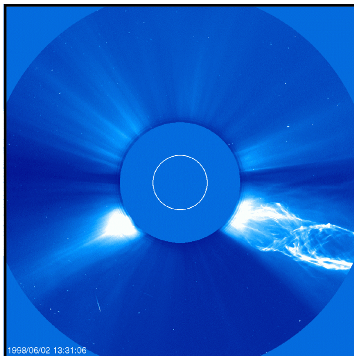

3D and twisted: MHD modeling of Coronal Mass Ejections

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Sarah Gibson 25 February 2002

TRACE movies from
http://vestige.lmsal.com/TRACE/Science/ScientificResults/trace_cdrom/html/mov_page.html

TRACE:
171 Angstroms

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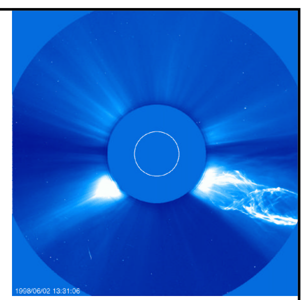
Outline and motivation



- **The CME from different views**
  - •Solar limb vs. solar disk
  - •Dependence on plasma observables (e.g. T, N_e)
- **Observations of twist**
  - •Apparent twist in coronal plasma associated with CMEs
  - •Corona nearly a perfect conductor --> flux freezing
  - •Coronal magnetic field is not directly/comprehensively observed
  - •Plasma observations <--models--> magnetic structures
- **CME models**
  - •Magnetic field topology: sigmoids, slinkies, and spheromaks?
  - •Full MHD model *(Gibson and Low, 1998)*
- **Conclusions**
  - •Potential implications of twist for CME energetics and prediction
  - •Models allow a 3-D deconstruction of observations

Coronal Mass Ejections

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- Episodic expulsions of plasma >~ 10^{15} grams each

Coronal Mass Ejections

- Affect the Earth:

  geomagnetic storms

Solar blast seen cradle to grave

By Tim Friend
USA TODAY

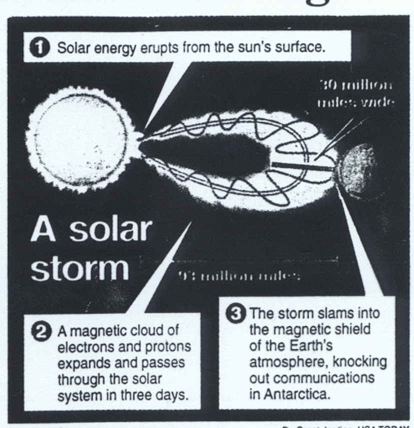
For the first time, scientists have recorded a massive burst of energy as it erupted from the sun, swept across the solar system and slammed into the magnetic shield that surrounds Earth, NASA said Wednesday.

The explosive release of solar energy known as a coronal mass ejection occurred Jan. 7 and traveled 1 million mph to the Earth as a magnetic cloud, growing to 30 million miles deep by the time it struck Jan. 10.

"What made this event so remarkable is that we got to see it as it was born, it came directly toward the Earth and we could observe it several days before it approached," said solar physicist Barbara Thompson of the International Solar Terrestrial Physics Program (ISTPP).

The eruption knocked out communications in Antarctica but had no other confirmed serious effects.

Solar storms can cause large scale power blackouts, interfere with sensitive military radar and disrupt global satellite systems and telecommunications.



Source: NASA — By Grant Jerding, USA TODAY

Detection and tracking of the solar storm was made with the ISTPP's sun-observing SOHO, WIND and POLAR spacecrafts. By the time the energy hit Earth, a total of 20 satellites and 12 countries had been watching.

Robert Hoffman, POLAR project physicist, says the successful observation marks the beginning of an era in which the scientists can predict when raging solar storms will strike the Earth and their effects.

The sun is now in a quiet period, but Hoffman says over the next five years an increasing number of solar eruptions with much greater force are expected.

White light CMEs

- 3-Part structure

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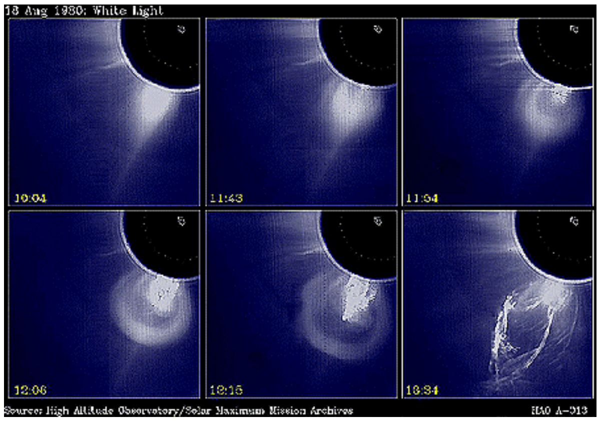
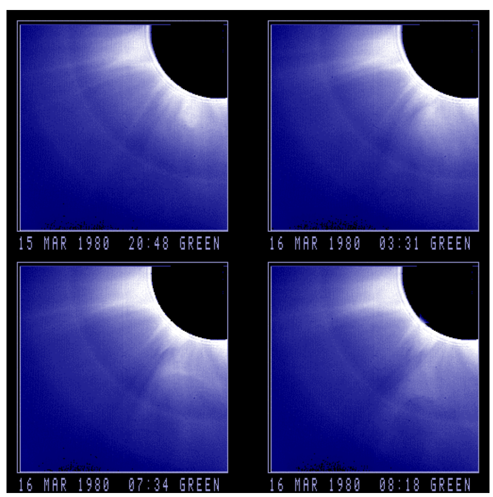


White light CMEs

- U-shape



White light CMEs

- Halo

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Video decompressor
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CMEs (and associated phenomena) in emission

- “Cold” emission ~ 10^4 K -- H-alpha): prominence eruption

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GIF decompressor
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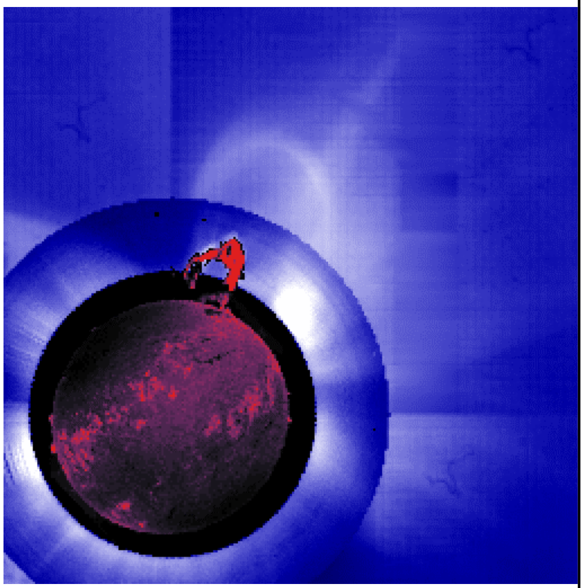

..or absorption

TRACE:
195 Angstroms

QuickTime™ and a
Photo decompressor
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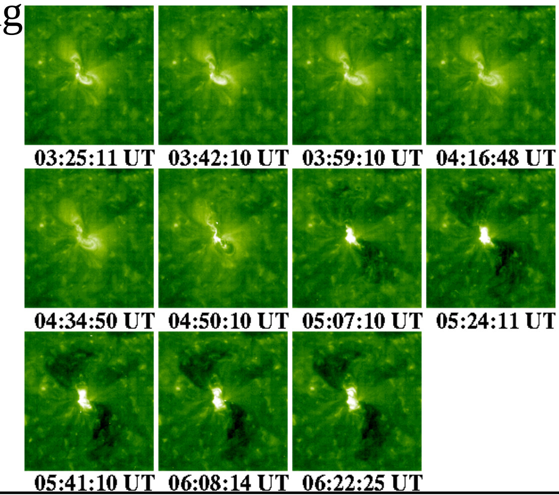
TRACE:
195 Angstroms

QuickTime™ and a
Photo decompressor
are needed to see this picture.

CMEs (and associated phenomena) in emission

- Hot emission (~ 10^6 K -- FeXII): Dimming

QuickTime™ and a decompressor are needed to see this picture.



CMEs (and associated phenomena) in emission

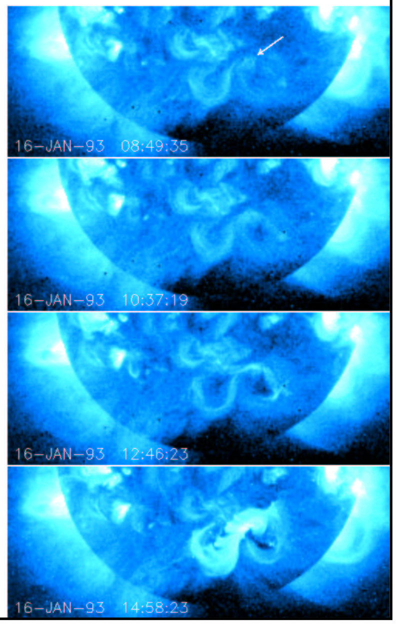
- Hot emission (~ 10^6 K -- FeXII): “EIT” waves

QuickTime™ and a Cinepak decompressor are needed to see this picture.

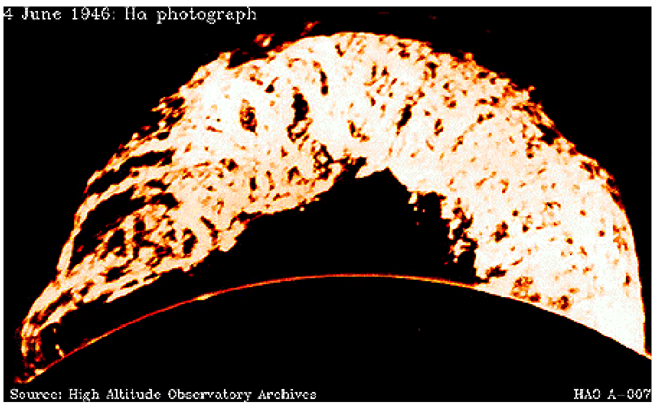
CMEs (and associated phenomena) in emission

- Hotter emission

(~ 3-4 X 10^6 K -- X-ray): dimmings, S-shaped "sigmoid"

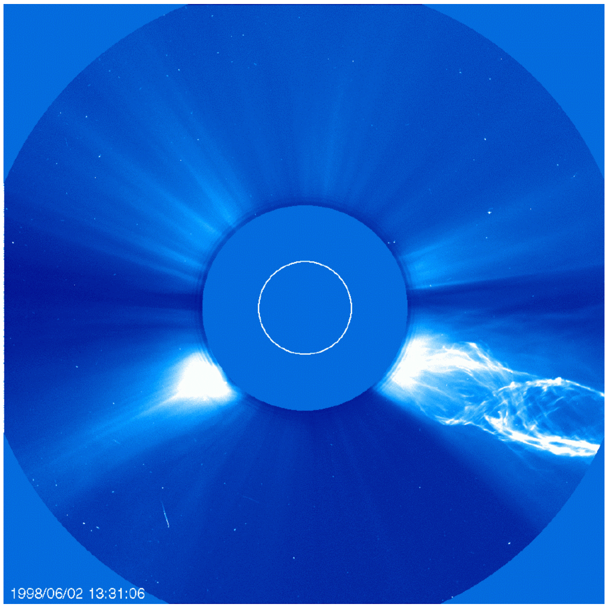


CMEs have a complex, 3D density and temperature structure.

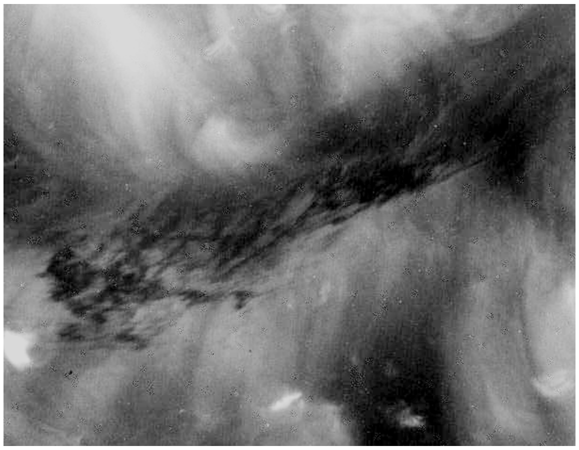


3D complexity is well illustrated by twisted structures associated with CMES

Apparent twist in white light CME core

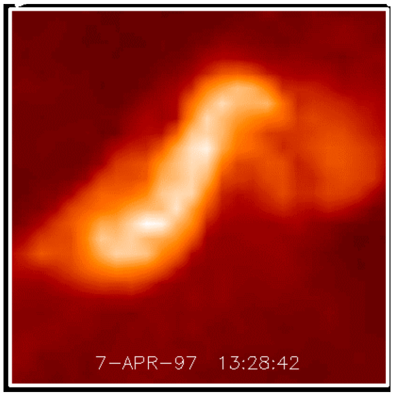


Apparent braided type structure seen in filament (projected on solar disk)



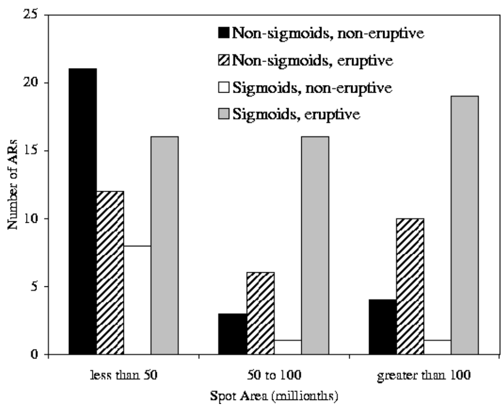
Sigmoids

- What are they?
  - S-shaped structures, most easily visible in X-rays
  - Can last for days, and disappear and reform multiple times



Sigmoids

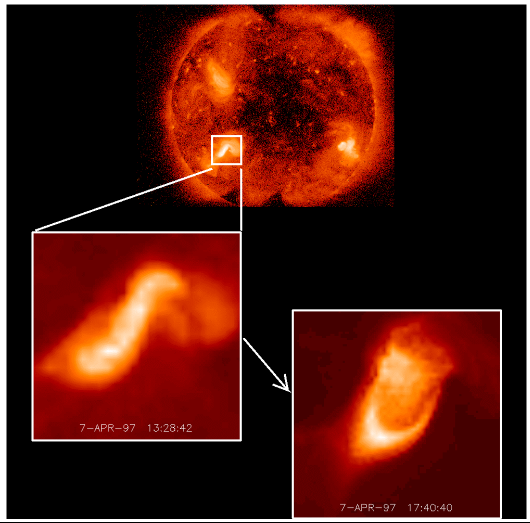
- How are they related to CMEs?
  - Statistically shown to be more likely to erupt than non-sigmoidal active regions



(Canfield et al, GRL, 26, 6, 627, 1999)

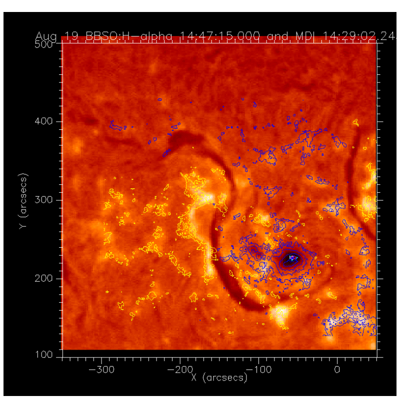
Sigmoids

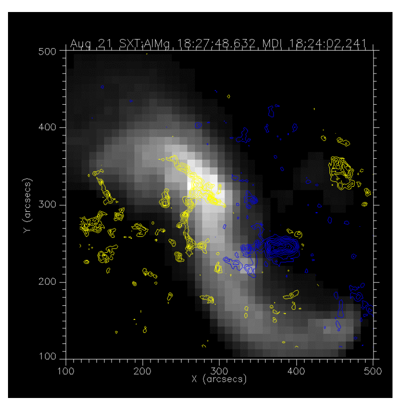
- S-shape --> cusp-shape in X-rays, sometimes followed by Halo CMEs in white light



Sigmoids

- How are they related to filament/prominence eruptions?
  - Sigmoidal filaments sometimes visible, roughly coaligned with X-ray sigmoid, above magnetic neutral line





Could filaments be better indicators of sigmoidicity than X-ray?

Sigmoids

- Are sigmoids good for predicting Earth-impacting events?
  - Must go off at right time and right place
  - Must be geo-effective ==> e.g. southward direction of field
  - Limited, but potentially useful space-weather prediction tool

Regardless of whether sigmoids are good forecast tools, they are important physical clues to the twisted nature of the CME and its precursor.

...but be careful of how you choose a name...

YAHOO! SEARCH RESULTS BY: Inktomi Help - Personalize

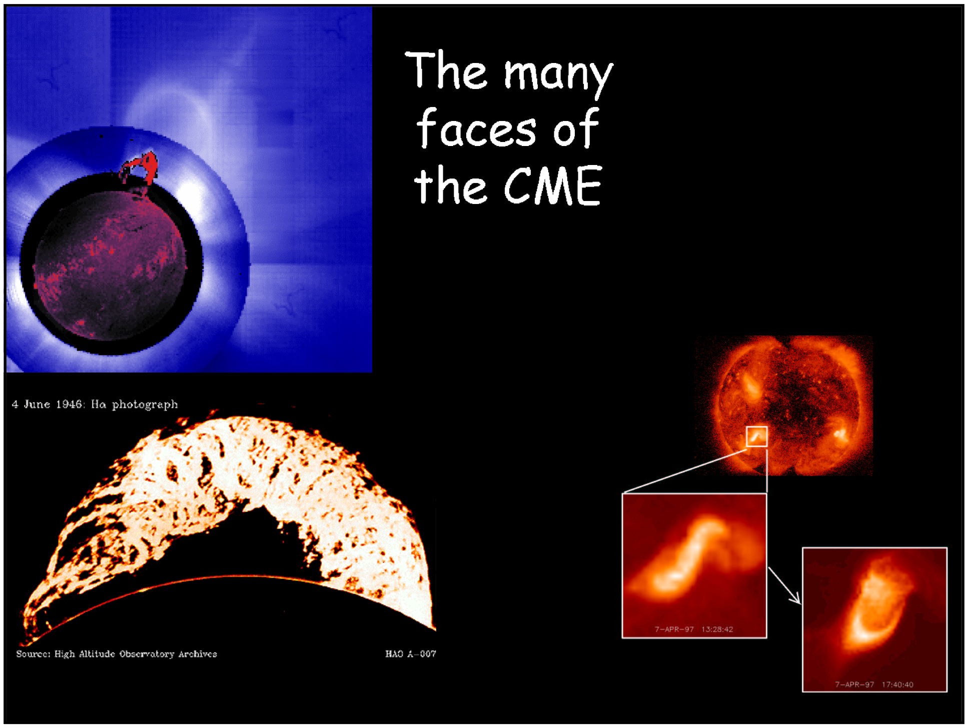
Search Result Found **3679** web pages for **sigmoid**

Gateway www.gateway.com All you need is this great idea and the biggest red bow you can find.

Categories Web Sites Web Pages Related News Net Events

Web Pages (1-20 of 3679)

- Tracking a **Sigmoid** January 16, 1993 with SXT - Tracking a **Sigmoid** January 16, 1993 Jan 13 Jan 14 Jan 15 Jan 16 Yohkoh mpg movie or anim_gif note bottom left & alternate color table Resources: SXT Jan 16 Movies Standard Color Table (500K anim_gif or 28K mpg) Alternate Color Table (450K anim_gif.
  --http://solar.physics.montana.edu/press/16jan93
- Colonic Removal of a 'Pop-Up Meat Thermometer' from the **Sigmoid** Colon - Colonic Removal of a 'Pop-Up Meat Thermometer' from the **Sigmoid** Colon by R. G. Norfleet and G. Skerven and H. T. Chatterton @article{NorSkeChaUNKNa, author = {R. G. Norfleet and G. Skerven and H. T. Chatterton}, journal = {{Journal of Clinical..
  --http://www.cs.uq.edu.au/~bof/Bib/NorSkeChaUNKNa.html



Theoretical description of CMEs

Need to solve ideal magnetohydrodynamic (MHD) equations in order to self-consistently describe the magnetic field and its interaction with the coronal plasma.

$$\rho\left[\frac{\partial \boldsymbol{v}}{\partial t} + (\boldsymbol{v}\cdot\nabla)\boldsymbol{v}\right] = \frac{1}{4\pi}(\nabla\times\boldsymbol{B})\times\boldsymbol{B} - \nabla p - \rho\frac{GM}{r^2}\hat{\boldsymbol{r}}\,, \quad (1)$$

$$\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho\boldsymbol{v}) = 0\,, \quad (2)$$

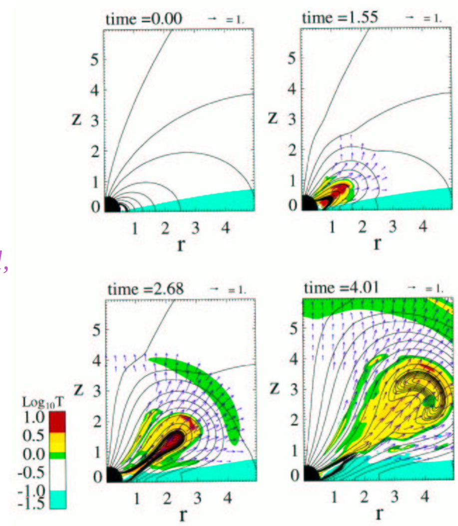
$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla\times(\boldsymbol{v}\times\boldsymbol{B})\,, \quad (3)$$

$$\frac{\partial}{\partial t}(p\rho^{-\gamma}) + (\boldsymbol{v}\cdot\nabla)(p\rho^{-\gamma}) = 0\,, \quad (4)$$

Model complexity must be sufficient to reproduce the essential observational complexities.

CME-type phenomena associated with accretion disks?

Figure 1 from *Hayashi et al, ApJ, 1996.*



Numerical simulation of sheared magnetic loops connecting a protostar and its disk. The color scale shows the temperature, solid curves denote magnetic field lines. The region of closely spaced field lines is included to identify the reconnection region in the subsequent frames. Arrows depict velocity vectors in the r-z plane. The unit velocity is shown by arrows at the top right of each panel.

Magnetic breakout model of CME (Antiochos et al, ApJ, 1999)

From *P. Macneice web page, http://ESS.gsfc.nasa.gov/macneice/cme.html*

QuickTime™ and a
BMP decompressor
are needed to see this picture.

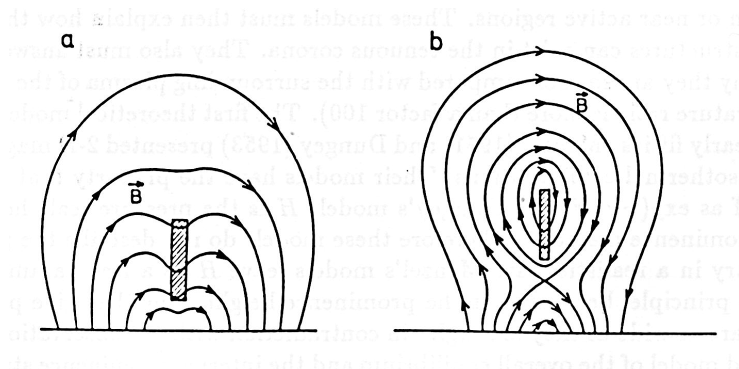
Magnetic field models

- Prominence mass could be supported by dips in magnetic arcades
- Magnetic flux rope (slinky) preferable to us for several reasons:
  - Bottoms of the winds - stable place for mass to collect
  - Matches observed "inverse" magnetic field configuration easily
  - Prominence/CME cavity observed to have sharp boundary, modeled by flux rope boundary
  - Twisted structures are observed, and theoretically expected because of conservation of helicity (related to twist)

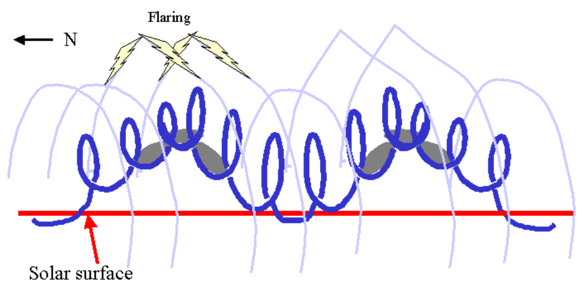
Slinky-type flux ropes have been used to model emerging magnetic flux, prominences, CMEs, and interplanetary magnetic clouds.

Prominence/filament magnetic field

Normal vs. inverse field geometry:



Magnetic field models



Slinky-type flux ropes have been used to model emerging magnetic flux, prominences, CMEs, and interplanetary magnetic clouds.

Spheromaks

Spherical, closed magnetic system containing comparable toroidal and poloidal magnetic fields generated by currents within the structure

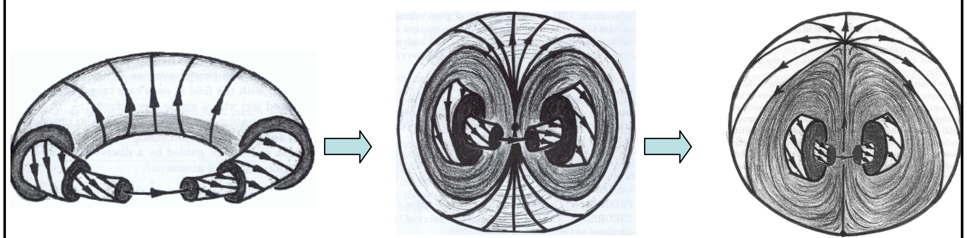
Why do we use them to model CMEs?

- Circular cross-section: CME observations don't support linear-type structure *(Fisher&Munro, 1984; Webb, 1988; Thompson et al, 1999)*
- Vector magnetogram observations of emerging field orientation and rotation well captured by spheromak model *(Lites et al, 1995)*
- Spheromak model solution yields plasma distributions satisfying a range of observed prominence structures and always yields a bubble-type cavity

Spheromaks represent the spheroidal nature of CMEs better than a linear slinky.

What are spheromaks?

Spherical, closed magnetic system containing comparable toroidal and poloidal magnetic fields generated by currents within the structure



Images from Cantarella, et al., 1999 ---> standard model of crab nebula, (*Woltjer, 1958*):

MHD Model: *Gibson and Low (1998)*

Interior (spheromak) solution (*Prendergast,1956; Woltjer, 1958; Lites et al, 1996*):

$$\boldsymbol{b}_{\rm int} = \frac{1}{r' \sin\theta'}\left(\frac{1}{r'}\frac{\partial A}{\partial \theta'}\,\hat{r}' - \frac{\partial A}{\partial r'}\,\hat{\boldsymbol{\theta}}' + \alpha_0 A \hat{\boldsymbol{\phi}}'\right),$$

$$A = \frac{4\pi a_1}{\alpha_0^2}\left[\frac{r_0^2}{g(\alpha_0 r_0)}\, g(\alpha_0 r') - r'^2\right]\sin^2\theta',$$

$$g(\alpha_0 r') = \frac{\sin(\alpha_0 r')}{\alpha_0 r'} - \cos(\alpha_0 r'),$$

$$J_{5/2}(\alpha_0 r_0) = 0,$$

MHD Model: *Gibson and Low (1998)*

External solution: split monopole with offset spherical flux surface:

$$\boldsymbol{b}_{\mathrm{ext}} = \frac{1}{r \sin\theta}\left(\frac{1}{r}\frac{\partial A}{\partial \theta}\,\hat{\boldsymbol{r}} - \frac{\partial A}{\partial r}\,\hat{\boldsymbol{\theta}}\right)$$

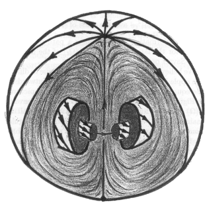
$$A = \Psi_0 + \Psi_1 + \Psi_2$$

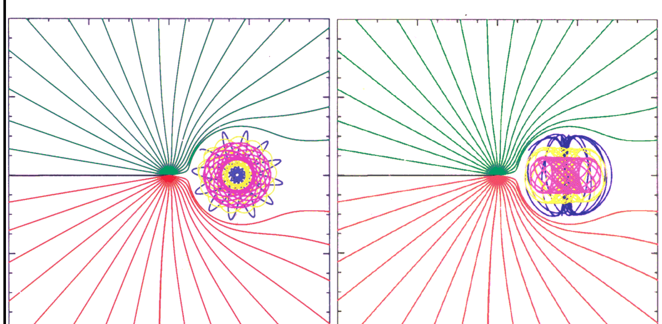
$$\Psi_0 = \cos\theta$$

$$\Psi_1 = -\frac{1}{r_0}\,\frac{r_1(r^2 + r_1^2 - r_0^2) + r\cos\theta(r_0^2 - 2r_1^2)}{[(r_0^2 - r_1^2)^2 + r_1^2 r^2 + 2rr_1(r_0^2 - r_1^2)\cos\theta]^{1/2}}$$

$$\Psi_2 = \frac{1}{r_0}(r^2 + r_1^2 - 2rr_1\cos\theta)^{1/2}$$

"Spheromak" field (e.g. magnetized star *(Prendergast,1956)*; **standard model of crab nebula,** *(Woltjer, 1958)*; **Delta sunspot** *(Lites et al, 1996)*):





MHD Model: *Gibson and Low (1998)*

MHD Model: *Gibson and Low (1998)*

- Spheromak-type field, radially stretched and tethered to solar origin
- Axisymmetry is broken, gravity is explicitly included

$$\frac{1}{4\pi}(\nabla \times \boldsymbol{b}) \times \boldsymbol{b} - \nabla \Pi = 0 \qquad \nabla \cdot \boldsymbol{b} = 0\,,$$

$$\xrightarrow{\Lambda = kr + a}$$

$$\frac{1}{4\pi}(\nabla \times \boldsymbol{B}) \times \boldsymbol{B} - \nabla p - \rho F(r)\hat{\boldsymbol{r}} = 0 \qquad \nabla \cdot \boldsymbol{B} = 0\,.$$

$$B_r(r, \theta, \phi) = \left(\frac{\Lambda}{r}\right)^2 b_r(\Lambda, \theta, \phi)\,,$$

$$B_\theta(\mathrm{r}, \theta, \phi) = \frac{\Lambda}{r}\frac{d\Lambda}{dr} b_\theta(\Lambda, \theta, \phi)\,,$$

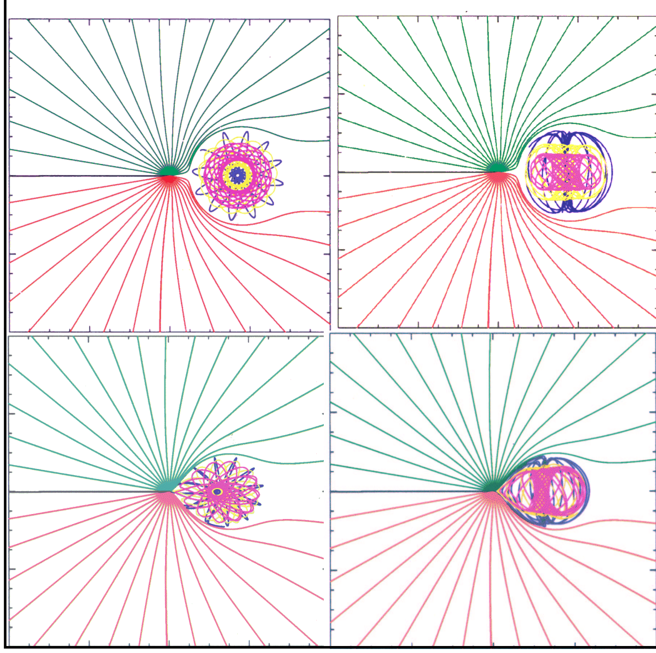
$$B_\phi(\mathrm{r}, \theta, \phi) = \frac{\Lambda}{r}\frac{d\Lambda}{dr} b_\phi(\Lambda, \theta, \phi)\,,$$

$$\Pi = a_1 A\,.$$

$$p = \frac{\Lambda^2}{r^2}\left(k^2 - \frac{\Lambda^2}{r^2}\right)\left(\frac{b_r^2}{8\pi}\right) + \frac{\Lambda^2}{r^2} k^2 \Pi\,.$$

$$\rho = \frac{1}{F(r)}\left[-\frac{\Lambda^2}{r^2} k\left(k^2 - \frac{\Lambda^2}{r^2}\right)\frac{d}{d\Lambda}\left(\Pi + \frac{b^2}{8\pi}\right) + 2\frac{\Lambda}{r}\frac{ak^2}{r^2}\Pi + \frac{1}{4\pi}\frac{\Lambda}{r}\frac{a}{r^2}\left(k^2 - 2\frac{\Lambda^2}{r^2}\right)b_r^2 + \frac{\Lambda^2}{r^2}k\left[\frac{a^2}{r^2} + \frac{2ka}{r}\right]\left[\frac{b_\theta^2 + b_\phi^2}{4\pi\Lambda}\right]\right].$$

MHD Model: *Gibson and Low (1998)*



MHD Model: *Gibson and Low (1998)*

- Spheromak-type field, radially stretched and tethered to solar origin
- Axisymmetry is broken, gravity is explicitly included
- "New" slinky-type feature suspended above imposed photosphere --> prominence!
- Describes self-similar expansion of CME moving radially outwards

Our model is a 3D, analytic solution satisfying time-dependent ideal MHD equations exactly for a CME expanding out into the corona.

MHD Model: *Gibson and Low (1998)*

Self-similar solution ***(Low, ApJ, 1986)*****:**

$$\zeta = \frac{r}{\Phi_{ss}}$$

$$\boldsymbol{v} = r\frac{1}{\Phi_{ss}}\frac{d\Phi_{ss}}{dt}\hat{\boldsymbol{r}}$$

$$\left(\frac{d\Phi_{ss}}{dt}\right)^2 = \frac{\eta\Phi_{ss} - 2\alpha}{\Phi_{ss}}$$

$$\boldsymbol{B} = \frac{1}{\Phi_{ss}^2}\boldsymbol{H}(\zeta, \theta, \phi)$$

$$p = \frac{1}{\Phi_{ss}^4}P(\zeta, \theta, \phi)$$

$$\rho = \frac{1}{\Phi_{ss}^3}D(\zeta, \theta, \phi)$$

$\gamma = 4/3$

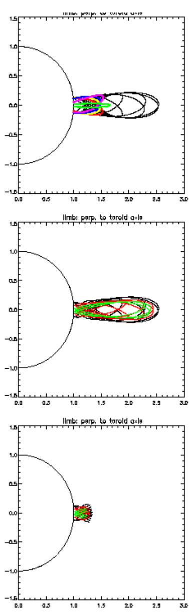
⇩

$$\frac{1}{4\pi}(\nabla_\zeta \times \boldsymbol{H}) \times \boldsymbol{H} - \nabla_\zeta P - D\left(\frac{GM}{\zeta^2} + \alpha\zeta\right)\hat{\boldsymbol{r}} = 0$$

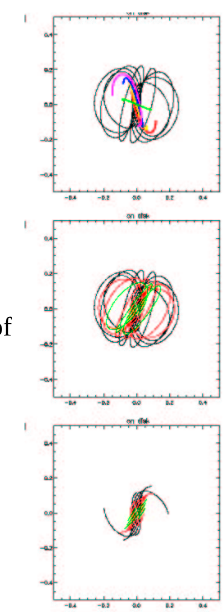
MHD Model Results

Lites and Low, 1996

Model magnetic field structure: filaments/prominences

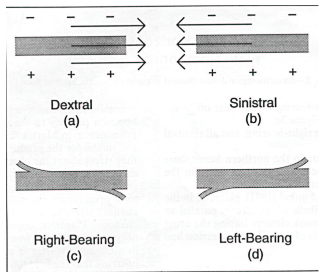


- "Two-flux" system - "axial flux rope" (twisted) and "simple bipole loops"
- Path-length of axial flux rope much longer than that of simple bipole loops
- Identify filament as mass-bearing portion of longest (most wound) portion of loop

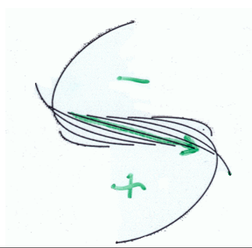


Field structure chirality classification

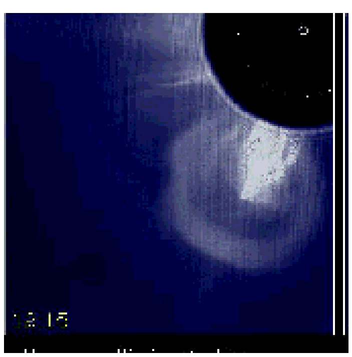
(Martin et al.)

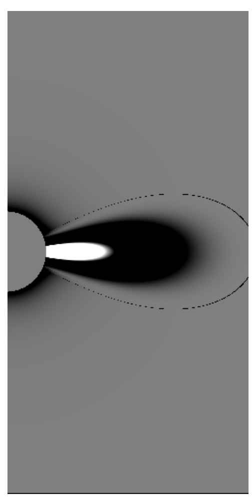


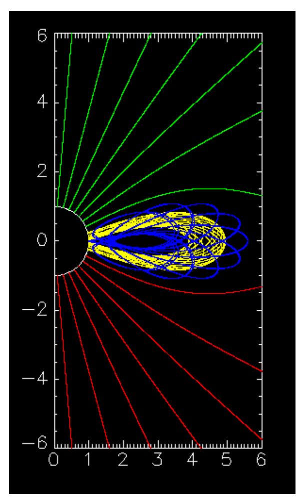
Model field: Dextral,
right bearing,
negative helicity



MHD Model predictions at the limb (white light)

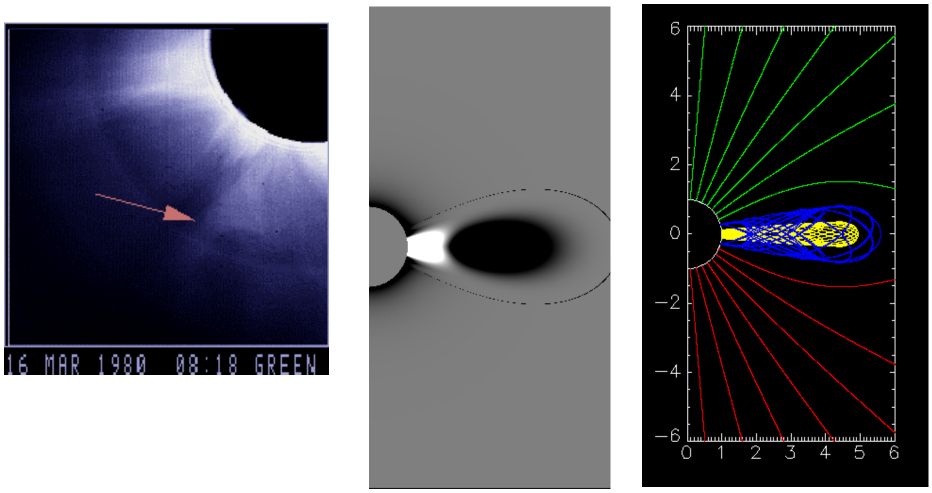






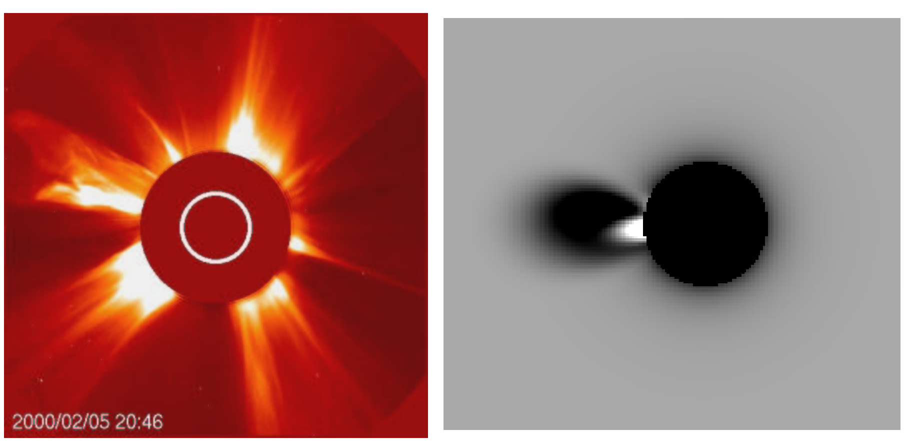
SMM CME observed Aug 18, 1980, Gibson & Low model CME, viewed along CME toroidal axis

MHD Model predictions at the limb (white light)



SMM CME observed March 15, 1980, Gibson & Low model CME, viewed perpendicular CME toroidal axis

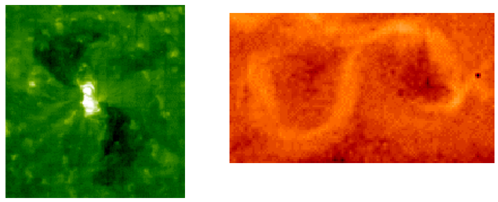
MHD Model predictions at the limb (white light)



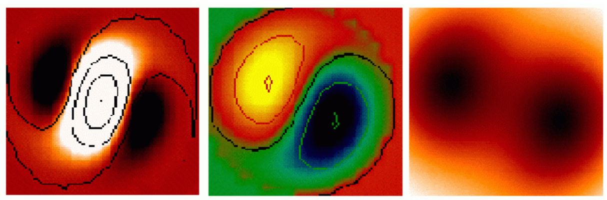
On-disk behavior - comparison to emission observations

(Gibson et al., 1999; Gibson and Low, 2000)

Observations



Model (at coronal base)



Density Magnetic field X-ray emission

What causes X-ray sigmoids?

In other words -- why is that particular part of the magnetic field heated?

- Dynamical evolution of magnetized fluid --> tangential magnetic discontinuities (current sheets) --> reconnection and dissipative heating *(Parker, 1994)*

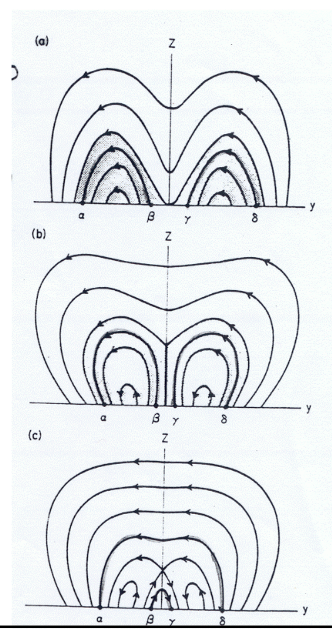
- Can occur not only at magnetic null points but also along separatrices between topologically distinct flux regions *(Titov and Demoulin, 1999; Low, 2001)*

TRACE:
1216 Angstroms

QuickTime™ and a
Photo decompressor
are needed to see this picture.

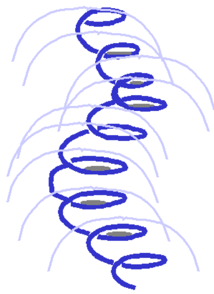
What causes X-ray sigmoids?

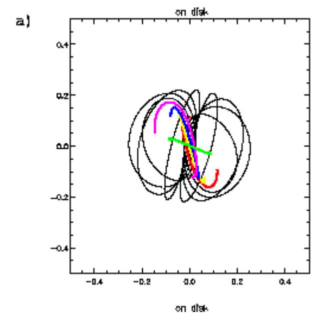
- Case of special interest: separatrices arising from imposition of photospheric boundary



What causes X-ray sigmoids?

- Photospheric induced separatrix could arise between. winding vs. non-winding field lines



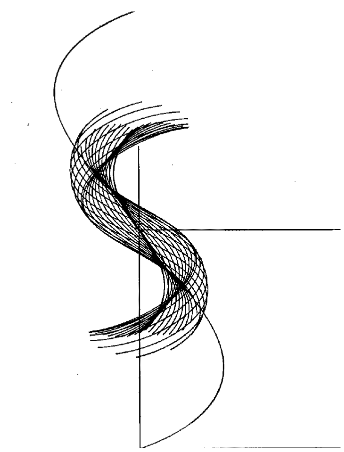


Geometric solution *(Low, 2001)*

$$\mathbf{B} = \frac{1}{r\sin(\theta)}\left[\frac{1}{r}\frac{\partial A}{\partial \theta}\hat{r} - \frac{\partial A}{\partial r}\hat{\theta} + Q\hat{\phi}\right]$$

$$A = r^2 - 2ar\sin(\theta)$$

$$Q = \lambda_o A$$



Equilibrium solution

$$\frac{1}{4\pi}(\nabla \times \mathbf{B}) \times \mathbf{B} - \nabla p = 0,$$

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

$$\mathbf{B} = \frac{1}{r\sin(\theta)}\left[\frac{1}{r}\frac{\partial A}{\partial \theta}\hat{r} - \frac{\partial A}{\partial r}\hat{\theta} + Q\hat{\phi}\right]$$

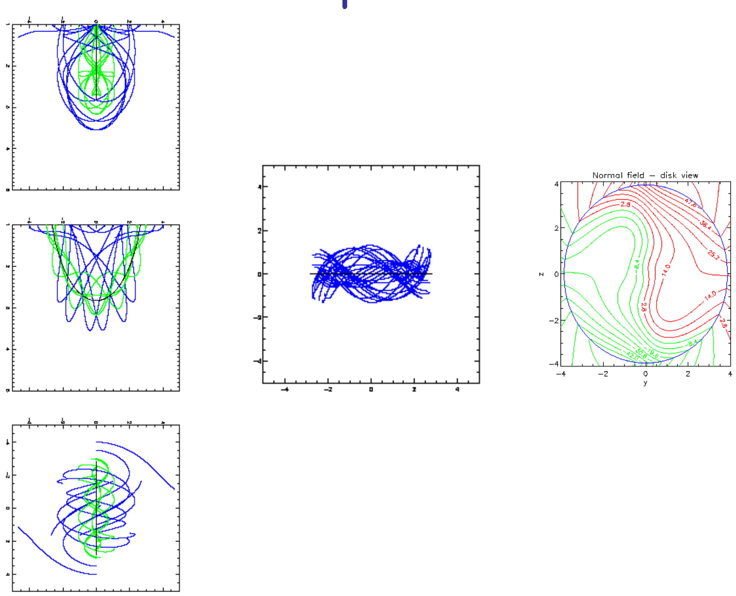
$$A_{int} = \frac{1}{2}\gamma_1 (r - r_o)^2 - \frac{2\pi}{5} p_o r^2 (r^2 - r_o{}^2)\sin^2(\theta) \qquad A_{ext} = \gamma_3 r_o{}^2 (r^2 - \frac{r_o{}^3}{r})\sin^2(\theta)$$

$$Q_{int}{}^2 = Q_o{}^2 - 2\gamma_1 A \qquad Q_{ext} = Q_o$$

$$p_{int} = p_o A \qquad p_{ext} = 0.0$$

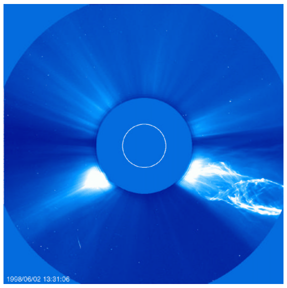
- Spheroidal, blends smoothly with external field
- 3-D (axisymmetric) exact solution of MHD equations
- Can be easily extended to break symmetry and include gravit and time-dependence
- Work in progress

Equilibrium solution



Conclusions

- Our analytic, time-dependent, self-consistent MHD model of a CME is unique in explicitly determining a plasma/field configuration that captures a range of observations from multiple viewing angles, and utilizes a truly 3D, twisted magnetic field structure
- The 3D density structure from this model can be used for the interpretation and deconstruction of observations of CMEs along multiple lines of sights



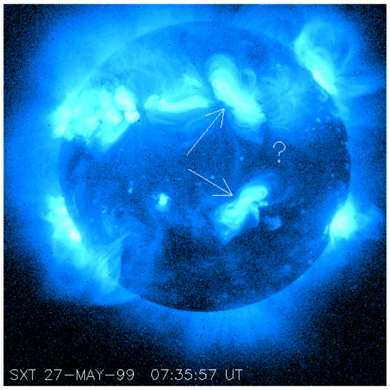
Why do we care if the CME is twisted?

- CME plasma ⟺ CME magnetic fields
- Energy stored in magnetic twist (helicity)
- Highly twisted CME precursor just needs a trigger
- CME carries magnetic flux and helicity with it
- CMEs - workhorses for solar cycle field reversal?

Conclusions

Magnetic twist matters:

- Global organizational principle - is the Sun labelling its North and South poles?



Understanding the origin, evolution, and removal of magnetic twist is fundamental to understanding the Sun, with relevance from the solar interior all the way out to the Earth.