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MULLARD SPACE SCIENCE LABORATORY

CMEs: observations and models, an incomplete overview

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What is a CME?

- “observable change in coronal structure that occurs on a timescale of a few minutes to several hours, and involves the appearanc± e and outward motion of a new, discrete, bright, white light feature in the coronagraph field of view.” (Hundhausen, 1986)

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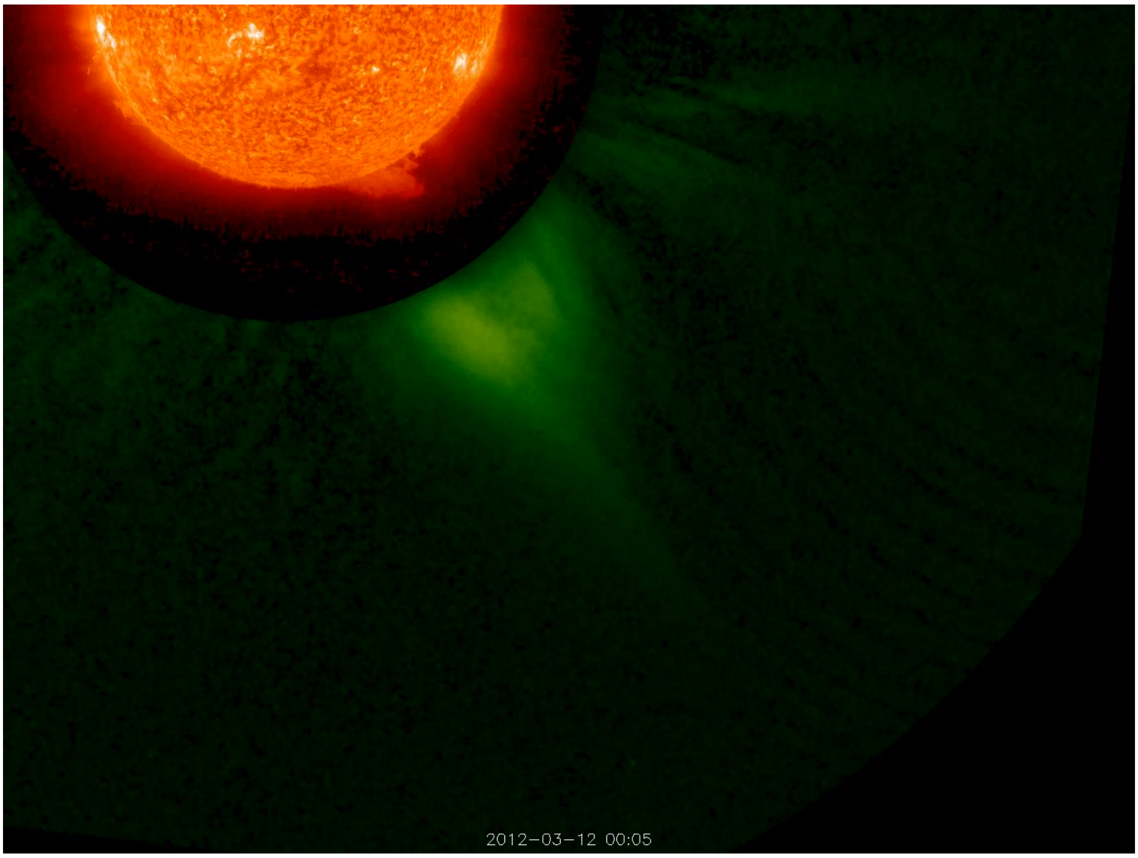

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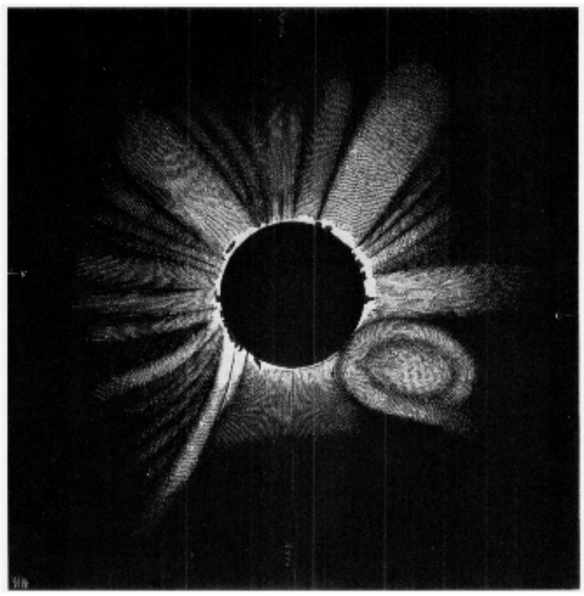
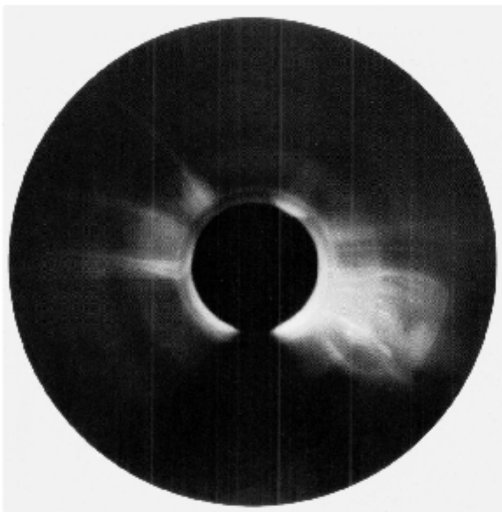
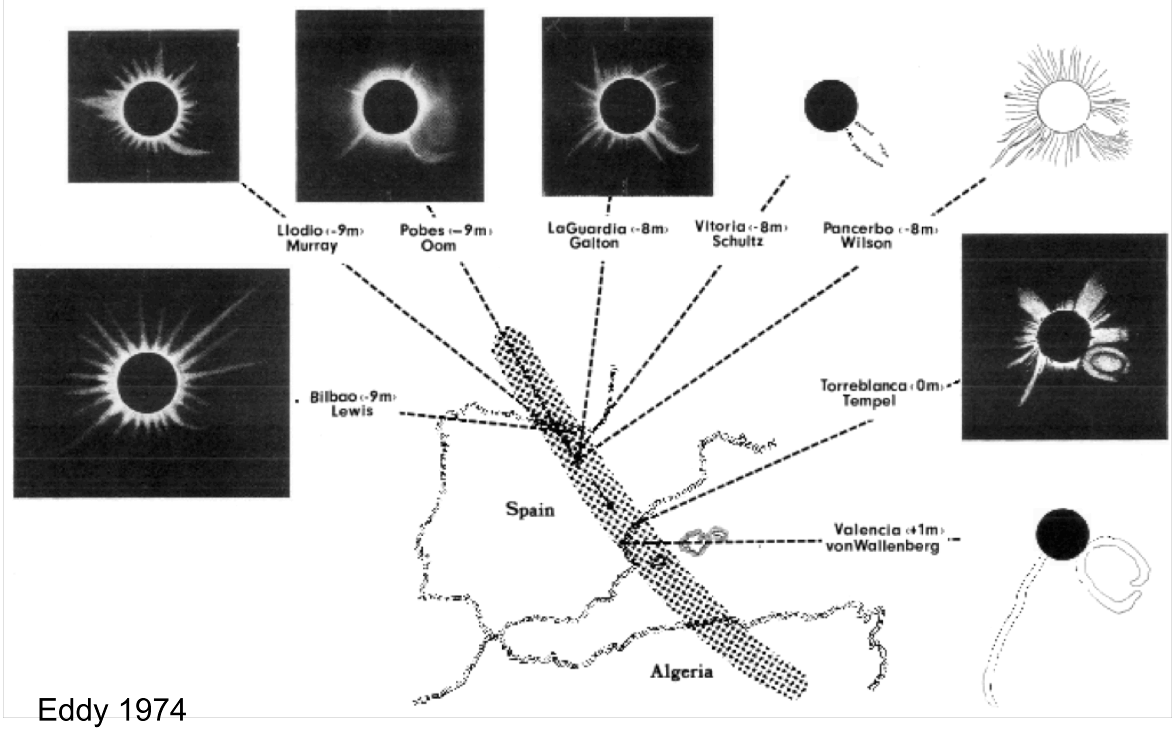
First observations



Eclipse drawing (Tempel) 18 Jul 1860



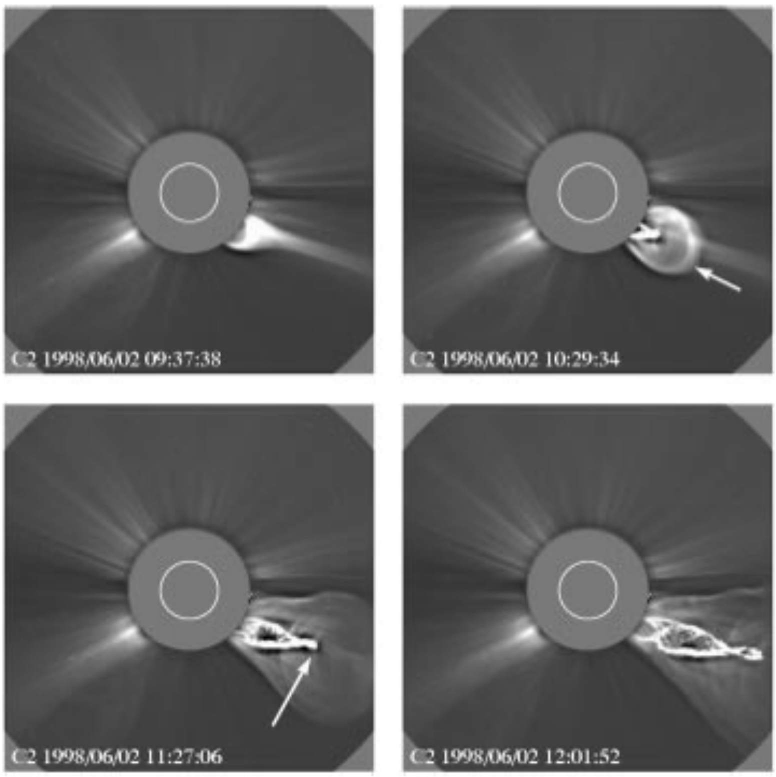
Skylab 10 June 1973
(MacQueen et al. 1974)



Eddy 1974

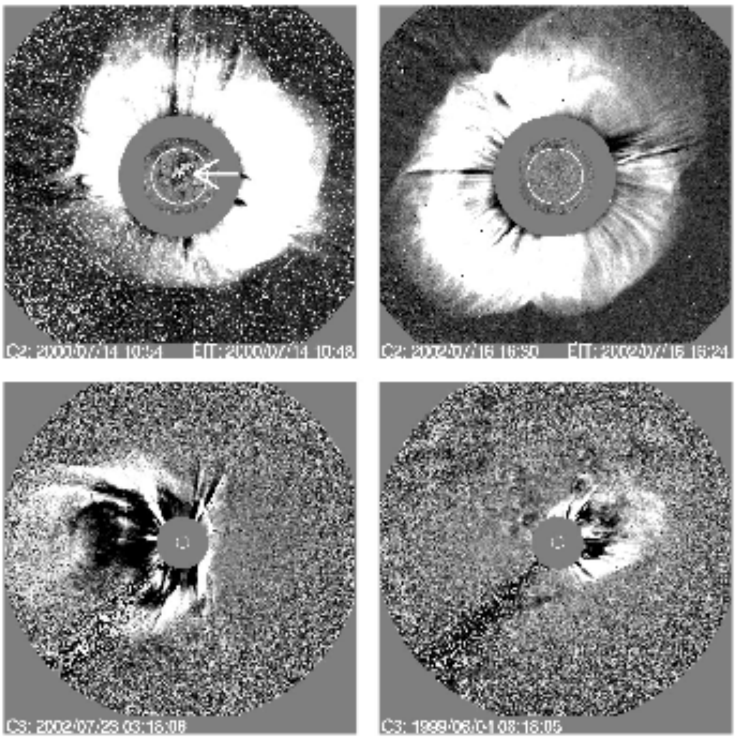
Morphology

- 3 part structure:
  - Bright fontal loop (overlying arcade)
  - Dark cavity (flux rope)
  - Bright core (filament/ prominence)
- ~30% show this structure



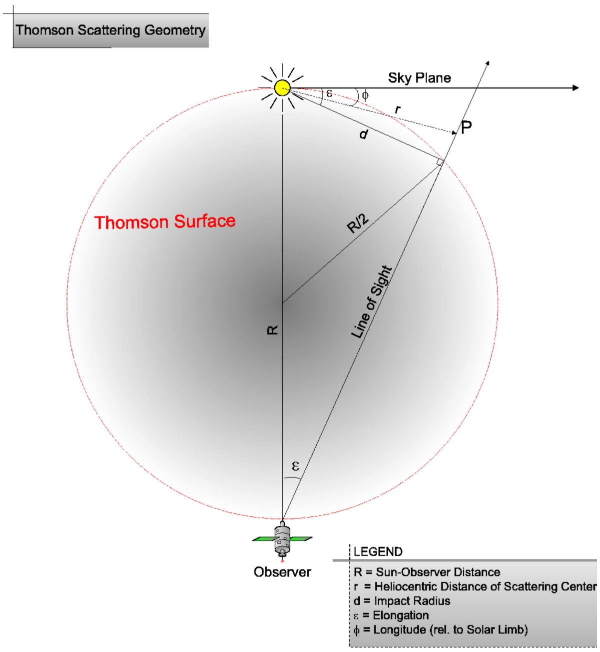
Jets, Halos and partial halos

- Narrow jet-like structures ~20°
- Partial and full halos (120 -360°)
- Directed along the Sun-Earth line.
- 10% of all CMEs are halos; 4% full.



Thomson scattering

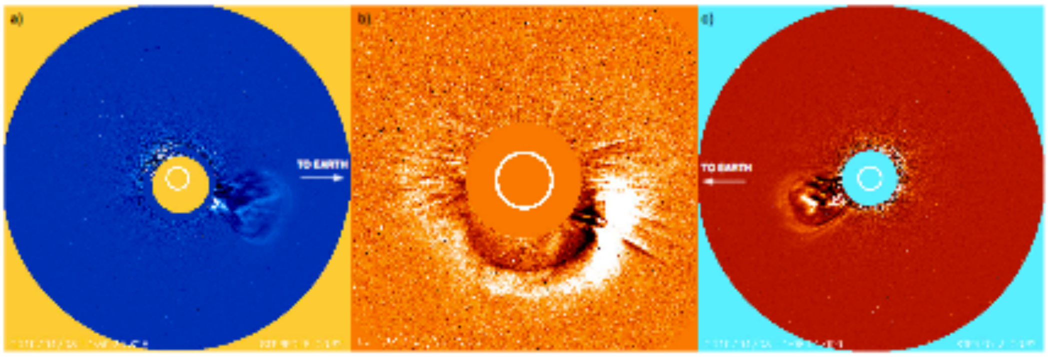
•CMEs are best observed in WL – Thomson scattering of photospheric light by coronal electrons
•Depends on density of scattering electrons and angle between incident radiation direction and the l.o.s.
•Scattering is strongest in the plane of the sky, i.e. limb CMEs are favoured.



Vourlidas & Howard, 2006

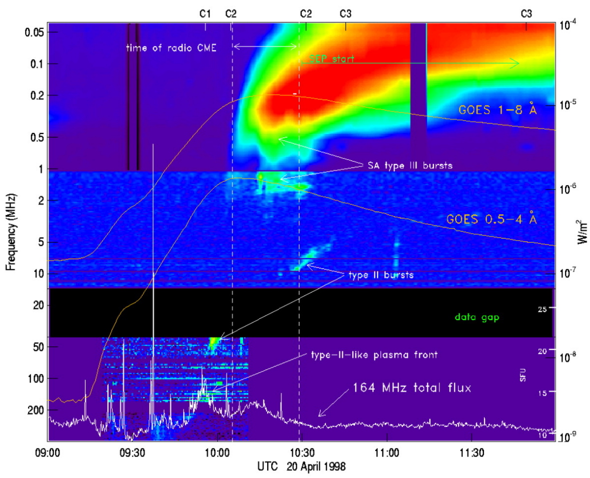
Different perspectives

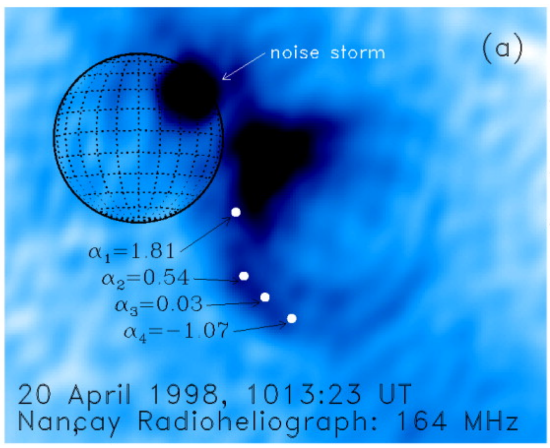
- Single viewing perspectives can be misleading and give skewed perception of angular widths and other properties.
- 70° separation of STEREO A and B from LASCO.



STEREO A LASCO STEREO B

Radio signatures



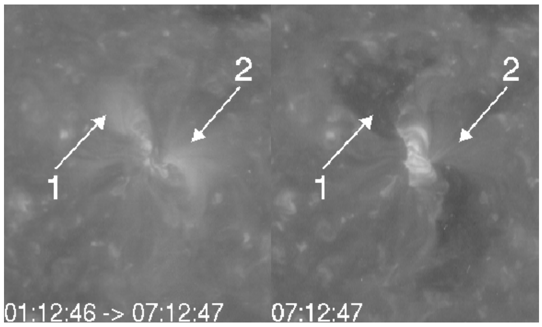


Bastian et al., 2001

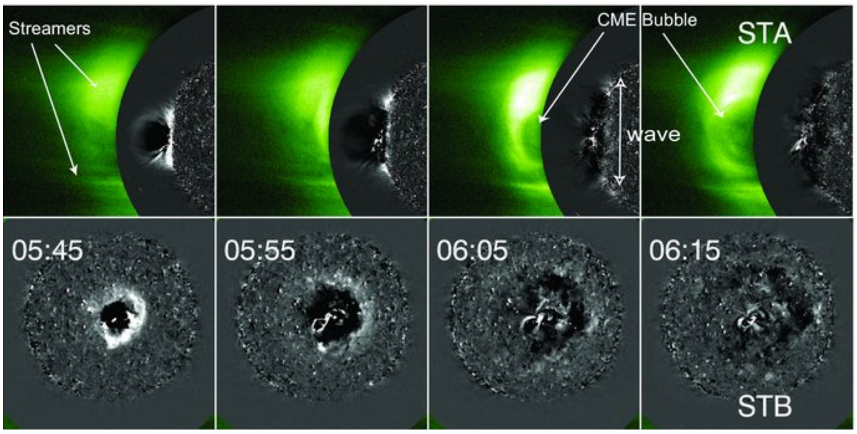
CME speeds > v_A drive a shock ahead of the CME which can accelerate electrons -> Langmuir waves -> Type II radio bursts

On-disk signatures

- Flare ribbons and arcades
- Coronal dimming
- EUV waves



Zhukov & Auchere, 2004



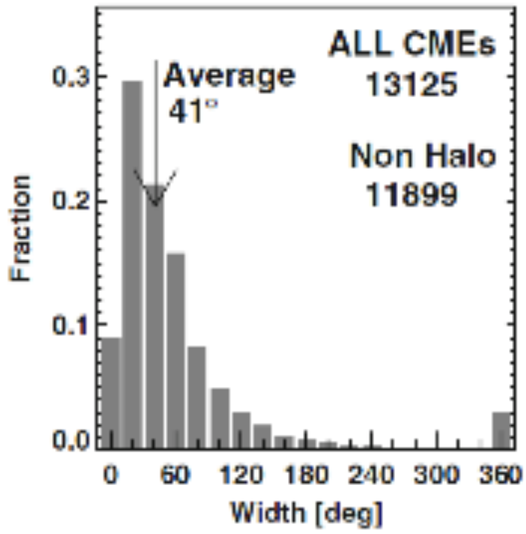
Patsourakos et al., 2009

Properties

- Contain coronal material ~ few MK
- Cool prominence material in the core ~ 8000 K
- Compressed sheath behind the shock higher T and n_e.
- Cavity lower density -> higher magnetic field for pressure balance. Virtually no measurements…

Statistical Properties: Angular width

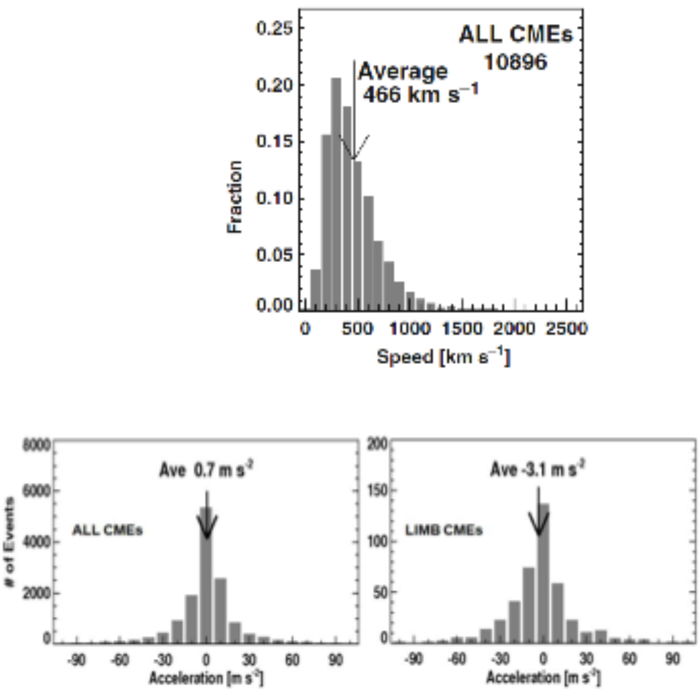
- Extent of PA in plane of the sky => only get accurate results for limb CMEs.
- Widths range from 5 - 360°.
- Average computed for < 120°.



Gopalswamy, 2010

Speed and Acceleration

- CMEs start from rest.
- Driving force close to the Sun, interaction with solar wind slows the CME.
- Speeds measured from fits to H-t plots
- Fast CMEs decelerate, slow accelerate.
- a = -0.015(V-466)



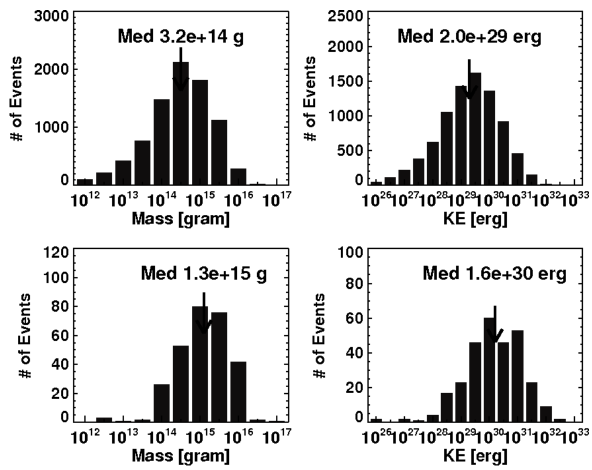
LASCO 1996 -2009 (Gopalswamy 2010)

Kinematics

- Mass: estimate number of electrons needed in plane of the sky to produce observed brightness.
- $\log M = 12.6 + 1.3 \log W$ M –mass (g); W-width(°)
- V =360 +3.64 W (Gopalswamy et al. (2009))
- Wider CMEs are generally faster and more massive.

Mass and KE

- Faster and wider CMEs have higher KE
- KE ranges from < 10^{26} to > 10^{33} erg
- Distributions become more symmetric if only limb CMEs are considered, and median values increase: 1.3×10^{15} g and 1.6×10^{30} ergs.



Gopalswamy 2010

Statistical properties

Table 1: Average statistical properties from near-Earth space borne coronagraph observations of CMEs. Updated from Gopalswamy (2004). [a] SMM values from Burkepile et al. (2004). [b] Updated by S. Yashiro (2011) priv. comm. [c] Solwind and LASCO masses and energies from Vourlidas et al. (2010).

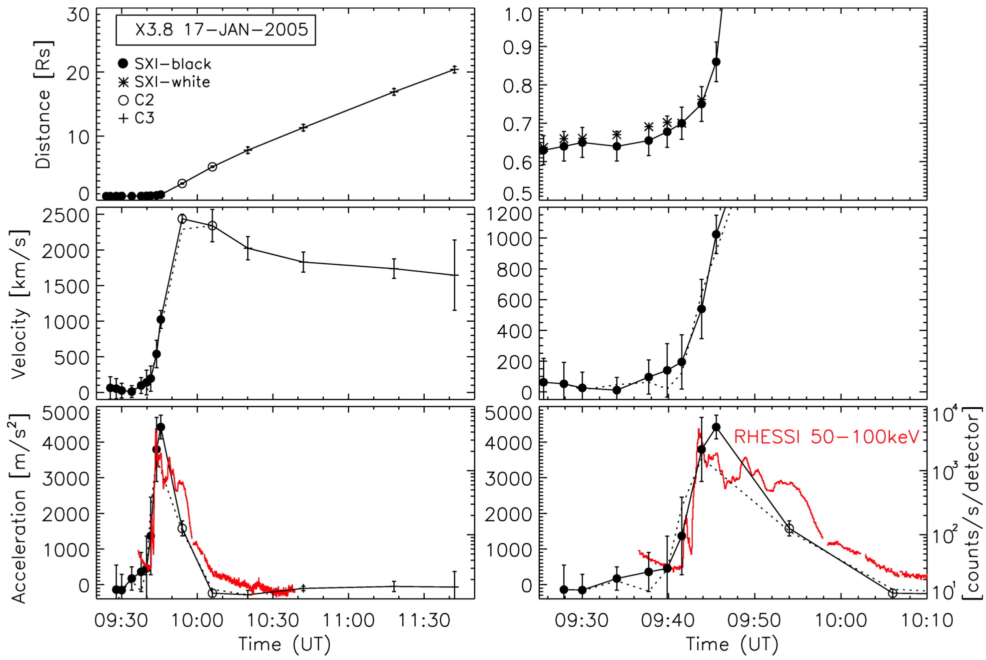
Coronagraph	OSO-7	Skylab	Solwind	SMM[a]	LASCO[b]
Epoch	1971	1973 – 74	1979 – 85	1980, 84 – 89	1996 – present
FOV ($R_{\odot}$)	2.5 – 10	1.5 – 6	3 – 10	1.6 – 6	1.2 – 32
Total # CMEs	27	115	1607	1351	> 10000
Speed (km s^{-1})	–	470	460	349	489
Acceleration (m s^{-2})	–	–	–	–	–16 to +5
Width (°)	–	42	43	46	47
Mass (10^{15}) g[c]	–	6.2	1.7	3.3	1.3
KE (10^{30}) erg[c]	–	–	4.3	8.0	2.0
Mech. E (10^{30}) erg[c]	–	–	–	–	4.2

Table from Webb and Howard, 2012

Flares and CMEs

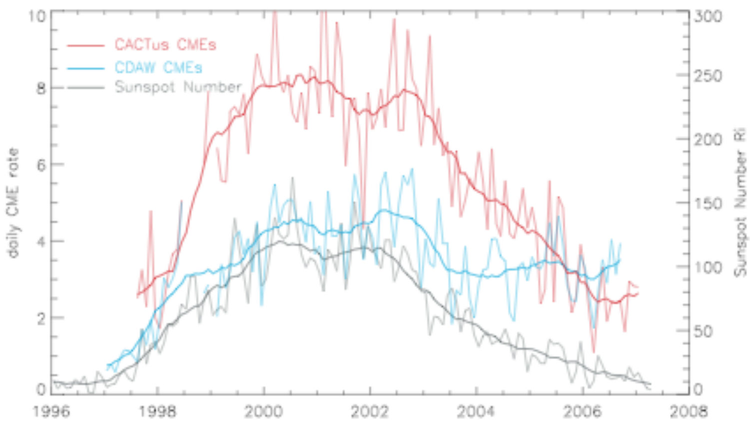
- Both arise due to reconfiguration and subsequent release of energy in the coronal magnetic field.
- Plenty of flares which are not accompanied by CMEs, or are failed eruptions.
- Most models predict flares as part of the eruption process.
- Correlation increases with flare size. 100% for >X3.0 (Yashiro et al., 2005)

Temmer et al., 2008



Occurrence rate

- Rate varies from <0.5/day and minimum to > 6 at max.
- Can be > 10/day
- Significant differences between catalogues – automatic vs manual; observer bias; sensitivity.

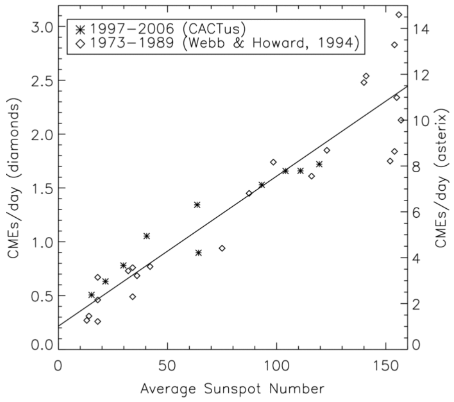


Robbrecht et al., 2009

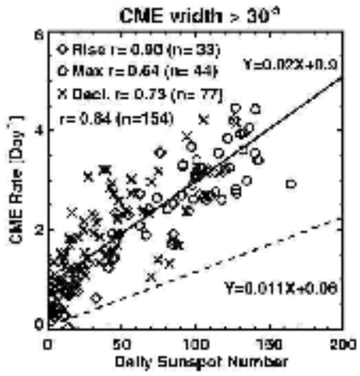
Solar cycle variation

•CME occurrence rate follows the solar cycle in phase and amplitude
•Linear relationship between CME rate and sunspot number (Webb & Howard, 1994; Robbrecht et al., 2009)
•But correlation is higher during rise and declining phases than during max.
•Speeds are generally higher at max.

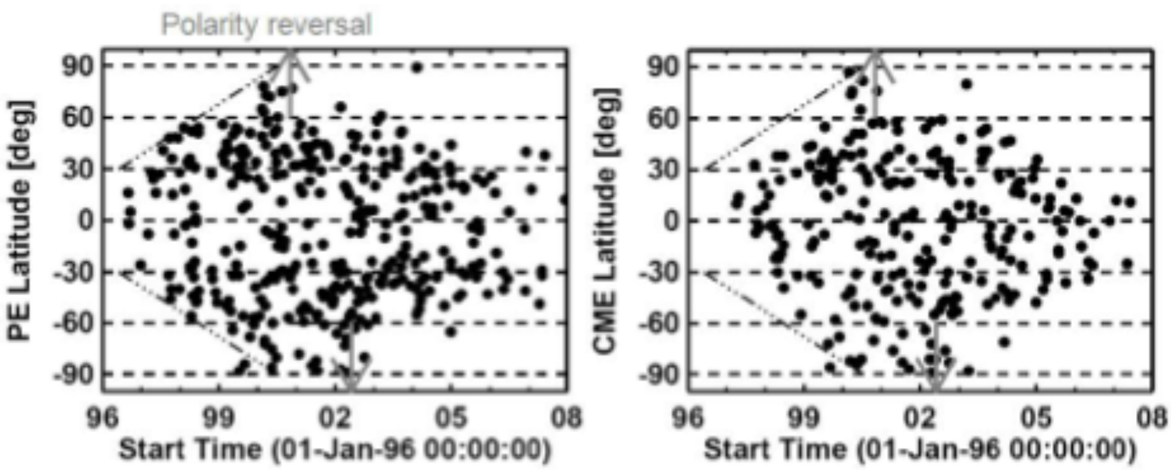
Robbrecht et al. 2009



Gopalswamy et al, 2010

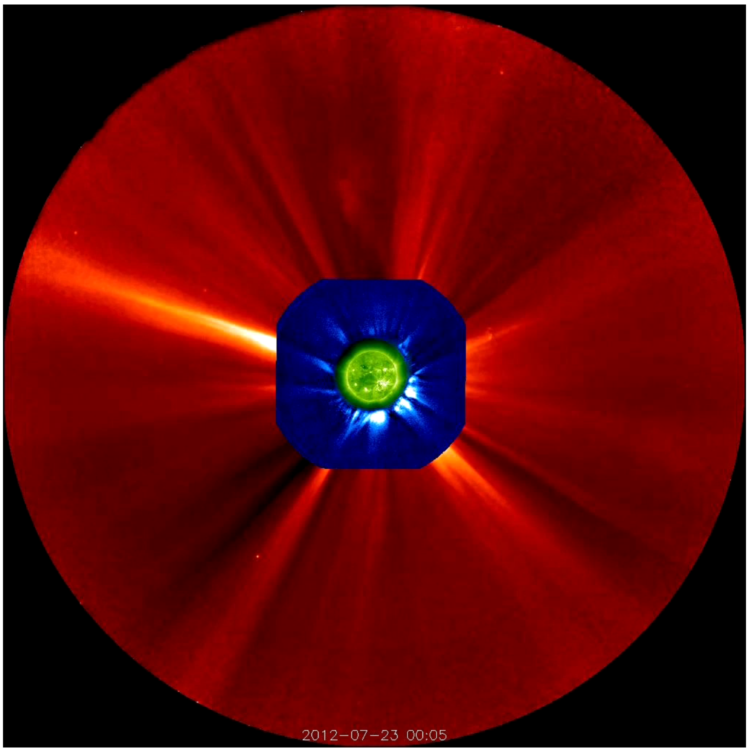


Latitudinal distribution

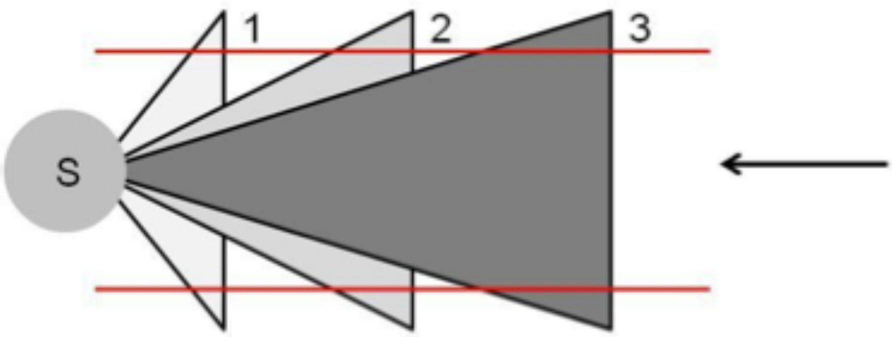


Gopalswamy 2010

Halos

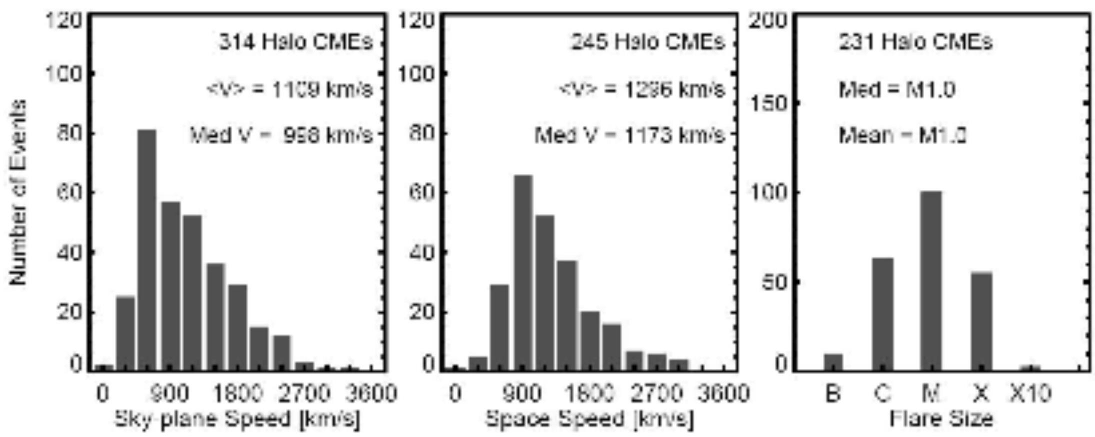


Are Halos different?



Gopalswamy, 2010

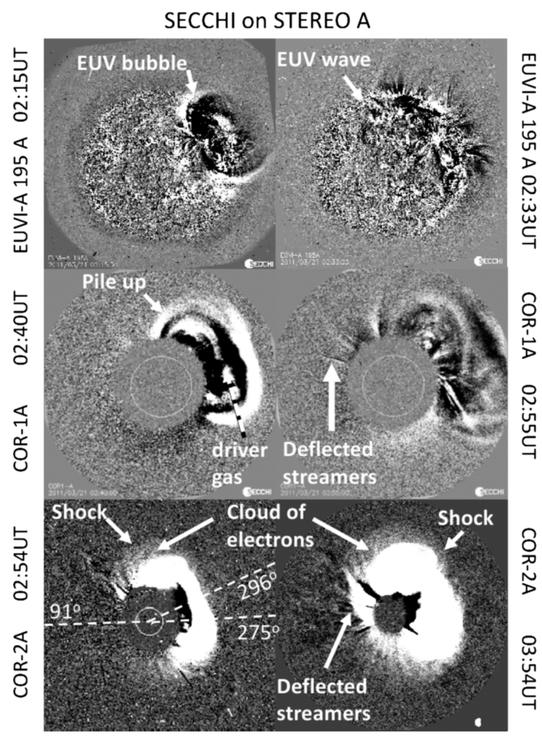
Halo speeds



Gopalswamy et al., 2010

Shocks

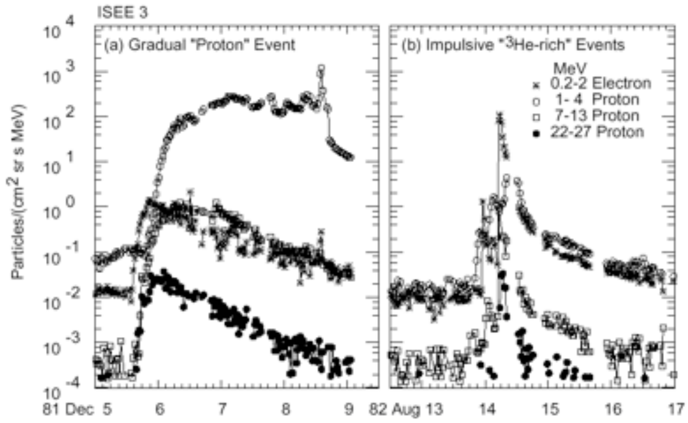
- •Fast CMEs drive shocks
- •Shock accelerates electrons, which produce Langmuir waves.
- •Converted to Type II radio emission at plasma frequency.
- •Drifts to decreasing frequency -> density.
- •Direct imaging of shock sheath only really just been recognized – cloud of electrons ahead of the CME.



Rouillard et al., 2012

CMEs and SEPs

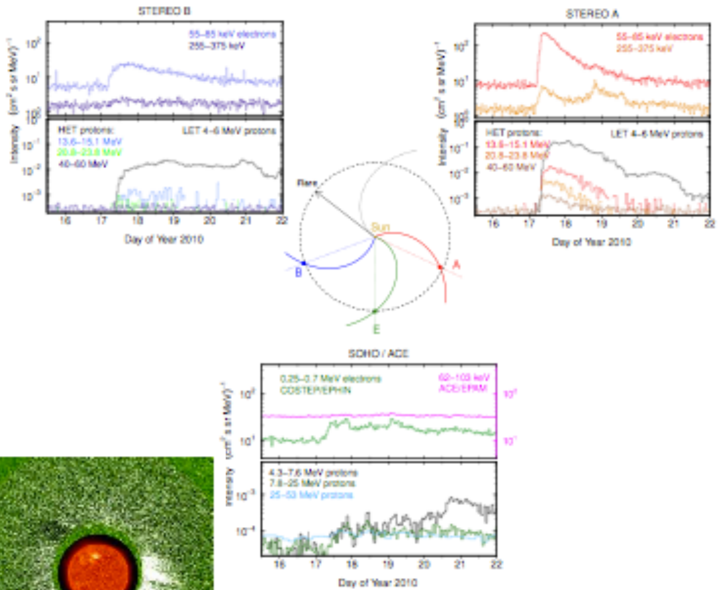
- Gradual SEP events strongly associated with CMEs
- Impulsive – flares
- Also hybrid events
- Sources in West magnetically well connected to Earth
- But CME flanks are wide.

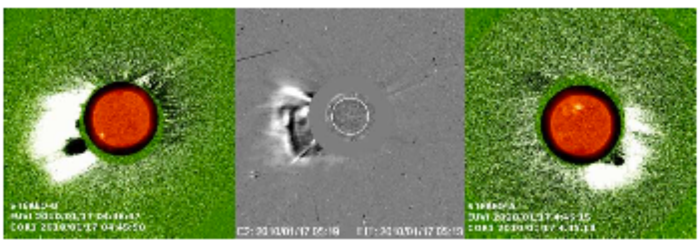


Reames (1999)

CMEs and SEPs

- STEREO is showing that SEP events have up to 360° impact.





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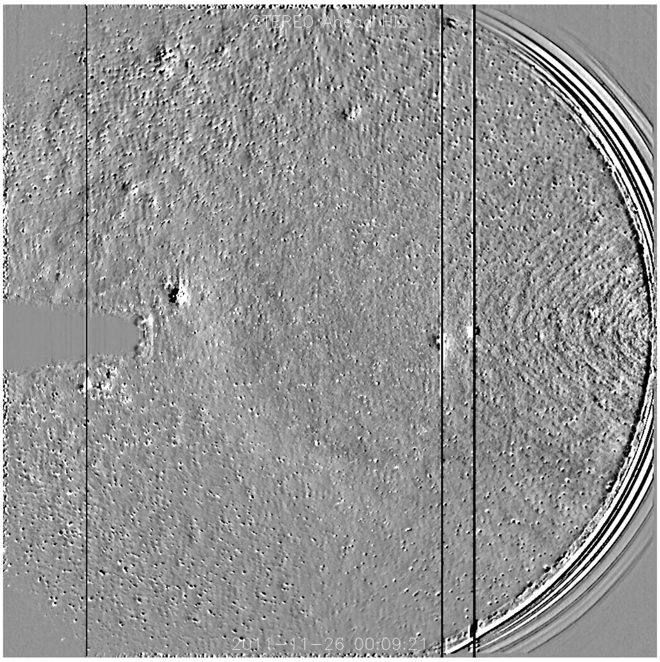
Interplanetary CMEs



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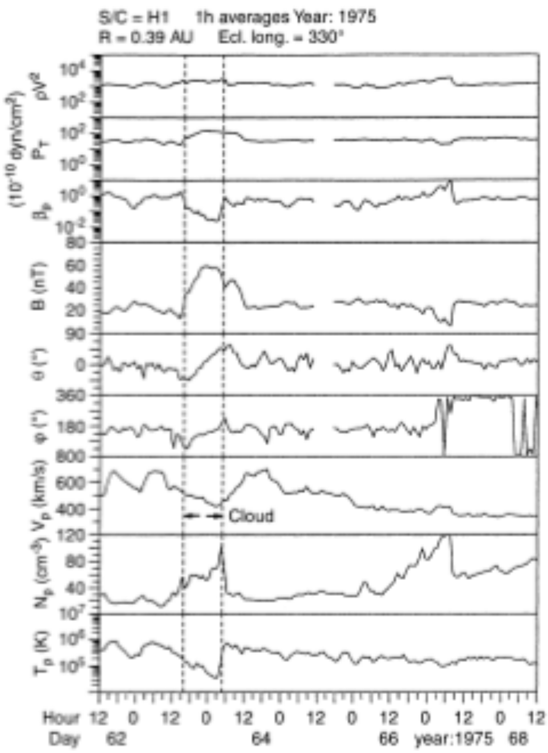
Magnetic clouds

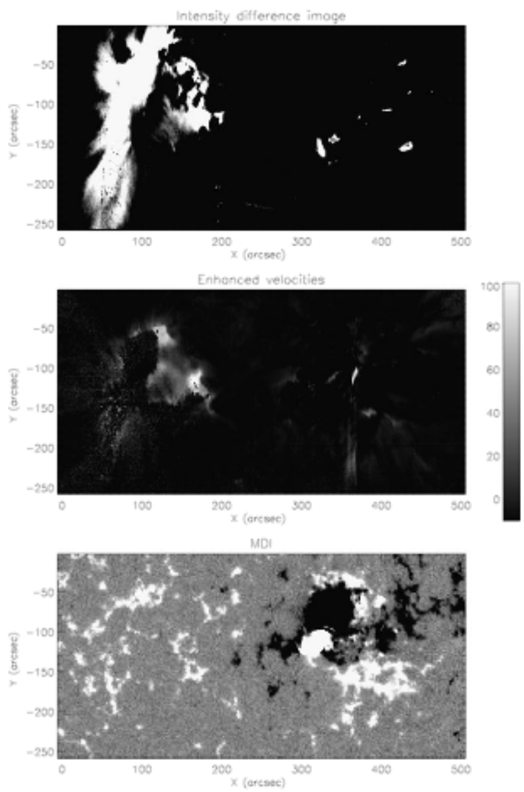
- Enhanced B
- Smooth rotation of B_z
- Low T_p



Bothmer & Schwenn 1998

Outflows and magnetic clouds

- Spectroscopic measurements of outflow velocity have been used to compute more reliable estimates of magnetic flux in a CME
- Good agreement with estimates of flux in associated magnetic cloud.



Harra et al., 2011

Aly-Sturrock

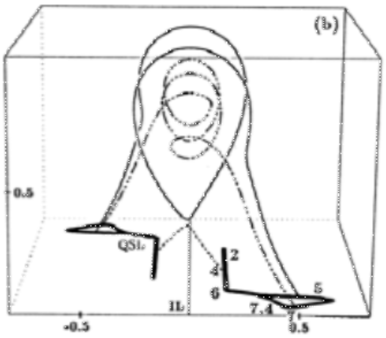
- If all field lines simply linked to the solar surface, total energy of any force-free field cannot exceed that of an open field with the same flux distribution on the surface.
- Implies ‘opening’ the field energetically unfeasible.
- Possible solutions:
  - Reconnection
  - Initial configuration not simply linked to the surface
  - Initial field not force-free – currents, gravity
  - Only part of the field is opened
  - 3D - flux rope can erupt by pushing the field aside.

The ‘Standard Model’

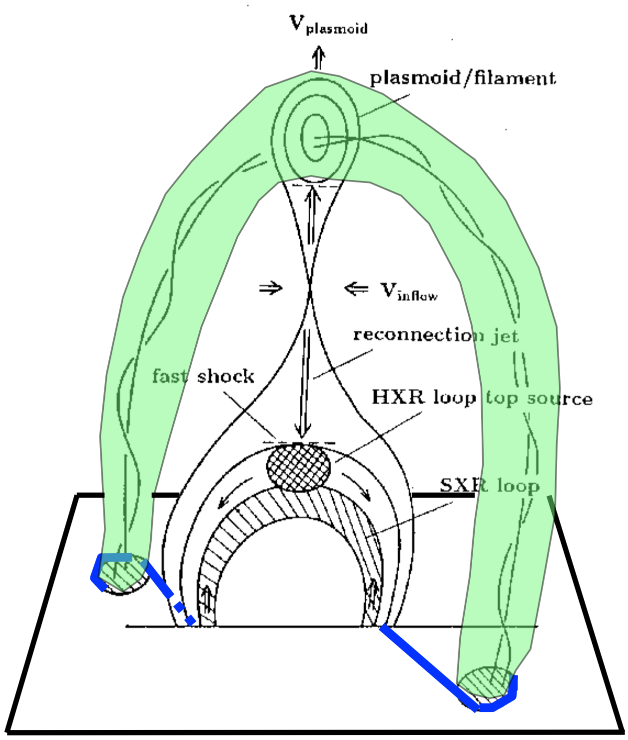
Figure 1 from Shibata et al. (1995)

After eruption onset:

- Observations of flux ropes at 1AU,
- CME acceleration during flare impulsive phase,
- flare ribbons and flare arcade loops,
- EUV & X-ray dimmings.

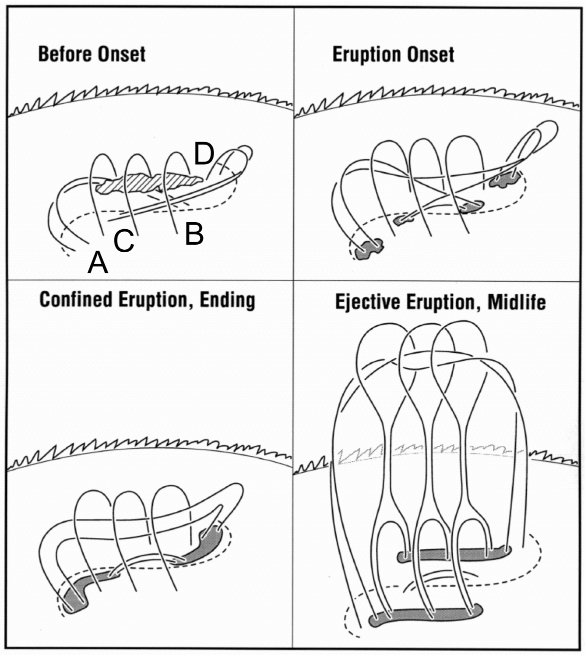


Demoulin et al., 1996



Resistive Models: Tether cutting

•Strongly sheared ‘core’ field near the PIL
•Overlying less sheared arcade
•As shear increases slow reconnection starts.
•Tethers (AB and CD) are cut and AD and CB are formed.
•Fast reconnection (flux rope formation & flare).
•Eruption if overlying field is weak enough.
•Doesn’t address flux rope ejection mechanism.

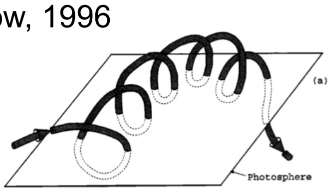


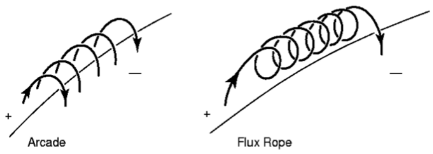
Moore et al., 2001

Resistive models: flux cancellation

By emergence:

B.C. Low, 1996

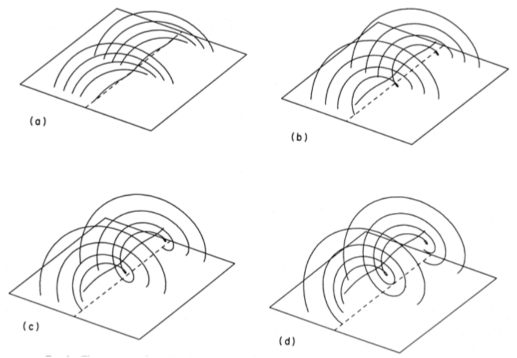




Debated!

By reconnection:

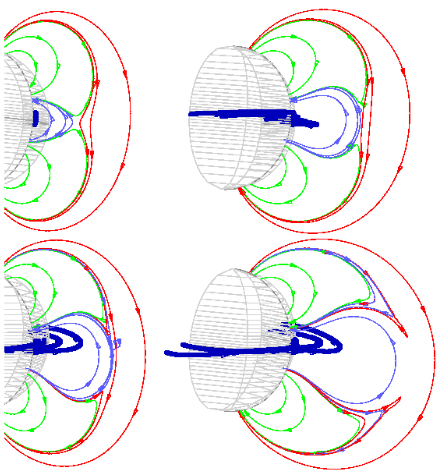
van Ballegooijen & Martens, 1989



Currently favoured:
accompanied by photospheric flux cancellation

Resistive Models: Break-out

- Quadrupolar configuration with a null point above the central flux system.
- Shearing motions cause the central flux system to expand upwards, forming a current sheet at the null point.
- Reconnection starts, removing higher magnetic loops and allowing the core field to erupt.
- Kind of external tether cutting.



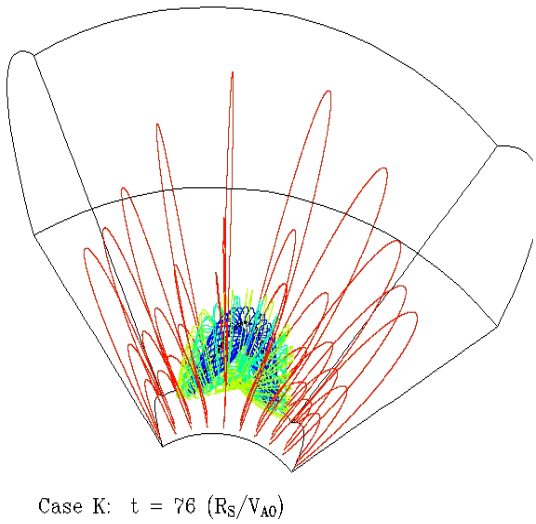
Antiochos et al., 1999

Ideal models: catastrophe/instability

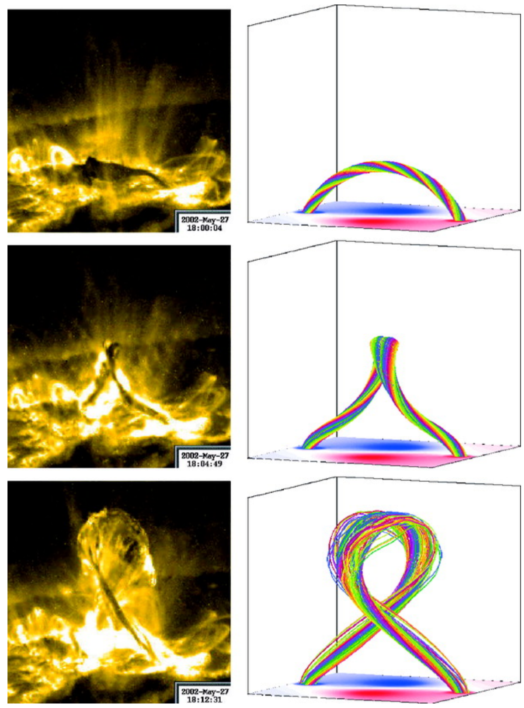
- Starts with a flux rope
- Critical value of filament current or twist leads to catastrophe – no neighbouring equilibrium
- Kink – super-critical flux rope twist
- Torus – sufficient drop in overlying field – mechanism that leads to catastrophe

Ideal models: Kink instability

- Can explain height-time profile of an erupting filament (Sakurai (1976)) as well as morphology.
- Kink: critical twist 2π to 6π (Hood & Priest, 1979)
- Helical deformation of flux rope axis.
- Possible eruption trigger and driving mechanism.

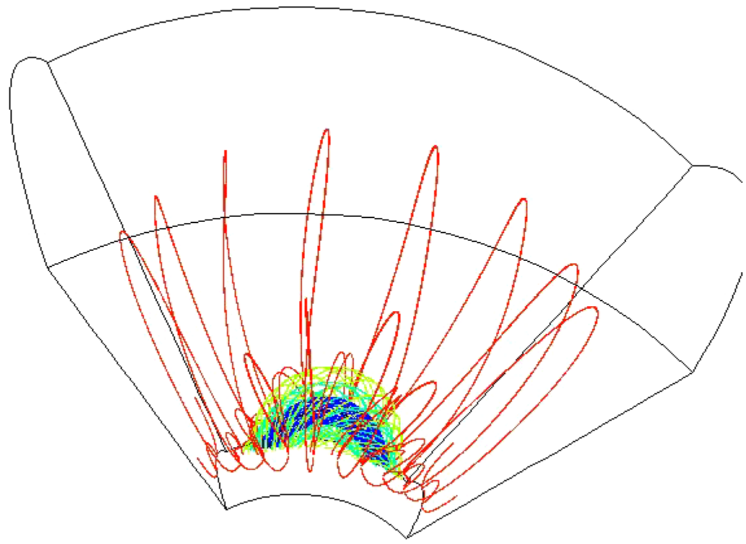


Fan 2005


Török & Kliem (2005)

Ideal models: Torus instability

- Current ring is unstable against expansion if external field decay is fast.
- Hoop force dominates over magnetic tension and flux rope can no longer be confined (Kliem & Török, 2005).
- Events with no helical deformation.



Case T: $t = 30\ (R_S/V_{A0})$

Fan (2005)

Similarities and differences

- All models involve a twisted flux rope early on – when is it formed?
- All have a vertical current sheet below the flux rope -> flare.
- Trigger mechanisms are different, but evolution is similar.

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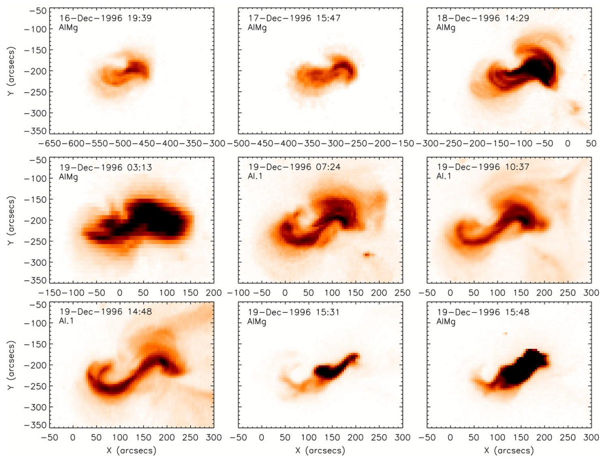
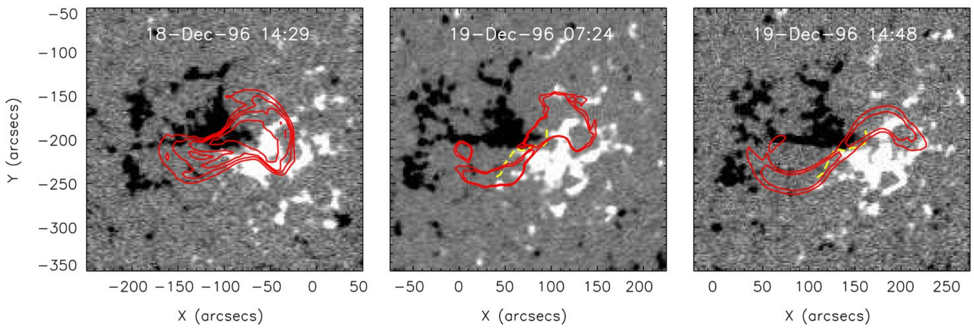
Flux rope formation

•Flux rope formed before eruption – in this case.
•Flux cancellation leads to formation of the flux rope from diffuse sheared arcade (Green & Kliem 2009).





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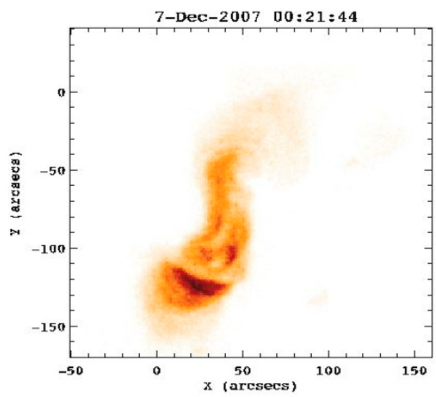
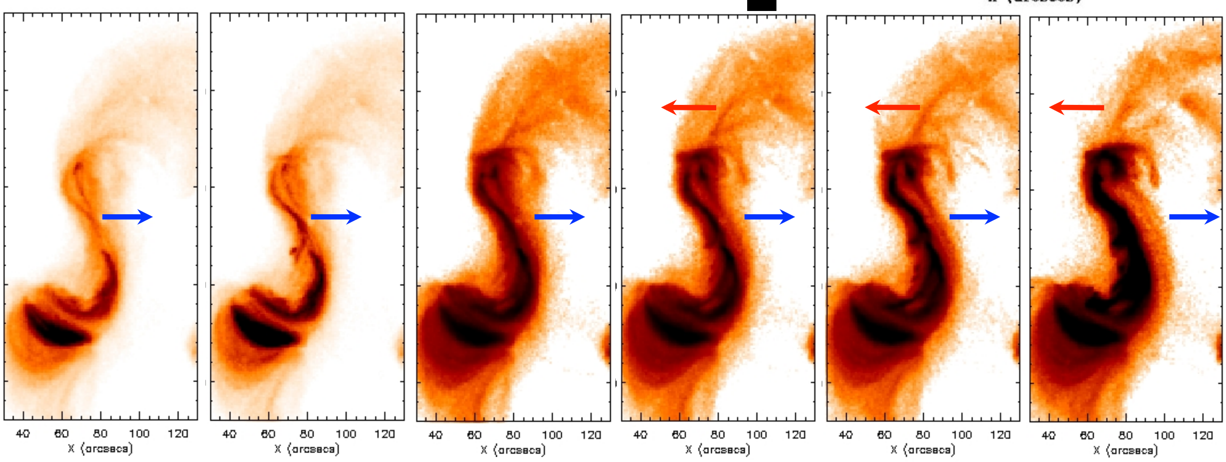
Signatures of the eruption

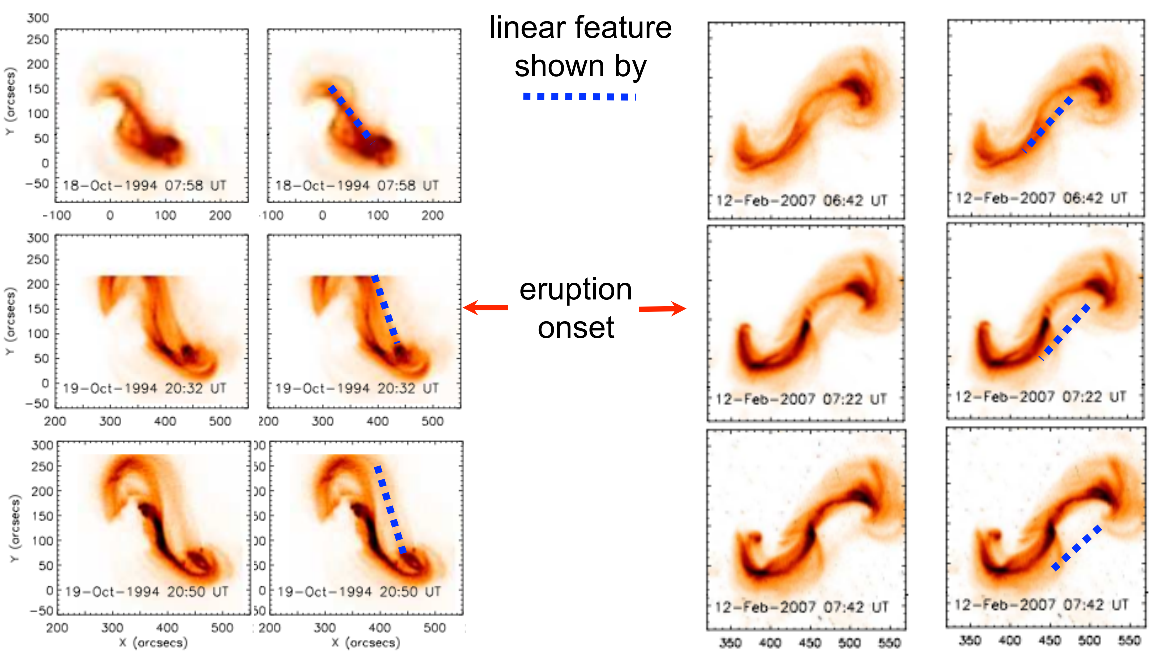
- Rise of ‘linear’ feature.
- Formation of flare arcade.
- Stationary sigmoid centre?
- Movement of sigmoid northern elbow toward the east.





Linear feature in previous events?

Moore et al., 2001 McKenzie & Canfield, 2008



Summary & conclusions

- We have learnt a lot in 40 years – too much to cover here!
- STEREO and SDO are providing new insights on initiation and evolution.
- A ‘standard’ model of CMEs is starting to emerge, it must have:
  - Flux rope dynamics, including the route to instability
  - Reconnection
  - Most likely elements of all existing models