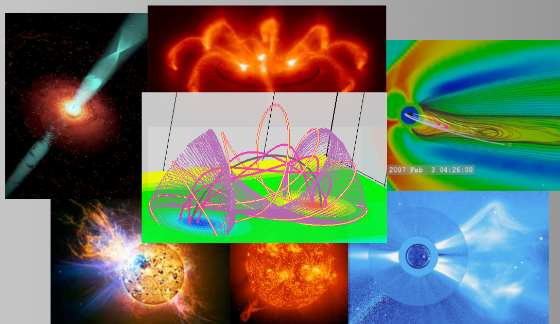
ASTR 7500: Solar & Stellar Magnetism

Hale CGEG Solar & Space Physics

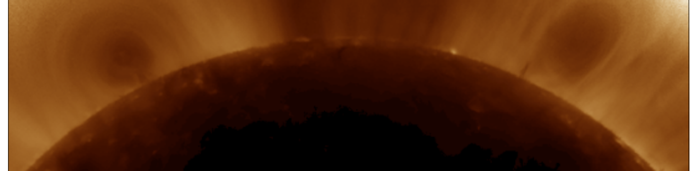


Sarah Gibson, Prof. Juri Toomre + HAO/NSO colleagues

Lecture 18 Thurs 21 Mar 2013

zeus.colorado.edu/astr7500-toomre

Outline



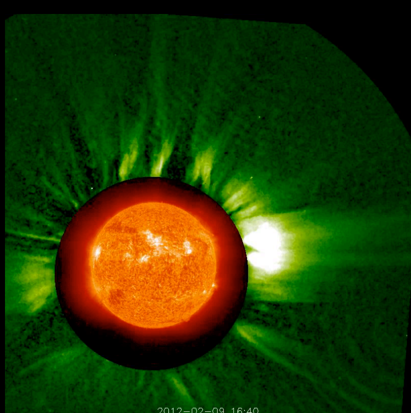
What can the Sun teach us about the storage and explosive release of magnetic energy in astrophysical plasmas?

How does magnetic energy build up in the solar corona?

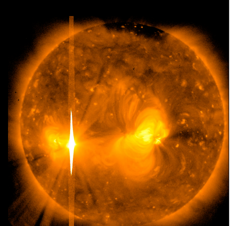
What are the magnetic thresholds and topologies for eruption?

How can we use observations to understand and predict magnetically-driven eruptions?

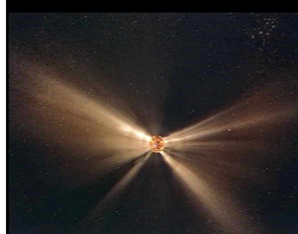
Release of magnetic energy (and helicity)



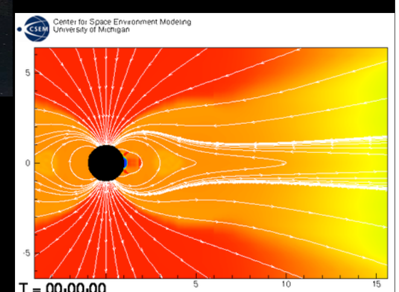
Eruptions
Fed by a release of magnetic energy, CMEs and solar flares send particles and radiation streaming into the *heliosphere*



Release of magnetic energy (and helicity)



CME keeps expanding as it moves through interplanetary space



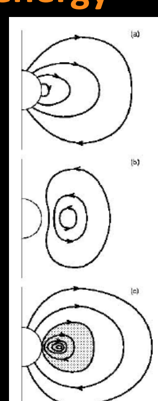
Threshold for magnetic energy

Many models that start with flux ropes **trigger a loss of equilibrium** by evolving the boundary condition in various ways to effectively **increase the detached flux relative to the anchored flux** *(Lin et al. 1998; Amari et al, 2000; 2003, 2004, 2005; Linker et al., 2003; Roussev, 2004; Fan and Gibson 2006)*

What do I mean by detached vs anchored flux?

$$E_0 = \int_{r>1} \frac{B^2}{8\pi} dV = \frac{1}{4}\int_{r=1} (B_r^2 - B_\theta^2 - B_\varphi^2)\sin\theta d\theta$$

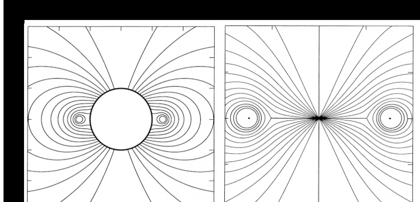
Upper limit on magnetic energy for a given radial flux at lower boundary *(Chandrasekhar Virial Theorem)*.

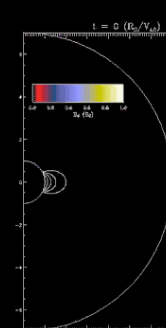


Zhang, Low and Flyer 2006

Threshold for magnetic energy

Many models that start with flux ropes **trigger a loss of equilibrium** by evolving the boundary condition in various ways to effectively **increase the detached flux relative to the anchored flux** *(Lin et al. 1998; Amari et al, 2000; 2003, 2004, 2005; Linker et al., 2003; Roussev, 2004; Fan and Gibson 2006)*

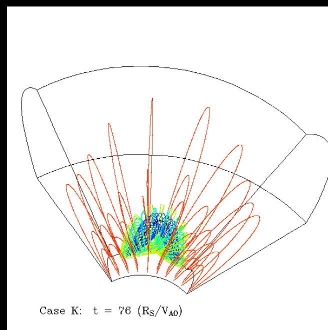




Loss of equilibrium

Kink-instability triggered (Fan, 2005)

- "hoop force" of toroidal flux rope pushes outwards, external poloidal loops confine it, until…
- magnetic kink instability threshold crossed
- flux rope writhes
- changes orientation relative to overlying field
- EQUILIBRIUM IS LOST!

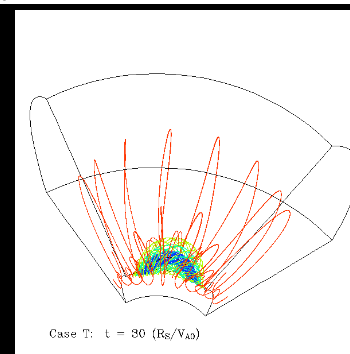


Loss of equilibrium

Torus-instability triggered (Fan and Gibson, 2008)

If overlying field falls off more quickly:

- "hoop force" of toroidal flux rope pushes outwards, external poloidal loops confine it, until…
- enough flux rope emerges to trigger "torus instability" to lateral expansion
- eruption happens before kink instability threshold is crossed
- little writhing, but..
- EQUILIBRIUM IS STILL LOST!

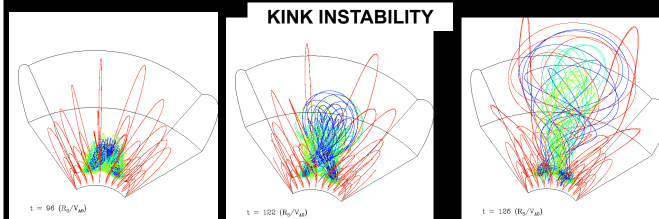


Threshold for magnetic helicity

Observations show both types of eruptions

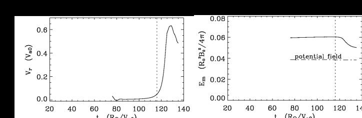
Threshold for magnetic helicity

KINK INSTABILITY



- At onset of eruption:

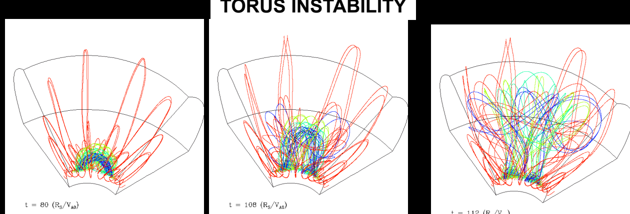
$$H_{m\,rope} = -1.4\,\Phi^2_{rope}$$
$$H_{m\,total} = -0.16\,\Phi^2_{total}$$
$$H_{m\,rope} = 0.33\,H_{m\,total}$$



Fan & Gibson (2007)

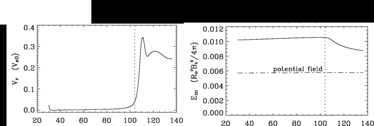
Threshold for magnetic helicity

TORUS INSTABILITY



- At onset of eruption:

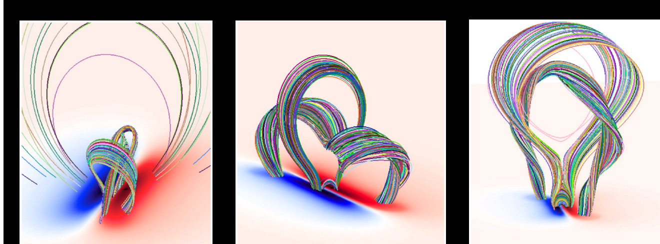
$$H_{m\,rope} = -0.63\,\Phi^2_{rope}$$
$$H_{m\,total} = -0.18\,\Phi^2_{total}$$
$$H_{m\,rope} = 0.07\,H_{m\,total}$$



THRESHOLD FOR MAGNETIC HELICITY? (Zhang et al. 2006)

Magnetic topologies leading to eruption

X line in sheared, reconnection leads to flux rope formation - but is unstable and erupts



Amari, 2003

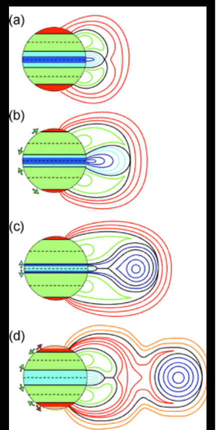
Magnetic topologies leading to eruption

Breakout: X point above sheared field

Is a flux rope necessary pre-eruption?

No - sheared field stores magnetic energy

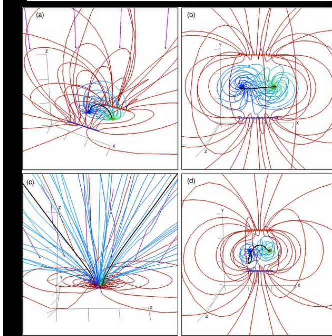
However, a rope forms during eruption through reconnections below



Antiochos et al., 1998; Lynch et al. 2008

Driver: ideal instability or reconnection?

Both ideal-instability and reconnection-driven eruptions have been demonstrated with simulations, and there is observational evidence for both

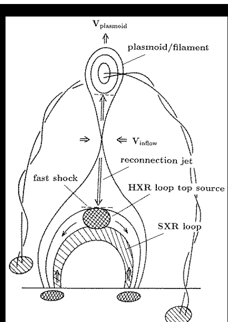


Just how ideal is ideal?

Reconnections are not required for eruption driven by an ideal instability (*Rachmeler et al., 2009*)

Driver: ideal instability or reconnection?

Both ideal-instability and reconnection-driven eruptions have been demonstrated via simulations, and there is observational evidence for both



Shibata et al., 1995

But generally it is accepted that reconnections occur behind the erupting rope (whether formed in situ or not)

Driver: ideal instability or reconnection?

Total eruption of pre-CME flux rope (Ideal):
Reconnections happen below escaping rope
Field lines of escaping rope have not experienced reconnection
Magnetic cloud should match properties of pre-CME rope

Flux rope formed *in situ* (reconnection-driven)
Reconnections happen between sheared field lines and with overlying fields, forming rope
Field lines of escaping rope are all products of reconnection
Magnetic cloud properties can be influenced by both sheared lines and overlying arcade

Importance of magnetic reconnection

Regardless of trigger, observations indicate that reconnection plays a significant role in eruptions

Observations of soft X-ray loops and chromospheric flare ribbons indicate reconnections occur closing down magnetic fields, initally along highly sheared loops, then later transition to potential arcade (*Martin & McAllister 1995; Canfield et al., 2000; Su et al. 2006a, b*)

Poloidal flux/twist in magnetic cloud may largely arise from mutual helicity between source region fieldlines and overlying fields (*Leamon et al., 2002; 2004; Qiu et al., 2007*)

Flare-associated heating along filament-mass-carrying fieldlines indicated in magnetic clouds (*Skoug et al., 1999; Gloeckler et al., 1999; Reinard 2005*)

Does this rule out ideal-instability driven eruptions?

No, but it may rule out ideal-driven TOTAL eruption (at least for most cases)

Importance of magnetic reconnection

Let's revisit kink-instability-driven eruption

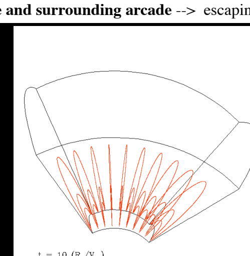
Gibson and Fan, 2006

Although eruption driver was ideal, reconnection played many roles throughout flux rope's evolution

Rope kinks during eruption, forming an **internal current sheet** where it splits in two.

Part of the flux rope with entrained filament is **carried away, part remains behind.**

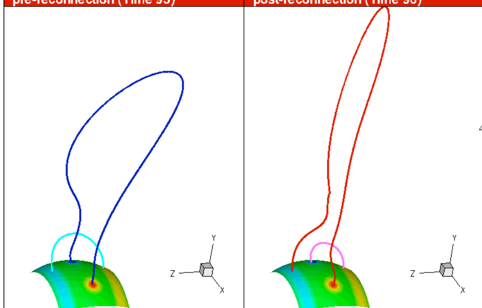
Reconnections **between rope and surrounding arcade** --> escaping rope rooted in external fields

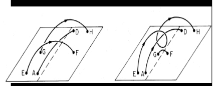


Reconnection: topology-mixing

Poloidal flux/twist in magnetic cloud may largely arise from mutual helicity between source region fieldlines and overlying fields

pre-reconnection (Time 95) | post-reconnection (Time 96)



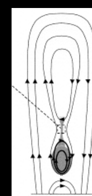


Van Ballegooijen & Martens, 1989

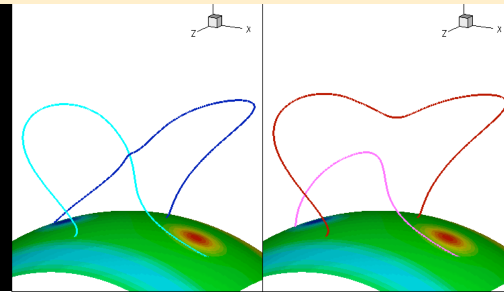
- Rope-arcade reconnection
- Transfers mutual helicity to self-helicity

Reconnection: rope-breaking

Observations of soft X-ray loops and chromospheric flare ribbons indicate reconnections occur closing down magnetic fields, initally along highly sheared loops...



Gilbert et al. (2002)

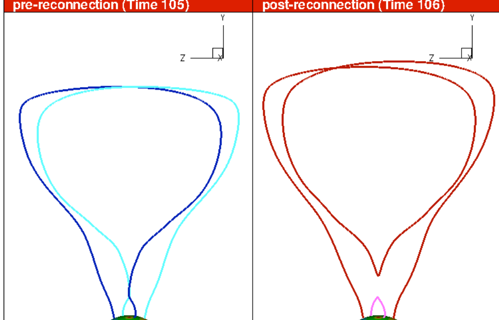


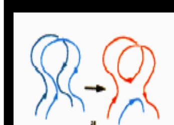
- Flux-breaking reconnection
- Rope writhes and expands upwards

Reconnection: flux-detaching

...then later transition....

pre-reconnection (Time 105) | post-reconnection (Time 106)





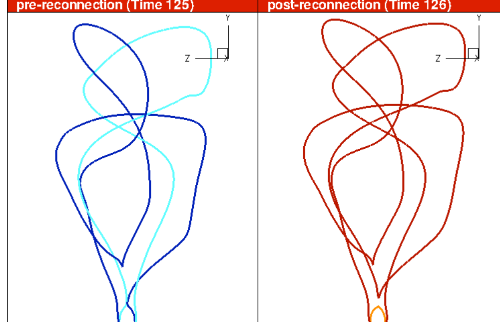
Gosling et al., 1995

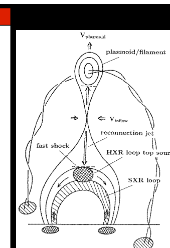
- Flux-detaching reconnection
- Increasing winding number

Reconnection: flux-close-down

...to potential arcade

pre-reconnection (Time 125) | post-reconnection (Time 126)



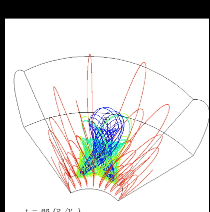


Shibata et al., 1995

- Flux-close-down reconnection
- Final detachment of escaping rope from sun

Reconnections

Flare-associated heating along filament-mass-carrying fieldlines indicated in magnetic clouds



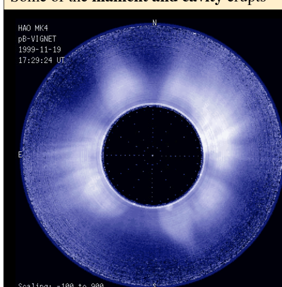
ALL the field lines in the escaping rope have undergone reconnection

Eruption: evolution

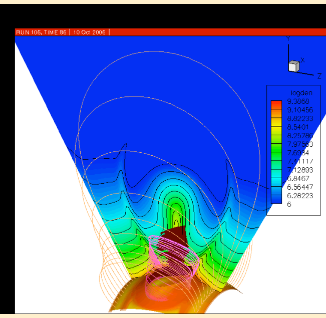
3-part structure created by **magnetic flux rope** (filament core, surrounding cavity, circular front).

This 3-part structure **erupts as coronal mass ejection** (CME).

Some of the **filament and cavity** erupts -- but a **portion remains behind**

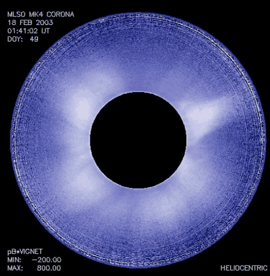


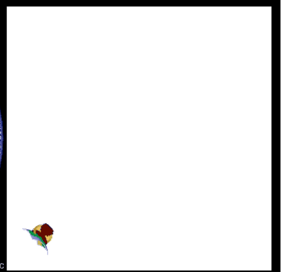
CME partial eruption of filament and cavity: HAO/MLSO Mk4 coronagraph, November 19, 1999

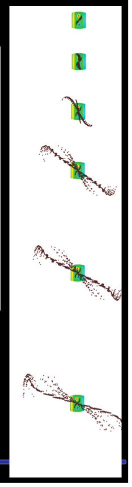


CME partial eruption of filament and cavity: splitting flux rope model. Isocontours show density; cool, dense filament mass location shown in brown.

Eruption: evolution

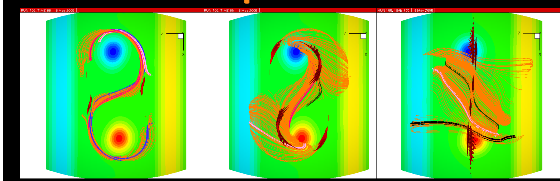




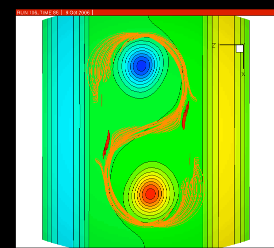


Rotates flux rope axis by approximately 115 degrees
Can explain subset of interplanetary CMEs that don't line up with source orientation

Eruption: evolution

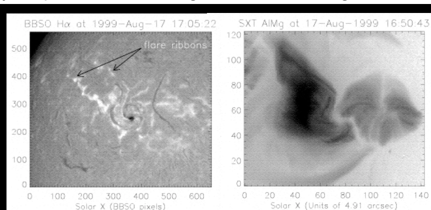


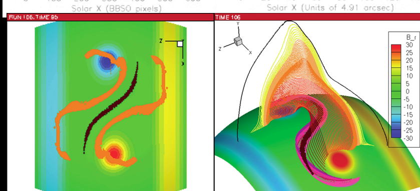
Reconnections occur at:
- Sigmoid separatrix surface
  - (similar to quiescent case)
- Between rope and arcade; At
  - current sheet within rope (split it in two)
- Behind escaping rope, classic
  - cusped arcade



Eruption: end state

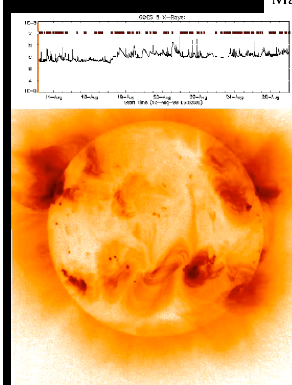
End state: Soft X-ray cusp over reformed sigmoid with surviving filament below.

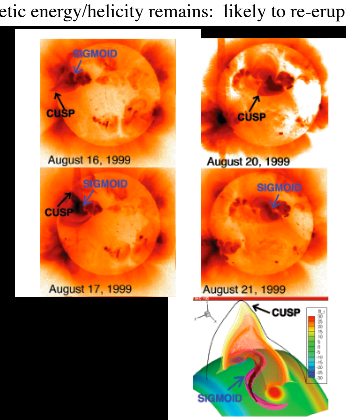




Eruption: end state

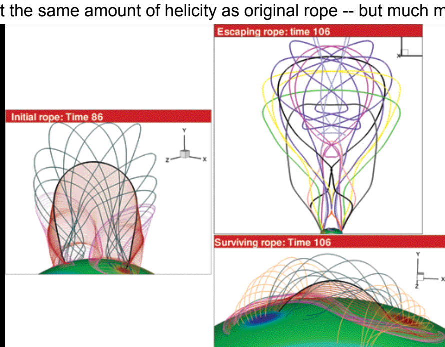
Magnetic energy/helicity remains: likely to re-erupt





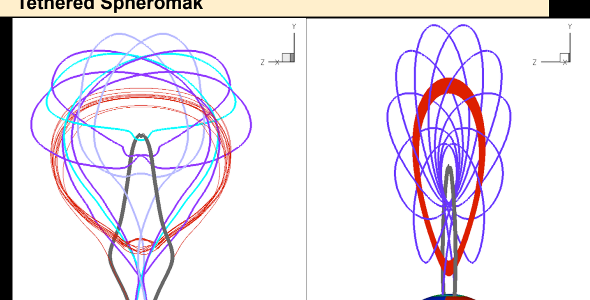
Eruption: end-state

- Rooted in "external" fields -- completely detached from original bipole
- Includes some of original rope helicity, also mutual helicity from rope-arcade
- Pre-eruption configuration: 38% rope self-helicity, 62% mutual helicity
- Escaping rope carries away 41% of total helicity of pre-eruption configuration
- About the same amount of helicity as original rope -- but much more twist!



Eruption: end-state

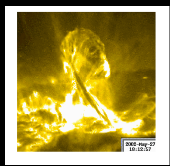
Writhing and reconnection has created a new topology:
Tethered Spheromak

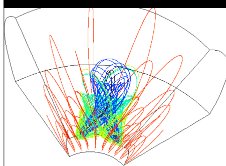


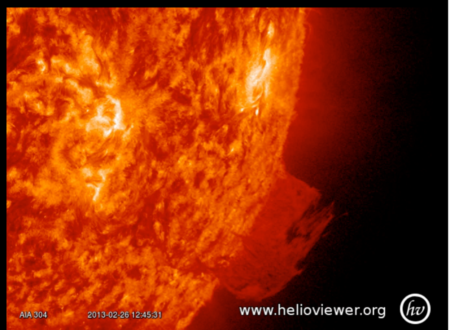
End-state of numerical model | Analytic model *Gibson and Low, 1998*

- Grey field lines -- poloidal axes
- Red field lines -- many times toroidally winding

Or, if failed eruption -- confined spheromak?





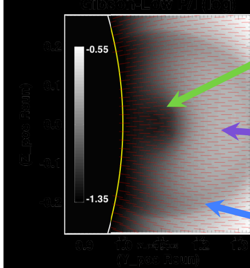


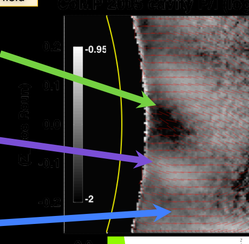
Cavity = Spheromak

Spheromak flux rope model polarization (left) and observed cavity polarization (right)

Dove et al., 2011

strong L (bright): POS field
weak L (dark): LOS field



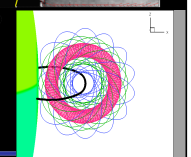


Dark central core: LOS axis

Bright ring: POS field

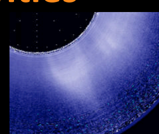
Dark ring: LOS outer field

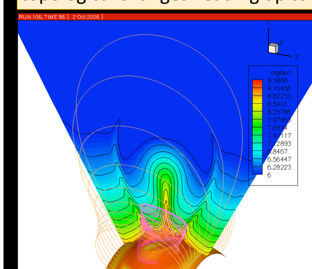
All 3 features are robust signatures of this model

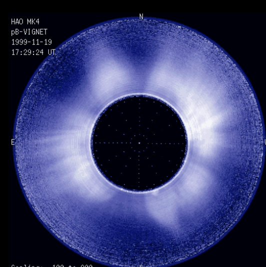


And so - back to cavities

- Cavities "bodily" erupt as CMEs - even if not necessarily "totally" erupt
- Their evolution tells us about magnetic topological changes leading up to the CME





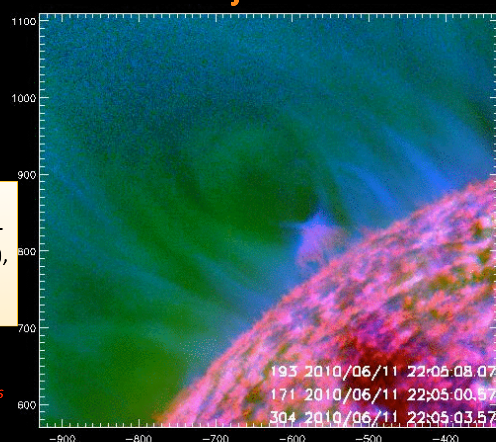


Gibson and Fan, 2008

Coronal Mass Ejections

Note the **shape** (tear-drop), **sub-structure** (horns), and **slow rise** before eruption

Courtesy Davina Innes

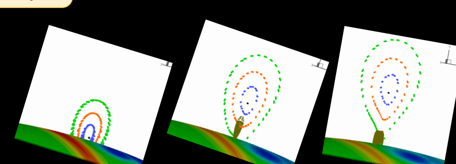


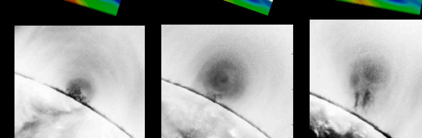
Cavity clues to CMEs

Note the **shape** (tear-drop), **sub-structure** (horns), and **slow rise** before eruption

Cavity clues to CMEs: teardrop shape

10% semicircular erupted
23% elliptical erupted
68% of tear-shaped erupted

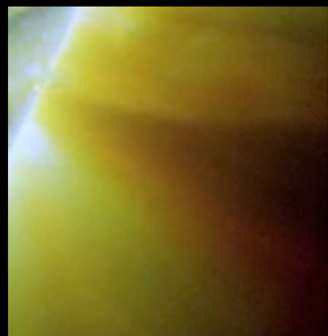




Forland et al. 2013

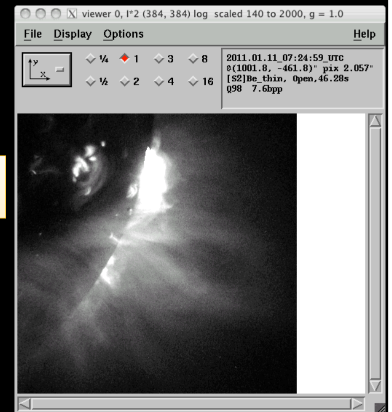
Cavity clues to CMEs: teardrop shape

This one won me a dozen donuts



Cavity clues to CMEs: teardrop shape

This one won me a dozen donuts

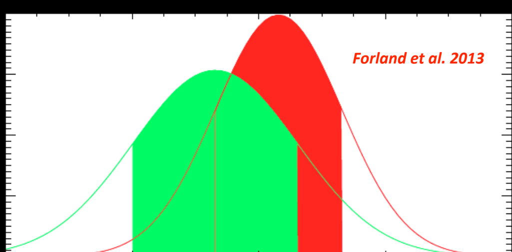


Courtesy K. Reeves

Cavity clues to CMEs: teardrop shape

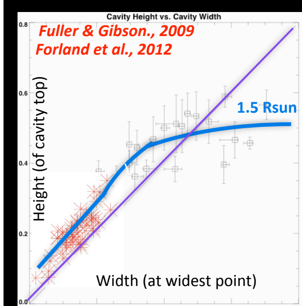
Aspect ratio skinnier for eruptive cases

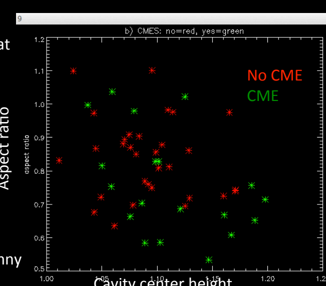
No CME
CME



Aspect ratio

Cavity clues to CMEs: height



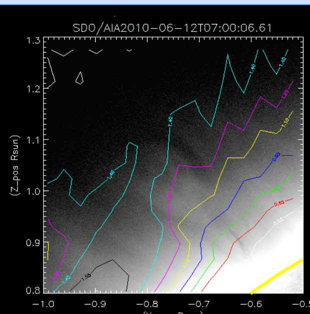


Upper limit - but not very strong correlation with eruption - need to consider how magnetic field drops off with height

Cavity clues to CMEs: height

"Torus instability" to lateral expansion is triggered when rope axis reaches a critical height that depends on the rate of falloff of the overlying potential field: index expected to reach threshold between 1 and 2 Kliem and Toeroek, 2006

Near-erupting cavity: index = ~1.4 at cavity center

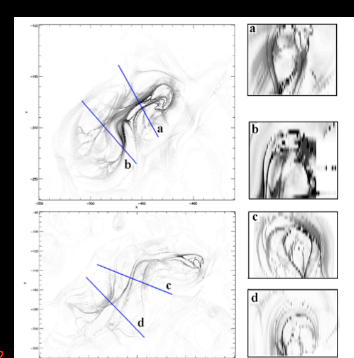


Early results: torus instability sufficient, but not necessary for eruption *de Toma al., 2013*

Cavity clues to CMEs

Currents (top-view left, side-view right) associated with extrapolation of vector photospheric field (with embedded flux rope) for Feb 7 2007 (top) and Feb 12 2007

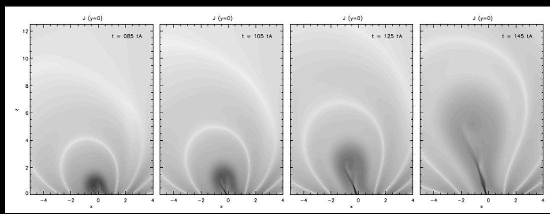
Flares occurred at locations (a) and (c) for the two days (tear-drop shaped in vertical cuts)



Savcheva et al., 2012

Magnetic topology (hyperbolic flux tube) → tear-drop shape
Presence of HFT → reconnection/flare

Cavity clues to CMEs: Conclusion



Aulanier et al., 2010

Also, Savcheva et al, 2012; Fan, 2012

Current sheet forms below flux rope → reconnections (horns)
Drives slow rise of flux rope (tear-shape forms)
Reaches height for torus instability → CME