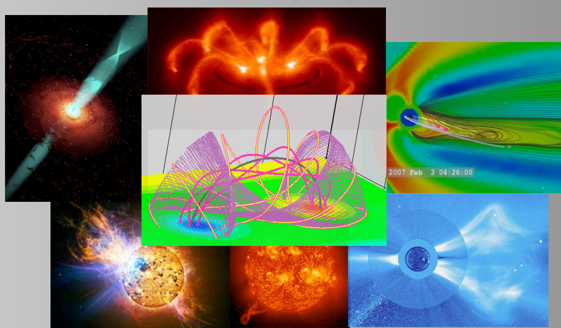
# ASTR 7500: Solar & Stellar Magnetism

Hale CGEG Solar & Space Physics




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

Lecture 17 Tues 19 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?



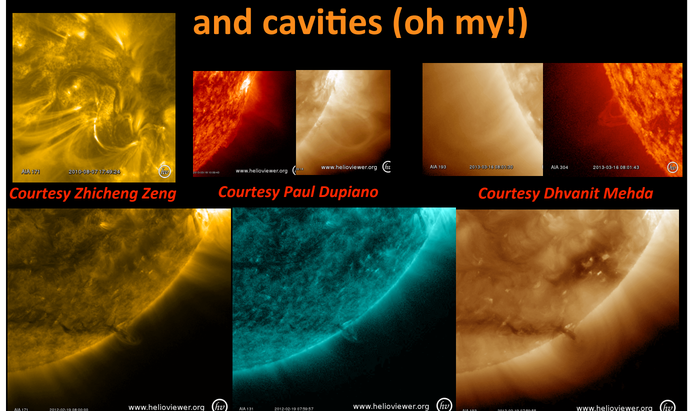
# Outline

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?**



# Examples: Sigmoids and prominences and cavities (oh my!)



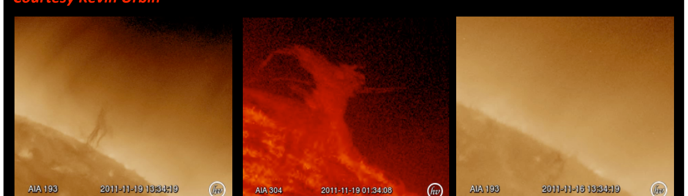

*Courtesy Zhicheng Zeng* *Courtesy Paul Dupiano* *Courtesy Dhvanit Mehda*

*Courtesy Natsuha Kuroda*

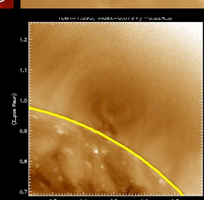


# Examples: Solar "tornados"

*Courtesy Kevin Urbin*




Transport magnetic energy and helicity into the prominence and cavity



*Yang et al., 2012*

http://adsabs.harvard.edu/abs/2012ApJ...756L..41S



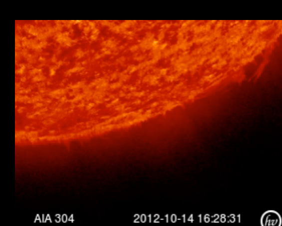
# Examples: Erupting prominence

Prominence is visible for several days, with intermittent flows.

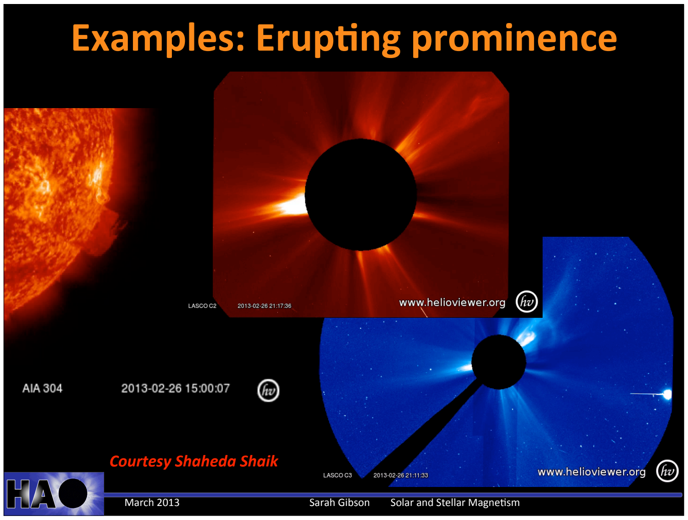
Cavity is visible surrounding it when it is centered on the solar limb.

Erupts as part of coronal mass ejection.

Transports stored magnetic energy and helicity away from Sun


*Courtesy Courtney Peck*


Examples: Erupting prominence
AIA 304
2013-02-26 15:00:07
www.helioviewer.org
Courtesy Shaheda Shaik
www.helioviewer.org
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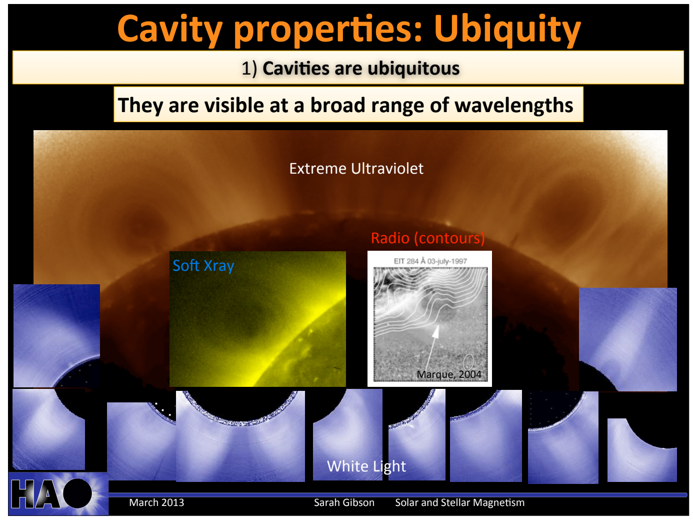
Cavity properties: Ubiquity
1) Cavities are ubiquitous
They are visible at a broad range of wavelengths
Extreme Ultraviolet
Radio (contours)
Soft Xray
Marque, 2004
White Light
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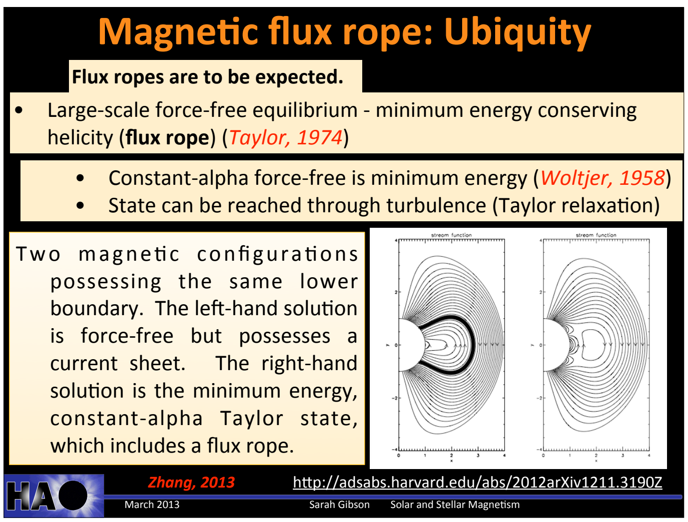
Magnetic flux rope: Ubiquity
Flux ropes are to be expected.
• Large-scale force-free equilibrium - minimum energy conserving helicity (flux rope) (Taylor, 1974)
• Constant-alpha force-free is minimum energy (Woltjer, 1958)
• State can be reached through turbulence (Taylor relaxation)
Two magnetic configurations possessing the same lower boundary. The left-hand solution is force-free but possesses a current sheet. The right-hand solution is the minimum energy, constant-alpha Taylor state, which includes a flux rope.
stream function
stream function
Zhang, 2013
http://adsabs.harvard.edu/abs/2012arXiv1211.3190Z
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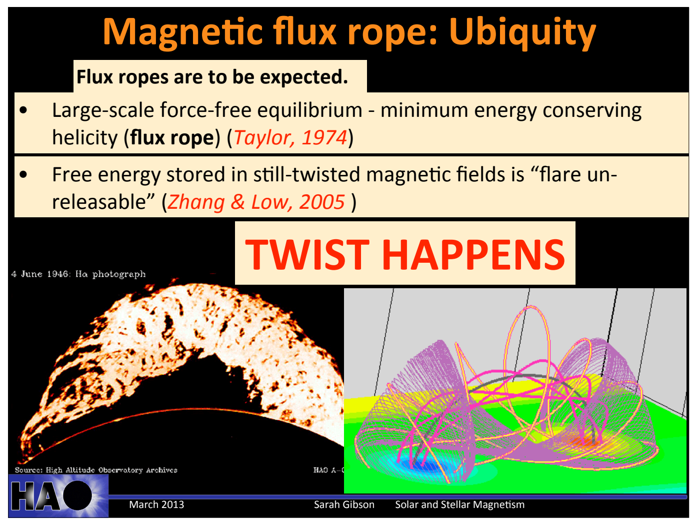
Magnetic flux rope: Ubiquity
Flux ropes are to be expected.
• Large-scale force-free equilibrium - minimum energy conserving helicity (flux rope) (Taylor, 1974)
• Free energy stored in still-twisted magnetic fields is "flare un-releasable" (Zhang & Low, 2005 )
TWIST HAPPENS
4 June 1946: Hα photograph
Source: High Altitude Observatory Archives
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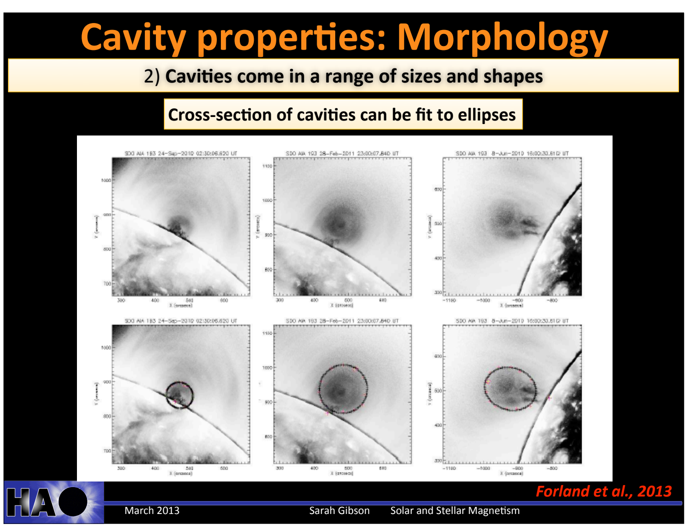
Cavity properties: Morphology
2) Cavities come in a range of sizes and shapes
Cross-section of cavities can be fit to ellipses
Forland et al., 2013
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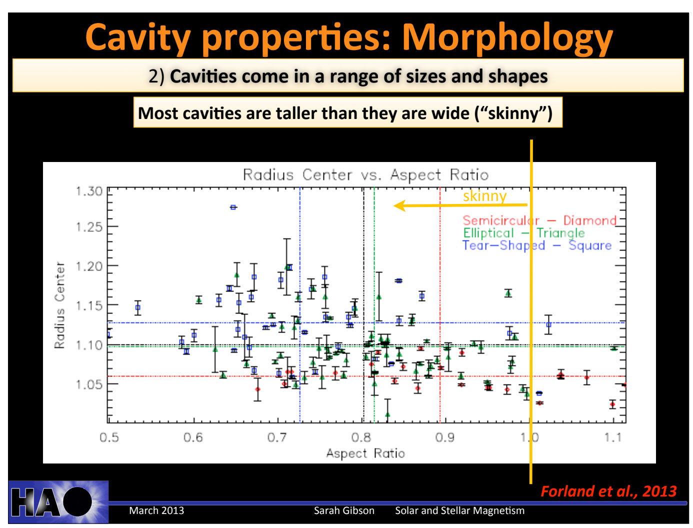
Cavity properties: Morphology
2) Cavities come in a range of sizes and shapes
Most cavities are taller than they are wide ("skinny")
Radius Center vs. Aspect Ratio
skinny
Semicircular – Diamond
Elliptical – Triangle
Tear–Shaped – Square
Radius Center
Aspect Ratio
1.30
1.25
1.20
1.15
1.10
1.05
0.5
0.6
0.7
0.8
0.9
1.0
1.1
Forland et al., 2013
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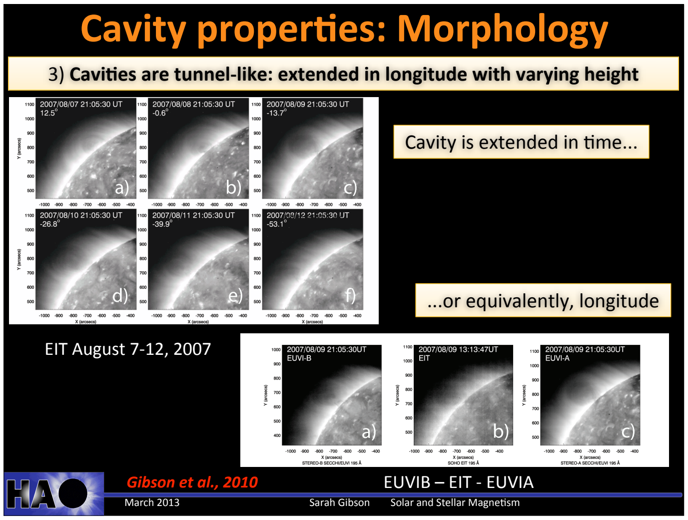
Cavity properties: Morphology
3) Cavities are tunnel-like: extended in longitude with varying height
Cavity is extended in time…
…or equivalently, longitude
EIT August 7-12, 2007
Gibson et al., 2010
EUVIB – EIT - EUVIA
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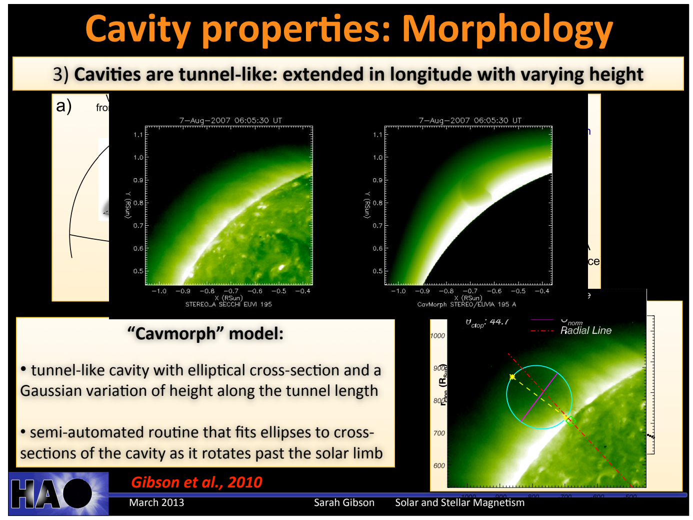
Cavity properties: Morphology
3) Cavities are tunnel-like: extended in longitude with varying height
a)
7-Aug-2007 06:05:30 UT
"Cavmorph" model:
• tunnel-like cavity with elliptical cross-section and a Gaussian variation of height along the tunnel length
• semi-automated routine that fits ellipses to cross-sections of the cavity as it rotates past the solar limb
Radial Line
Gibson et al., 2010
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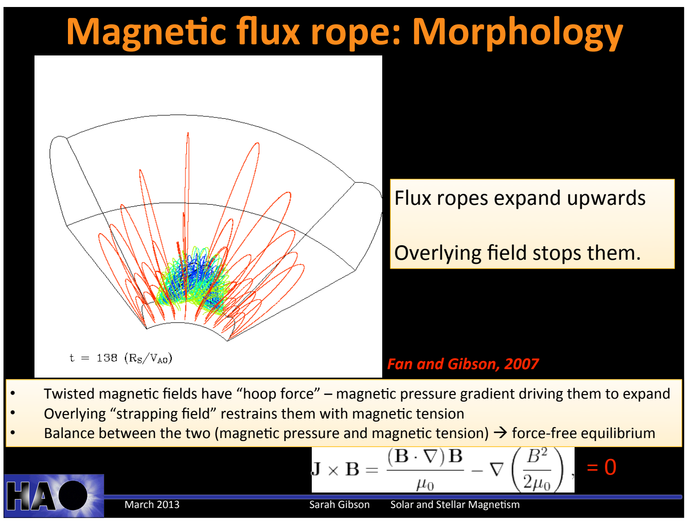
Magnetic flux rope: Morphology
t = 138 (Rs/VA0)
Flux ropes expand upwards
Overlying field stops them.
Fan and Gibson, 2007
• Twisted magnetic fields have "hoop force" – magnetic pressure gradient driving them to expand
• Overlying "strapping field" restrains them with magnetic tension
• Balance between the two (magnetic pressure and magnetic tension) → force-free equilibrium
$\mathbf{J}\times\mathbf{B} = \frac{(\mathbf{B}\cdot\nabla)\mathbf{B}}{\mu_0} - \nabla\left(\frac{B^2}{2\mu_0}\right)$ = 0
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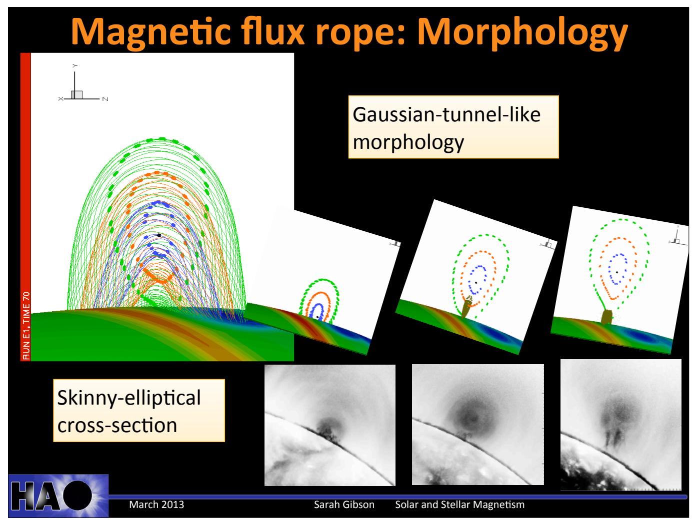
Magnetic flux rope: Morphology
Gaussian-tunnel-like morphology
RUN E1, TIME 70
Skinny-elliptical cross-section
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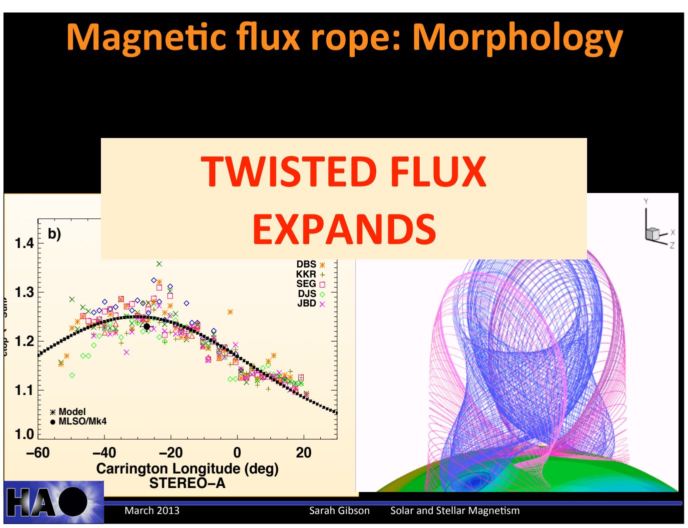
Magnetic flux rope: Morphology
TWISTED FLUX EXPANDS
b)
DBS
KKR
SEG
DJS
JBD
Model
MLSO/Mk4
Carrington Longitude (deg)
STEREO–A
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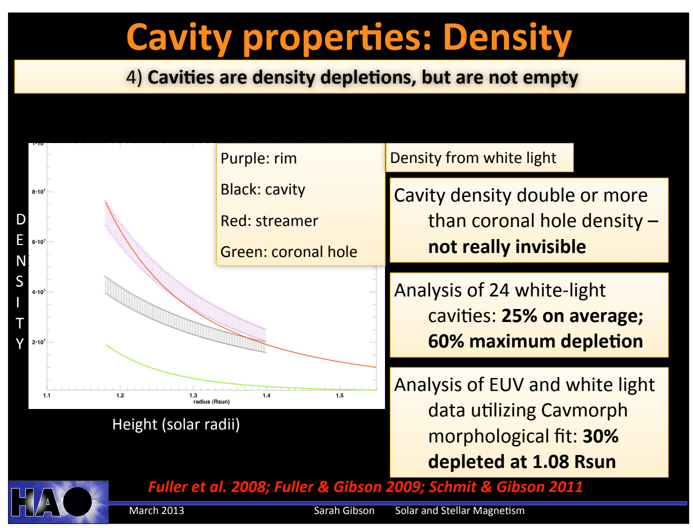
Cavity properties: Density
4) Cavities are density depletions, but are not empty
Purple: rim
Black: cavity
Red: streamer
Green: coronal hole
Density from white light
Cavity density double or more than coronal hole density – not really invisible
Analysis of 24 white-light cavities: 25% on average; 60% maximum depletion
Analysis of EUV and white light data utilizing Cavmorph morphological fit: 30% depleted at 1.08 Rsun
DENSITY
Height (solar radii)
Fuller et al. 2008; Fuller & Gibson 2009; Schmit & Gibson 2011
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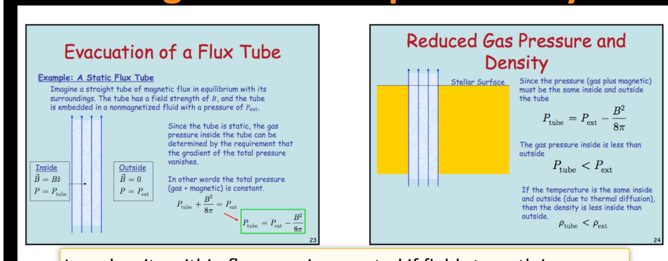
# Magnetic flux rope: Density




Low density within flux rope is expected if field strength is stronger inside than outside (e.g., due to axial component of

But: this pressure continuity jump only has to apply at the boundary -- twist profile could mean no (or little) axial component at outer surface of rope

And, low beta means a tiny difference of large fields could create a large density depletion (at least locally, and assuming constant temperature).

**Why do we see only a factor of ~two?**



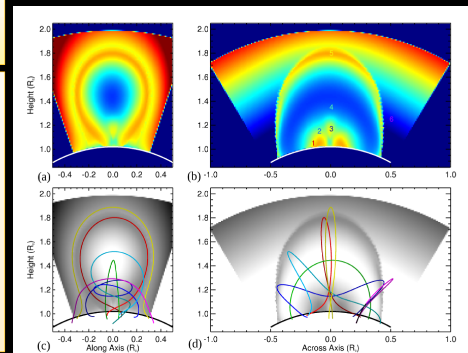
# Magnetic flux rope: Density

Short, axial field = density cavity

Need to think more carefully about pressure

Solving equations of hydrostatic equilibrium under uniform heating along flux rope field lines: short axial field lines are depleted ~35%

Length-to-height aspect ratio a fundamental limit

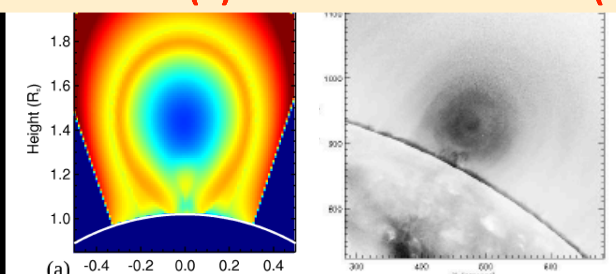



*Schmit, 2012*



# Magnetic flux rope: Density

**SHORT AXIAL FLUX: UNDERDENSE?**
**BOUNDARY(S) STILL FLUX SURFACE(S)**



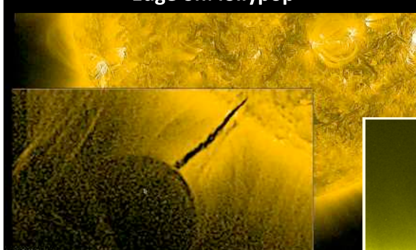


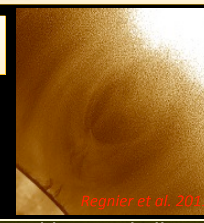

# Cavity properties: Sub-structure

5) **Cavities have sub-structure**

**Horn-like structures, above prominence and within cavity**

**Edge on: lollypop**






Cavities within cavities?

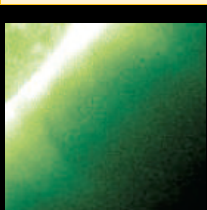

*Courtesy T. Berger*

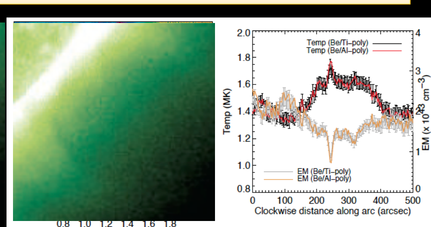


# Cavity properties: Sub-structure

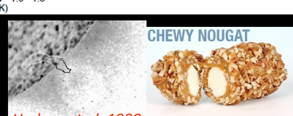
5) **Cavities have sub-structure**

**High-temperature soft-X-ray cores**






*Reeves et al., 2012*

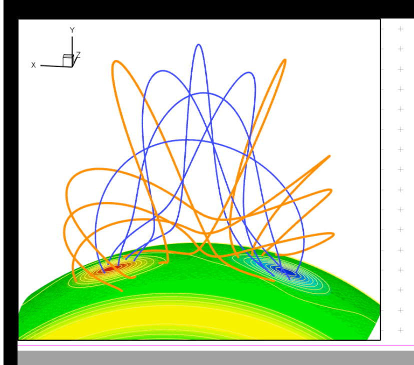



*Hudson et al. 1999*



# Magnetic flux rope: Sub-structure

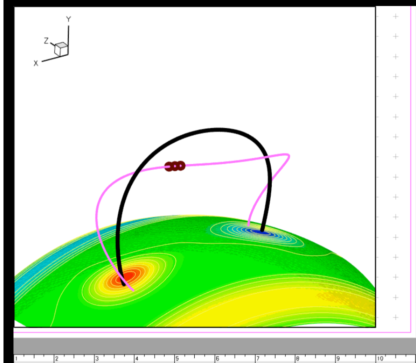
Dipped vs. nondipped field lines



- Flux rope winds just over one full turn
- Some field lines (orange) are dipped
- The inner field lines (blue) are undipped and fill most of the rope volume
- Prominence mass may collect on the (not-very-deeply) dipped field lines

# Magnetic flux rope: Sub-structure

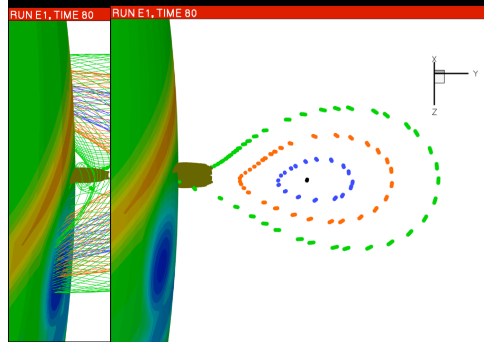
Dipped vs. nondipped field lines



• Prominence mass may collect on the (not-very-deeply) dipped field lines



# Magnetic flux rope: Sub-structure



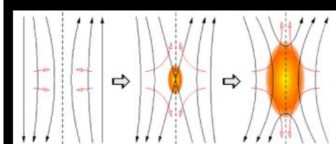

…it arches upwards, most …d lines do not have dips …upport prominence mass …avity

…l dips up to a prominence …cale height - would form a …prominence (brown)

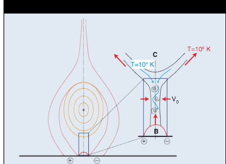
…rt of cavity (nondipped …ve prominence (lollypop)



# Magnetic flux rope: Sub-structure



Sub-structure may arise from magnetic X-line topology --> **reconnection**



Berger (2012)

Current sheet forms below center of flux rope, with dense horn-like enhancement

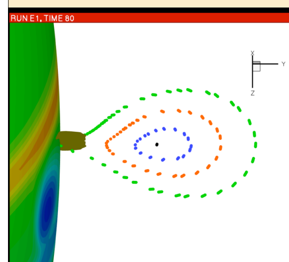
Reconnections lead to flows and low-density/high-temperature center internal to cavity (lollypop-like) Fan (2012)

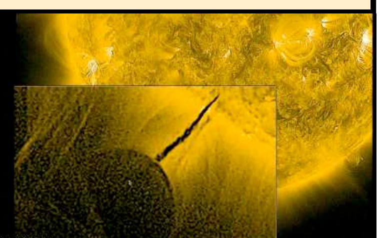
Remember sigmoids?



# Magnetic flux rope: Sub-structure

**SHAPE AND TOPOLOGY MATTERS**



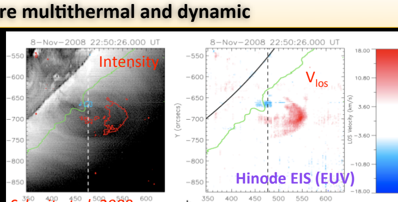


# Cavity properties: Dynamics

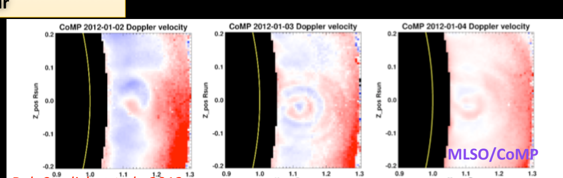
6) **Cavities are multithermal and dynamic**

**Line-of-sight flow in cavities**

**Doppler observations: Speeds of 5-10 km s−1, length scales of tens of megameters, persisting for at least one hour**




Schmit et al. 2009

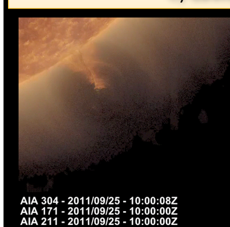



Bak-Steslicka et al., 2013



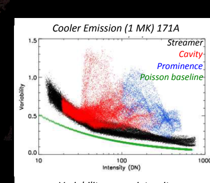
# Cavity properties: Dynamics

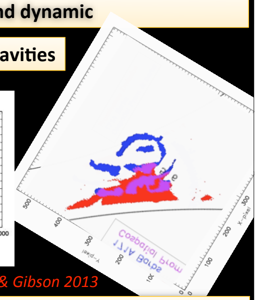
6) **Cavities are multithermal and dynamic**




Li et al., 2012

**Plane-of-sky flow in cavities**



Schmit & Gibson 2013

Swirling motions in plane of sky projection

Spatial and temporal correlation between coronal cavity (plane-of-sky) flows and prominence flows

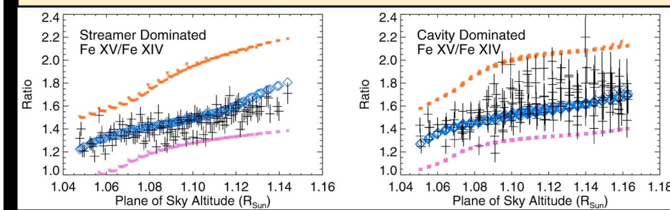
**Cavity and prominence flows are connected**

# Cavity properties: Dynamics

6) **Cavities are multithermal and dynamic**

**Cavity temperature:** building on 3D morphology (cavmorph) and density model, fit to observations of multiple Fe temperature-sensitive line ratios

A lot of variability in line ratios indicates multiple temperatures are present at a given height




Temperature-sensitive line-ratios, observations vs. model

Is cavity hotter or cooler than surrounding streamer? Yes

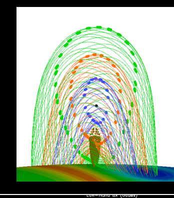
*Kucera et al. 2012*

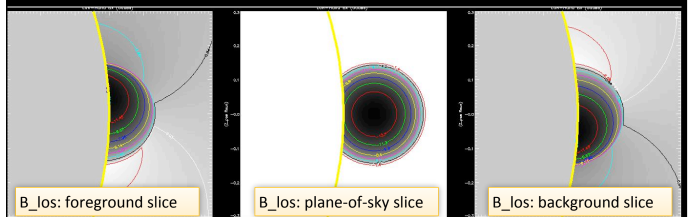


# Magnetic flux rope: Dynamics

Flows on flux surfaces

- field-aligned flow would peak at axis assuming constant velocity
- projection in front or behind the plane of sky would introduce asymmetries

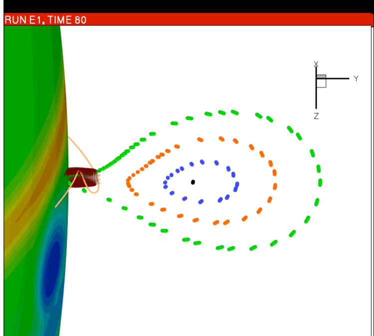




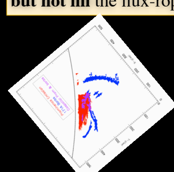



# Magnetic flux rope: Dynamics

Cavity-prominence connection




- *Schmit 2012* analyzed 1D hydrodynamic evolution along dipped magnetic field line --> thermal nonequilibrium *(Antiochos 1999)*
- Consistent with dynamic observations of EUV brightenings (horns) followed by formation of prominence
- Such flows would project throughout **but not fill** the flux-rope cavity volume

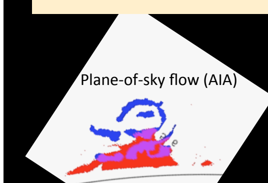


*See also Luna et al.* http://adsabs.harvard.edu/abs/2012ApJ...746...30L

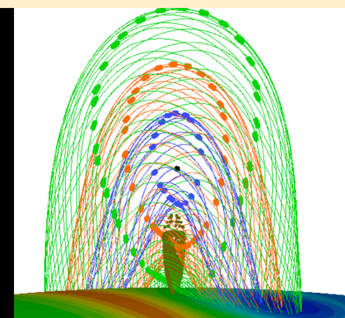


# Magnetic flux rope: Dynamics

**FLUX SURFACES MAKE BULLS-EYES!**



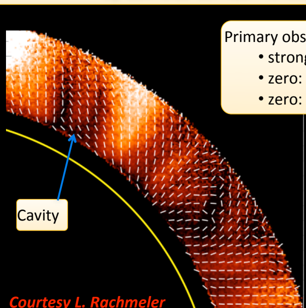

Line-of-sight flow (CoMP)





# Cavity properties: Linear Polarization

6) **Cavities contain linear polarization lagomorphs**




*Courtesy L. Rachmeler*

Primary observable: fraction of linearly-polarized light (P/I)
- strong signal: **B** in plane-of-sky (POS)
- zero: **B** along line-of-sight (LOS)
- zero: Van Vleck angle between **B** and radial = 54

P/I direction = POS component of B (integrated along LOS!)
- flips by 90 degrees at Van Vleck angle

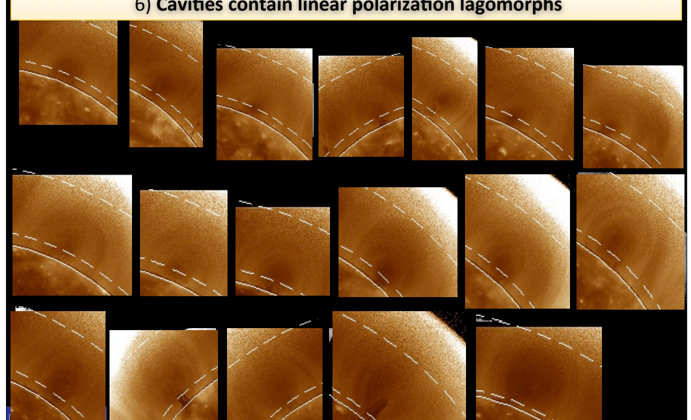
Sensitive to presence of coronal currents (Judge et al., 2006)

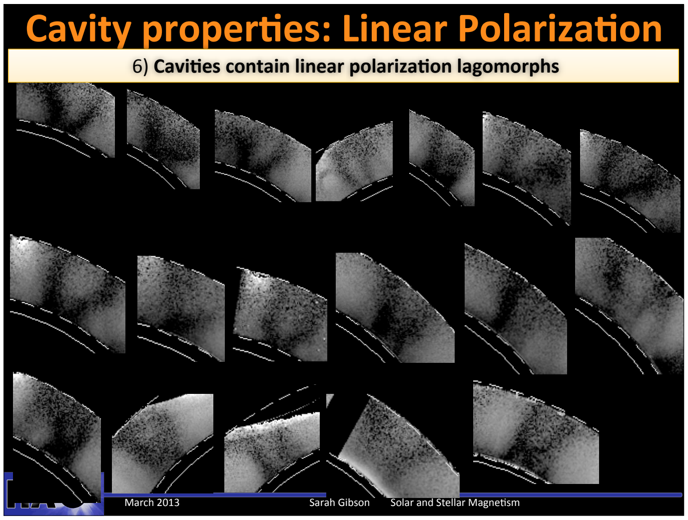
Coronal Multichannel Polarimeter (CoMP): new coronagraph that measures the Stokes vectors and the velocities in optically thin coronal emission lines



# Cavity properties: Linear Polarization

6) **Cavities contain linear polarization lagomorphs**




Cavity properties: Linear Polarization
6) Cavities contain linear polarization lagomorphs
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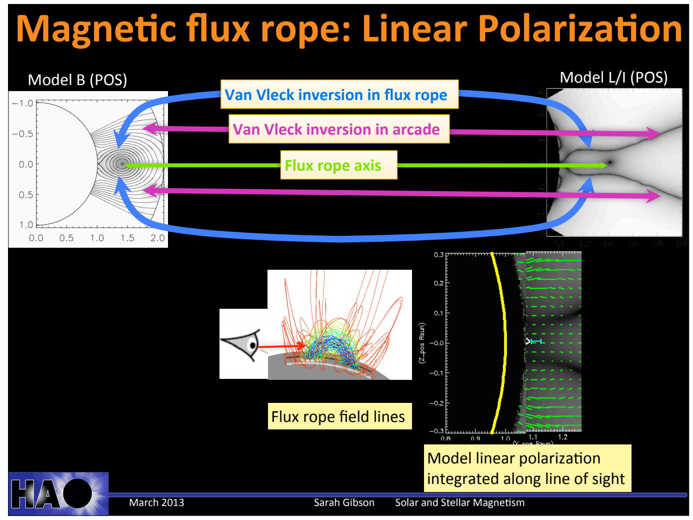
Magnetic flux rope: Linear Polarization
Model B (POS)
Model L/I (POS)
Van Vleck inversion in flux rope
Van Vleck inversion in arcade
Flux rope axis
Flux rope field lines
Model linear polarization integrated along line of sight
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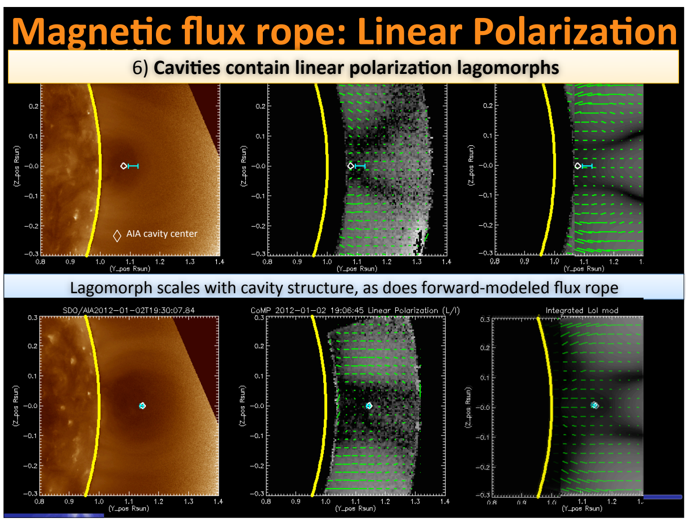
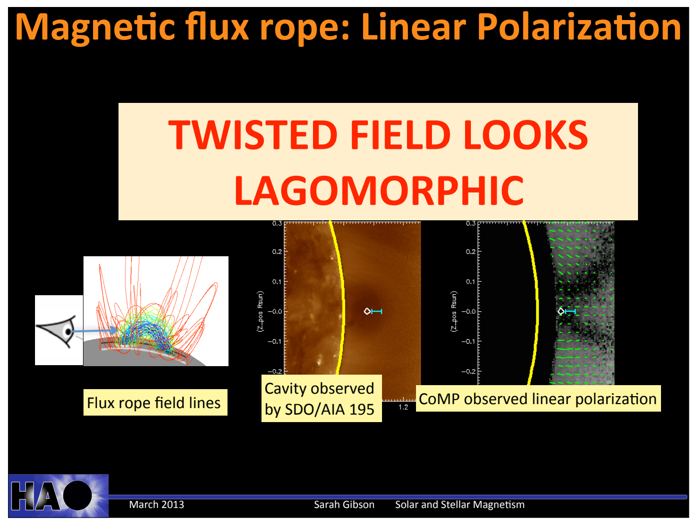

Magnetic flux rope: Linear Polarization
6) Cavities contain linear polarization lagomorphs
AIA cavity center
Lagomorph scales with cavity structure, as does forward-modeled flux rope


Magnetic flux rope: Linear Polarization
TWISTED FIELD LOOKS LAGOMORPHIC
Flux rope field lines
Cavity observed by SDO/AIA 195
CoMP observed linear polarization
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