/heliospheric observations



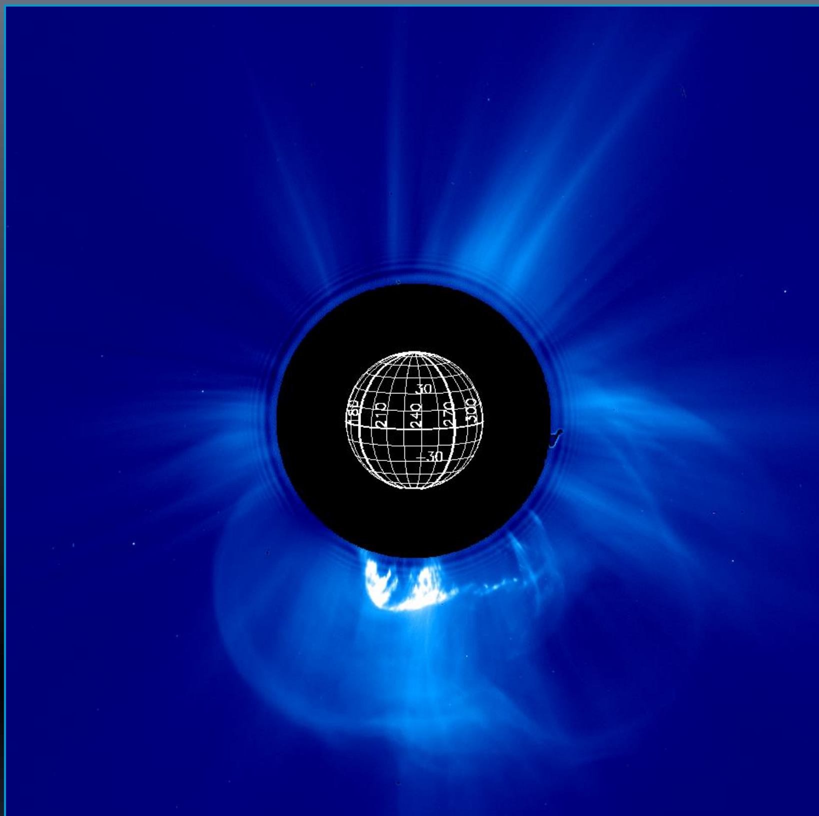


CMEs often show a three part structure:

- bright leading front
- dark cavity
- bright trailing core (prominence material)

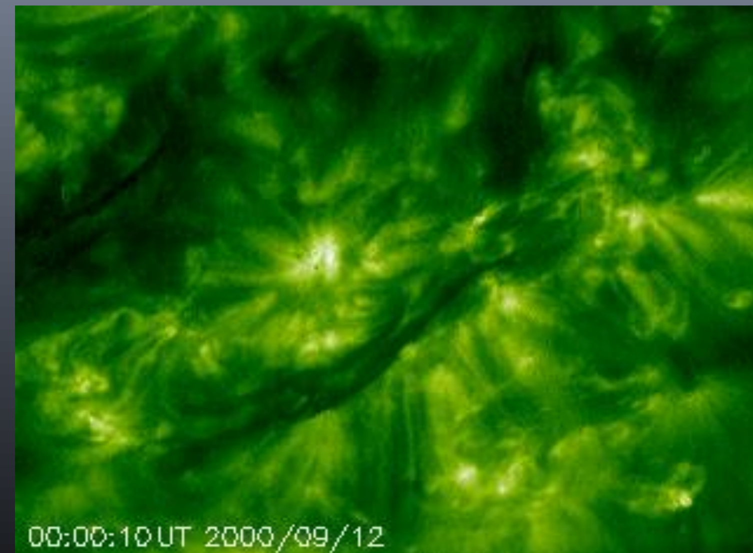
Filament, arcade and variation of the photospheric magnetic flux in a CME's source regions

SOHO/LASCO C2

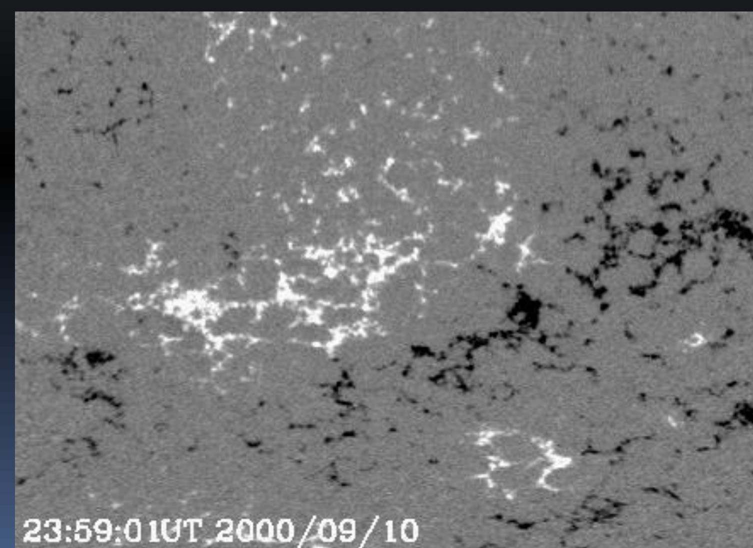


EIT

195 Å



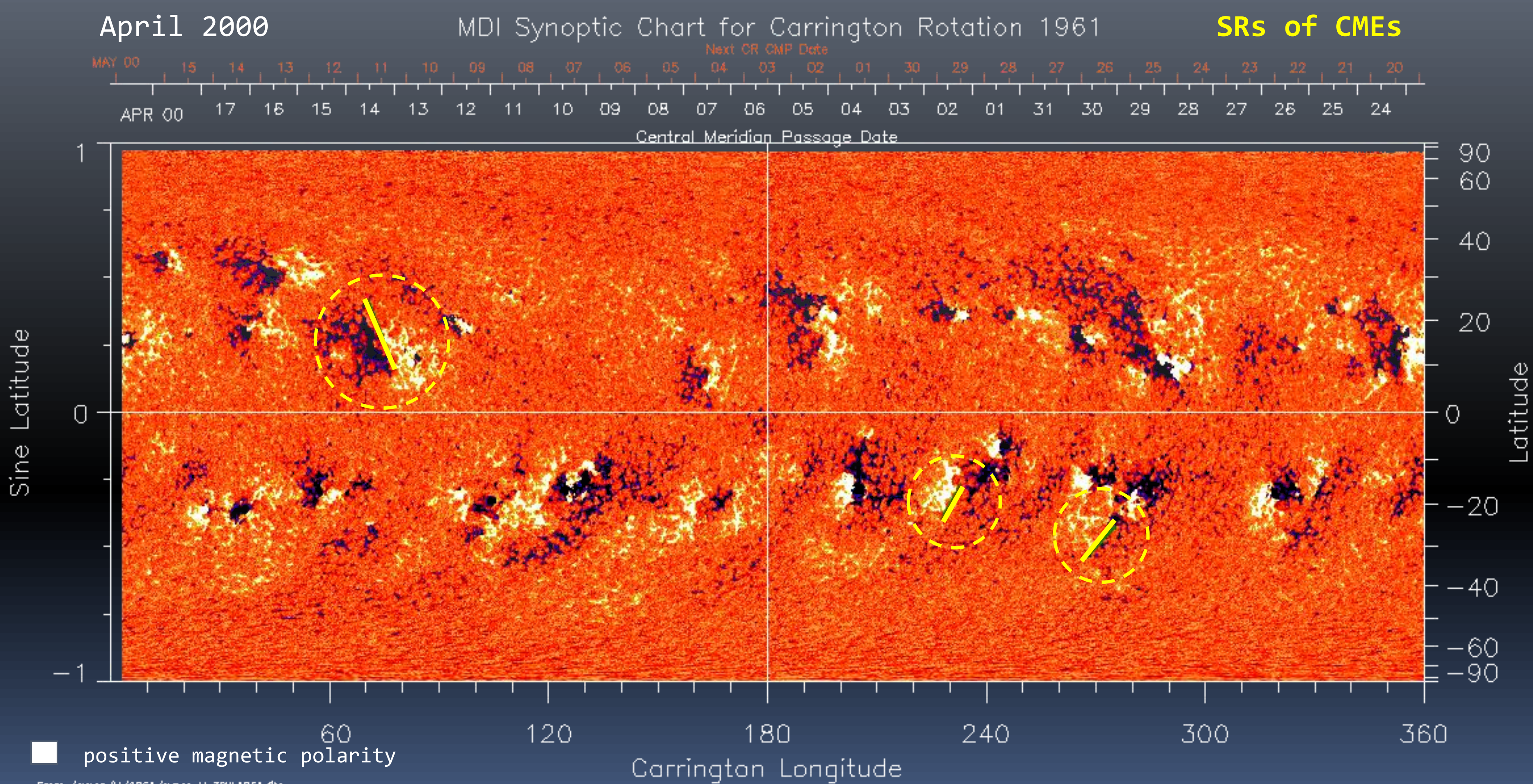
MDI



A detailed study was undertaken to investigate the evolution of the photospheric flux in the source regions of CMEs

(Tripathi, Bothmer, Cremades, A&A, 2004)

Photospheric bipoles as CME source regions

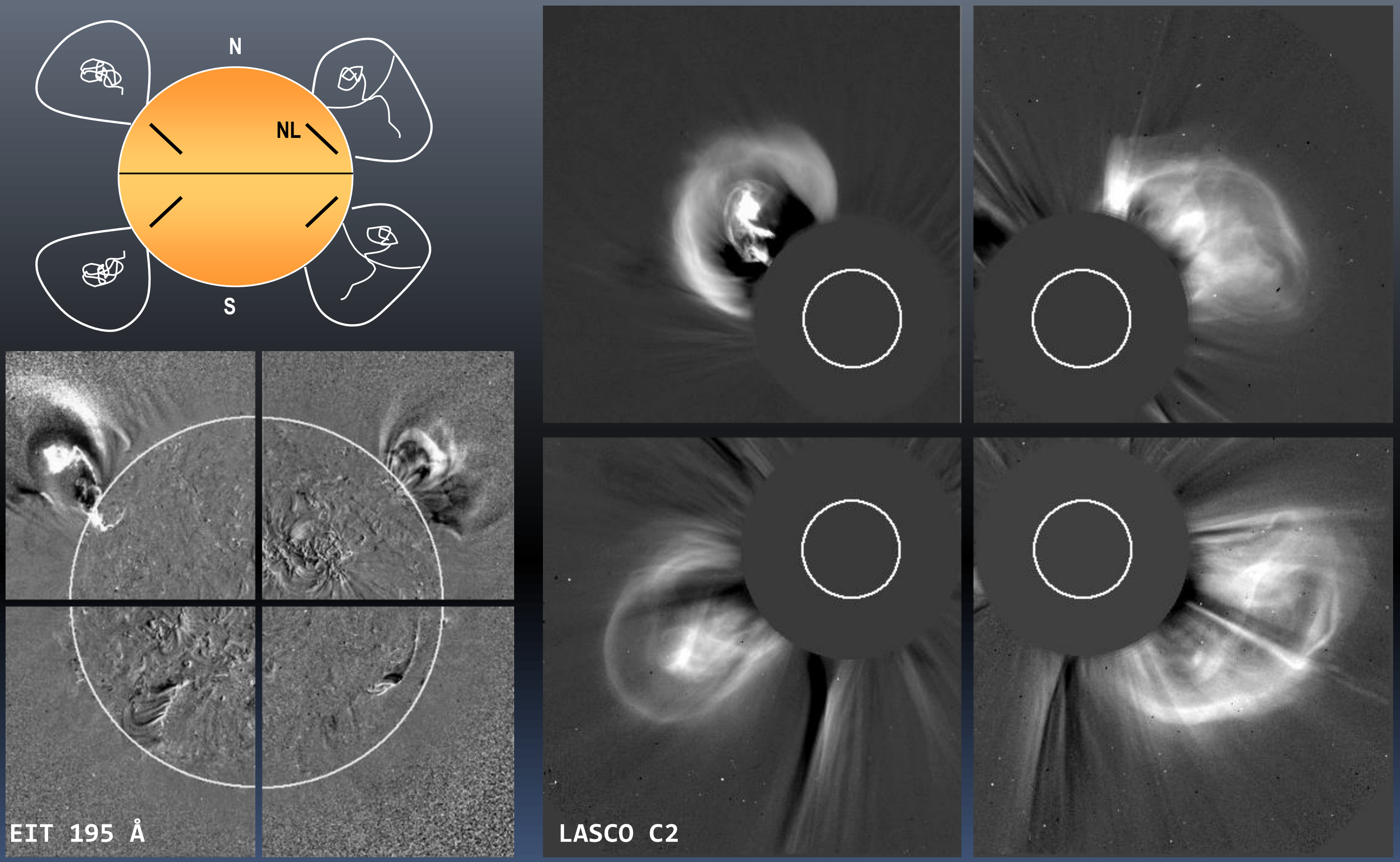


positive magnetic polarity

negative magnetic polarity

Cremades, H., and V. Bothmer, On the Three-Dimensional Configuration of Coronal Mass Ejections, Astron. and Astrophys., 422, Issue 1, 307-322, 2004.

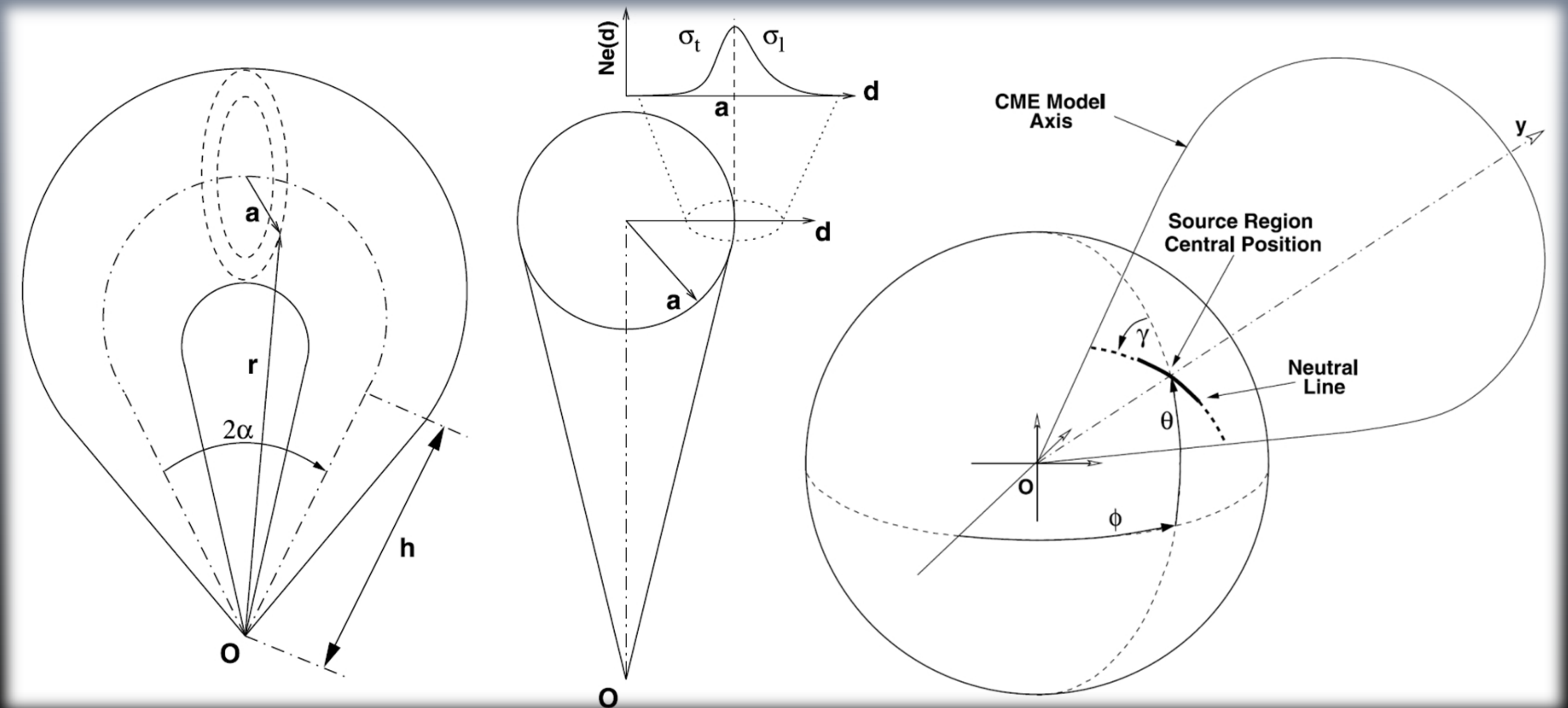
Basic scheme explaining the 3D structure of CMEs



Cremades, H., and V. Bothmer, On the Three-Dimensional Configuration of Coronal Mass Ejections, Astron. and Astrophys., 422, Issue 1, 307-322, 2004.

The Graduated Cylindrical Shell (GCS) model

Thernisien, A.F.R., R.A. Howard, A. Vourlidas, Modeling of Flux Rope Coronal Mass Ejections, The Astrophys. J., 652, 763-773, 2006.



Position on Sun

Longitute: ϕ *Latitude:* θ

Electron model

Gaussian width of density profile inside GCS: σ_t

Electron density: N_e

Gaussian width of density profile outside GCS: σ_l

Geometrical parameters

Angle between both legs:	2α
Radius of cross-section:	a
Distance between sun center & boundary point of GCS:	r
Height of the legs:	h
Tilt angle:	γ
Distance between O (sun center) & leading edge:	h_{front}

Other CME modelling techniques and reviews:

Coronal Mass Ejections: Models and Their Observational Basis, P. F. Chen, Living Rev. Solar Phys., 8, (2011), 1.

The flux rope nature of coronal mass ejections, Angelos Vourlidas, Plasma Phys. Control. Fusion 56 (2014) 064001 (6pp).

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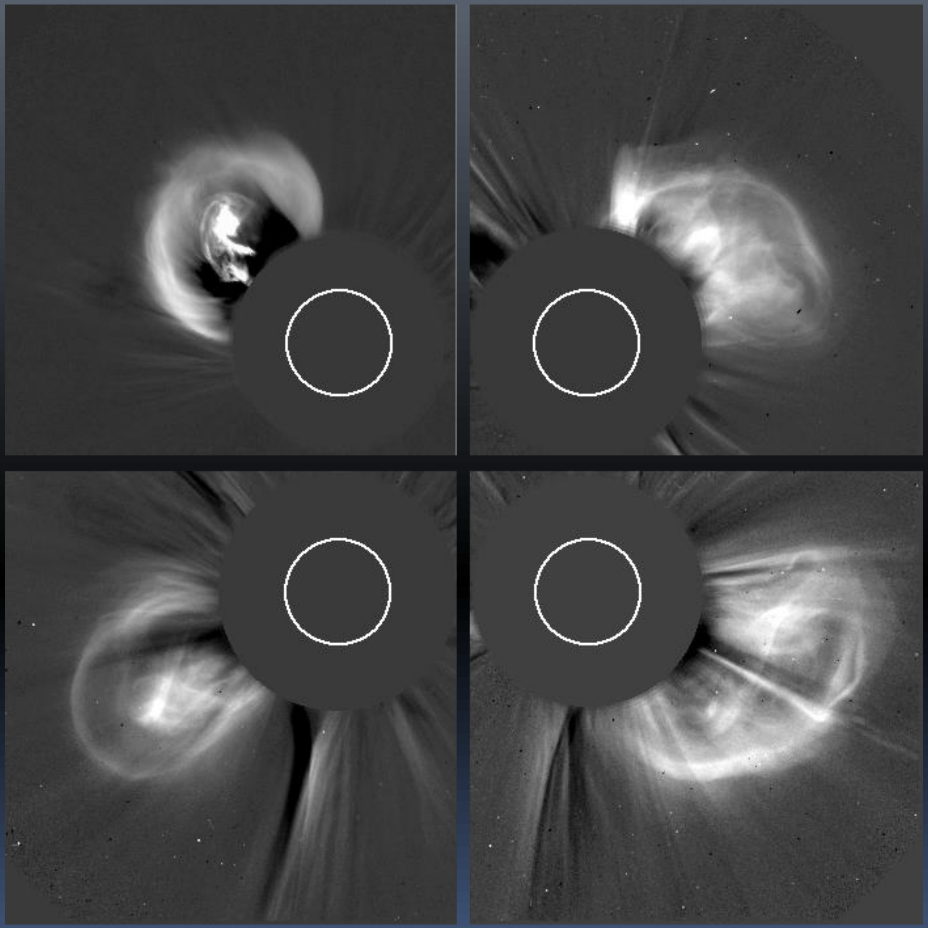
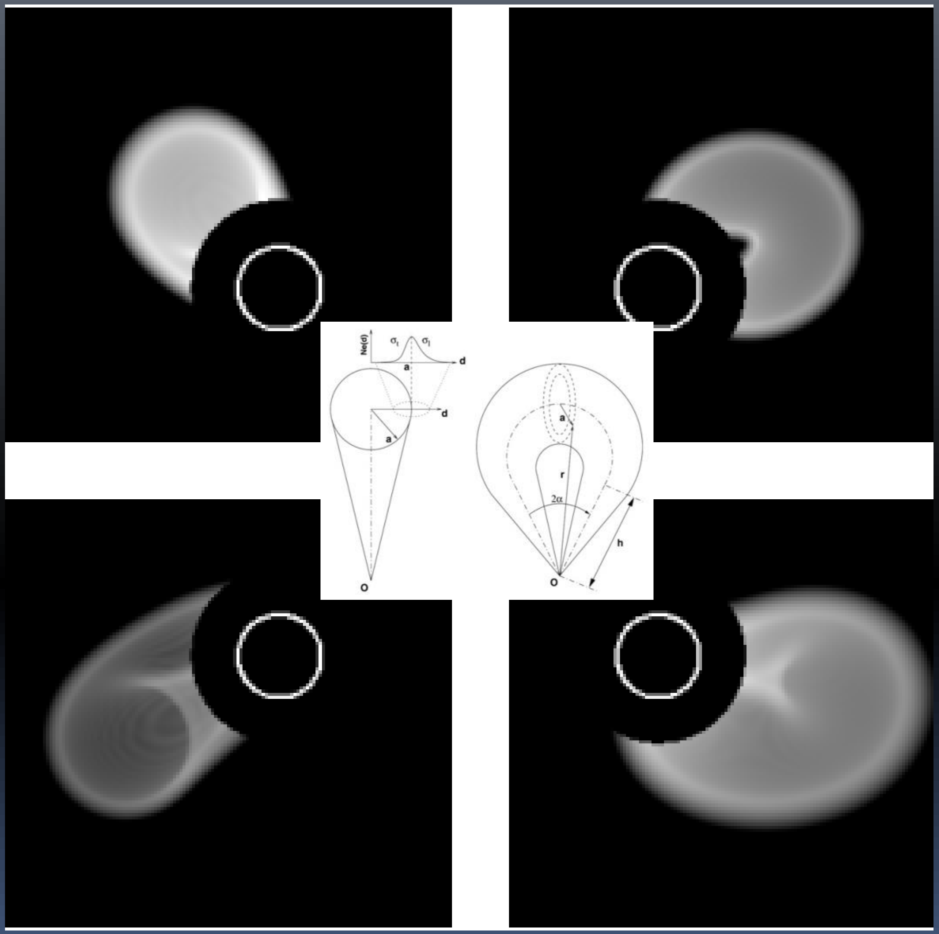
Modelling the Electron Density Distribution

LASCO Observations



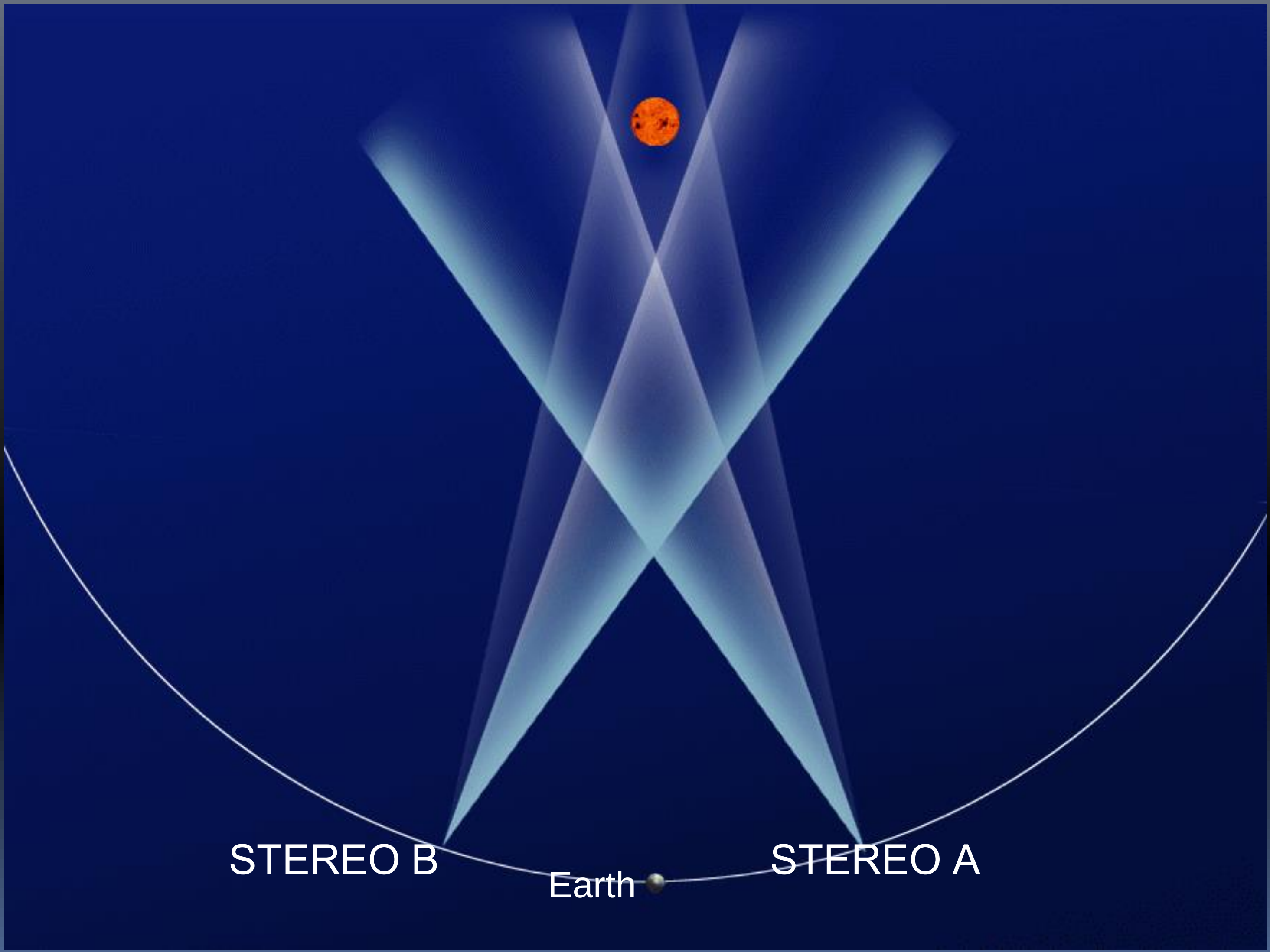
Simulations (GCS-model, $\int n_e dV$)



Cremades, H., and V. Bothmer, On the Three-Dimensional Configuration of Coronal Mass Ejections, Astron. and Astrophys., 422, Issue 1, 307-322, 2004.

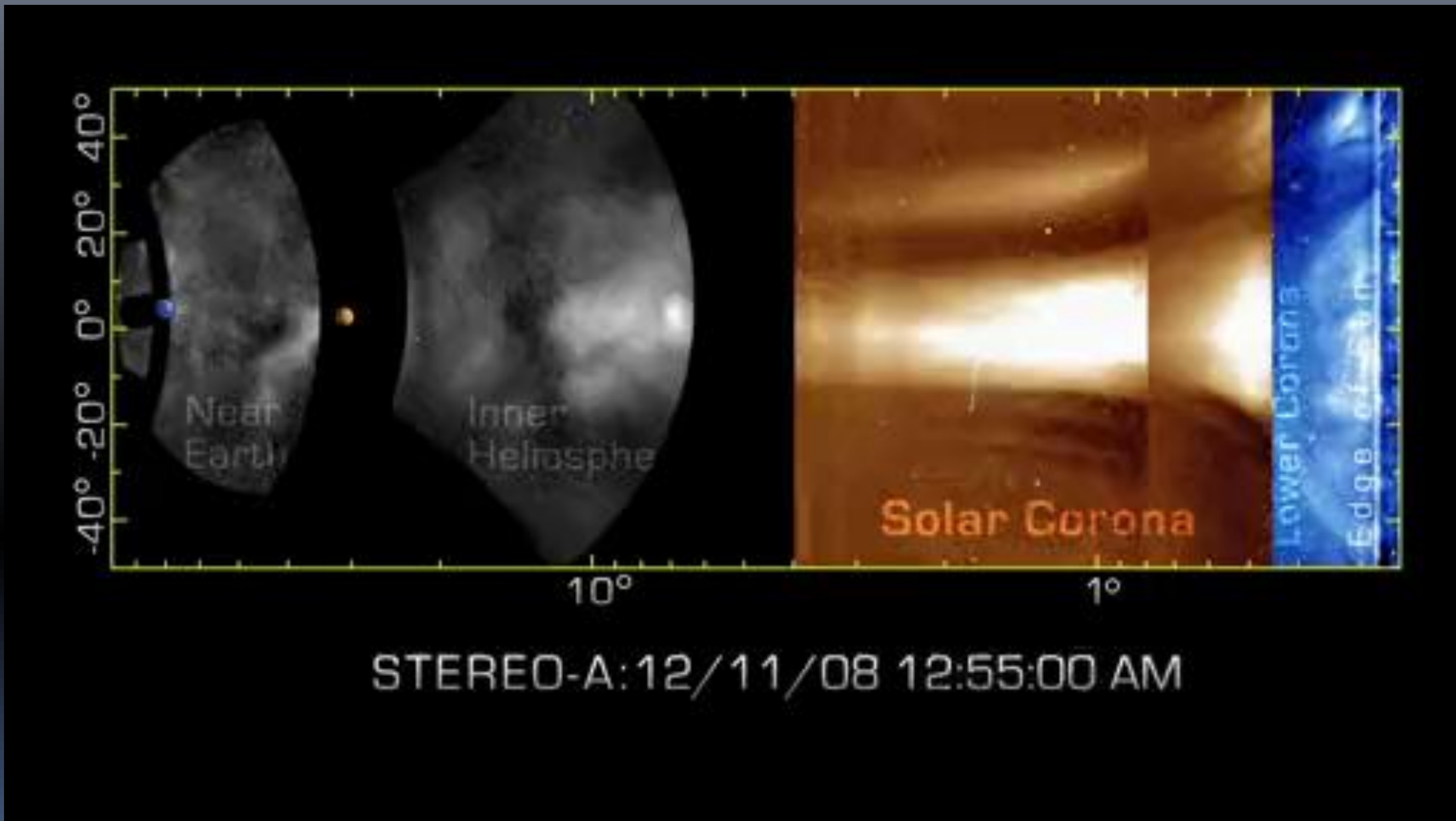
Thernisien, A.F.R., R.A. Howard, A. Vourlidas, Modeling of Flux Rope Coronal Mass Ejections, The Astrophys. J., 652, 763-773, 2006.

First stereoscopic observations of CMEs – The NASA STEREO mission launched in 2006



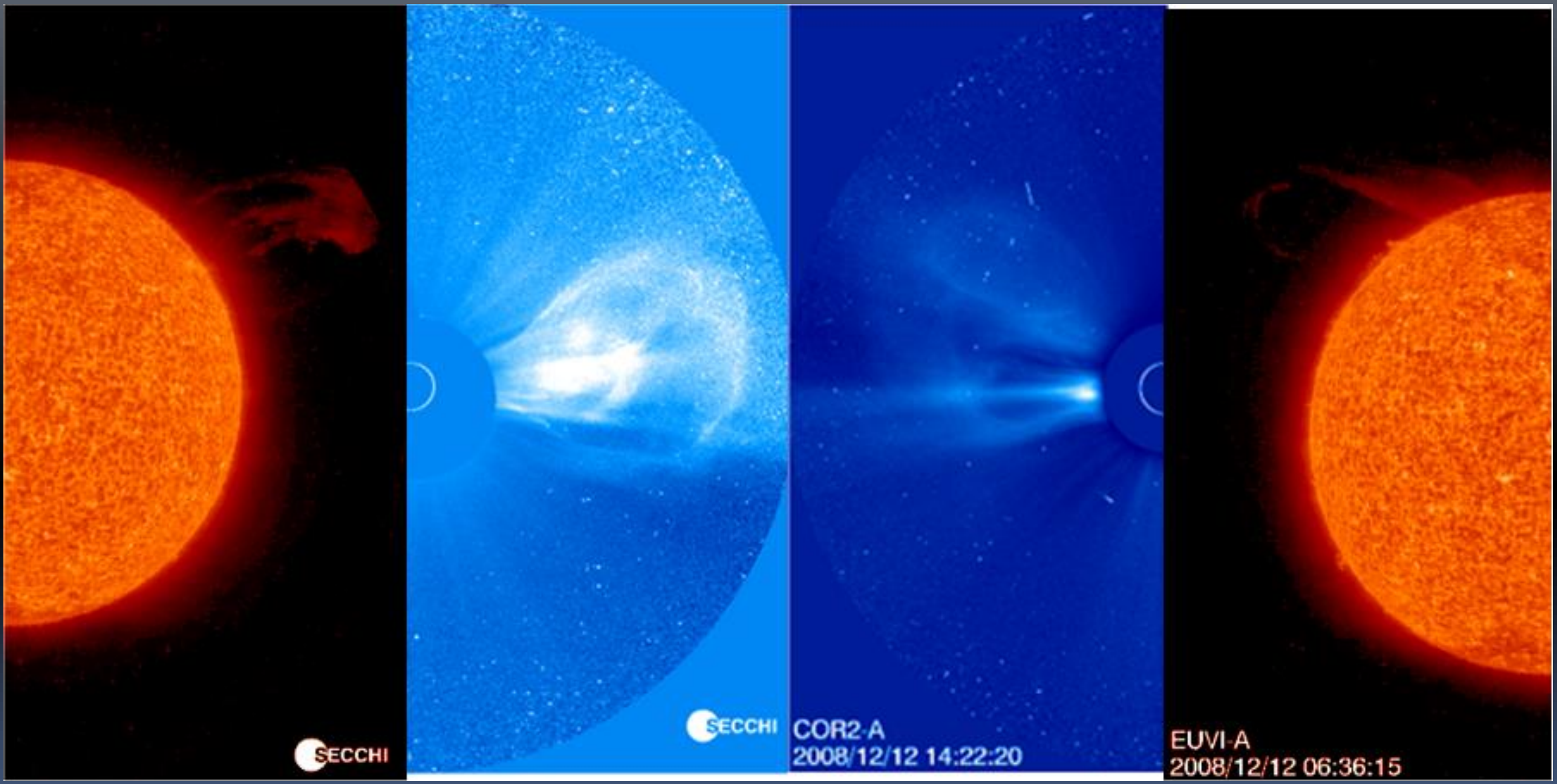
Credit: NASA

CMEs have been tracked Sun to Earth



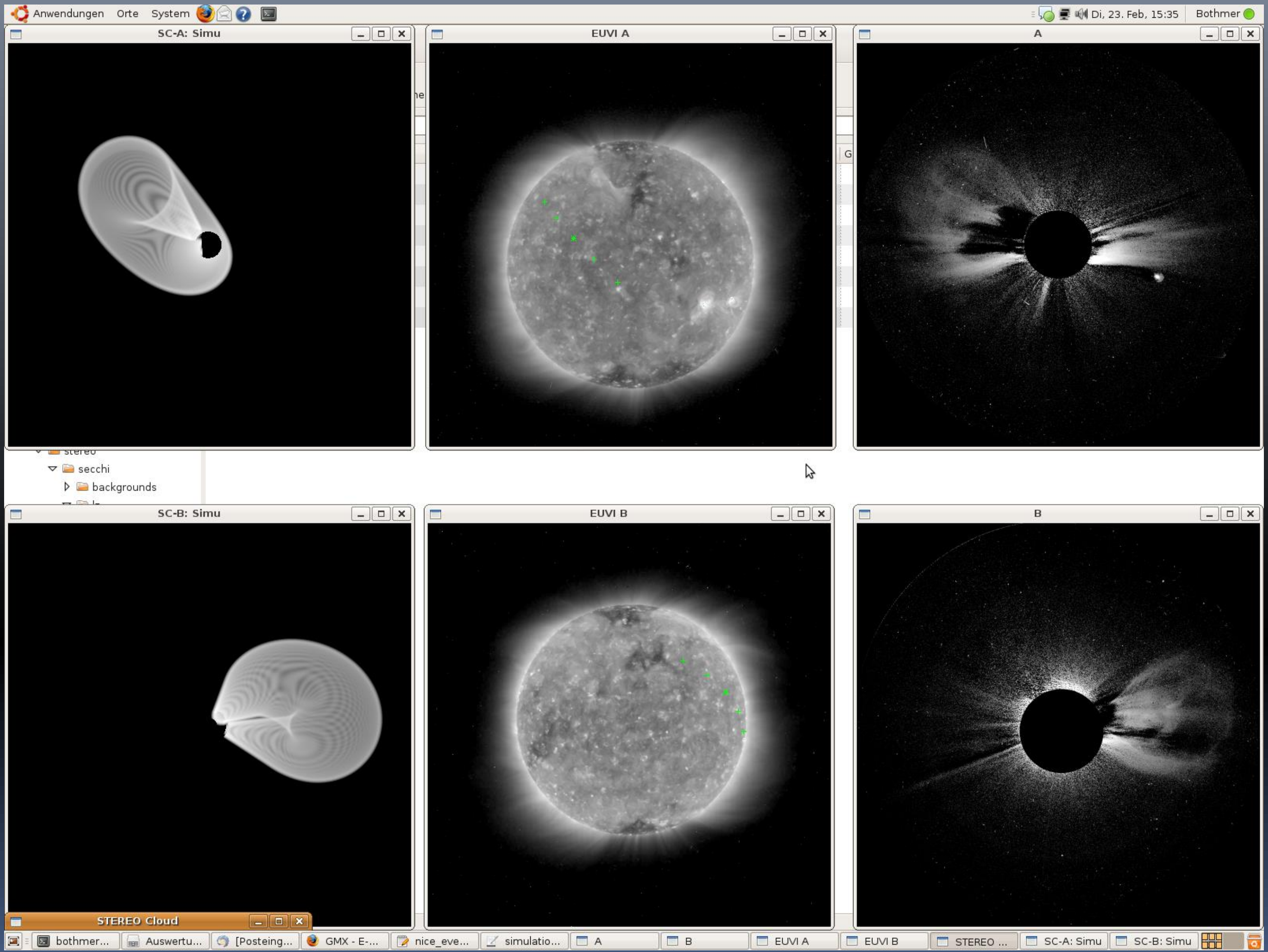
NASA STEREO/SECCHI Consortium

STEREO SECCHI/EUVI A, B 304 Å and COR 2 A,B observations in December 2008



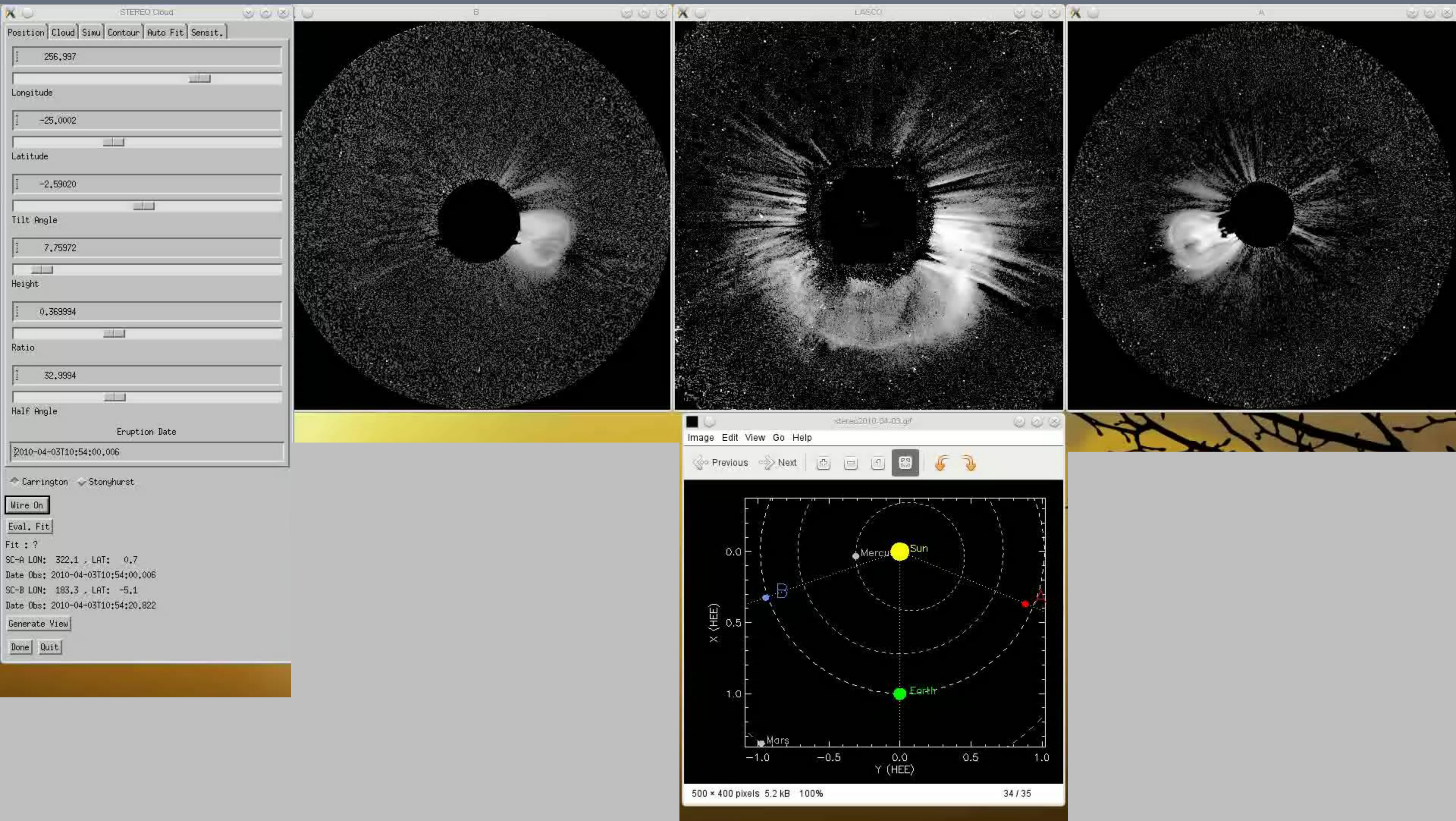
NASA STEREO/SECCHI Consortium

CME Modeling – December 12, 2008

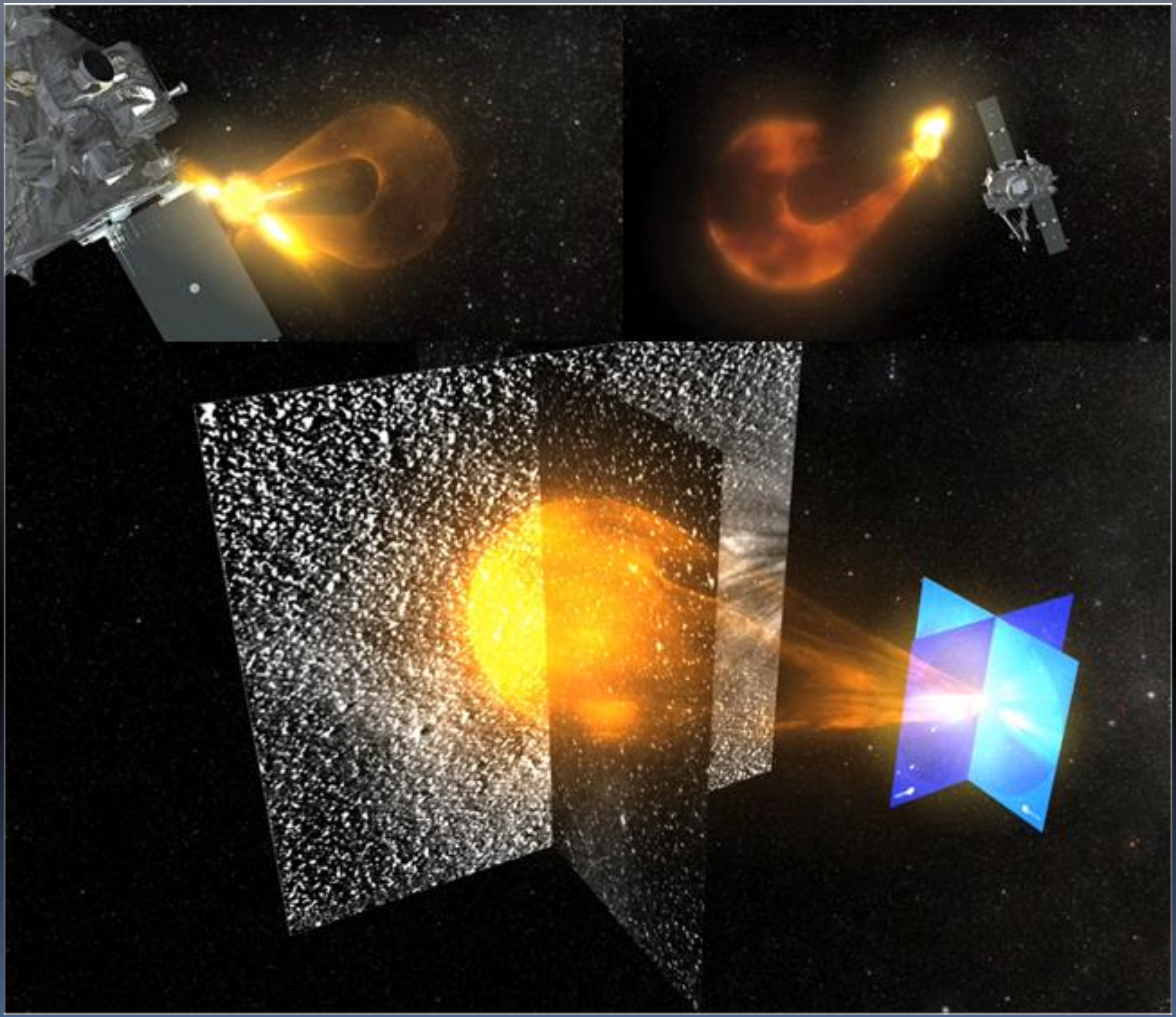


Three-Dimensional Properties of Coronal Mass Ejections from STEREO/SECCHI Observations , E. Bosman, V. Bothmer, G. Nisticò, A. Vourlidas, R.A. Howard, J.A. Davies, Solar Phys (2012) 281:167–185.

Sample GCS Modeling – HELCATS EU FP7

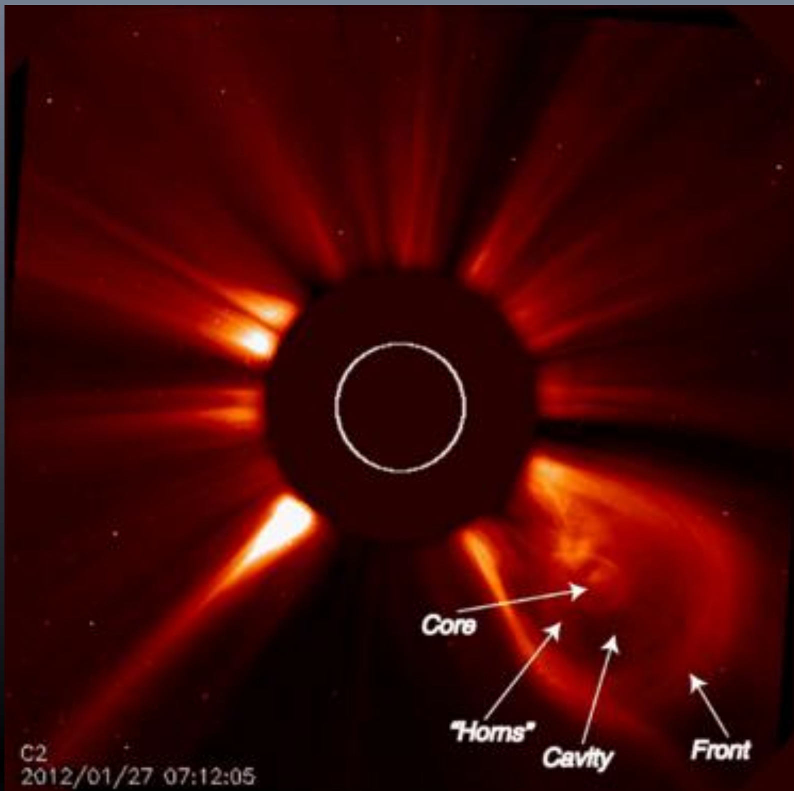


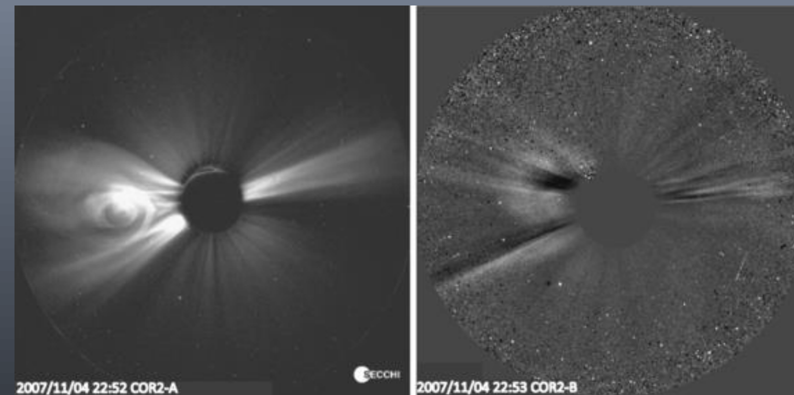
STEREO has verified the FR structure of CMEs

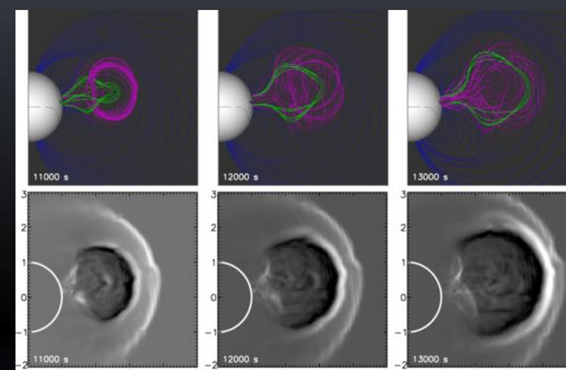


STEREO/SECCHI Consortium

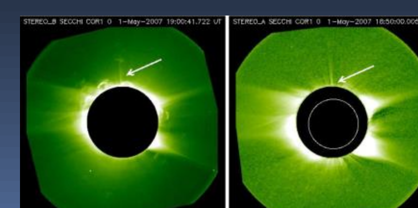
How many CMEs are FRs? – Vourlidas et al., Sol. Phys., 284, 2013

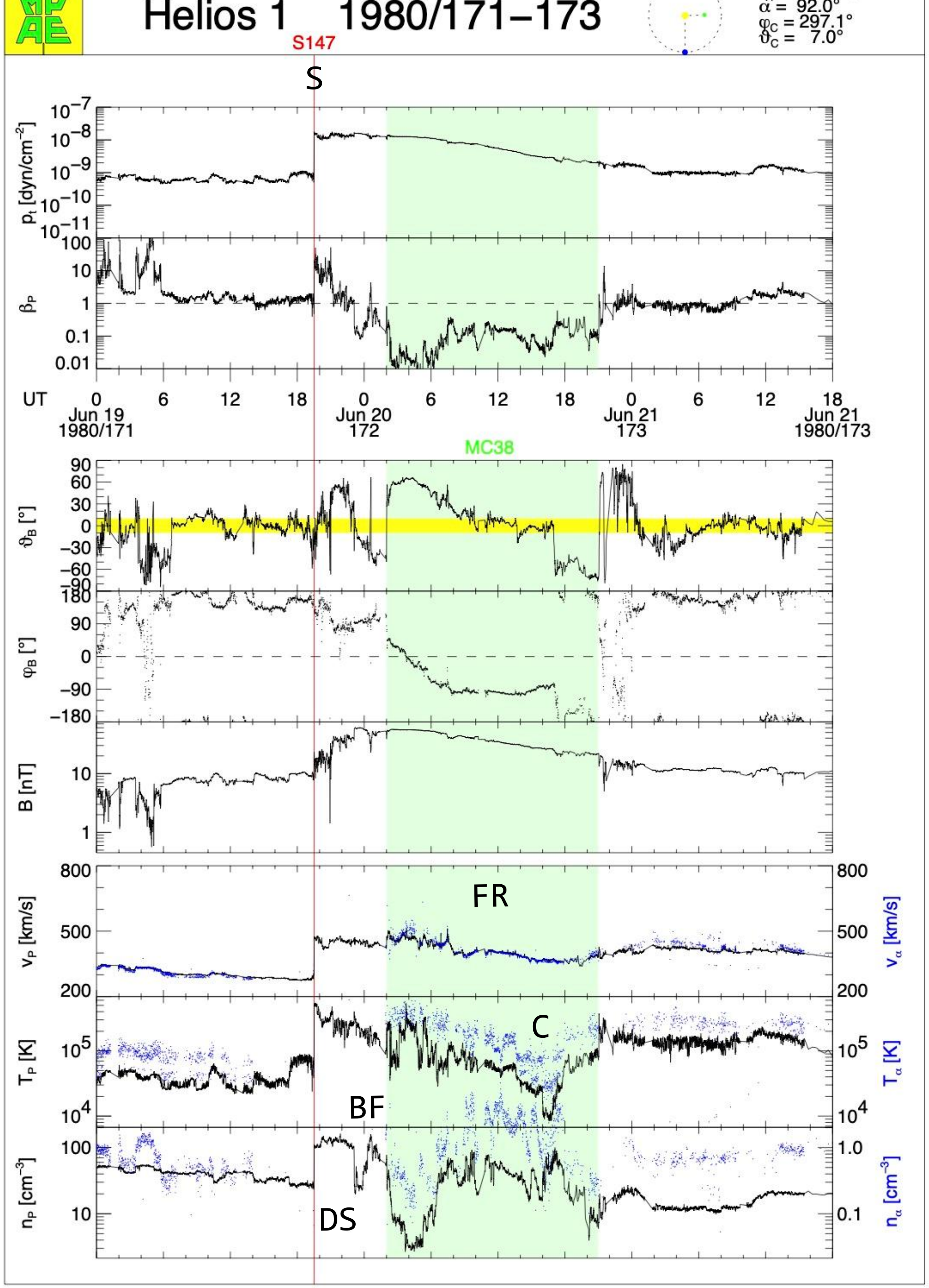






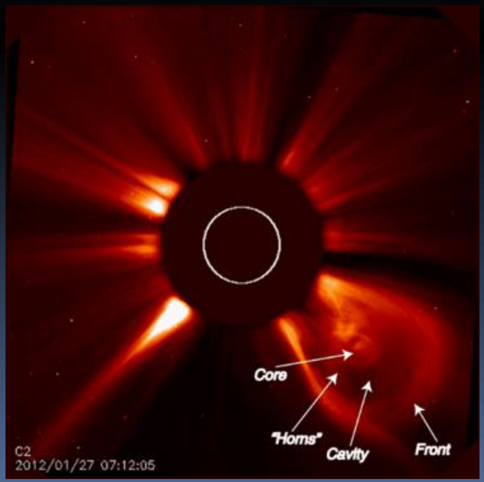
- A CME is the eruption of a magnetic flux rope with its emission measure dominated by coronal-temperature plasma, carrying a prominence along its bottom dips, piling up the overlying streamer plasma, and driving a wave ahead (if the acceleration is sufficiently high).
- Interpretation of bright front loop as pileup of material at the boundary of the FR
- Faint fronts ahead of bright loops are compression waves
- Fast CMEs exhibit 5 parts: shock front, diffuse sheath, bright front, cavity and core
- Are there any CMEs that are not FRs? maybe: jets





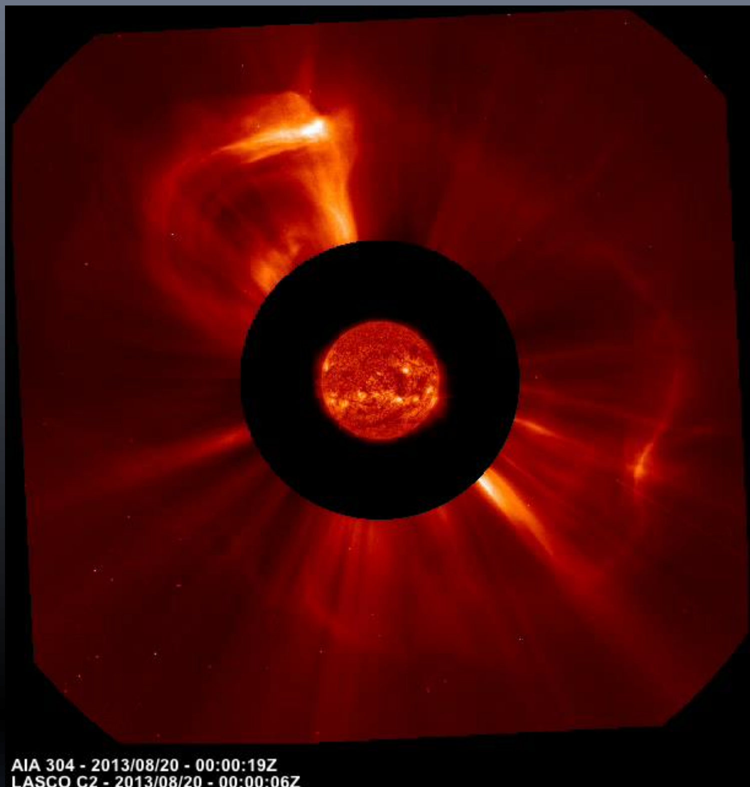
The 5 parts identified in MC events detected by the Helios s/c

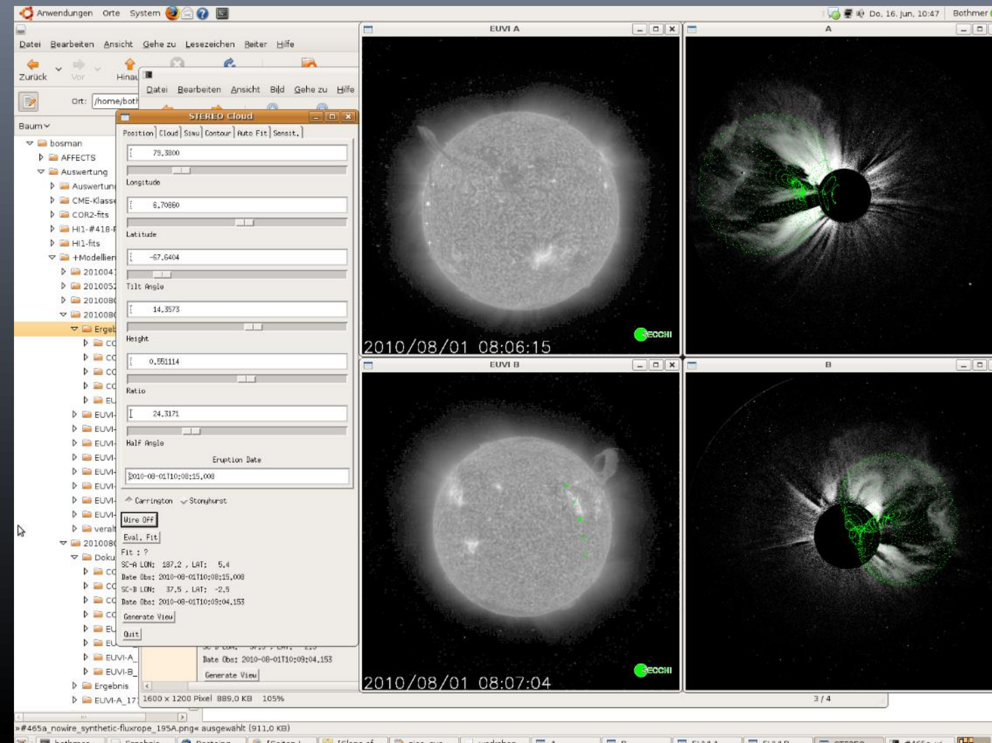
- S = Shock or compression wave
- DS = Diffuse sheath
- BF = Bright front
- FR = Flux rope (Cavity)
- C = Core

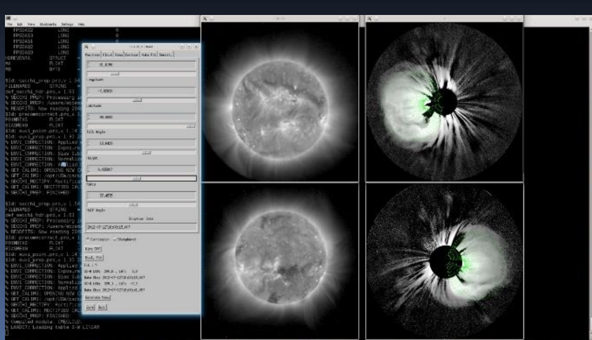


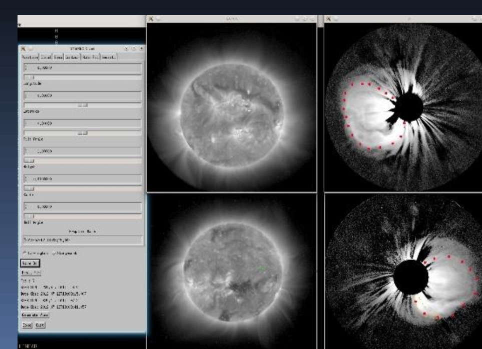
Processes leading to complexity of FR CMEs/ICMEs

Distorted CME fronts

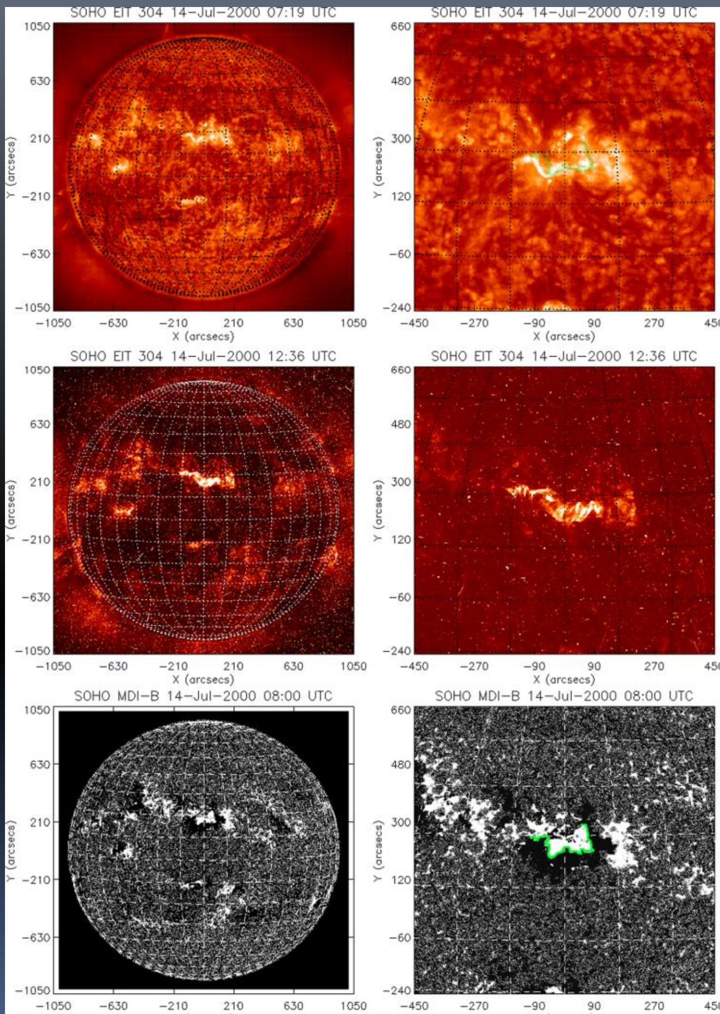


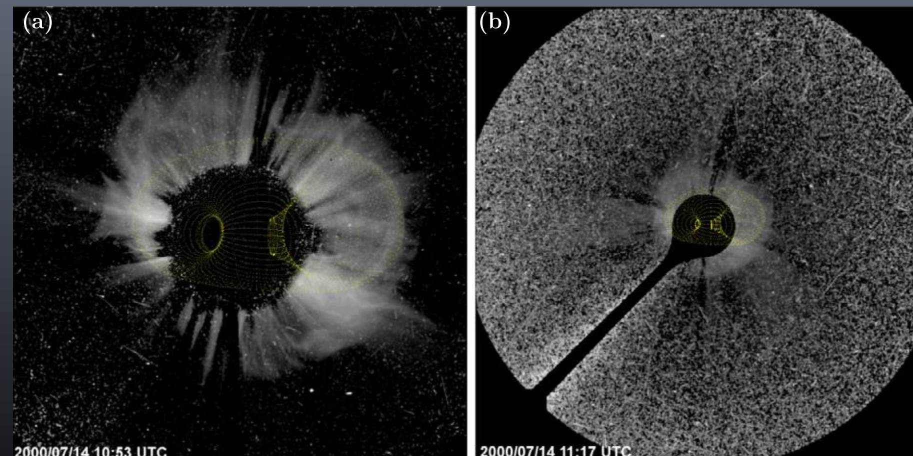


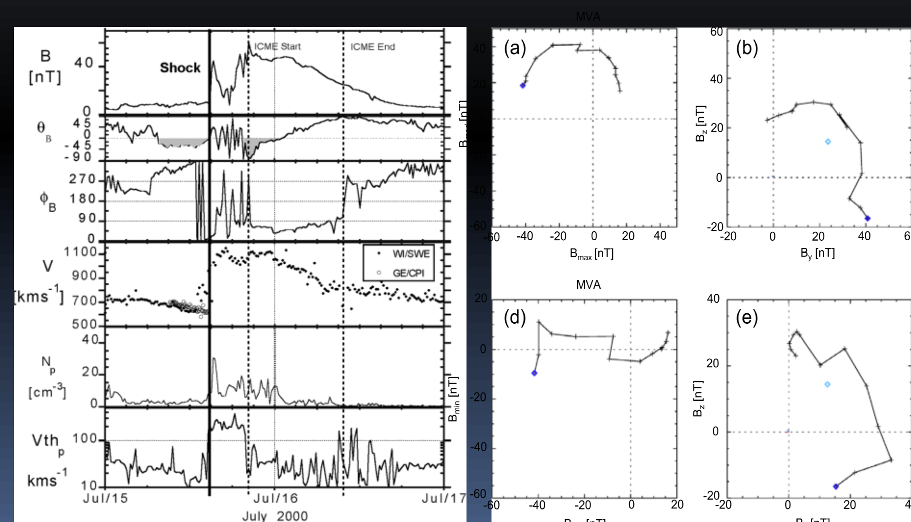




The July 2000 FR CME/ICME – expansion of FR-kinks

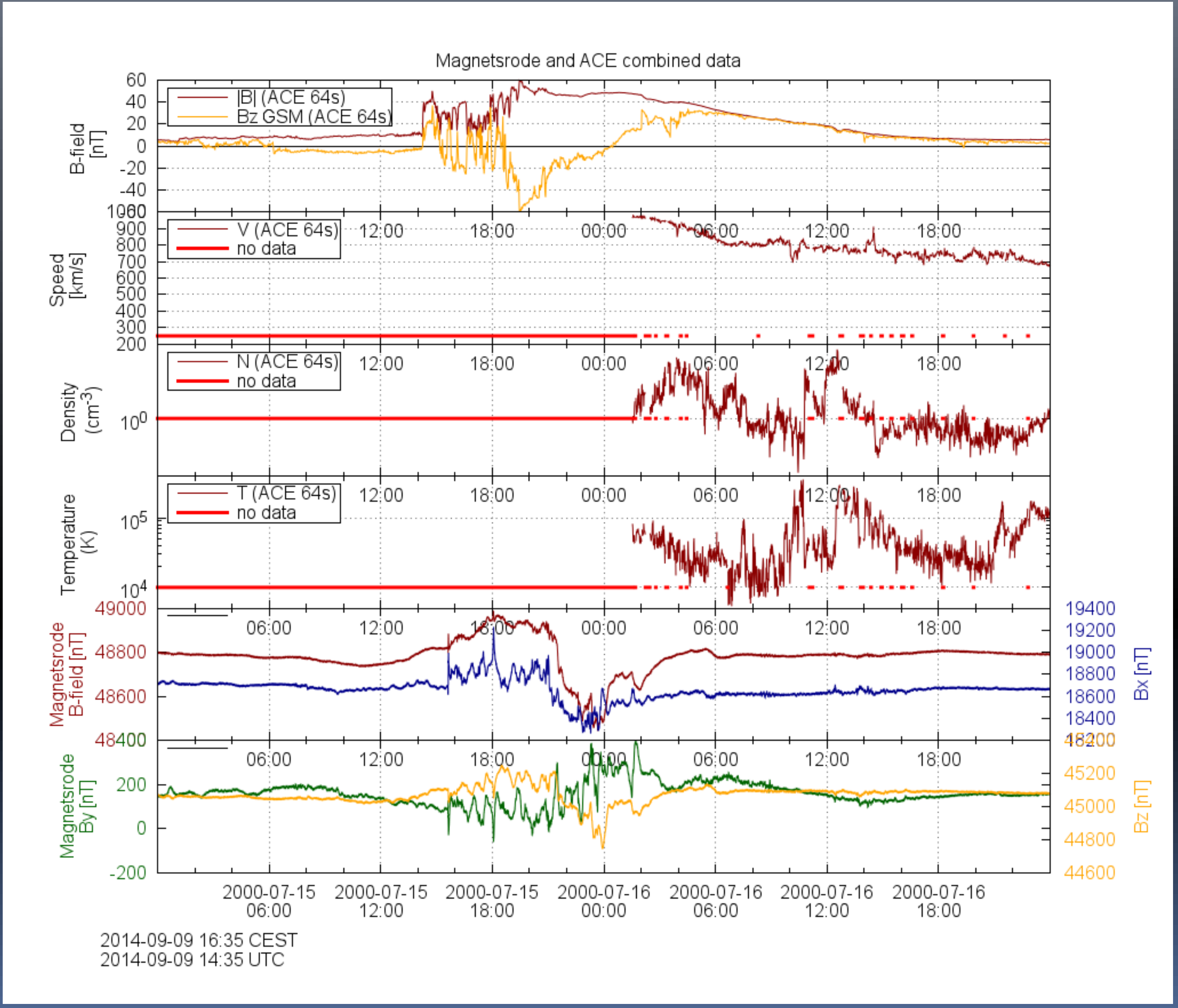






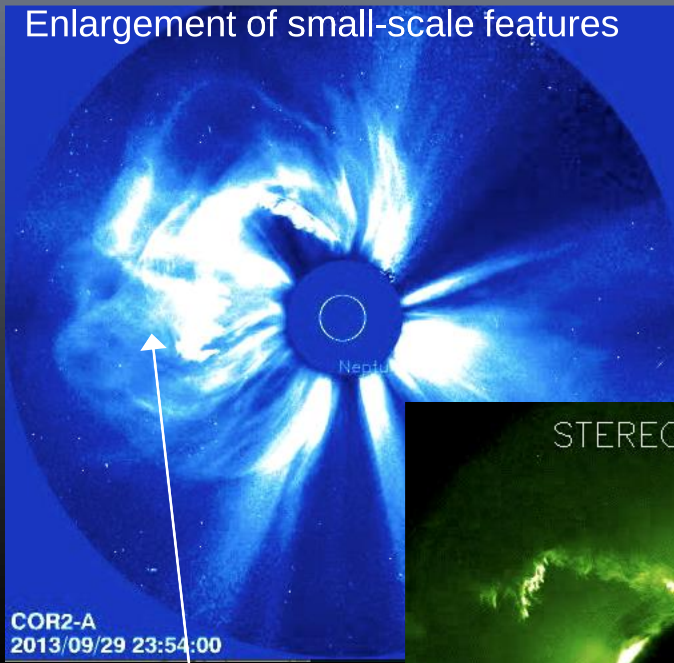
Comparison of CME and ICME Structures Derived from Remote-Sensing and In Situ Observations, V. Bothmer, N. Mrotzek, Solar Phys (2017) 292:157.

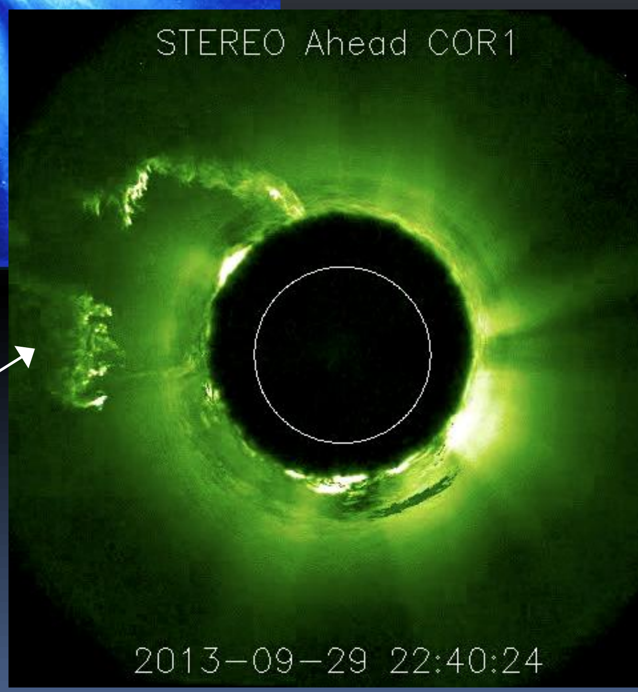
Localized geomagnetic response recorded near Braunschweig/Göttingen

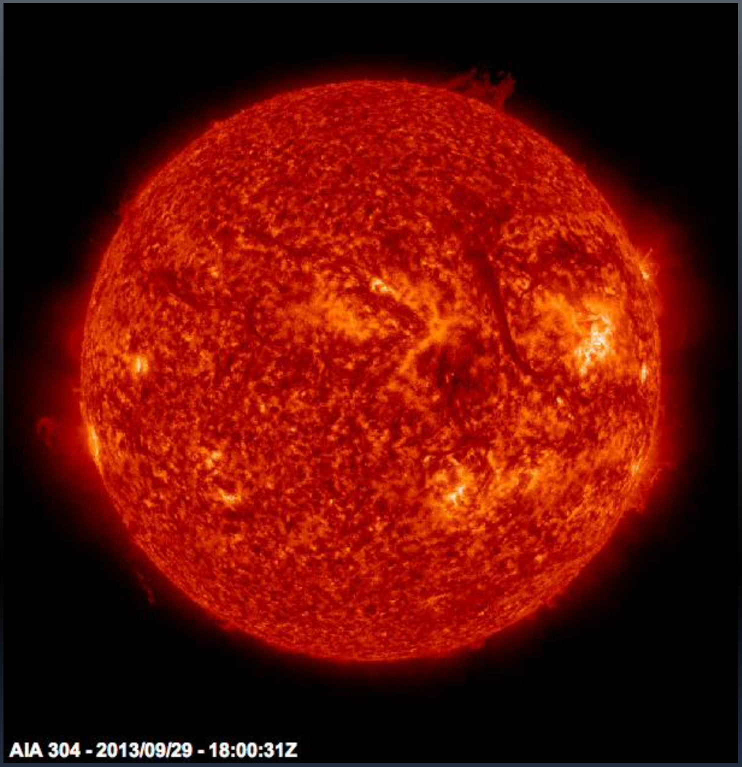


Credit: M. Venzmer

CME on 29 September 2013: SDO, STEREO/SECCHI/COR2 & COR1 A observations – Complexity of underlying coronal magnetic field structure

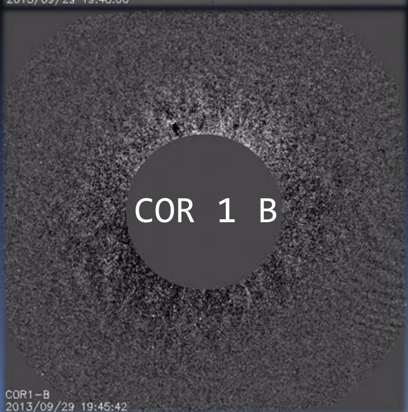


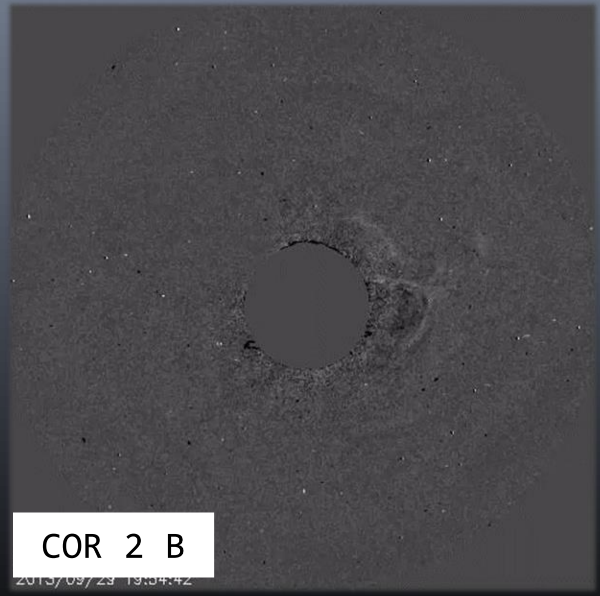


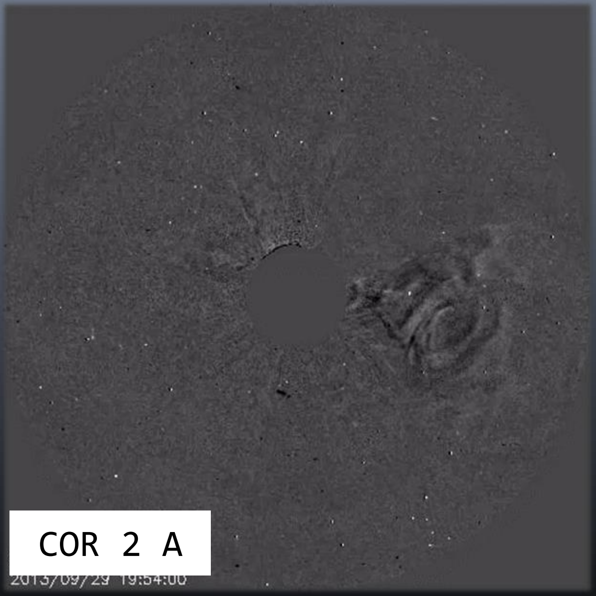


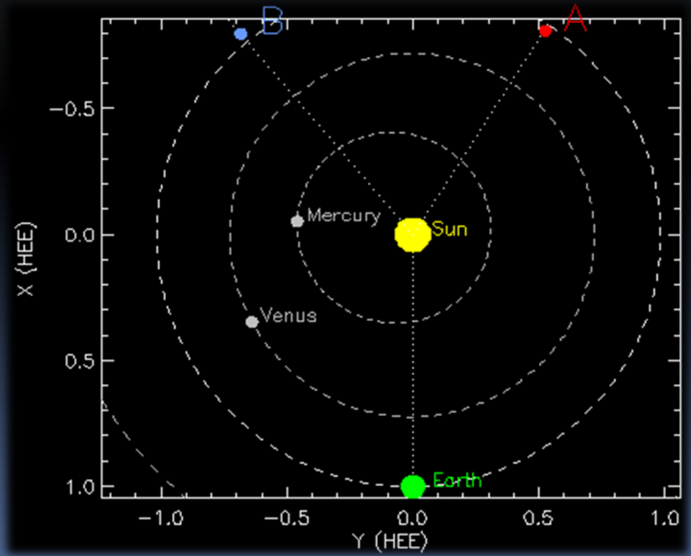
Expansion of fine-scale features.
- Arrival times will depend on observer's position w.r.t. CME SR

Three eyes on the corona - CME on 29 September 2013, HELCATS EU FP7

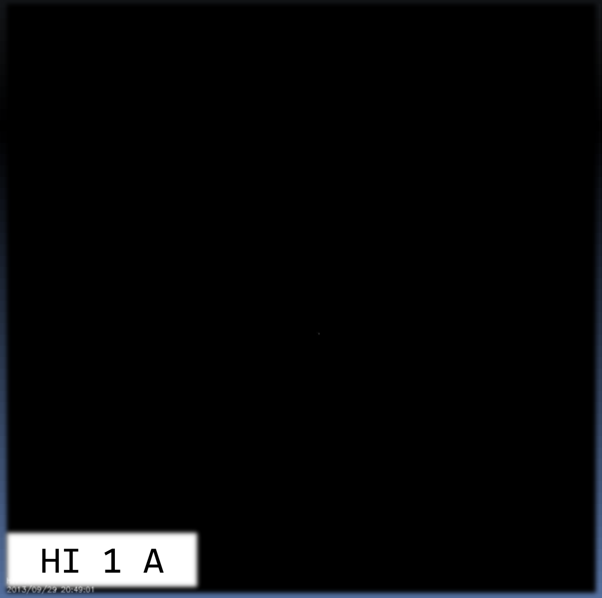




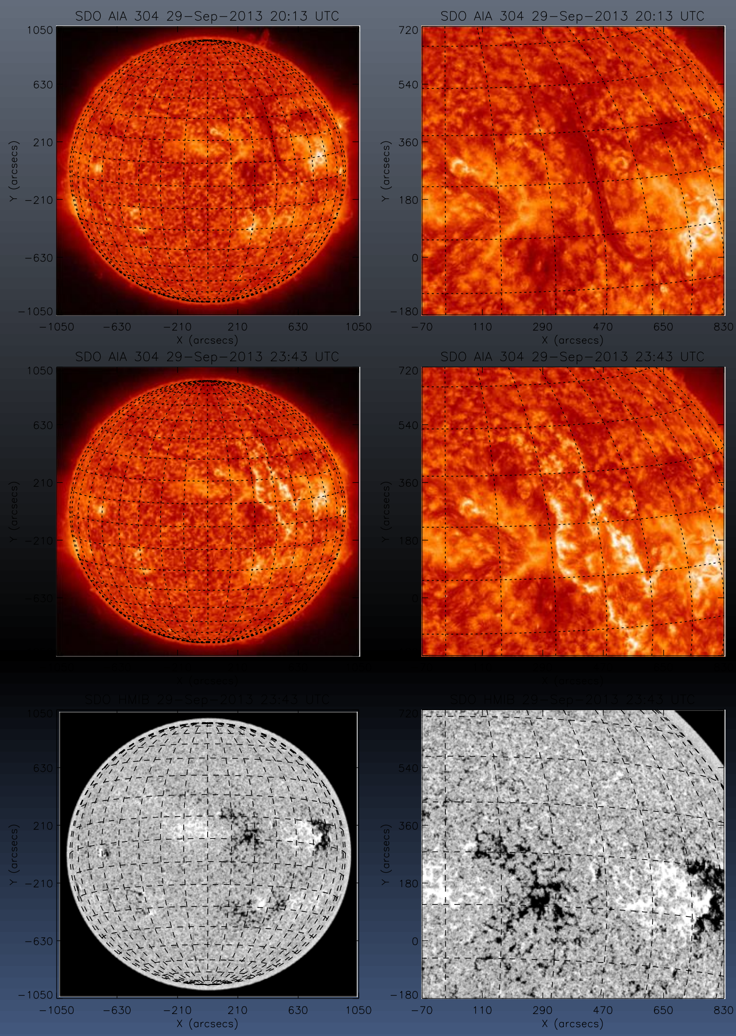


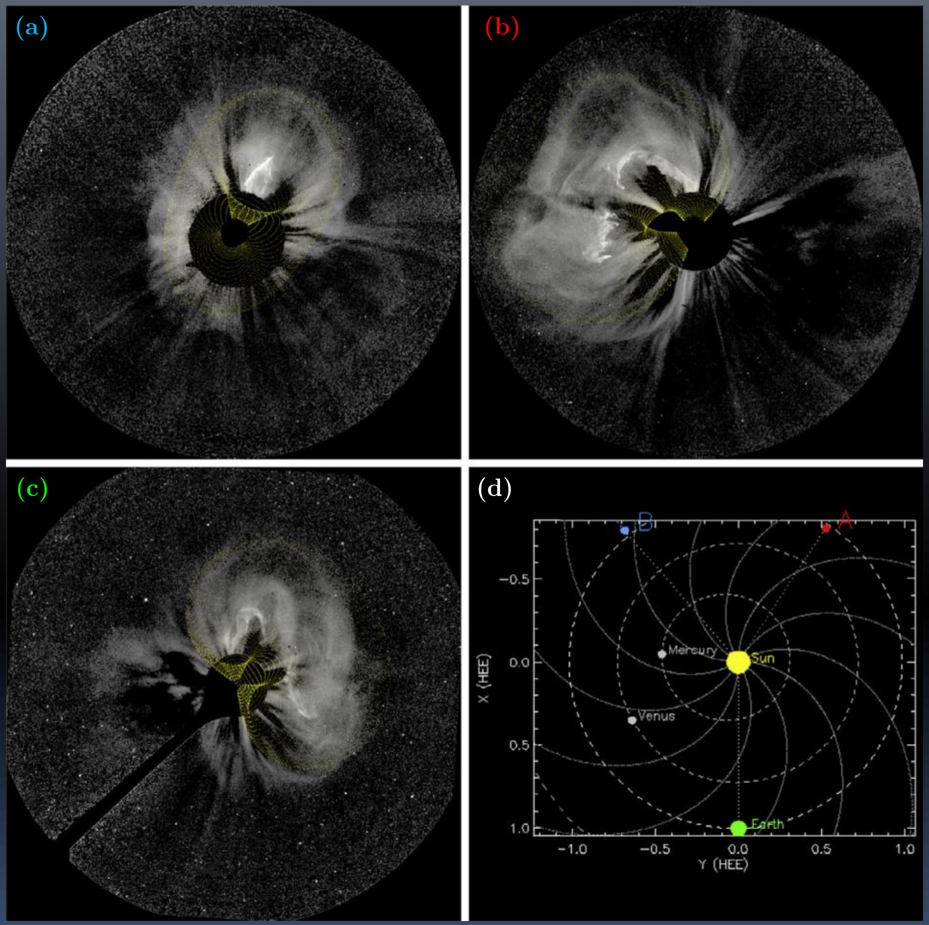


(Stereo Orbit Tool)



Emerging flux triggering a FR CME between two bipolar regions

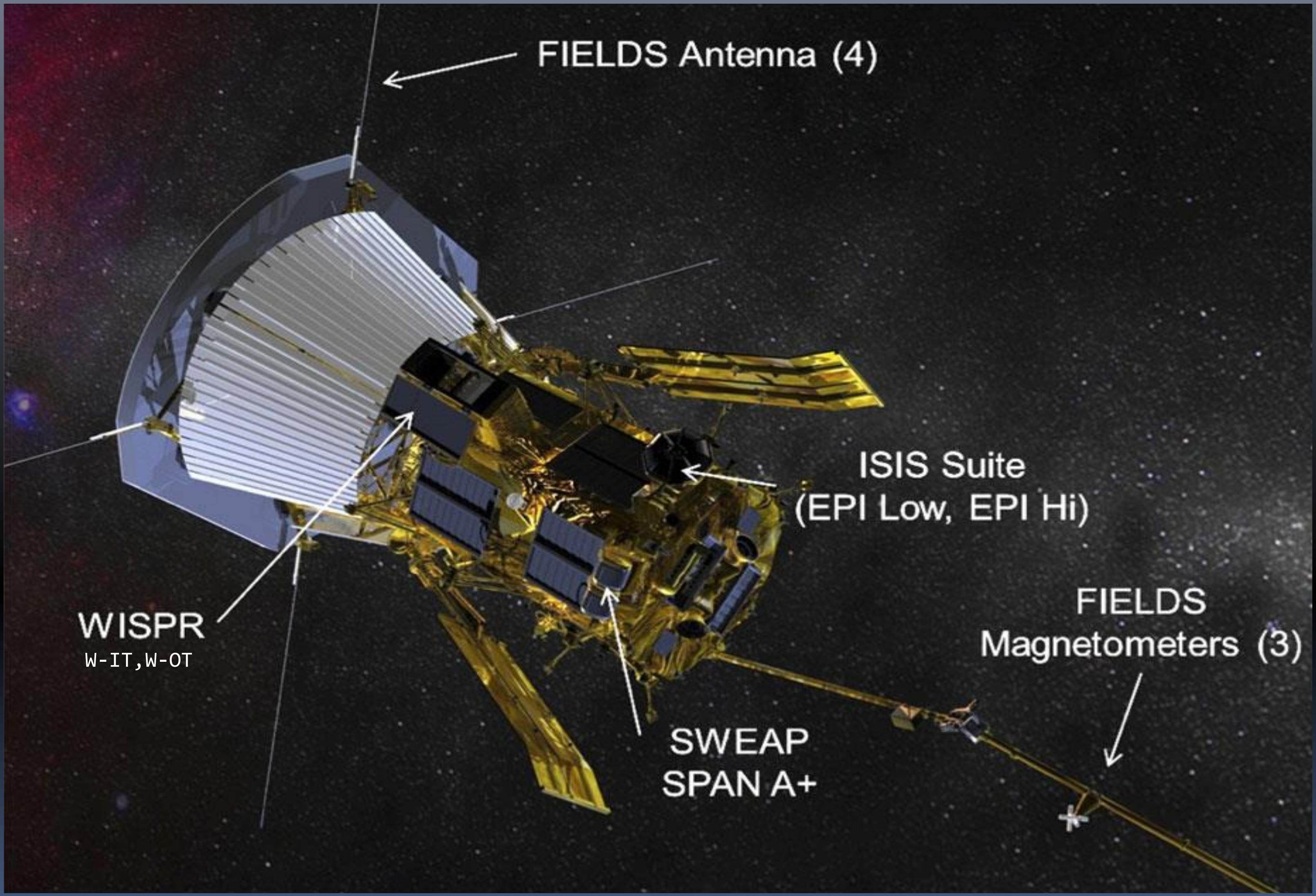




Comparison of CME and ICME Structures Derived from Remote-Sensing and In Situ Observations, V. Bothmer, N. Mrotzek, Solar Phys (2017) 292:157.

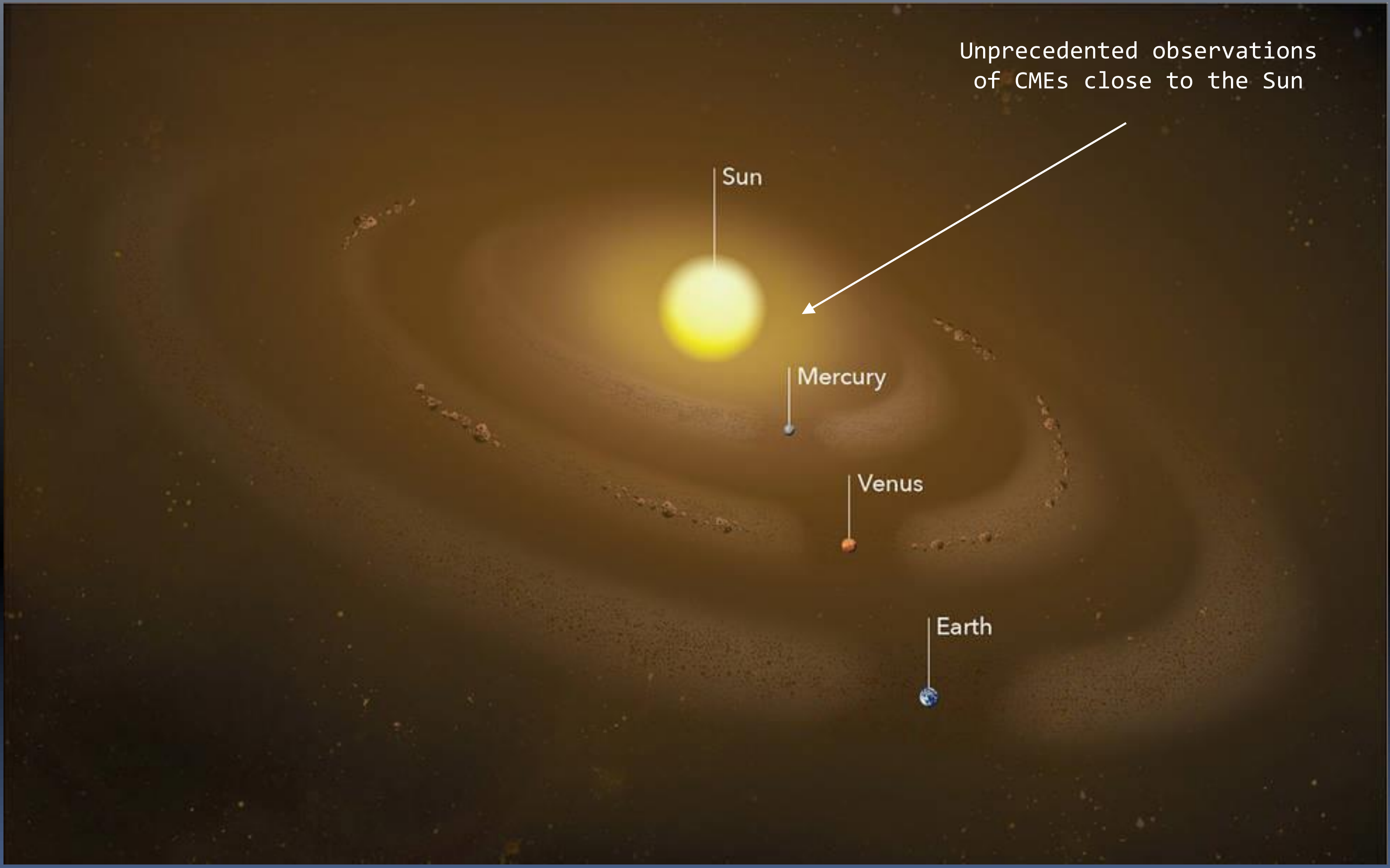
Fine structure of CMEs in the corona, CME-flythroughs by Parker Solar Probe and further FR-complexities

Parker Solar Probe provides near-Sun observations of CMEs and explores the source regions of the solar wind



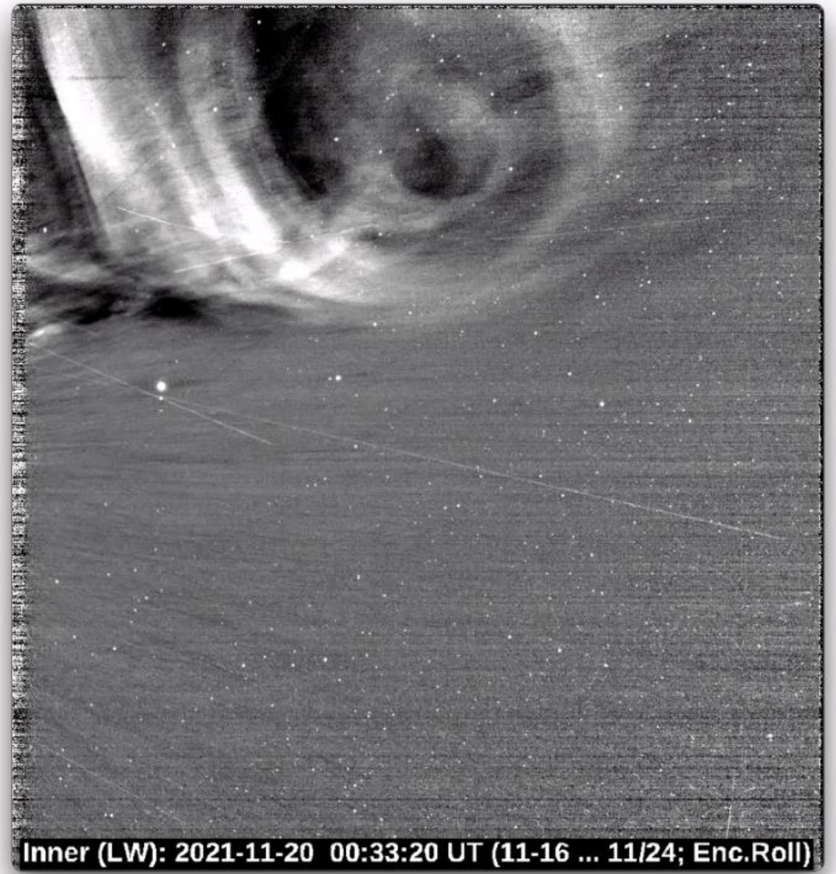
Ram facing view - WISPR could be mounted in flight direction

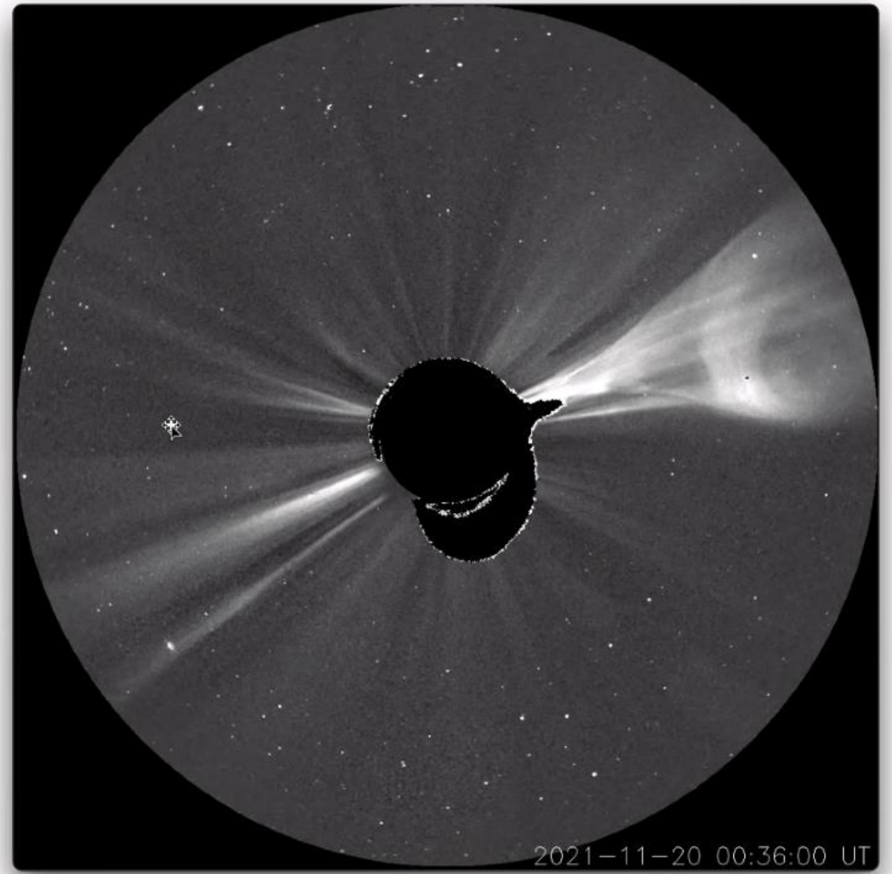
Dust in the inner solar system



Credits: NASA’s Goddard Space Flight Center/Scott Wiessinger

Fine structures observed in a CME on 21 November 2021 with PSP/WISPR-I at 0.10 au and the simultaneous view with STEREO/SECCHI/COR2A at 1 au – WISPR acts as coronal microscope and reveals hitherto unseen details



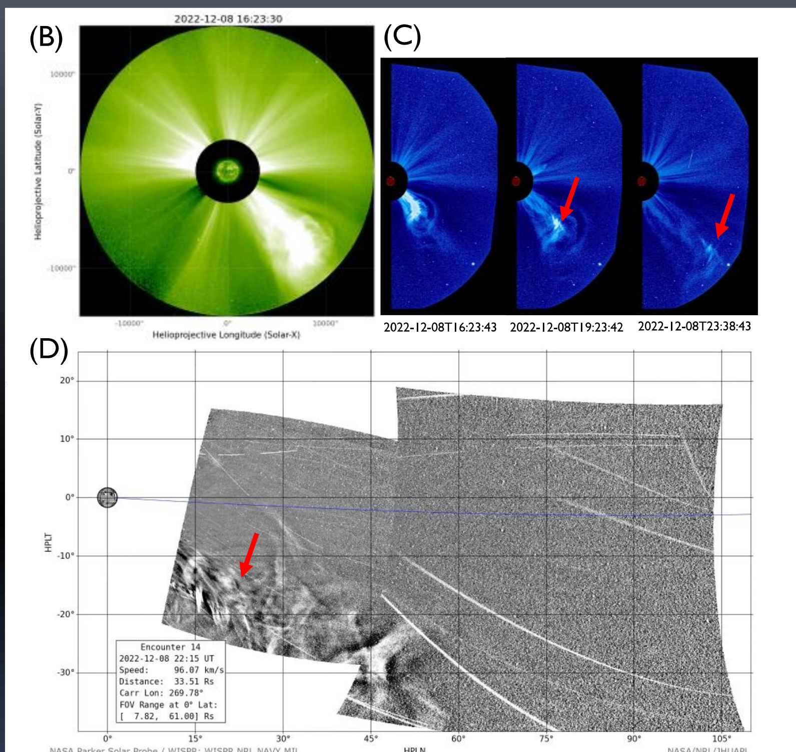


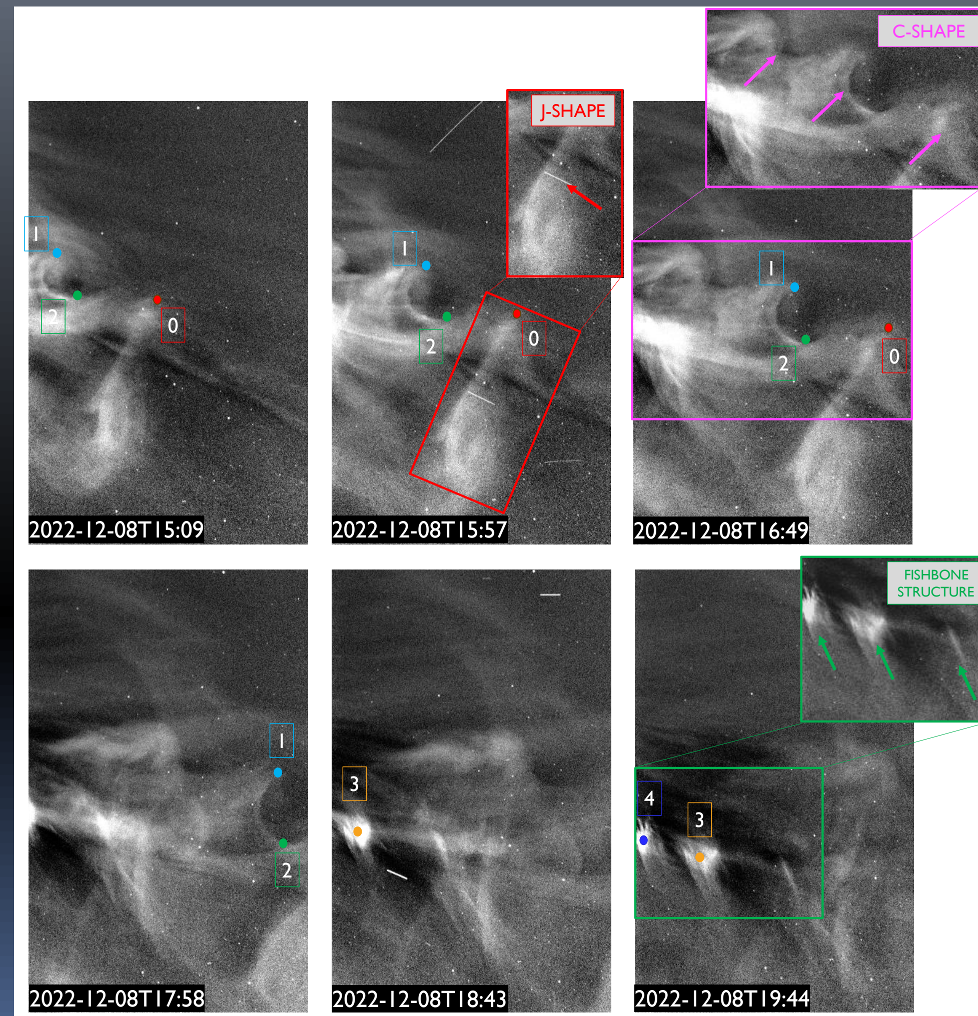
WISPR-I

STEREO/SECCHI/COR2A

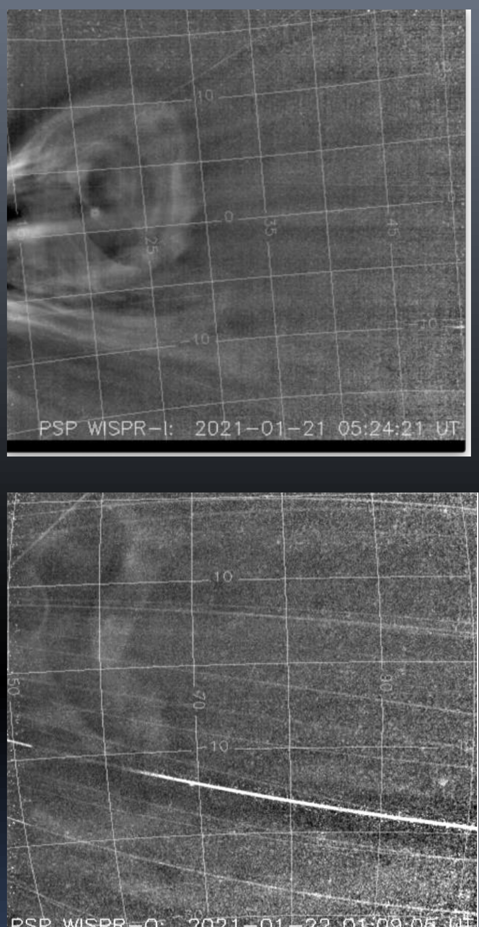
Overview of the Remote Sensing Observations from PSP Solar Encounter 10 with Perihelion at 13.3 R_S, Russell A. Howard, Guillermo Stenborg, Angelos Vourlidas, Brendan M. Gallagher, Mark G. Linton, Phillip Hess, Nathan B. Rich, and Paulett C. Liewer, The Astrophysical Journal, 936:43 (17pp), 2022 September 1.

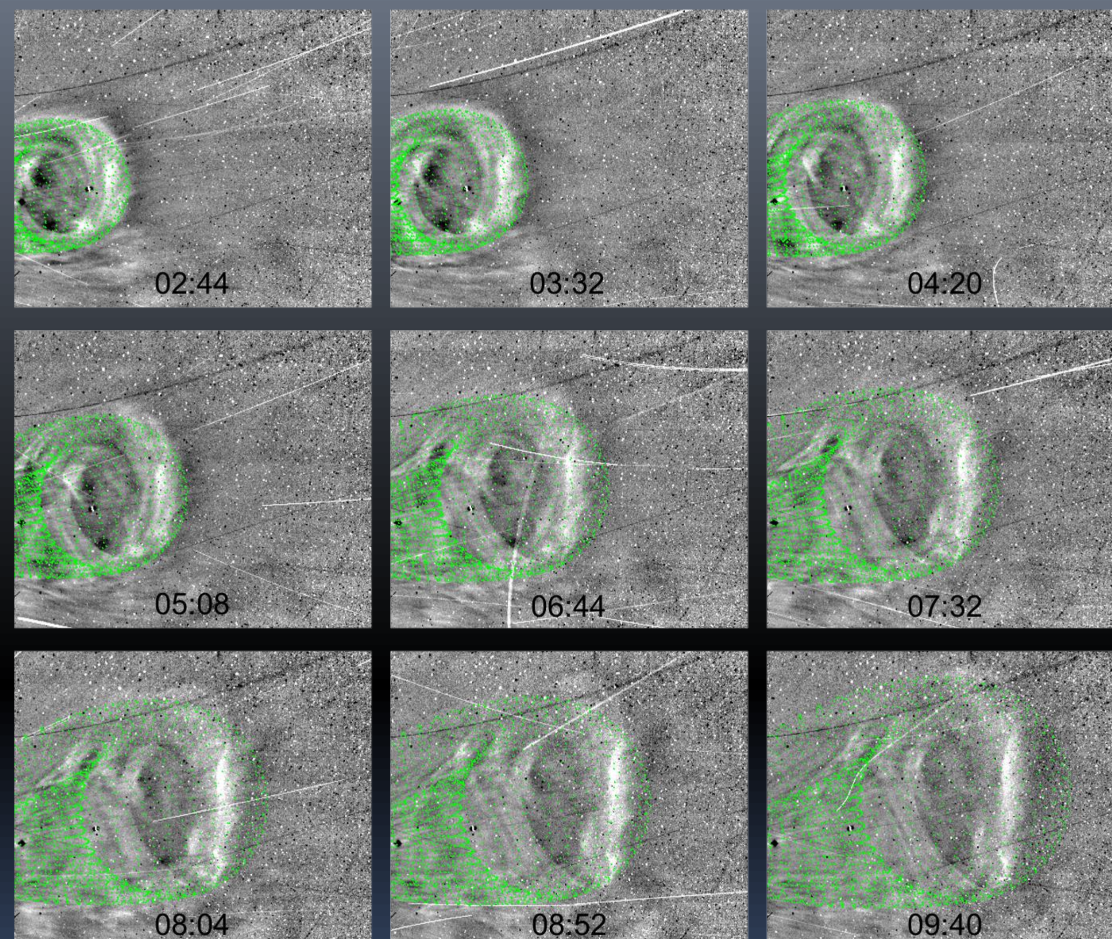
Internal magnetic field structures observed by PSP/WISPR in a filament-related coronal mass ejection, G.M. Cappello, M. Temmer, A. Vourlidas, C. Braga, P.C. Liewer, J. Qiu, G. Stenborg, A. Kouloumvakos, A.M. Veronig, V. Bothmer, A&A in press





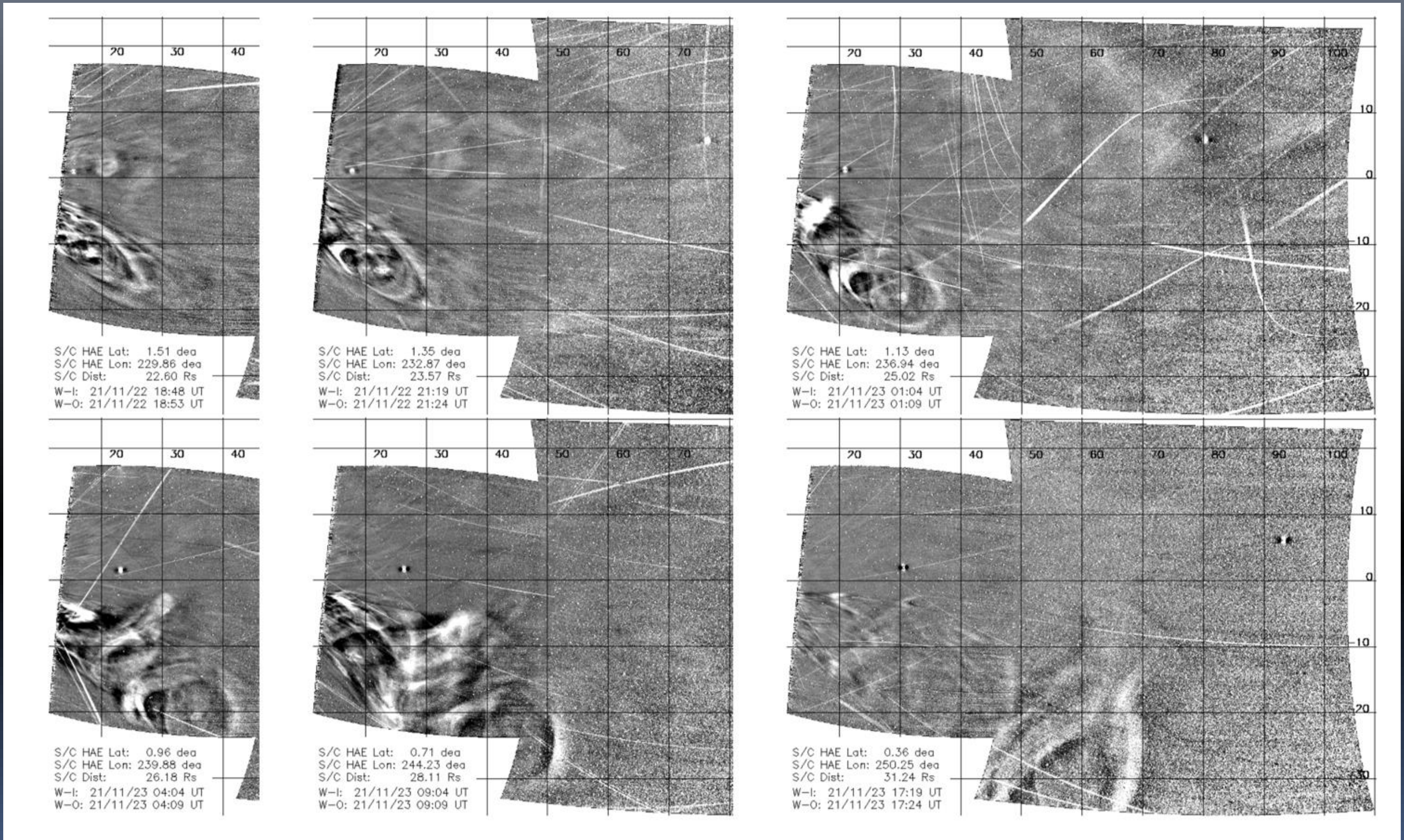
CME deformations seen by WISPR-I at 0.1 au





Coronal mass ejection deformation at 0.1 au observed by WISPR, Carlos R. Braga, Angelos Vourlidas, Paulett C. Liewer, Phillip Hess, Guillermo Stenborg , and Pete Riley, arXiv:2209.13057.

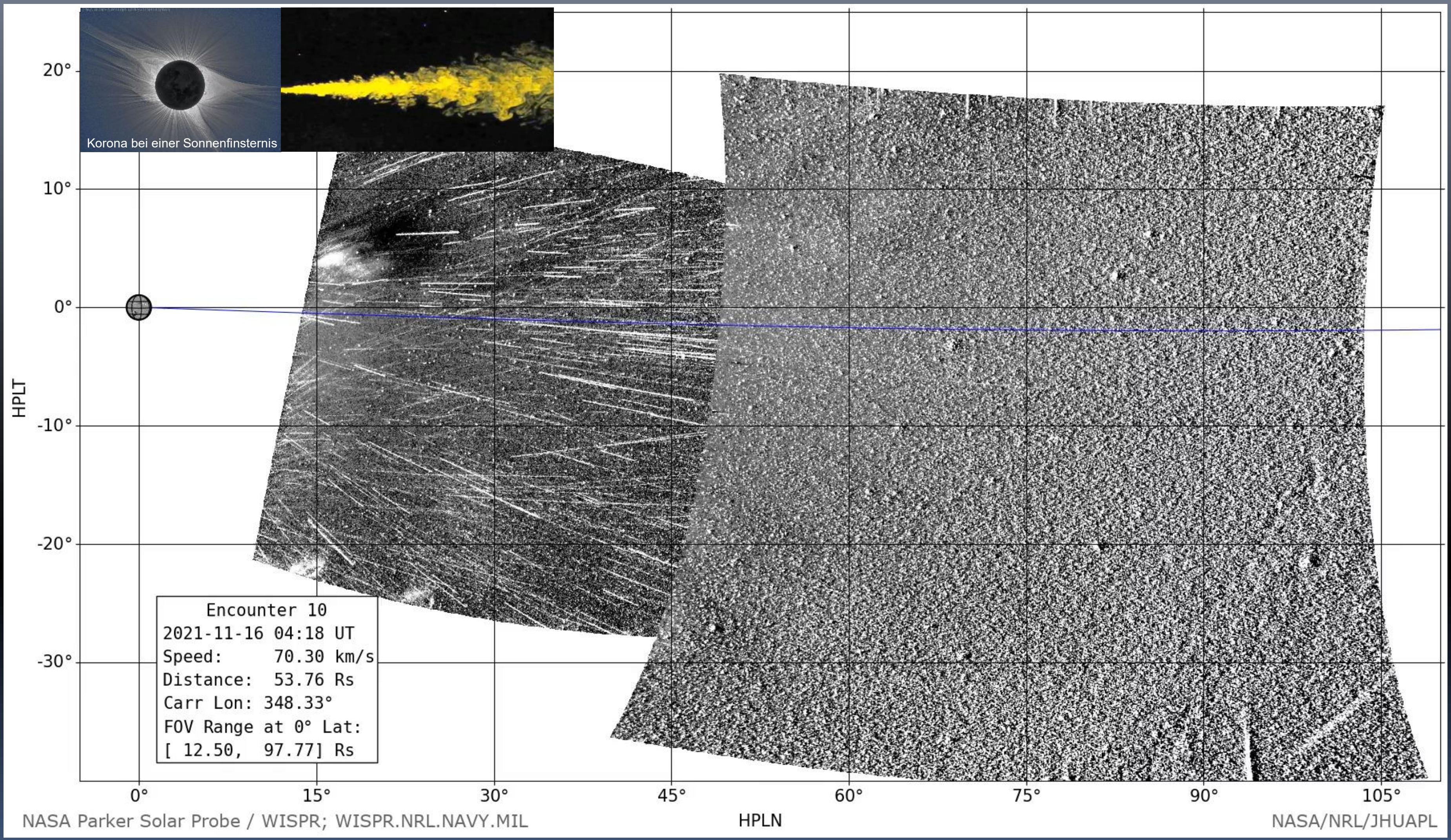
„WISPR-Composite“ Images from Encounter 10, Perihelion at 0.07 au, 16-26 November 2021 – CME-Dynamics, Interactions and Deformations and they can cause compund ICME-streams in the interplanetary medium (see „Structure and evolution of compound streams at ≤1 AU“, K. W. Behannon, L. F. Burlaga, A. Hewish, JGR, Volume 96, A12, 1991



Credit: Howard et al., ApJ, 2022

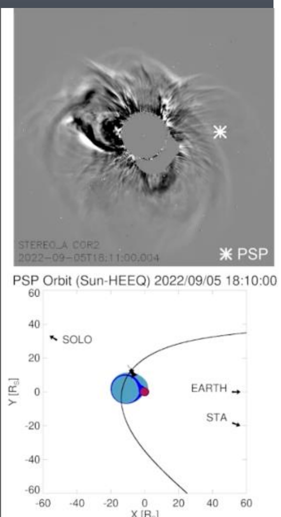
Overview of the Remote Sensing Observations from PSP Solar Encounter 10 with Perihelion at 13.3 R_S, Russell A. Howard, Guillermo Stenborg, Angelos Vourlidas, Brendan M. Gallagher, Mark G. Linton, Phillip Hess, Nathan B. Rich, and Paulett C. Liewer, The Astrophysical Journal, 936:43 (17pp), 2022 September 1.

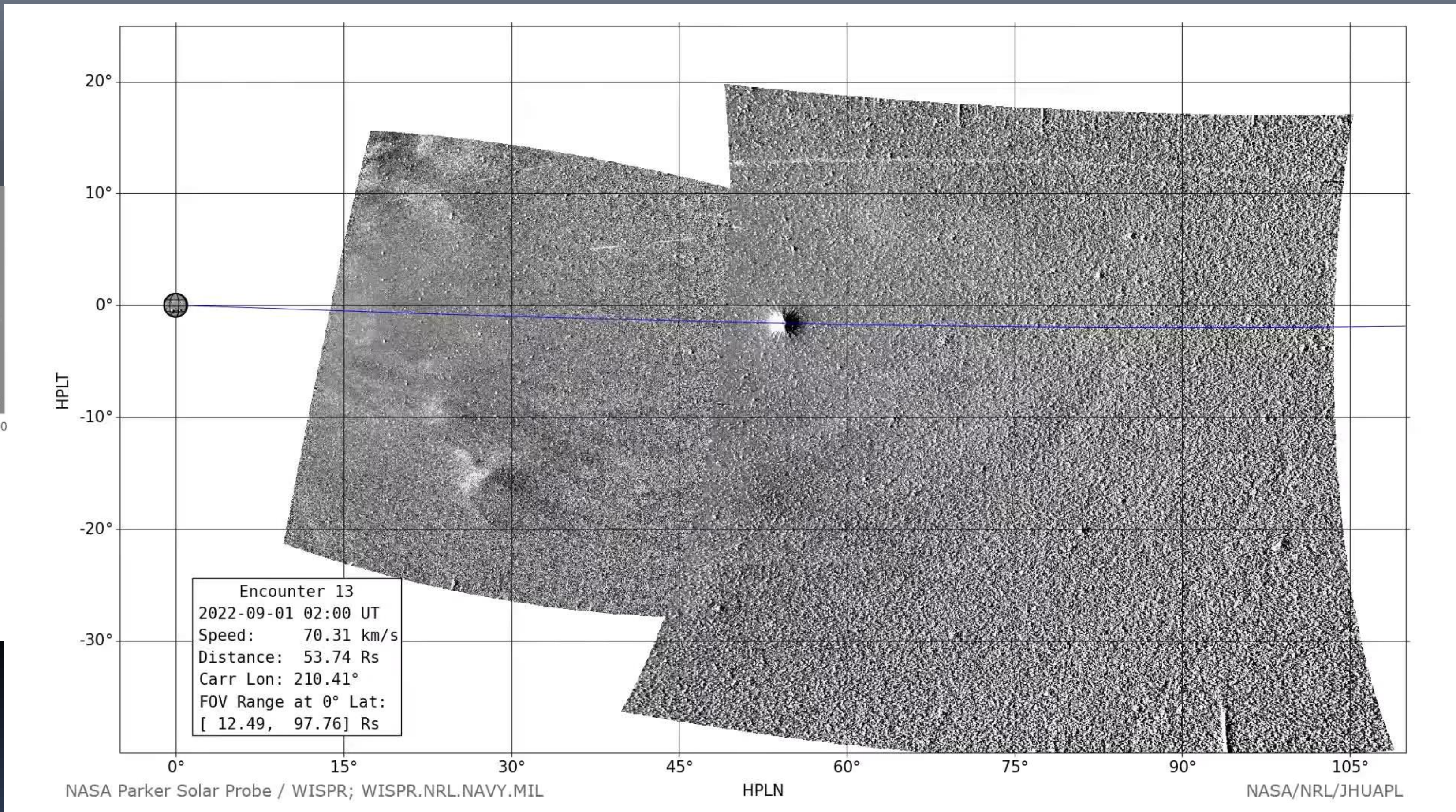
„WISPR-Composite“ Images from Encounter 10, Perihelion at 0.07 au, 16-26 November 2021 – CME-Dynamics, Interactions and Deformations



Credit: B. Gallagher/WISPR Consortium

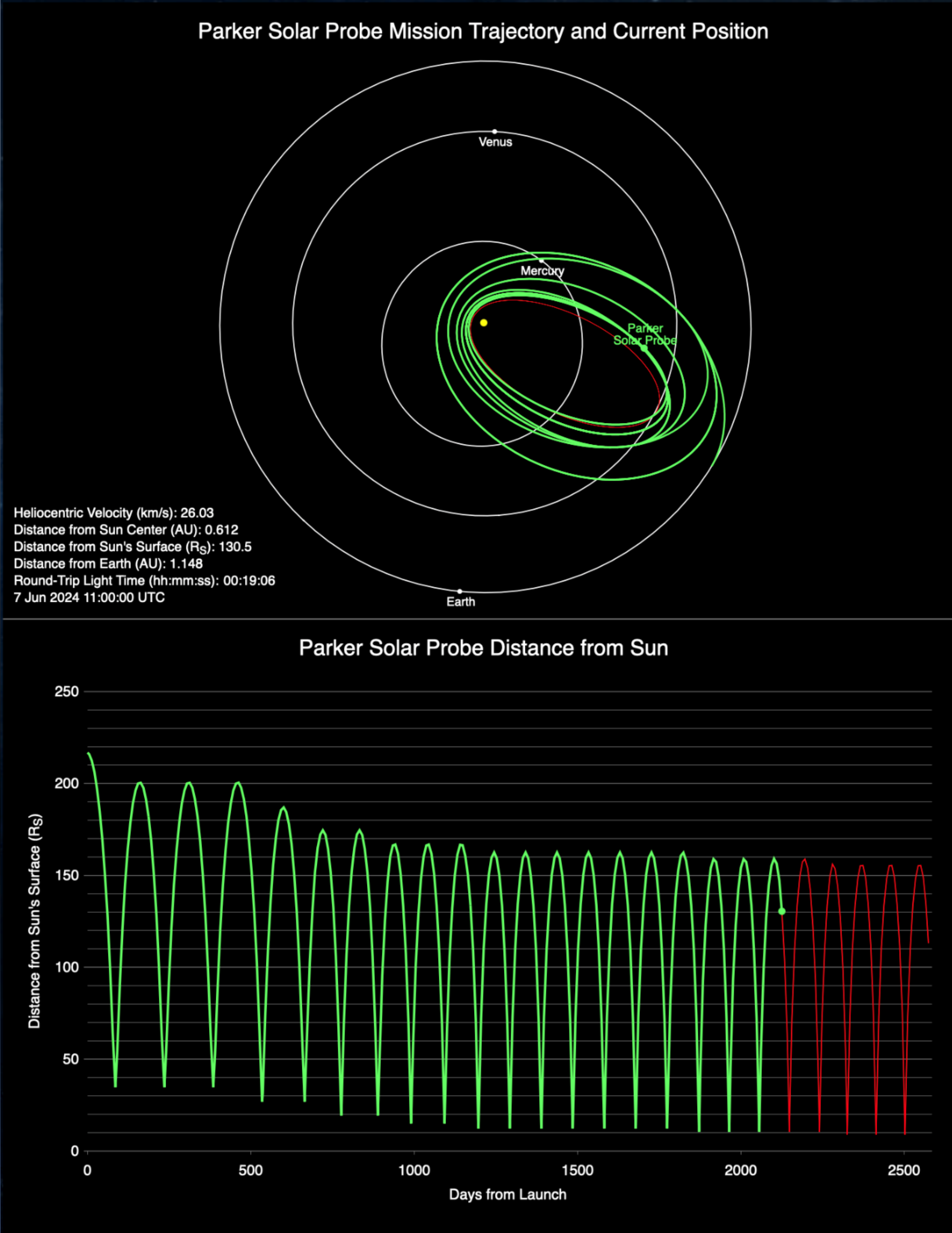
First ever passage through a CME inside the solar corona on 5 September 2022 – The magnetic field measurements have been converted to audio signals





Credit: NASA/Johns Hopkins APL/Naval Research Laboratory/Brendan Gallagher/Guillermo Stenborg/Emmanuel Masongsong/Lizet Casillas/Robert Alexander/David Malaspina

Near-Sun In Situ and Remote-sensing Observations of a Coronal Mass Ejection and its Effect on the Heliospheric Current Sheet, O. M. Romeo, C. R. Braga, S.T. Badman, D. E. Larson, M. L. Stevens, J. Huang, T. Phan, A. Rahmati, R. Livi, S. T. Alnussirat, P. L. Whittlesey, A. Szabo, K. G. Klein, T. Niembro-Hernandez, K. Paulson, J. L. Verniero, D. Lario, N. E. Raouafi, T. Ervin, J. Kasper, M. Pulupa, S. D. Bale, and M. G. Linton, The Astrophysical Journal, 954:168 (18pp), 2023 September 10.



- VF 7 on 6 November 2024

- The closest planned approach of the Sun - below 10 R_S - by PSP will take place during its 22 nd perihelion on 24 December 2024!

Credit: JHU/APL

Summary & Conclusions

- Coronal mass ejections (CMEs) are extremely faint objects and have been first been systematically observed by space borne coronagraphs in the early seventies – later on the ESA/NASA SOHO and NASA STEREO missions set new milestones in the exploration of CMEs
- CMEs originate from bipolar (quadrupolar) photospheric regions
- CMEs are magnetic flux ropes (to be distinguished from coronal jets)
- CMEs can exhibit complex structures due to
  - the nature of the eruption and complexity of the underlying photospheric fields
  - kinks in prominences
  - non-selfsimilar expansions and speed gradients across their global structures
  - distortions through interactions with the ambient corona, solar wind or other CMEs and can form compound streams
- Parker Solar Probe will help further explore the near-Sun evolution of CMEs and their internal fine structures
- We now know CMEs a whole lot better but there are still important questions remaining to be answered, e.g., FR formation, nature of trailing portions, sheath

Thanks and Acknowledgements

I'm very grateful

- For the funding of my projects by the German Space Agency (Deutsches Zentrum für Luft- und Raumfahrt DLR).

DLR

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für Wirtschaft
und Klimaschutz

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des Deutschen Bundestages