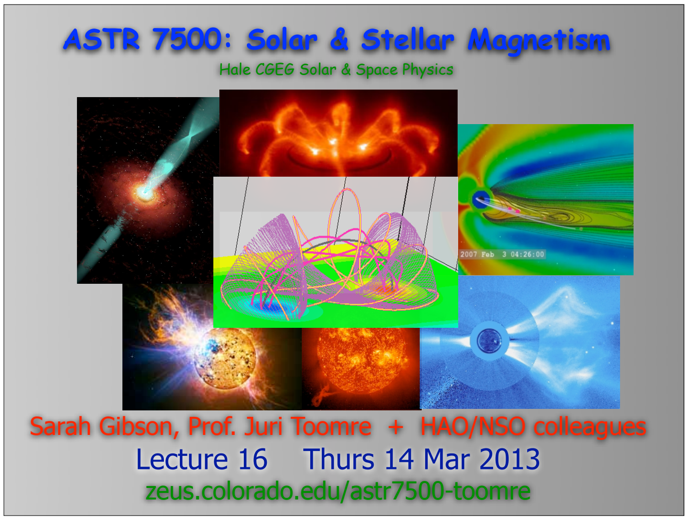
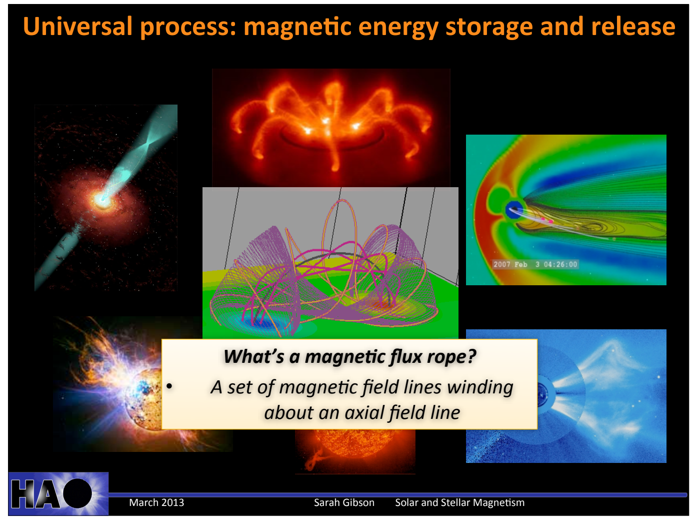

ASTR 7500: Solar & Stellar Magnetism
Hale CGEG Solar & Space Physics
2007 Feb 3 04:26:00
Sarah Gibson, Prof. Juri Toomre + HAO/NSO colleagues
Lecture 16 Thurs 14 Mar 2013
zeus.colorado.edu/astr7500-toomre


Universal process: magnetic energy storage and release
2007 Feb 3 04:26:00
What's a magnetic flux rope?
• A set of magnetic field lines winding about an axial field line
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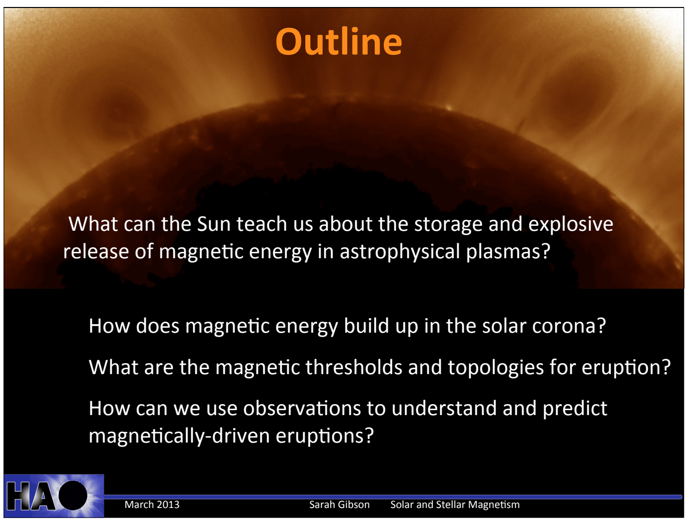
Outline
What can the Sun teach us about the storage and explosive release of magnetic energy in astrophysical plasmas?
How does magnetic energy build up in the solar corona?
What are the magnetic thresholds and topologies for eruption?
How can we use observations to understand and predict magnetically-driven eruptions?
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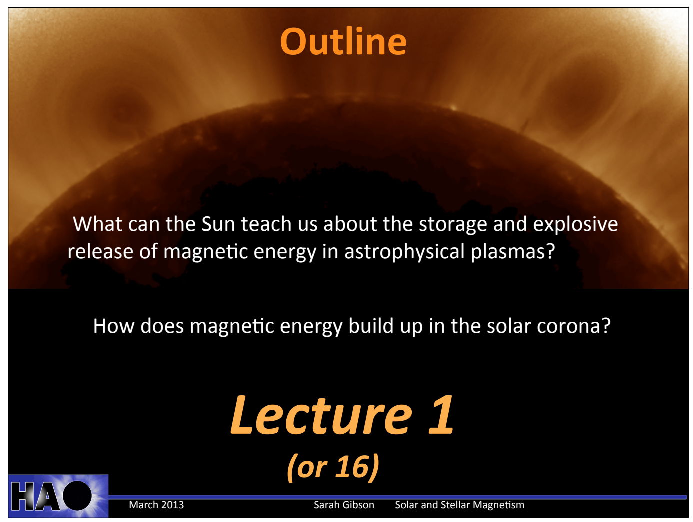
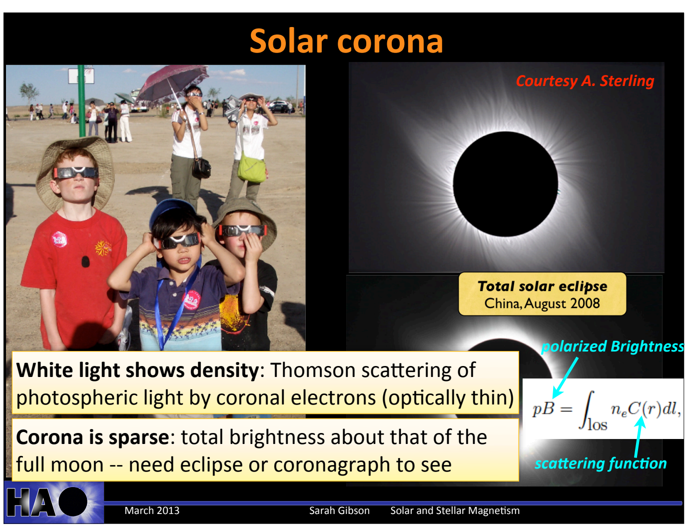
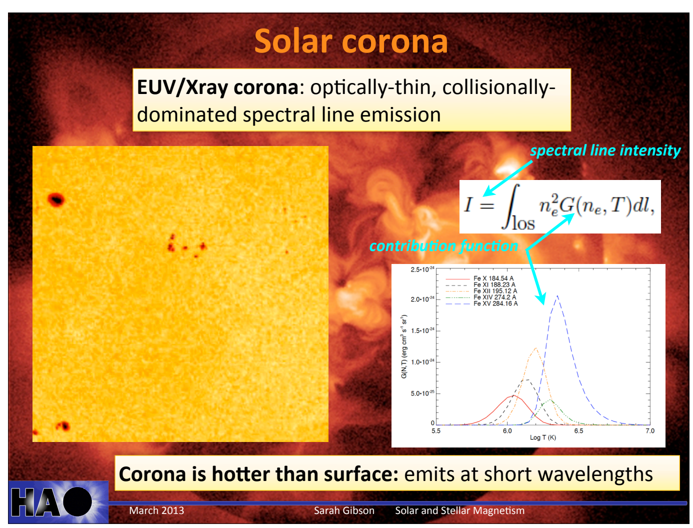
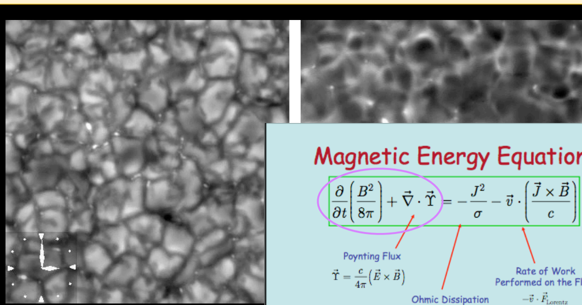

Outline
What can the Sun teach us about the storage and explosive release of magnetic energy in astrophysical plasmas?
How does magnetic energy build up in the solar corona?
Lecture 1
(or 16)
March 2013 Sarah Gibson Solar and Stellar Magnetism


Solar corona
Courtesy A. Sterling
Total solar eclipse
China, August 2008
polarized Brightness
$pB = \int_{\rm los} n_e C(r)\,dl,$
scattering function
White light shows density: Thomson scattering of photospheric light by coronal electrons (optically thin)
Corona is sparse: total brightness about that of the full moon -- need eclipse or coronagraph to see
March 2013 Sarah Gibson Solar and Stellar Magnetism


Solar corona
EUV/Xray corona: optically-thin, collisionally-dominated spectral line emission
spectral line intensity
$I = \int_{\rm los} n_e^2 G(n_e, T)\,dl,$
contribution function
Log T (K)
Corona is hotter than surface: emits at short wavelengths
March 2013 Sarah Gibson Solar and Stellar Magnetism

Coronal energy source

Continuous flows and magnetic flux emergence through the solar surface



Hinode SOT: High resolution movies in G-band (430nm) and Ca II H (397nm) showing the motion of granules and small magnetic flux

Magnetic Energy Equation

$$\frac{\partial}{\partial t}\left(\frac{B^2}{8\pi}\right) + \vec{\nabla}\cdot\vec{\Upsilon} = -\frac{J^2}{\sigma} - \vec{v}\cdot\left(\frac{\vec{J}\times\vec{B}}{c}\right)$$

Poynting Flux

$$\vec{\Upsilon} = \frac{c}{4\pi}\left(\vec{E}\times\vec{B}\right)$$

Ohmic Dissipation

Rate of Work Performed on the Fluid

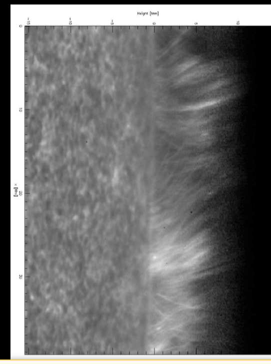
$$-\vec{v}\cdot\vec{F}_{Lorentz}$$

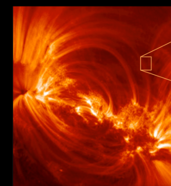
$$c_v\frac{DT}{Dt} = -(\gamma-1)c_v T\vec{\nabla}\cdot\vec{v} + \sigma^{-1}J^2 + \cdots$$

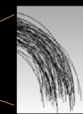
If the resistivity, σ^{-1}, is large enough, one might need to include resistive heating (ohmic dissipation) in the internal energy equation.

40

Coronal heating







Courtesy J. Klimchuk

Long timescale (slow, quasi-static stressing of the field)

Microflares (DC)

Short timescale (fast motions)

Waves (AC)

Parnell & de Moortel, 2012

http://arxiv.org/abs/1206.6097

Solar wind

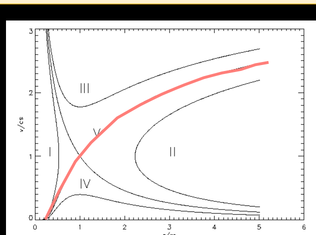
Hot corona --> solar wind

Parker wind: isothermal, steady, spherically symmetric

sound speed

$$\left(v - \frac{c_s^2}{v}\right)\frac{dv}{dr} = 2\frac{c_s^2}{r^2}\left(r - r_c\right)$$

Physical solution: supersonic above critical point, match interstellar pressure



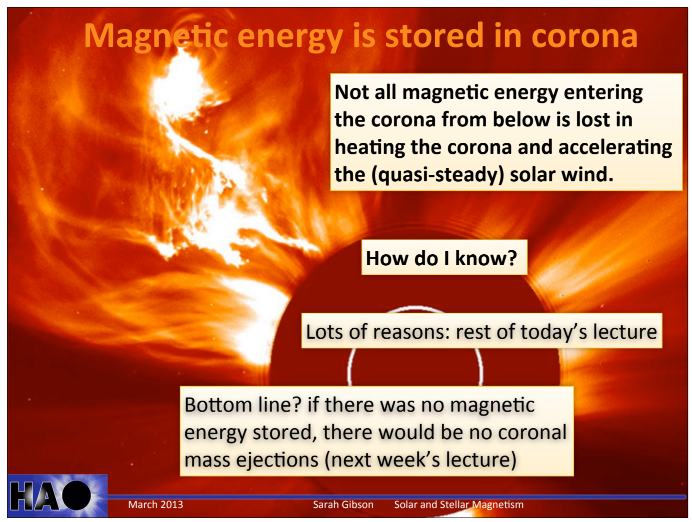
Details of acceleration - where and how energy is deposited

Wood, 2004 http://solarphysics.livingreviews.org/Articles/lrsp-2004-2/

Cranmer, 2009 http://solarphysics.livingreviews.org/Articles/lrsp-2009-3/

Ofman, 2010 http://solarphysics.livingreviews.org/Articles/lrsp-2010-4/

Magnetic energy is stored in corona



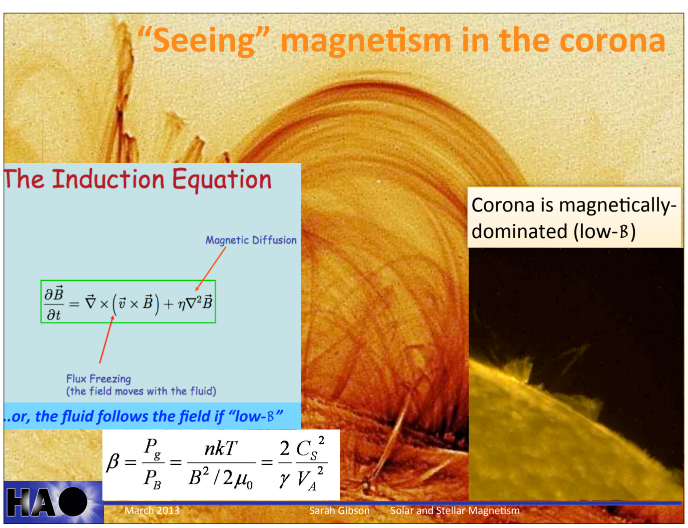
Not all magnetic energy entering the corona from below is lost in heating the corona and accelerating the (quasi-steady) solar wind.

How do I know?

Lots of reasons: rest of today's lecture

Bottom line? if there was no magnetic energy stored, there would be no coronal mass ejections (next week's lecture)

"Seeing" magnetism in the corona



The Induction Equation

Magnetic Diffusion

$$\frac{\partial\vec{B}}{\partial t} = \vec{\nabla}\times\left(\vec{v}\times\vec{B}\right) + \eta\nabla^2\vec{B}$$

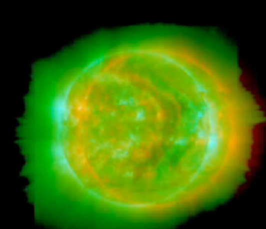
Flux Freezing
(the field moves with the fluid)

..or, the fluid follows the field if "low-β"

$$\beta = \frac{P_g}{P_B} = \frac{nkT}{B^2/2\mu_0} = \frac{2}{\gamma}\frac{C_S^2}{V_A^2}$$

Corona is magnetically-dominated (low-β)

Coronal magnetic fields



What we see is limited by where the plasma is - yet magnetism is everywhere!

One solution: Extrapolate

$$B_r(r,\theta,\phi) = \sum_{l=0}^{\infty}\sum_{m=-l}^{l} b_{lm}c_l(r)P_l^m(\cos\theta)e^{im\phi},$$

$$B_\theta(r,\theta,\phi) = -\sum_{l=0}^{\infty}\sum_{m=-l}^{l} b_{lm}d_l(r)\frac{dP_l^m(\cos\theta)}{d\theta}e^{im\phi},$$

$$B_\phi(r,\theta,\phi) = -\sum_{l=0}^{\infty}\sum_{m=-l}^{l}\frac{im}{\sin\theta}b_{lm}d_l(r)P_l^m(\cos\theta)e^{im\phi},$$

Coronal magnetic fields

But wait: what did we assume?

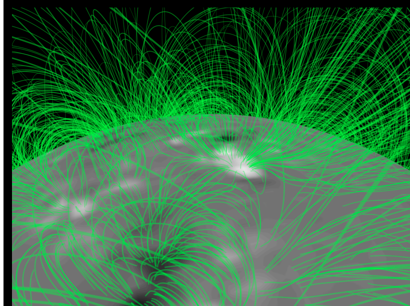
Potential field

no current $\nabla \times \mathbf{B} = 0,$

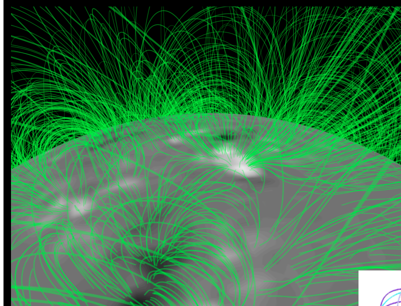
$\mathbf{B} = -\nabla\Psi,$

Solenoidal $\nabla \cdot \mathbf{B} = 0$

Laplace's equation $\nabla^2\Psi = 0,$



Coronal magnetic fields



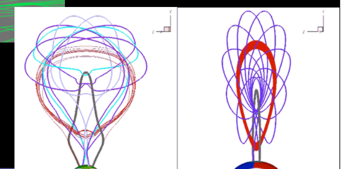
Free energy

Magnetic energy above that of potential field with the same boundary condition

$$F(\boldsymbol{B}) = E(\boldsymbol{B}) - E(\boldsymbol{B}_P)$$

$$E(\boldsymbol{B}) = \frac{1}{2\mu_0}\int_V B^2\, dV$$

Corona can store "free" magnetic energy in twisted (current-carrying) field



Force-free fields

Is there any other constraint we can apply?

Corona is magnetically-dominated (low-ß)

$$\rho\frac{D\vec{v}}{Dt} = \mathbf{X} + \frac{1}{4\pi}(\vec{\nabla}\times\vec{B})\times\vec{B} + \mathbf{X} + \mathbf{X} = 0$$

Pressure Force, Lorentz Force, Gravitational Force, Viscous Stress

Equilibrium

$$\nabla \times \mathbf{B} = \alpha\mathbf{B}$$

Currents parallel to field

The Lorentz force becomes (Magnetic Pressure Force, Magnetic Tension Force)

$$\frac{1}{4\pi}(\vec{\nabla}\times\vec{B})\times\vec{B} = -\vec{\nabla}\left(\frac{B^2}{8\pi}\right) + \frac{(\vec{B}\cdot\vec{\nabla})\vec{B}}{4\pi} = 0$$

Magnetic pressure and tension forces balance

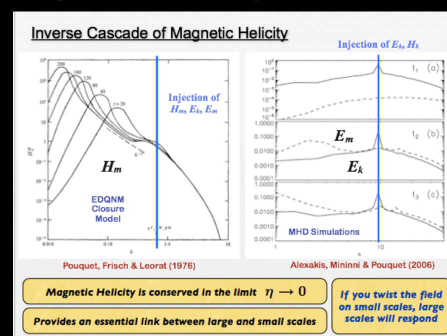
Wiegelmann & Sakurai, 2012 http://solarphysics.livingreviews.org/Articles/lrsp-2012-5

Mackay & Yeates, 2012 http://solarphysics.livingreviews.org/Articles/lrsp-2012-6

Magnetic helicity

$$H_k = \langle \boldsymbol{\omega}\cdot\boldsymbol{v}\rangle$$
$$H_m = \langle \boldsymbol{A}\cdot\boldsymbol{B}\rangle$$
$$H_c = \langle \boldsymbol{J}\cdot\boldsymbol{B}\rangle$$

$$\boldsymbol{\omega} = \nabla\times\boldsymbol{v}$$
$$\boldsymbol{B} = \nabla\times\boldsymbol{A}$$
$$\boldsymbol{J} = \frac{c}{4\pi}\nabla\times\boldsymbol{B}$$



Coronal magnetic helicity very nearly conserved as a global quantity (*Berger and Field, 1984*)

Just how twisted is it?

Helicity from snapshot at the photosphere?

If linear-force-free, current helicity (easy to observe) same sign as magnetic helicity

- Force-free assumption may not hold at photosphere
- helicity is a global quantity -- local observations may not reliably indicate global properties

Can we measure buildup of helicity by monitoring evolution of magnetic field at the photosphere?

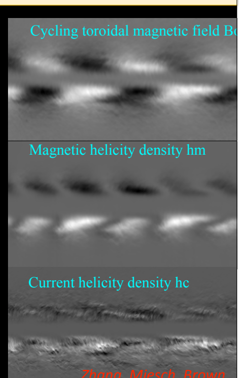
emergence

$$\left.\frac{dH}{dt}\right|_S = 2\int_S(\mathbf{A}_p\cdot\mathbf{B}_t)V_{\perp n}dS - 2\int_S(\mathbf{A}_p\cdot\mathbf{V}_{\perp t})B_n dS,$$

shear

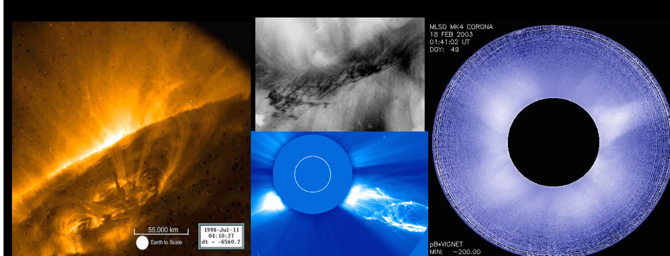
Perhaps (assuming you can measure flows) (*Demoulin&Berger 2003*), but

- Only see one side of sun
- Reconnection between evolving structures complicates things



How about coronal observations?

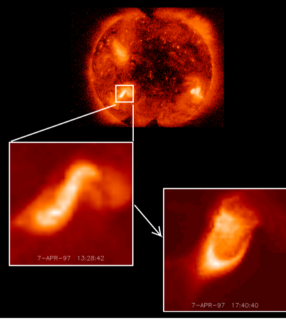
Would we recognize twist if we saw it?



Maybe --
twisting motions, braided morphologies....

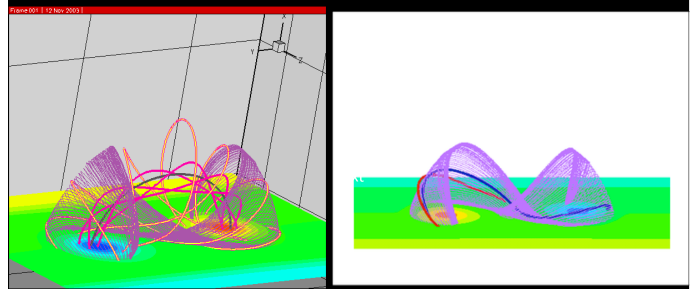
Would we recognize twist if we saw it?

Sigmoids…



Active regions are significantly more likely to produce flares or CMEs when associated with sigmoid structures. (*Canfield et al., 1999*)
Such structures are especially well-defined at the onset of an eruption, but also **exist quiescently**

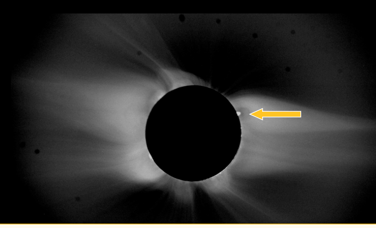
Would we recognize twist if we saw it?

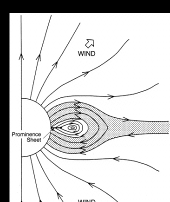


Dynamic evolution of flux rope field lying above and within separatrix surface relative to the shorter, arcade-type field below and external to it, could result in tangential discontinuities, leading to the the formation of electric current sheets along the separatrix surface *(Parker, 1994; Titov and Demoulin, 1999; Low and Berger, 2000; Gibson et al., 2004)*.

Would we recognize twist if we saw it?

Cavities





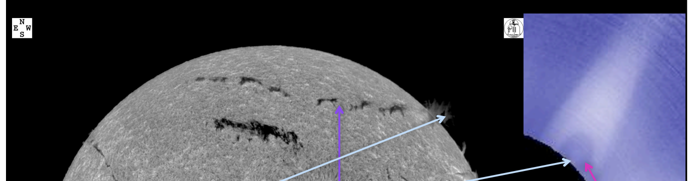
Low & Hundhausen, 1995

Flux rope model of 3-part quiescent structure

- Prominence core sits in dips of flux rope
- Cavity is region of relatively strong magnetic pressure, isolated from surrounding fields
- Streamer shows outer boundary of magnetic flux rope

Stored energy: prominence cavities

Storage stage: prominences and cavities lie above solar-surface magnetic neutral lines; stable for days/weeks

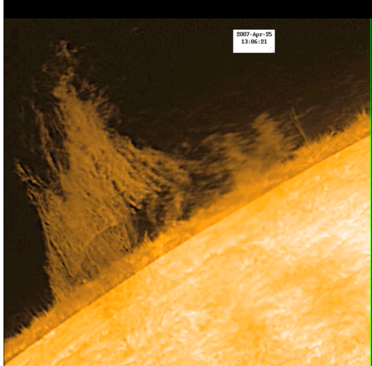


Prominence: (relatively) cool, dense plasma suspended in the corona, supported by magnetic fields

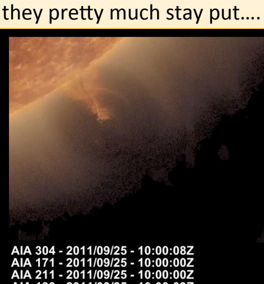
Surrounded by dark, **coronal cavity**

Called a **filament** if seen on the solar disk

Stored energy: prominence cavities

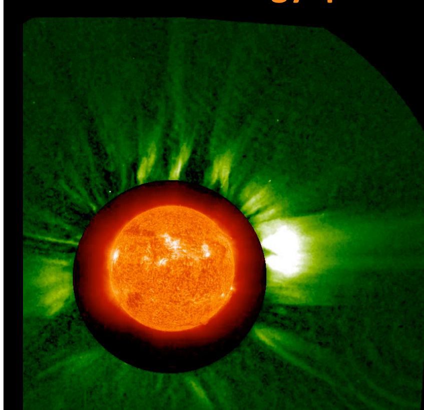


…Actually they are quite dynamic when you look close enough -- but on large-scale, they pretty much stay put….



Li et al. 2012

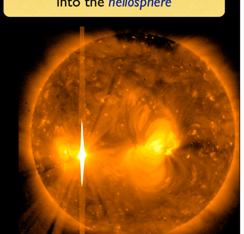
Released energy: prominence cavities



…until BANG!!

Coronal Mass Ejection

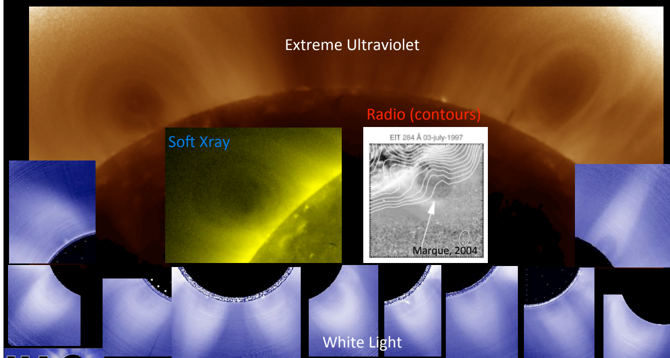
Eruptions
Fed by a release of magnetic energy, CMEs and solar flares send particles and radiation streaming into the *heliosphere*



Cavity properties

1) **Cavities are ubiquitous**

They are visible at a broad range of wavelengths

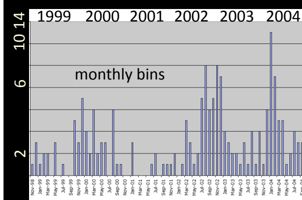


Cavity properties

1) **Cavities are ubiquitous**

Most days you can see them (except maybe at solar maximum)

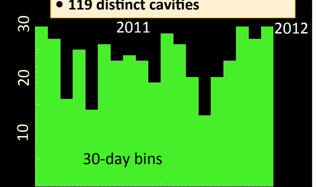
November 1998 -- September 2004
- **206/2162 days with clear cavities**
- **98 distinct cavities**



Only cavities **> occulter (1.15 Rs)** can be identified

Gibson et al., 2006

June 1, 2010 - Dec 31. 2012
- **449/575 days with clear cavities**
- **119 distinct cavities**



The EUV corona (193 A) during the ascending phase of the cycle has proven to be an excellent period for studying cavities: **one or more cavities are visible most days.**

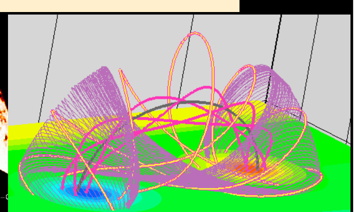
Forland et al., 2013

Magnetic flux rope: Ubiquity

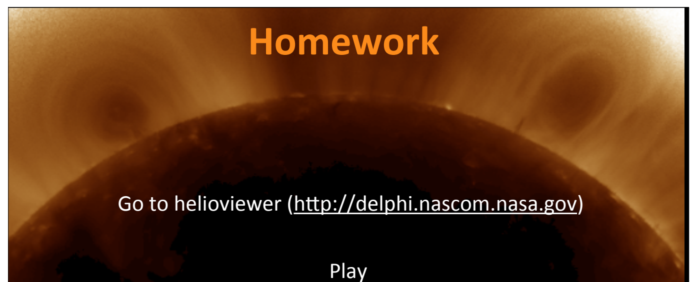
Flux ropes are to be expected.

- 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



Homework



Go to helioviewer (http://delphi.nascom.nasa.gov)

Play

Find an example of stored magnetic energy

Email me image, and explanation of what indicates stored energy, by Monday PM (sgibson@ucar.edu)