The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

2292-18

School and Conference on Analytical and Computational Astrophysics

14 - 25 November, 2011

Models for Coronal Mass Ejections

Carla Jacobs

K.U. Leuven, Centre for Plasma Astrophysics, Leuven Belgium

Strada Costiera 11, 34151 Trieste, Italy - Tel.+39 040 2240 111; Fax +39 040 224 163 - sci_info@ictp.it

Models for Coronal Mass Ejections

Carla Jacobs

Centrum voor Plasma-Astrofysica
K.U.Leuven, Belgium

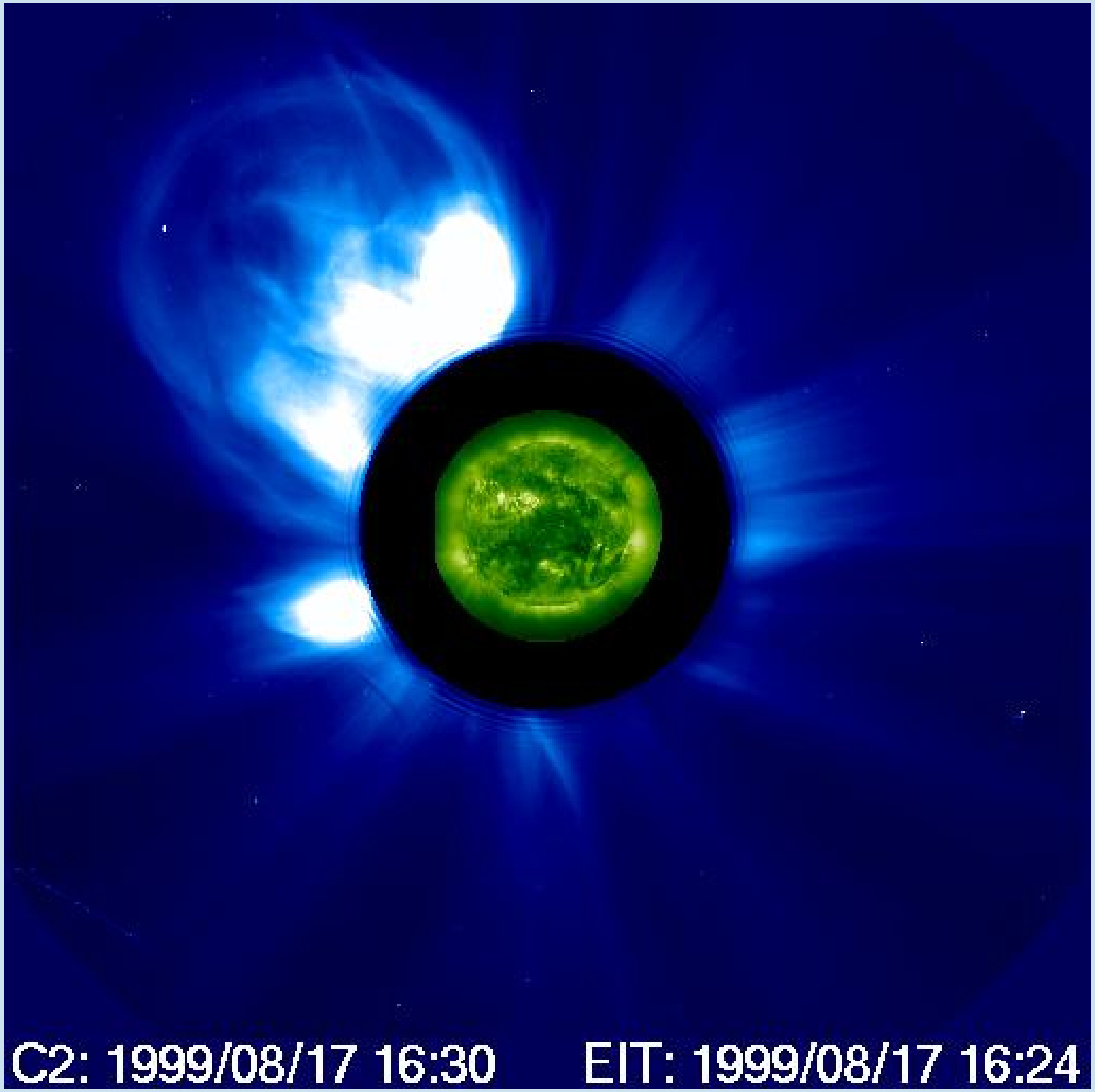
ICTP, Trieste, 22 November 2011

Outline

Outline

1. Observations
2. Theoretical Models
3. Numerical Models
4. Conclusions

Coronal Mass Ejections (CMEs)



Coronal Mass Ejections (CMEs)

What?

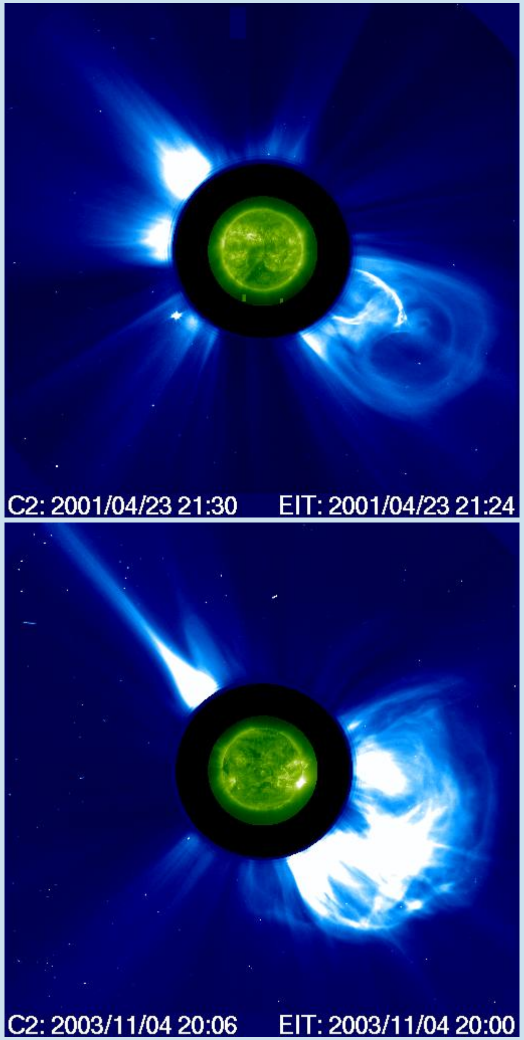
An observable change in the coronal structure that (1) occurs on a time scale of a few minutes to several hours and (2) involves the appearance and outward motion of a new, discrete, bright, white light feature in the coronagraph field of view. (Hundhausen et al. 1984).

- Coronagraph: instrument that creates artificial solar eclipse.
- Discovered in the '70s.
- LASCO (1996): observed $> 10\,000$ CMEs.

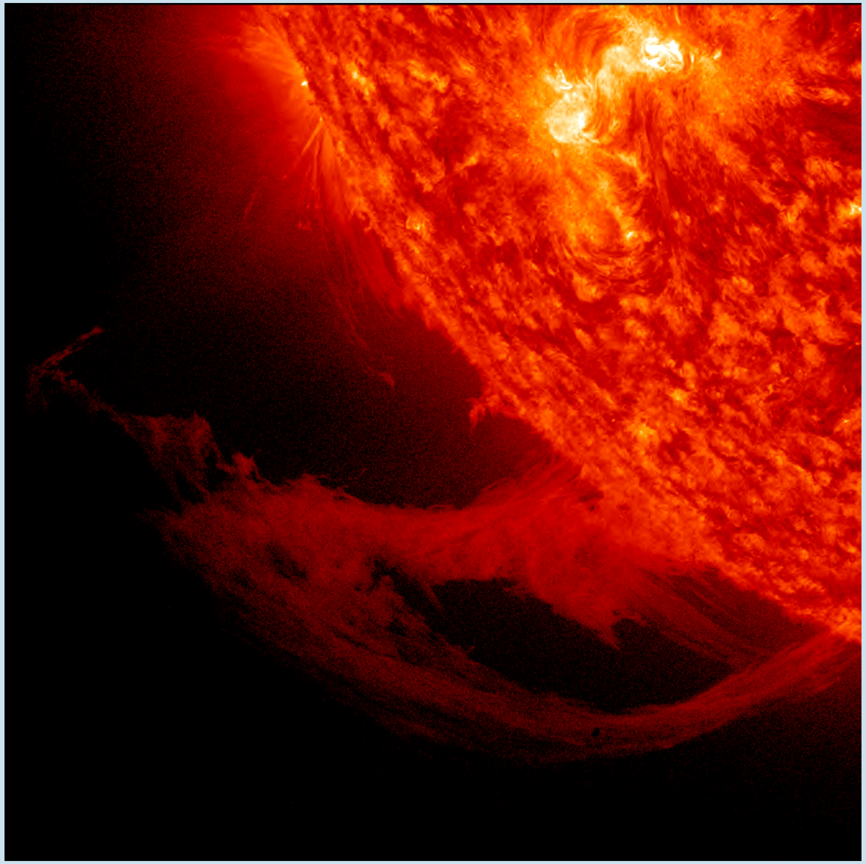
CMEs

CME properties

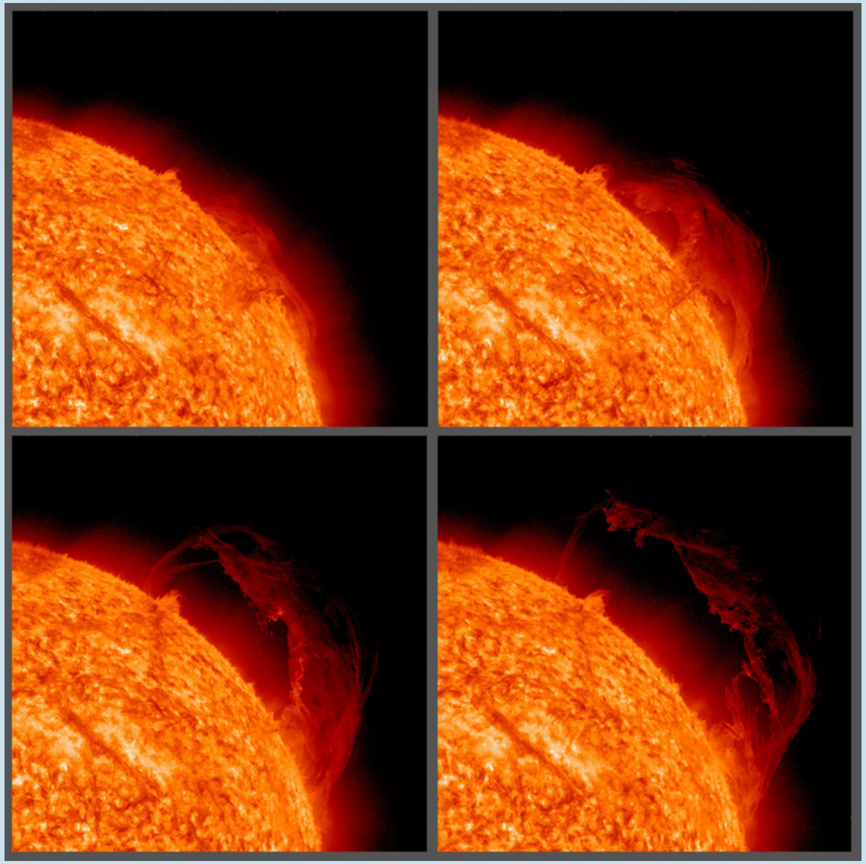
- CMEs are a common phenomenon: 1/week – > 6/day.
- V_{cme}: 100 - 3000 km/s, typ. 450 km/s
- Mass $= 10^{13} - 10^{16}$ g.
- Energy $= 10^{27} - 10^{33}$ erg
- Many CMEs show (initially) a self-similar evolution.
- Three-part structure: front–cavity–core.
- Often associated with prominence eruptions.



Observations: prominence eruptions



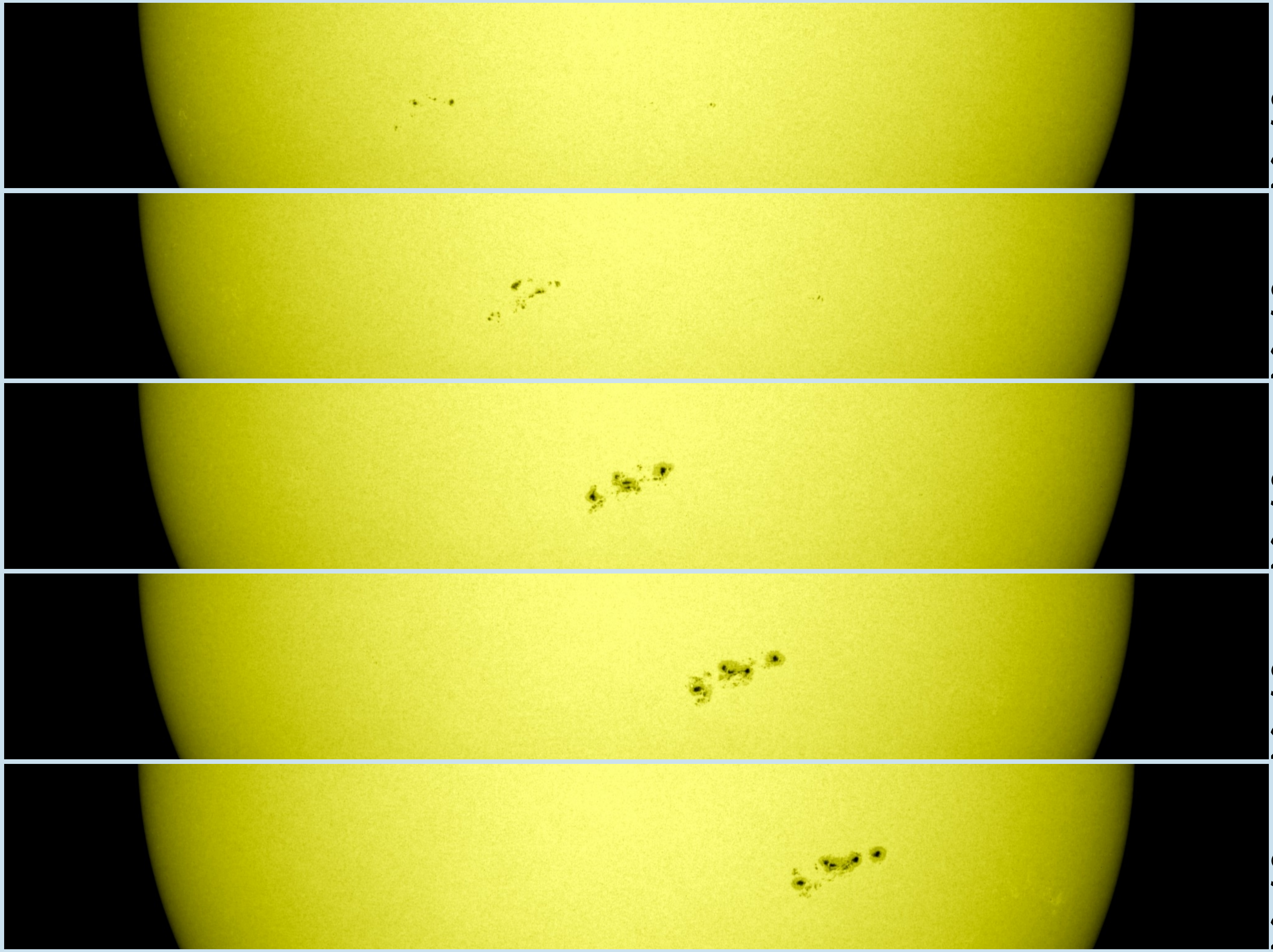
SDO AIA 304



SDO AIA 304

Observations

February 2011: Sunspot 1158 is developing fast...



SDO 4500 2011-02-12

SDO 4500 2011-02-13

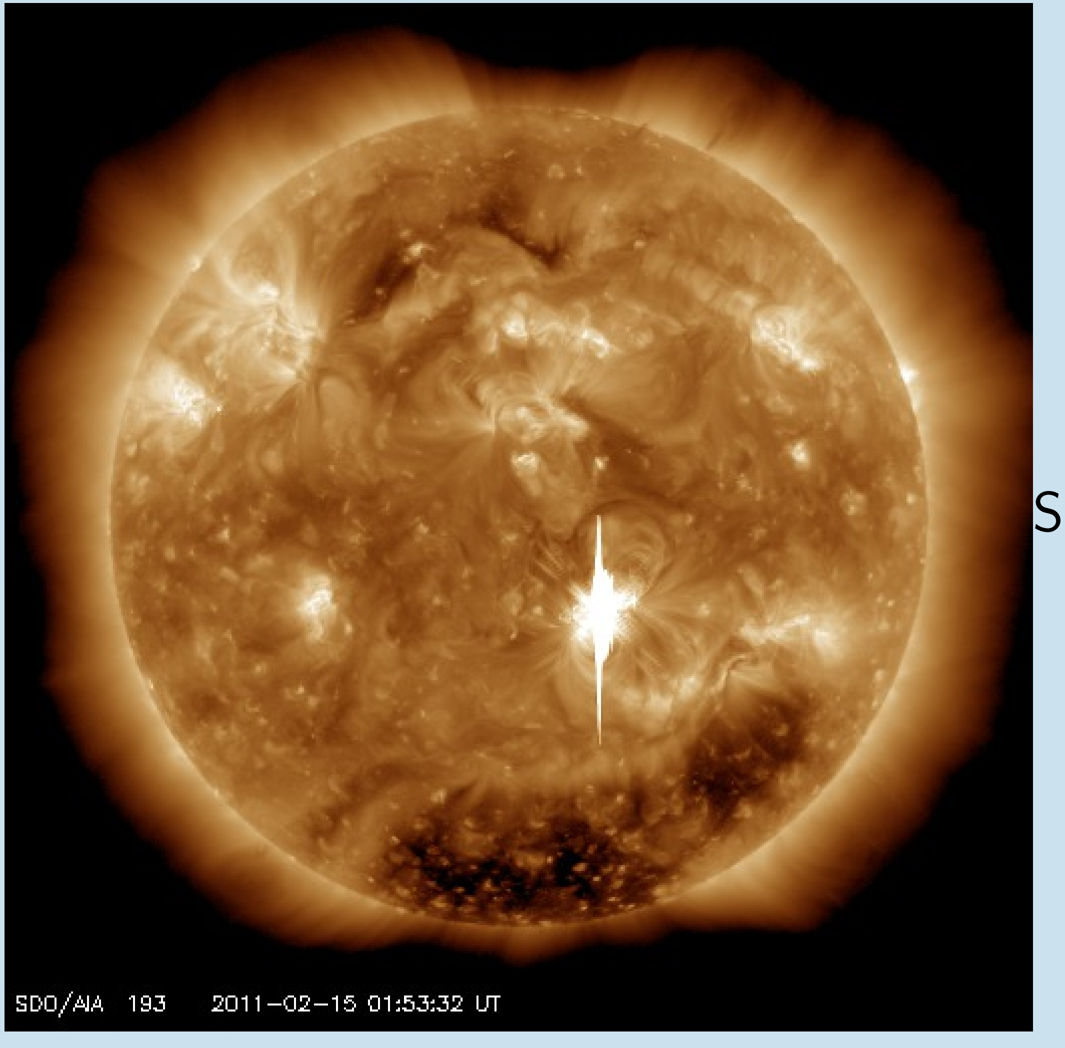
SDO 4500 2011-02-14

SDO 4500 2011-02-15

SDO 4500 2011-02-16

Observations

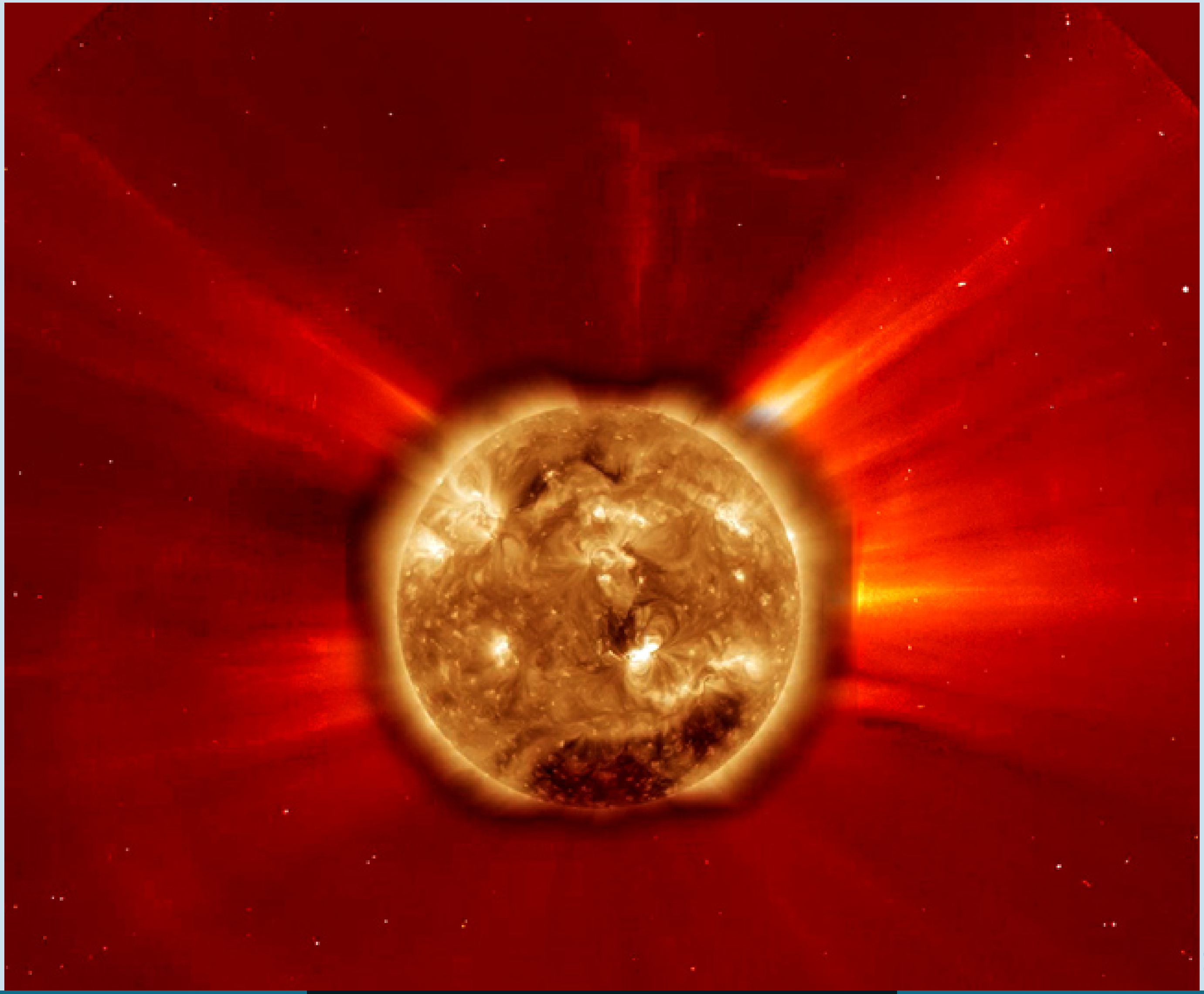
...with consequences: first X-class flare of solar cycle 24...



SDO AIA 193

Observations

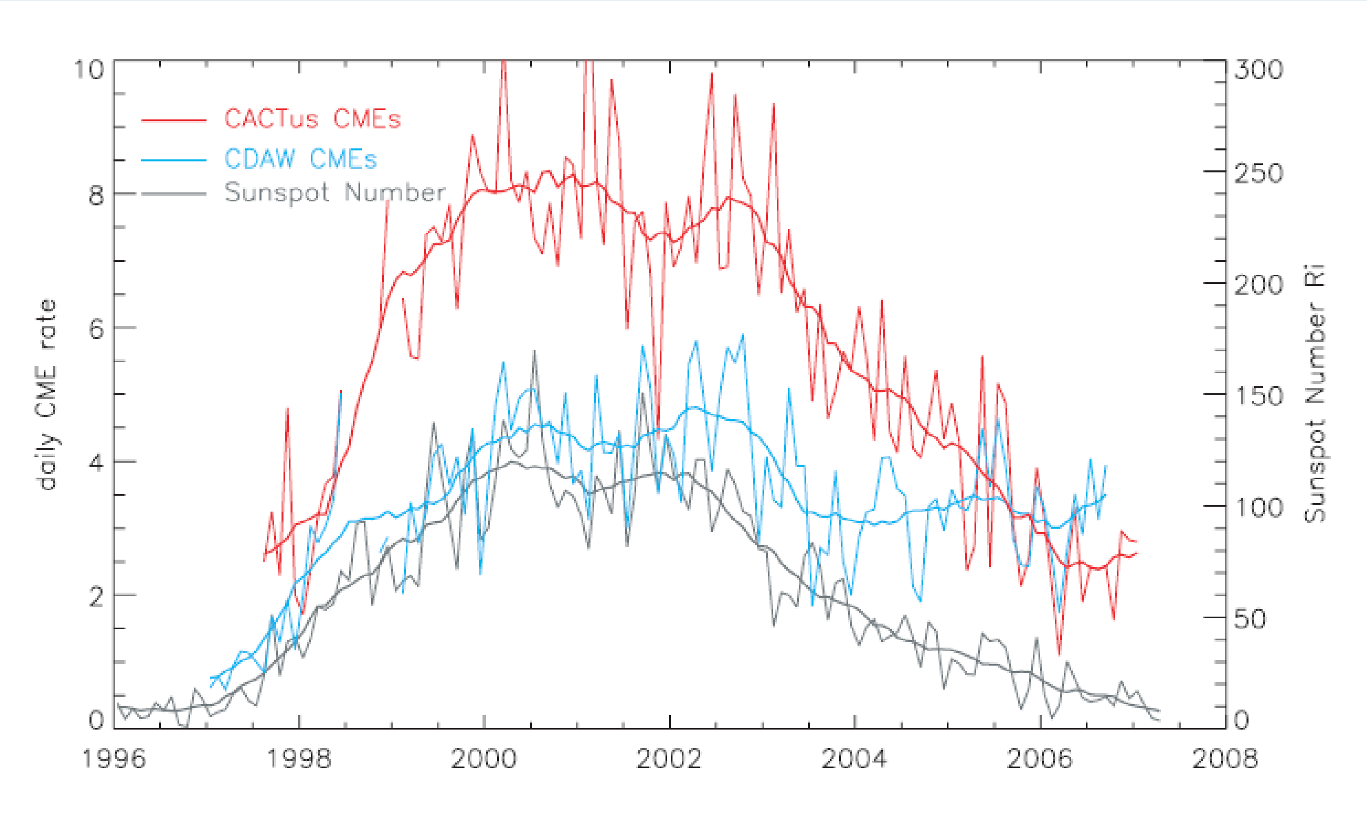
... and an Earth directed CME.



CMEs

From statistical analysis: (Robbrecht et al. 2009, ApJ)

- A clear relation exists between the solar magnetic field and the occurrence of CMEs.

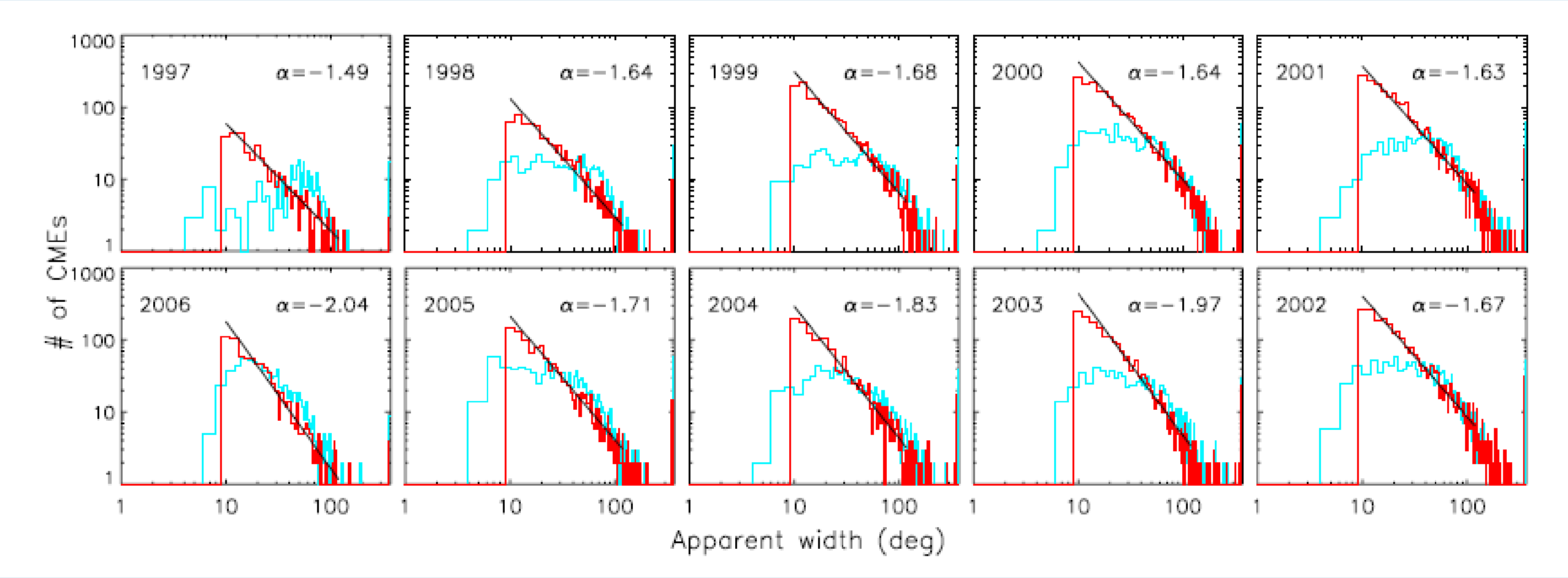


- CME width and speed distributions do not show a great variation over the solar cycle.

CMEs

From statistical analysis: (Robbrecht et al. 2009, ApJ)

- A clear relation exists between the solar magnetic field and the occurrence of CMEs.
- CME width and speed distributions do not show a great variation over the solar cycle.
- The apparent width of CMEs follows a power law distribution $N(\theta) = N_0\theta^{\alpha}$. $\Rightarrow$ there is no typical size of a CME.



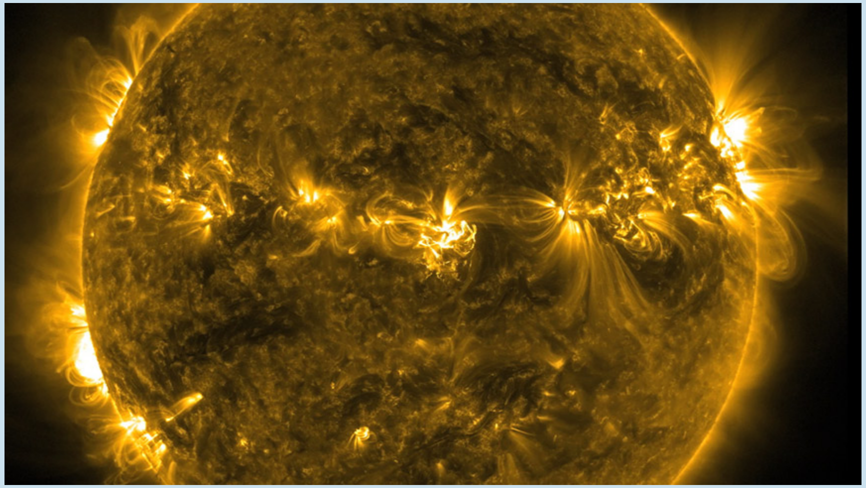
CMEs

- Subramanian & Dere 2001, ApJ: Sample of 32 CMEs. 41% associated with ARs and no prominence eruption; 44% associated with prominence eruption embedded in AR; 15% associated with prominence eruption outside AR.
- Zhou et al. 2006, A&A: tried to identify the CME's large-scale source structure.

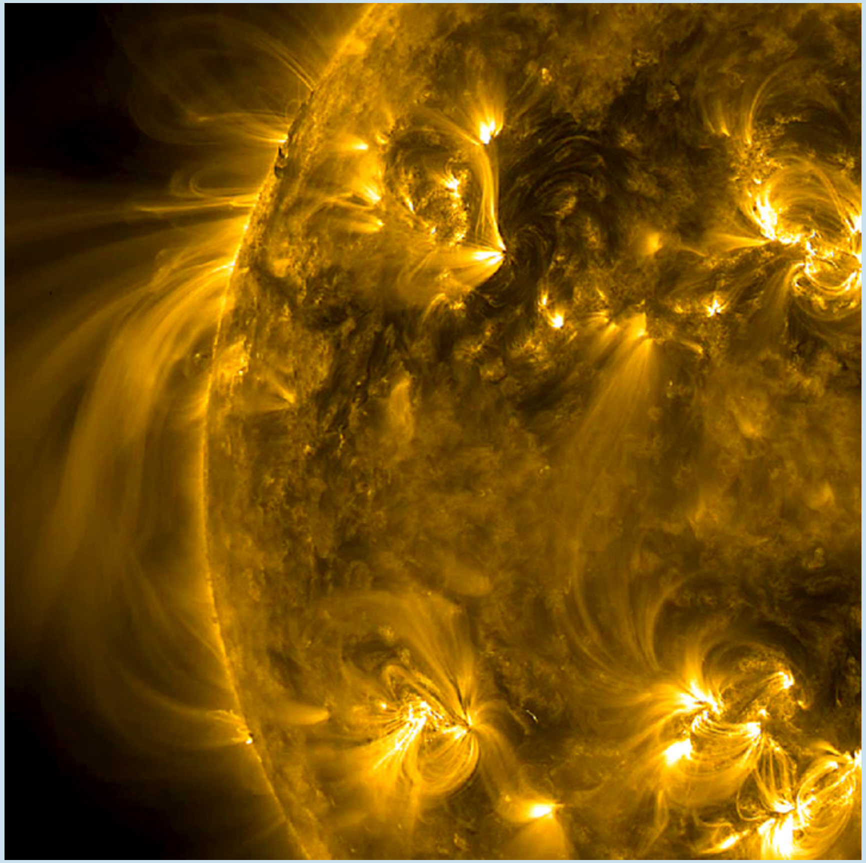
Table 1. Categories of CME large-scale source structures

Associa. large-scale source structures	CME number	percent
C1, EBRs	104	36%
C2, transequatorial magnetic loops	116	40%
C3, transequatorial filaments	37	13%
C4, filaments along the boundaries of EBRs	31	11%
Total earth-directed CMEs	288	100%

Observations



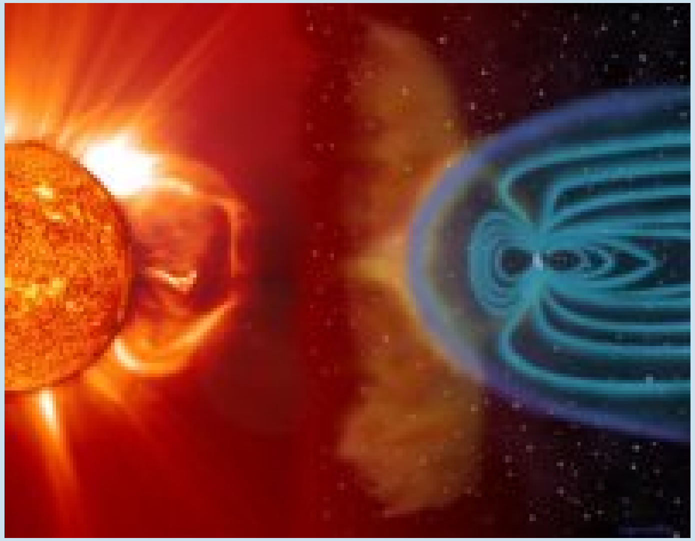
SDO AIA 171 2011/09/28-2011/10/02



SDO AIA 171 2011/10/6

CMEs – consequences

- Large-scale changes in the coronal structure – disturbances in the solar wind.
- CMEs cause gigantic clouds of solar material to leave the Sun ⇒ causes density waves that might steepen into shocks.
- In the shock waves particles can get accelerated: SEP events.



The shocks, energetic particles, and magnetic clouds created by CMEs can interact with the magnetosphere of the Earth ⇒ geo-magnetic storms.

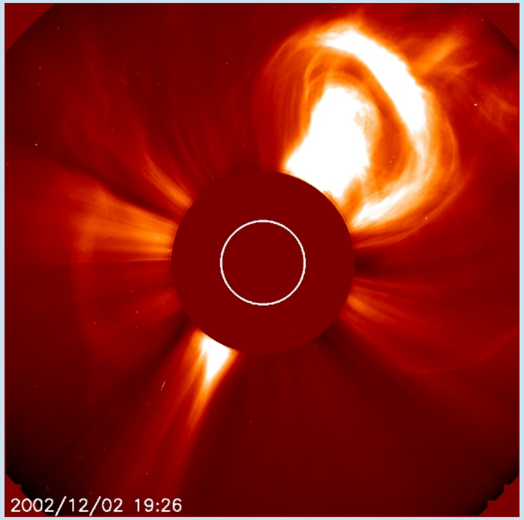
CMEs are one of the most important drivers of the space weather.

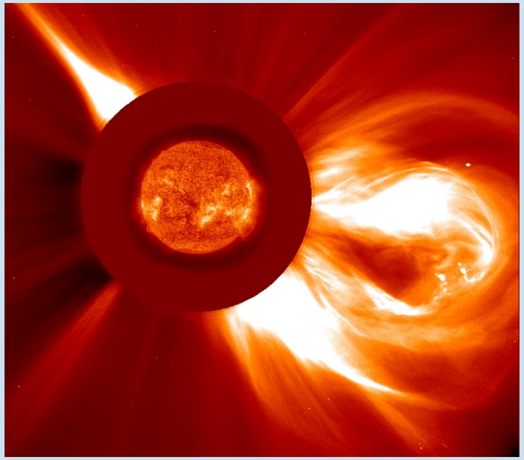
Outline

CMEs

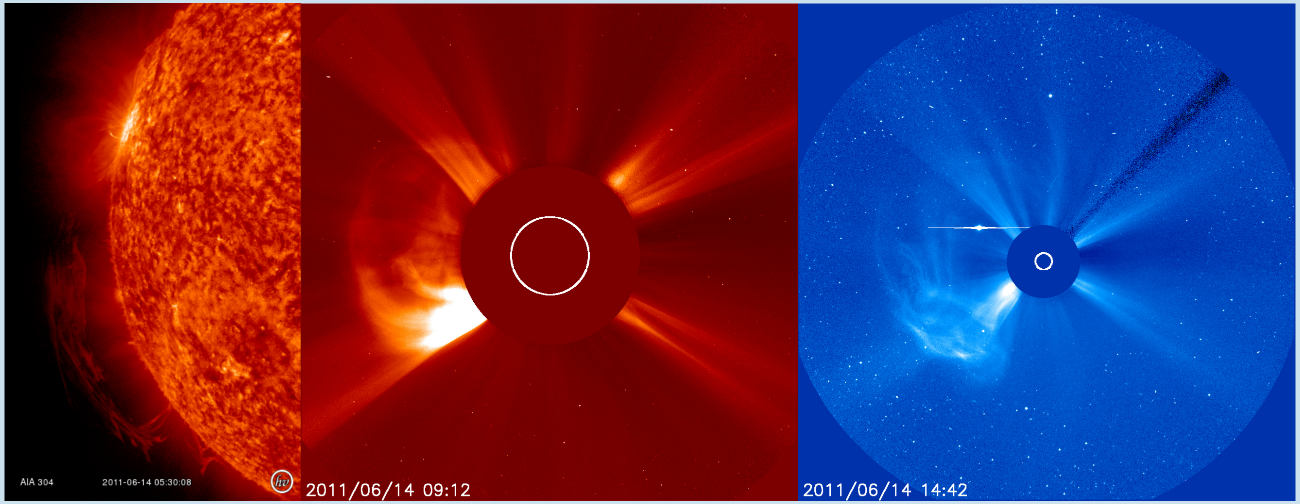
- Shearing motions – sunspot rotations – emergence/cancellation of magnetic flux often observed pre- and post-CME.
- Closed magnetic structures seem to play a key role in CME initiation.
- Also CMEs without clear photospheric or low coronal activity.

Despite the plethora of observations, the exact trigger mechanism remains unknown.





2011, June 14



SDO 304 LASCO C2 LASCO C3

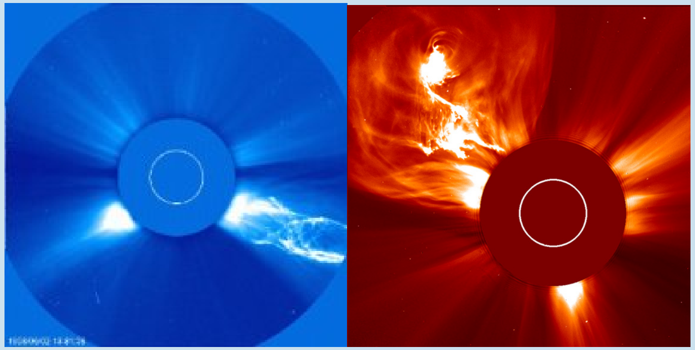
The energy needed to drive the eruption is provided by the solar magnetic field.

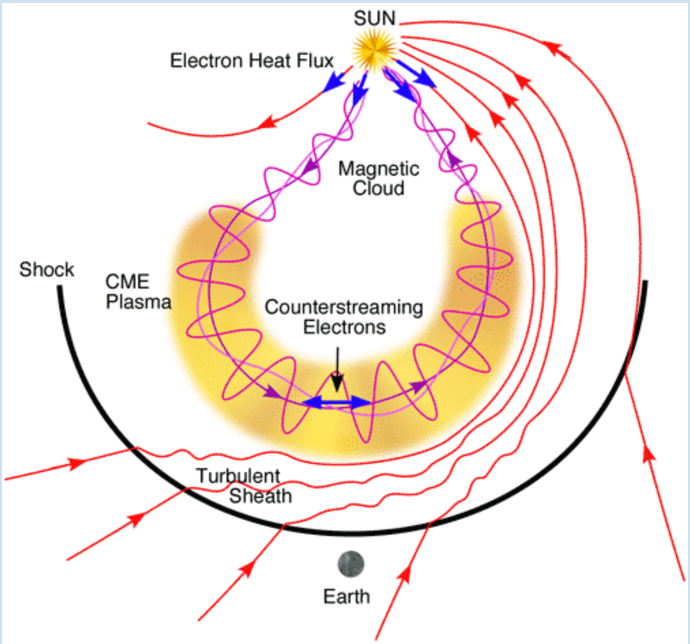
At photosphere: $\tau_A \approx 14$hr. **At base corona**: $\tau_A \approx 1 - 2$min.

$\Downarrow$

Rapid onset of flares and CMEs consequence of rapid changes in the coronal magnetic field. (Forbes 2010)

Free magnetic energy: difference energy between the magn. field and a potential field with same photospheric flux. The non-potential part is due to currents built up in the corona.





*Z*urbuchen and Richardson 2006

- Presence of helical structures in coronagraph images.
- Magn. field in prominences is believed to possess some twist.
- ICMEs: 1/3 contain magnetic cloud **smooth rotation of B**.

The current models all assume the presence of magnetic flux ropes

- existing prior to the eruption
  - initially stable structure that erupts.
  - flux rope emerging from below the photosphere.
- a flux rope is formed during the eruption.

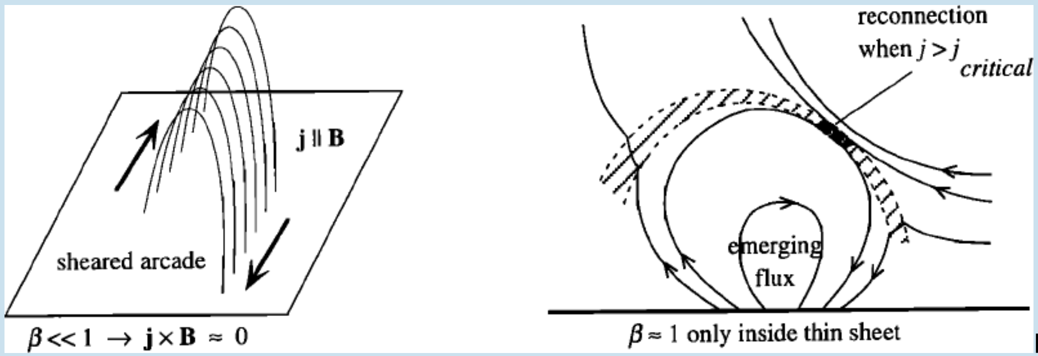
Roussev & Sokolov 2006

Storage and release models

[Forbes (2000,2010), Klimchuk (2001)]

Slow build-up of magnetic stress

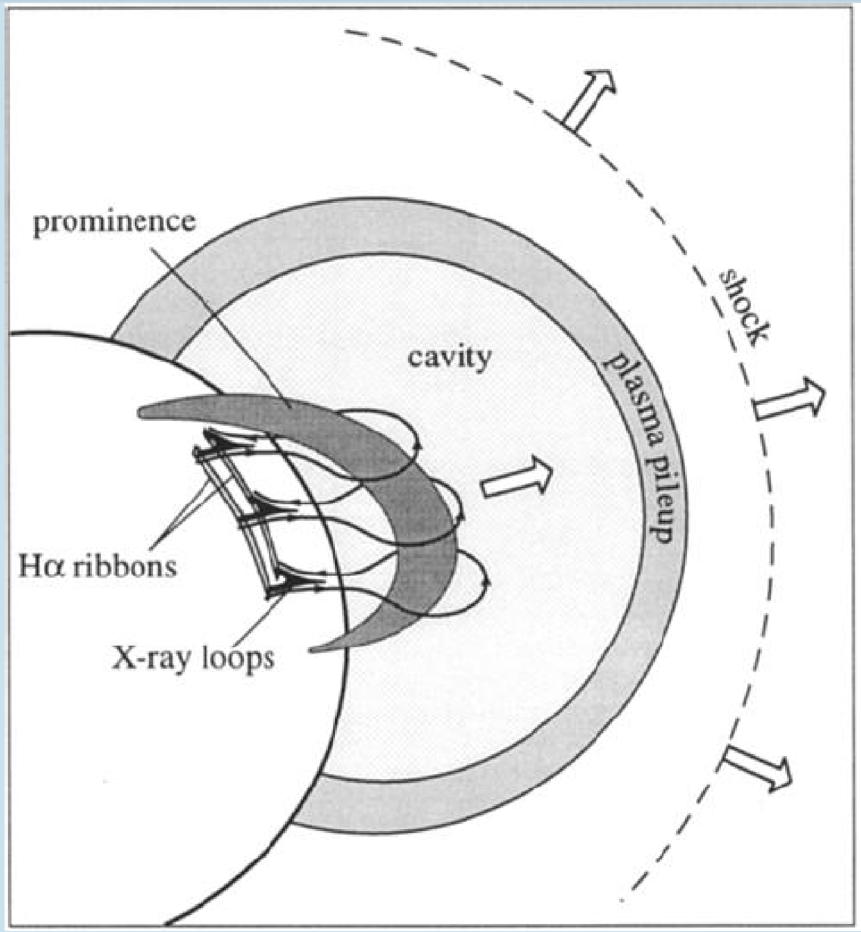
- Slowly evolving coronal field, driven by changes in the photosphere as a result of convection
  $\Rightarrow$ increase in the free magnetic energy of the corona (storage)
  $\Rightarrow$ reaches a point where a stable equilibrium is no longer possible (release)
- Force free models ($\mathbf{J} \times \mathbf{B} = 0$); pre-existing current sheet $\rightarrow$ micro-instability triggers reconnection in CS.



Forbes, JGR (2000)

CME Models

All models involve **magnetic reconnection**, as either the cause of the eruption or as a consequence of the eruption.

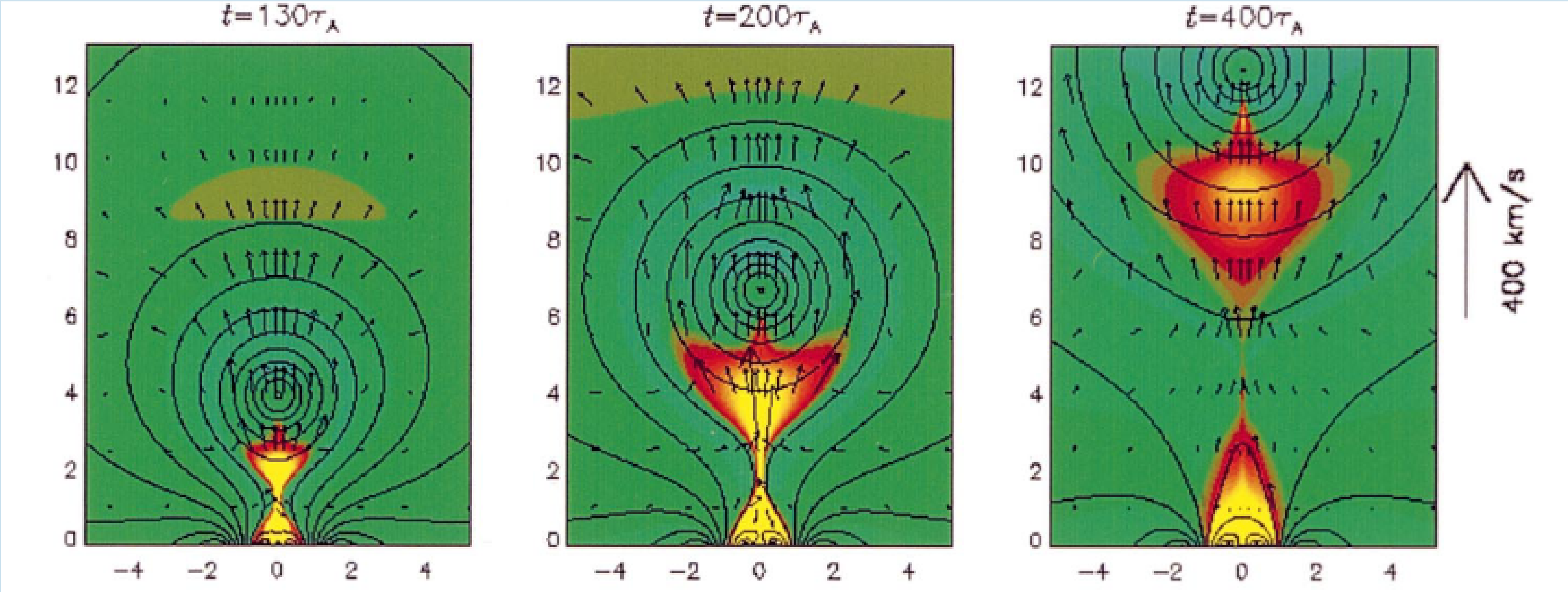


Forbes, JGR (2000)

Outline

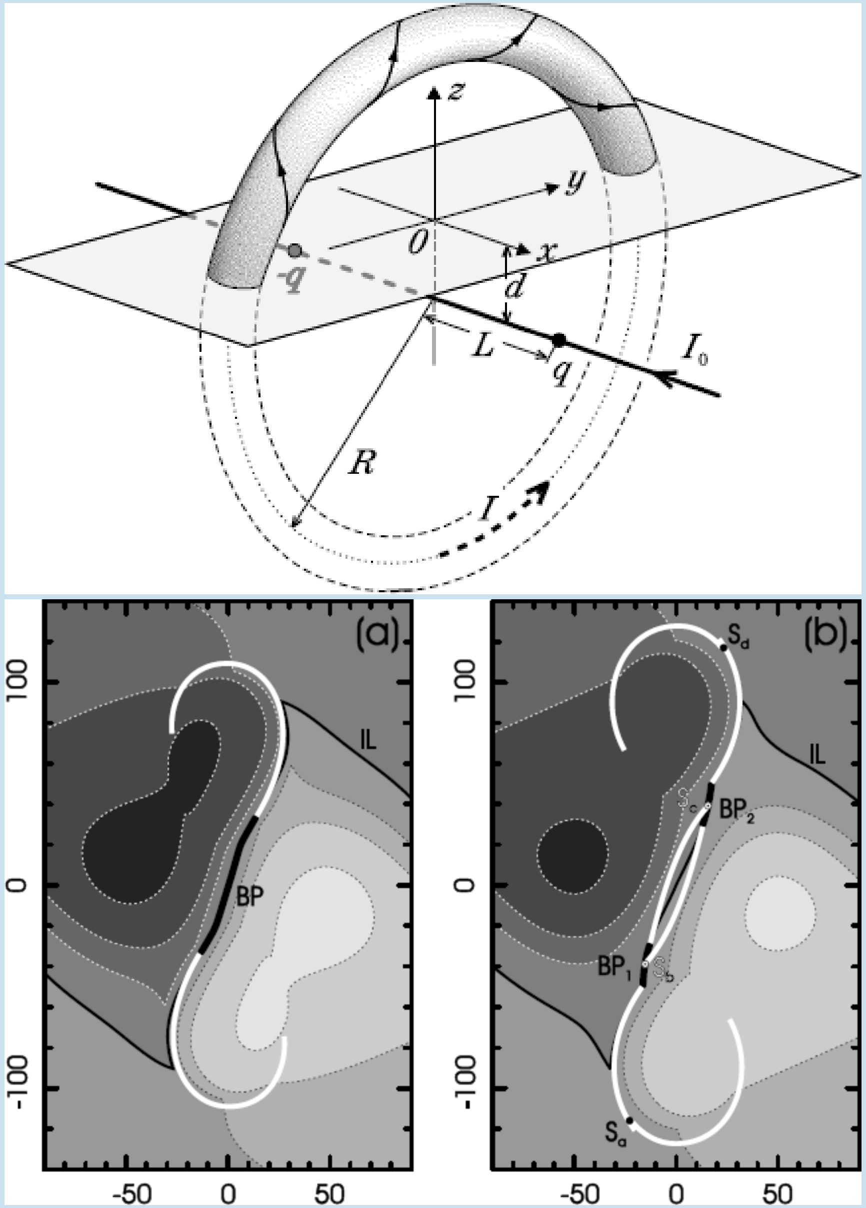
Outline

[Chen & Shibata, ApJ (2004)]



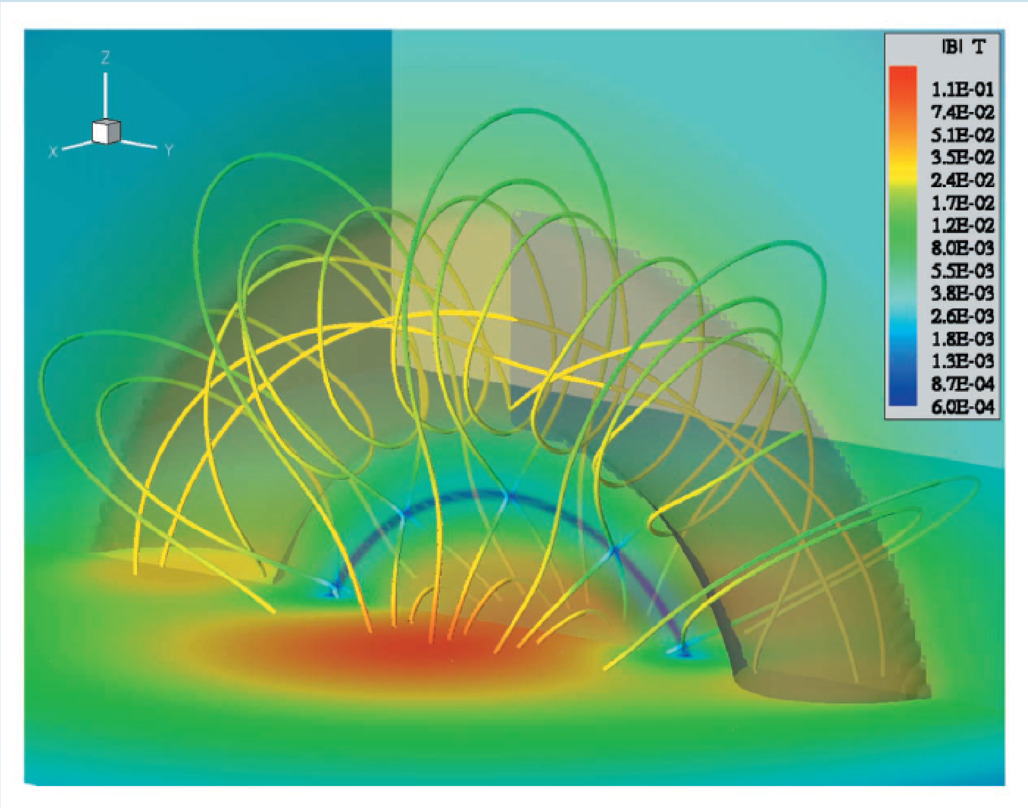
- Initially stable flux rope.
- 2D MHD simulation.
- Newly emerging flux destabilizes existing flux rope.
- The fast magnetic reconnection in the current sheet leads to the eruption of the CME and the cusp-shaped solar flare or X-ray arcade.

[Titov & Demoulin, A&A (1999)]



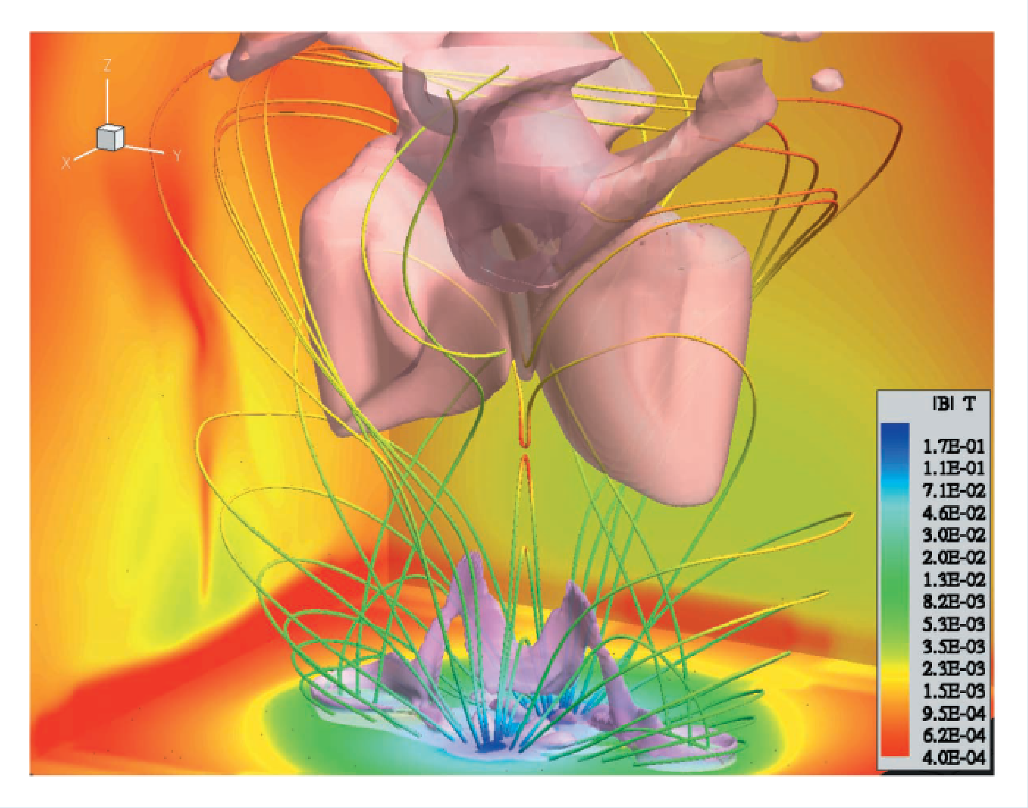
- 3D force-free circular flux tube with toroidal ring current I
- embedded in a dipolar field with magnetic charges $\pm q$, to balance the outward directed Lorentz-force
- and line-current I_0 determines the toroidal field component (without I_0, the field lines at surface FT are purely poloidal).
- The line current I_0 defines the twist in the flux rope (from highly twisted FR to sheared arcade without FR).
- Instability for sufficient large radii $R \gtrsim \sqrt{2}L$.

[Roussev et al., ApJ (2003)]



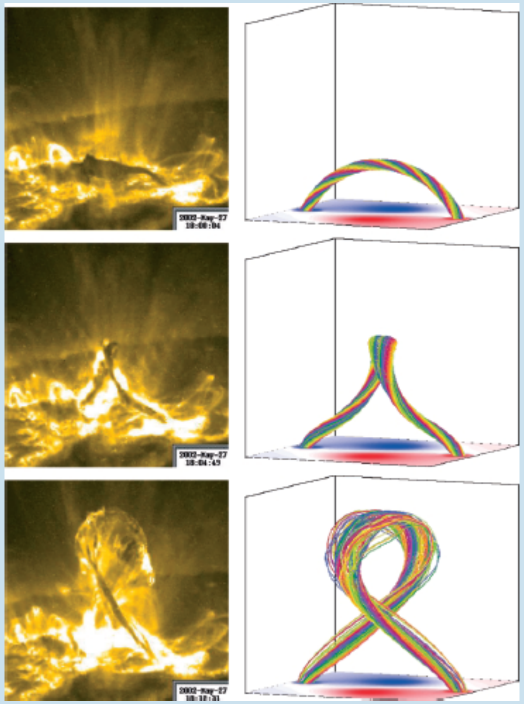
- 3D flux rope configuration of Titov & Démoulin (1999).
- MHD simulation (stratified atmosphere + line-tying).
- Highly twisted field at surface FR needed to obtain CME like eruption.
- Used in many CME event studies within the SWMF (Tóth t al. 2005).

[Roussev et al., ApJ (2003)]



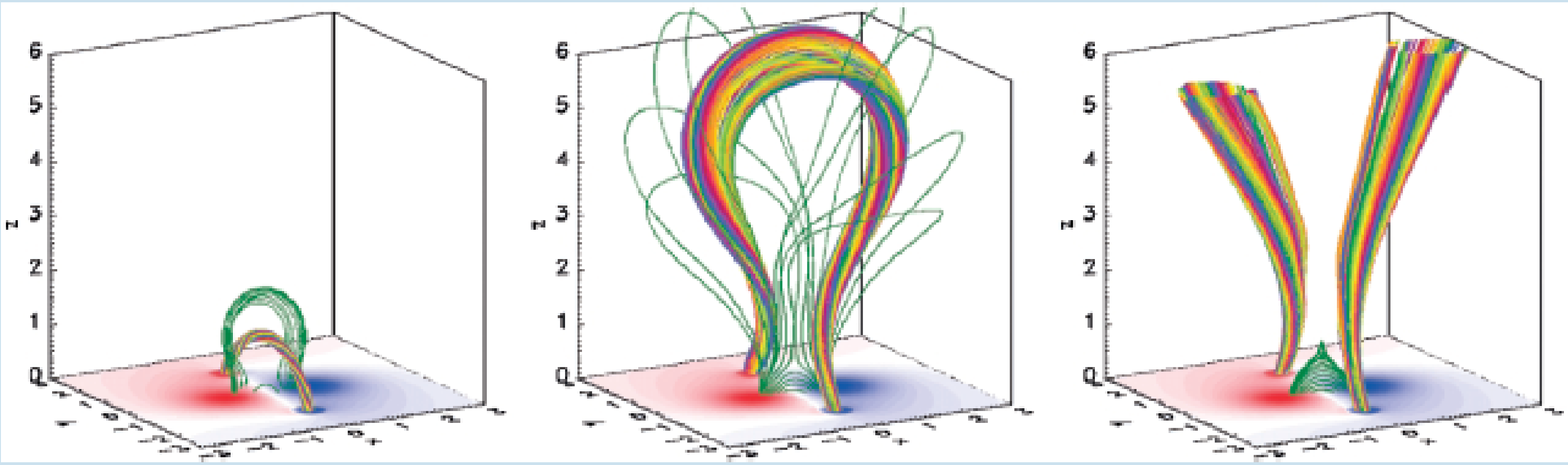
- 3D flux rope configuration of Titov & Démoulin (1999).
- MHD simulation (stratified atmosphere + line-tying).
- Highly twisted field at surface FR needed to obtain CME like eruption.
- Used in many CME event studies within the SWMF (Tóth t al. 2005).

Kink instability



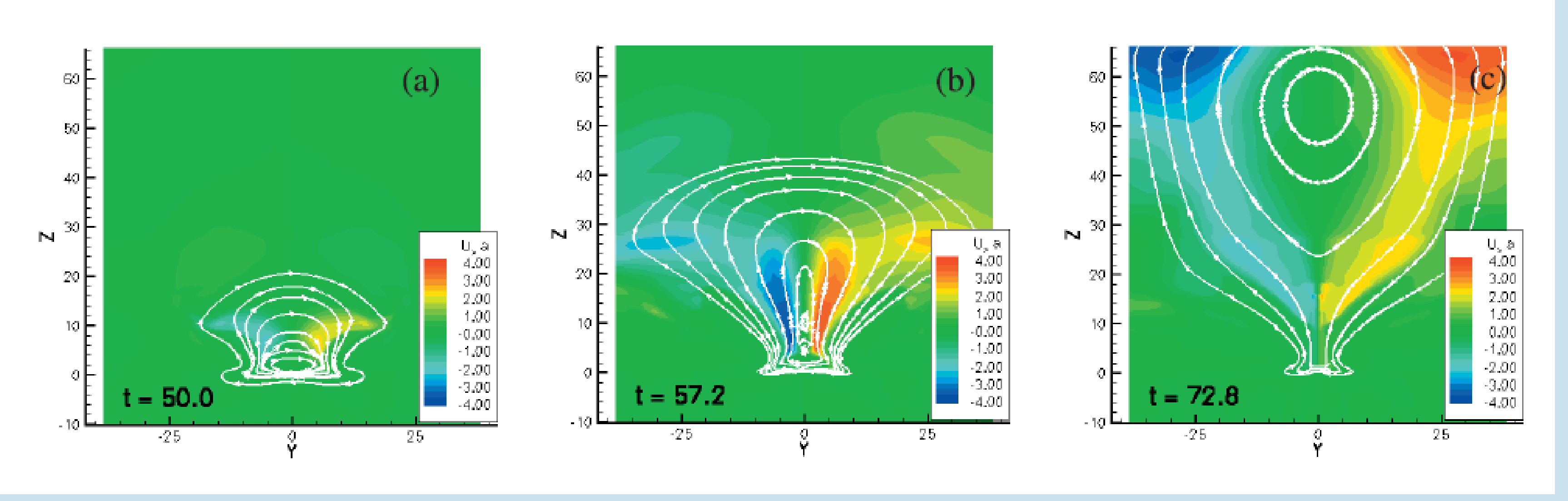
Torok & Kliem (2004,2005)

- Titov & Demoulin (1999) model.
- MHD simulation (zero-β).
- Flux rope is kink unstable for twist $\Phi > \Phi_C$.
- Model reproduces initially exponential rise with the rapid development of a helical shape.
- The decrease of the overlying field with height determines whether the instability leads to a confined event or to a CME.



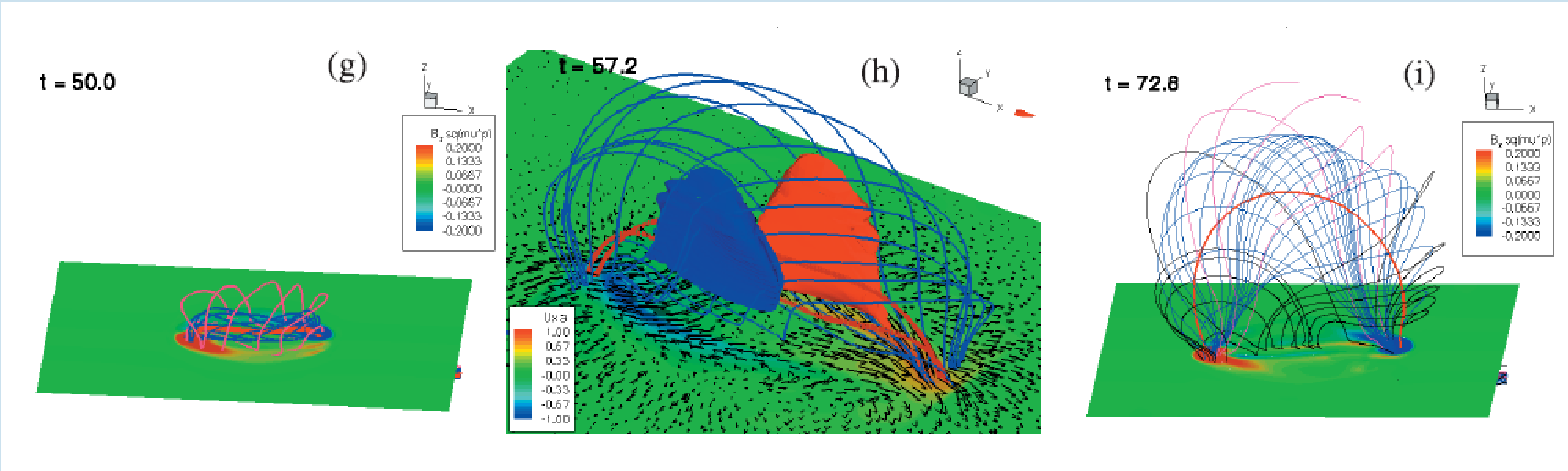
[Manchester et al. 2004, ApJ]

3D MHD simulation of buoyantly rising flux tube from below the photosphere • Uniformly twisted flux rope • Middle of the rope rises to the photosphere and expands in the corona • Shearing motions driven by the Lorentz force occur naturally as the rope expands in the pressure-stratified atmosphere → driving the eruption.

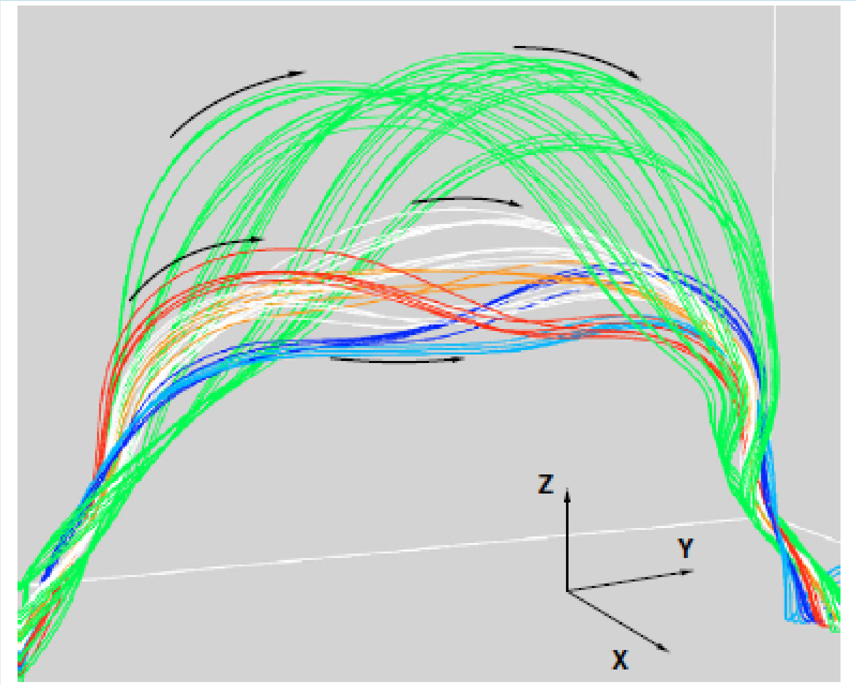


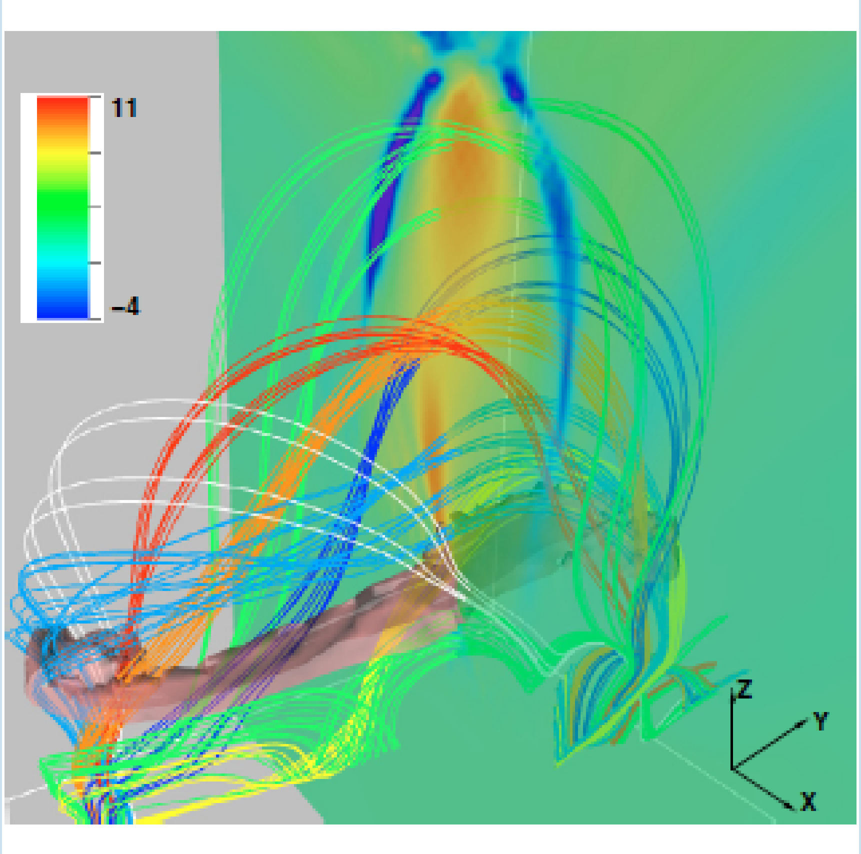
[Manchester et al. 2004, ApJ]

3D MHD simulation of buoyantly rising flux tube from below the photosphere • Uniformly twisted flux rope • Middle of the rope rises to the photosphere and expands in the corona • Shearing motions driven by the Lorentz force occur naturally as the rope expands in the pressure-stratified atmosphere → driving the erution.



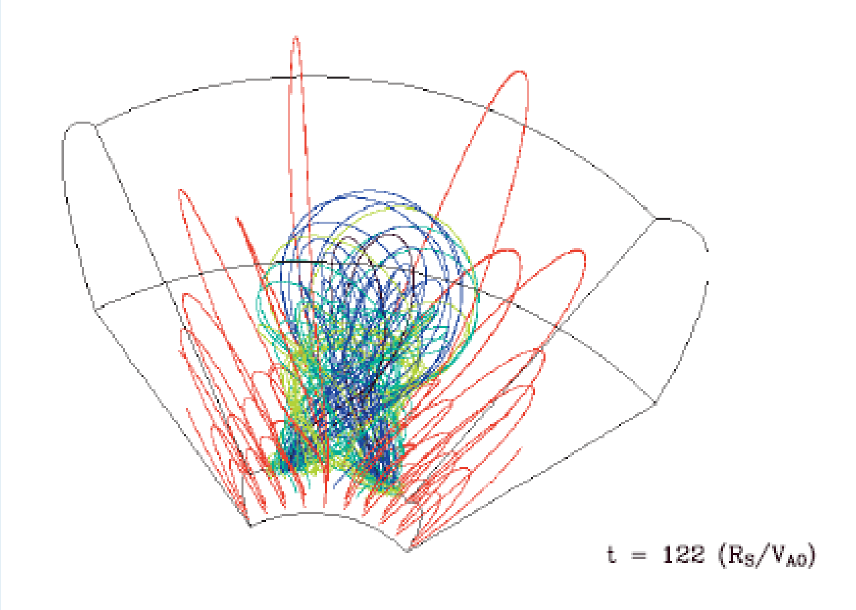
[Archontis & Török 2008, A&A]

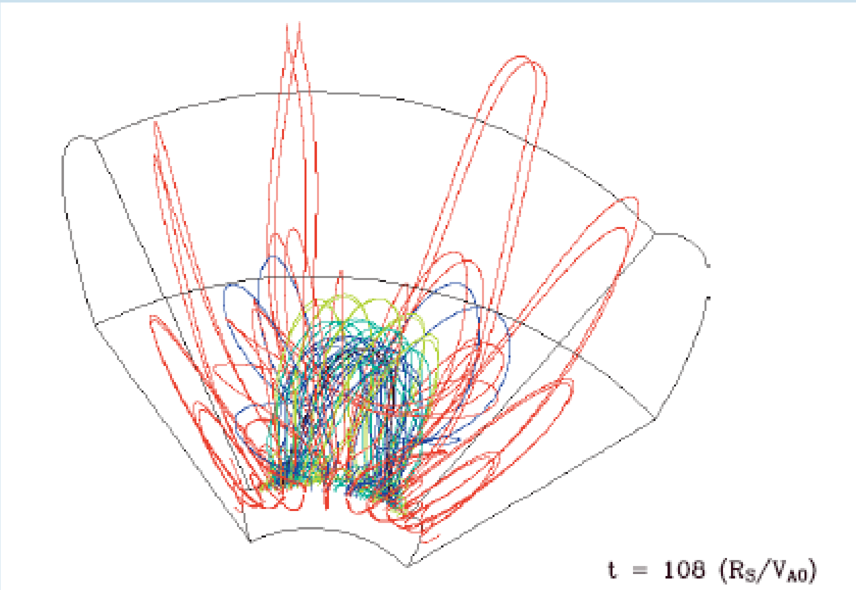




- Sub-photospheric twisted flux tube rises and expands into the corona.
- In non-magnetized atmosphere: the flux rope remains confined.
- In magnetized atmosphere: full eruption is obtained if reconnection can reduce the tension of the overlying field.

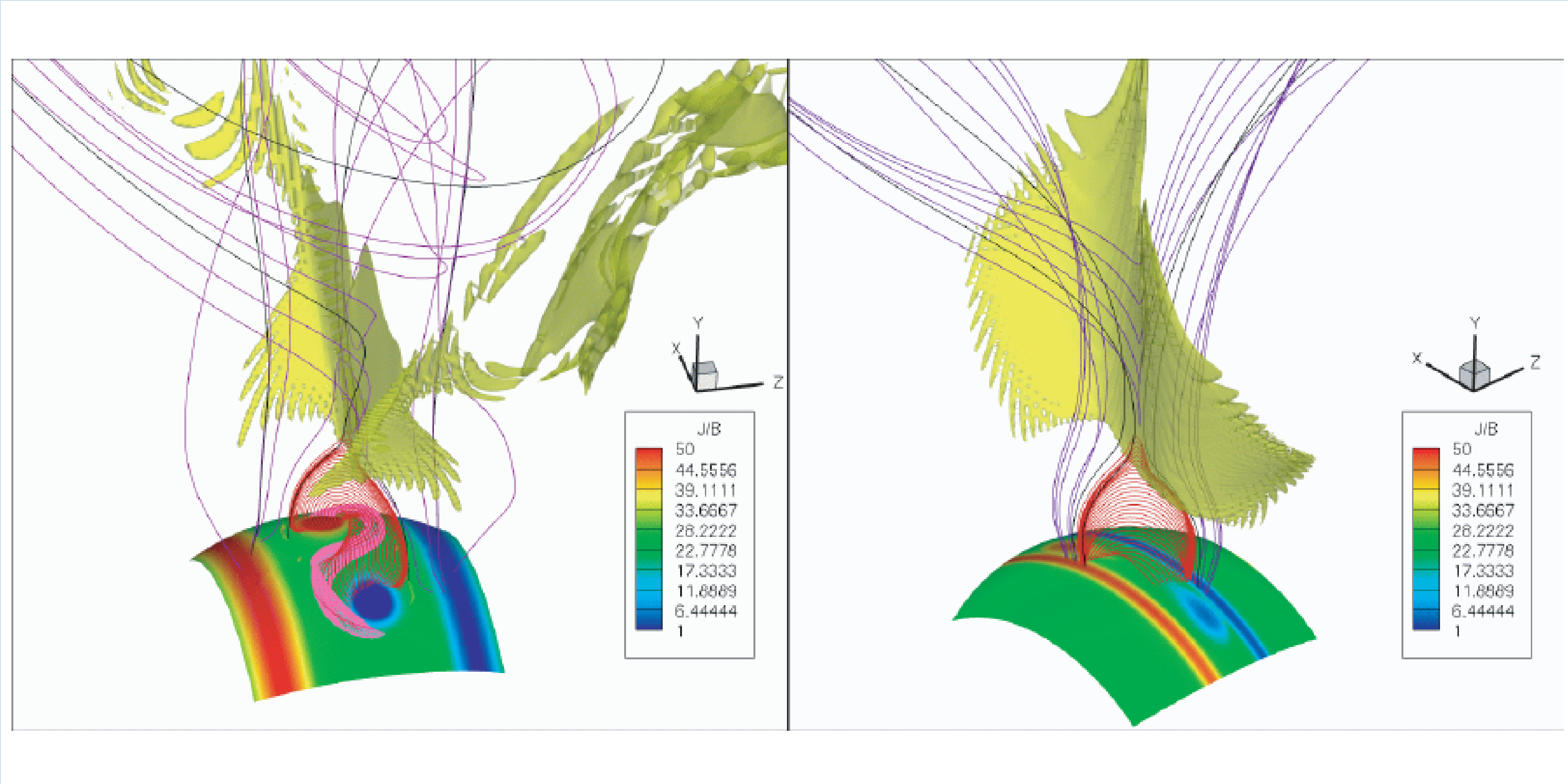
[Fan & Gibson 2007, ApJ]



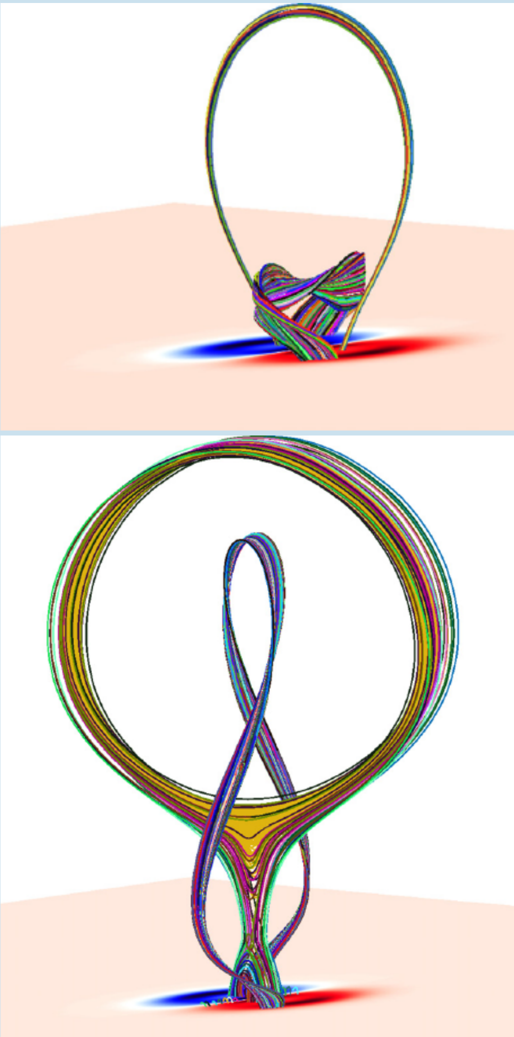


- Flux rope emerging quasi-statically into a pre-existing coronal arcade field.
- Case 1: overlying arcade field declines with height slowly. Emerging flux rope remains confined at first and shows kinking later on, leading to an eruption.
- Case 2: overlying field declines more rapidly with height. Emerging flux rope is found to lose equilibrium and erupt via the torus instability.
- Total, normalized relative magnetic helicity of the entire coronal magnetic field is of similar magnitude when the eruption takes place (≈ -0.18).

[Fan & Gibson 2007, ApJ]



Sheared arcade models

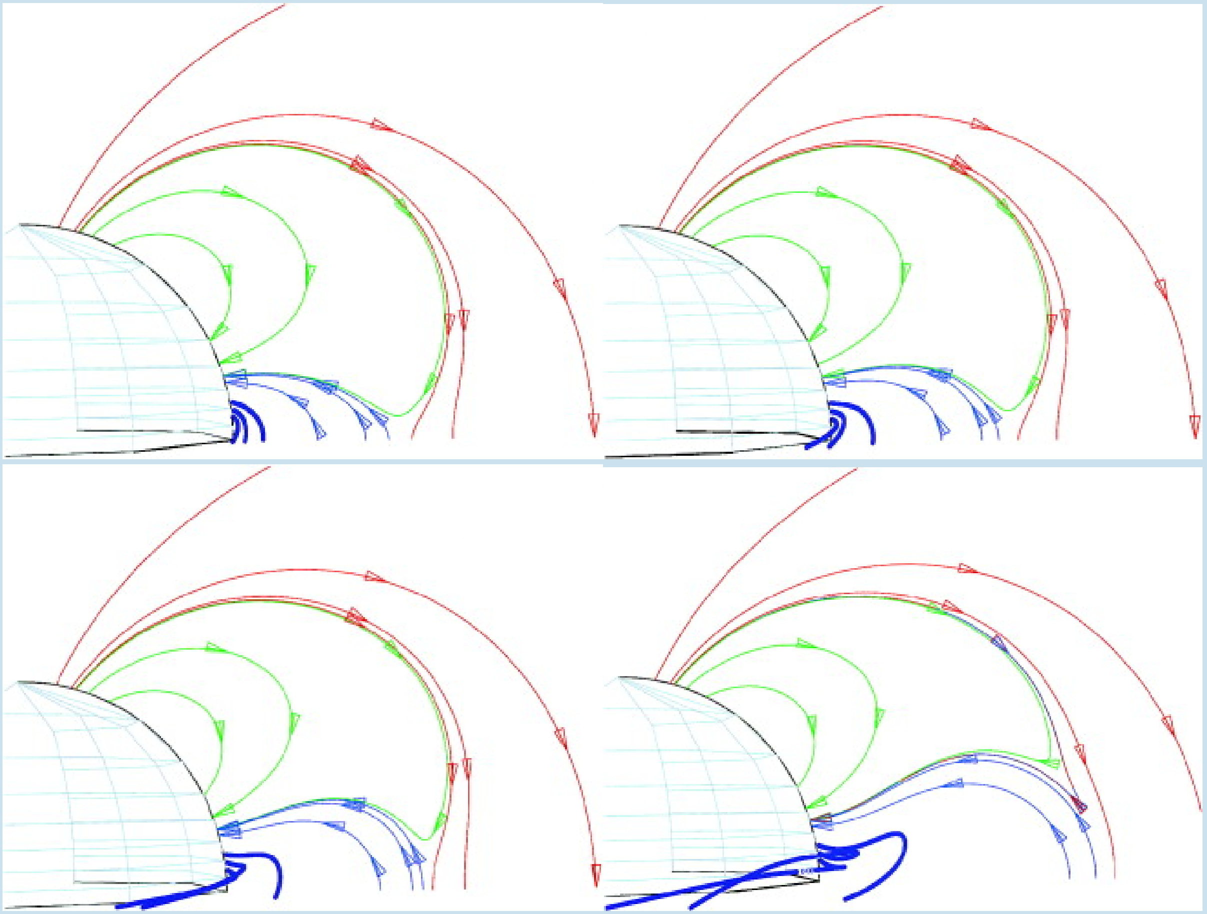


[Amari et al., ApJ (2003,2008,2010,2011)

- Evolution of bipolar AR.
- Rotating flow cause highly sheared field along the PIL.
- After relaxation, large scale flow with diverging structure causes part of the magnetic flux to be transported towards the PIL.
- Evolution of initially sheared force free field leads to formation of twisted flux rope.
- FR stays in equilibrium and suddenly undergoes disruption.

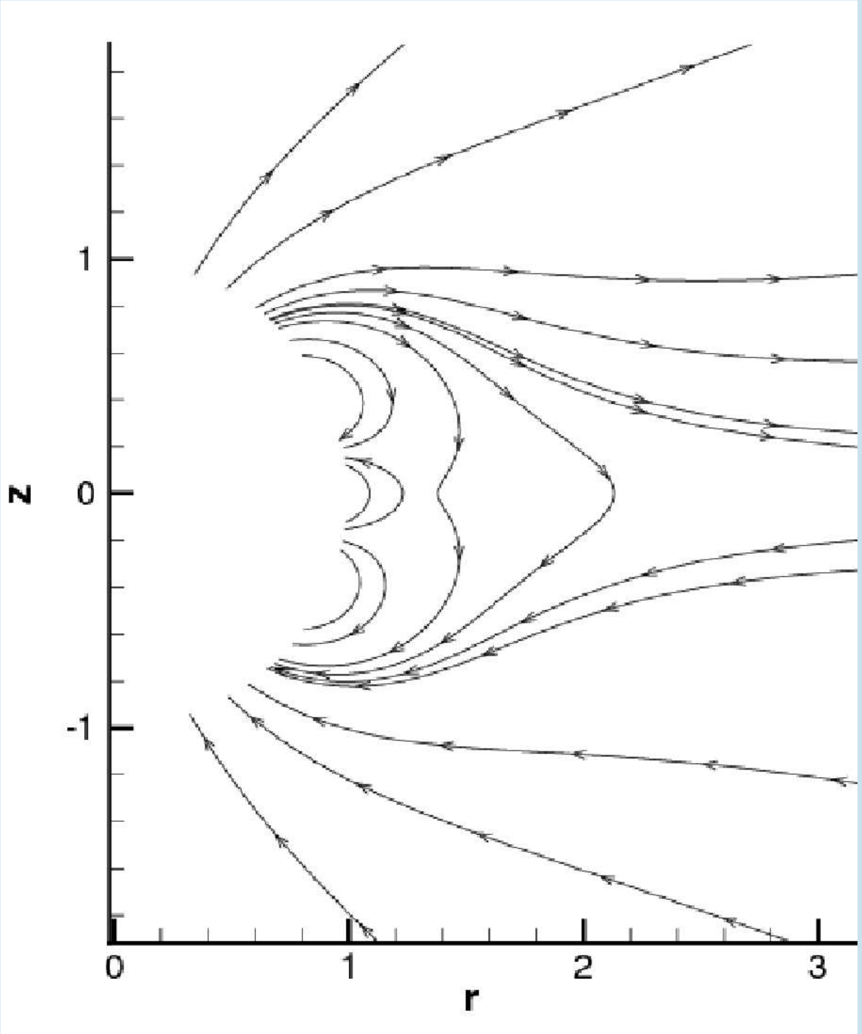
Breakout model

[Antiochos et al. 1999, ApJ]



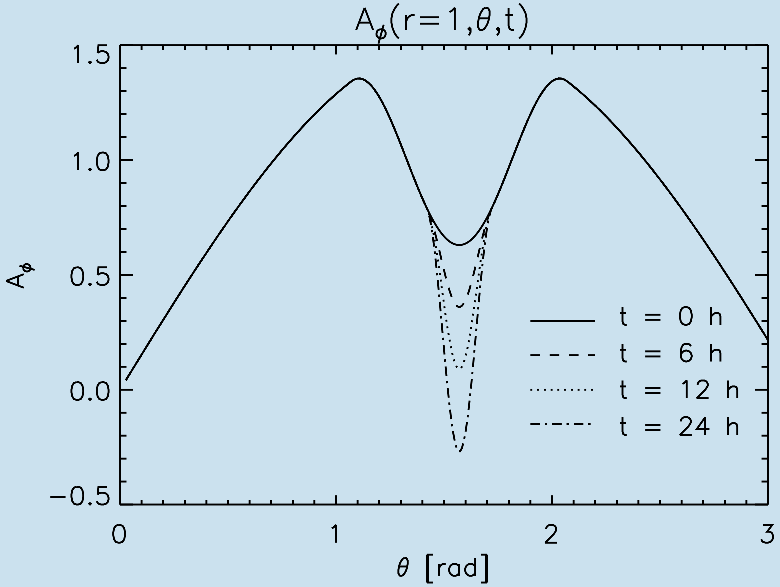
In the breakout model the flux rope is formed during the eruption. The eruption is driven by reconnection in front of a sheared arcade.

Zuccarello et al. 2009, A&A

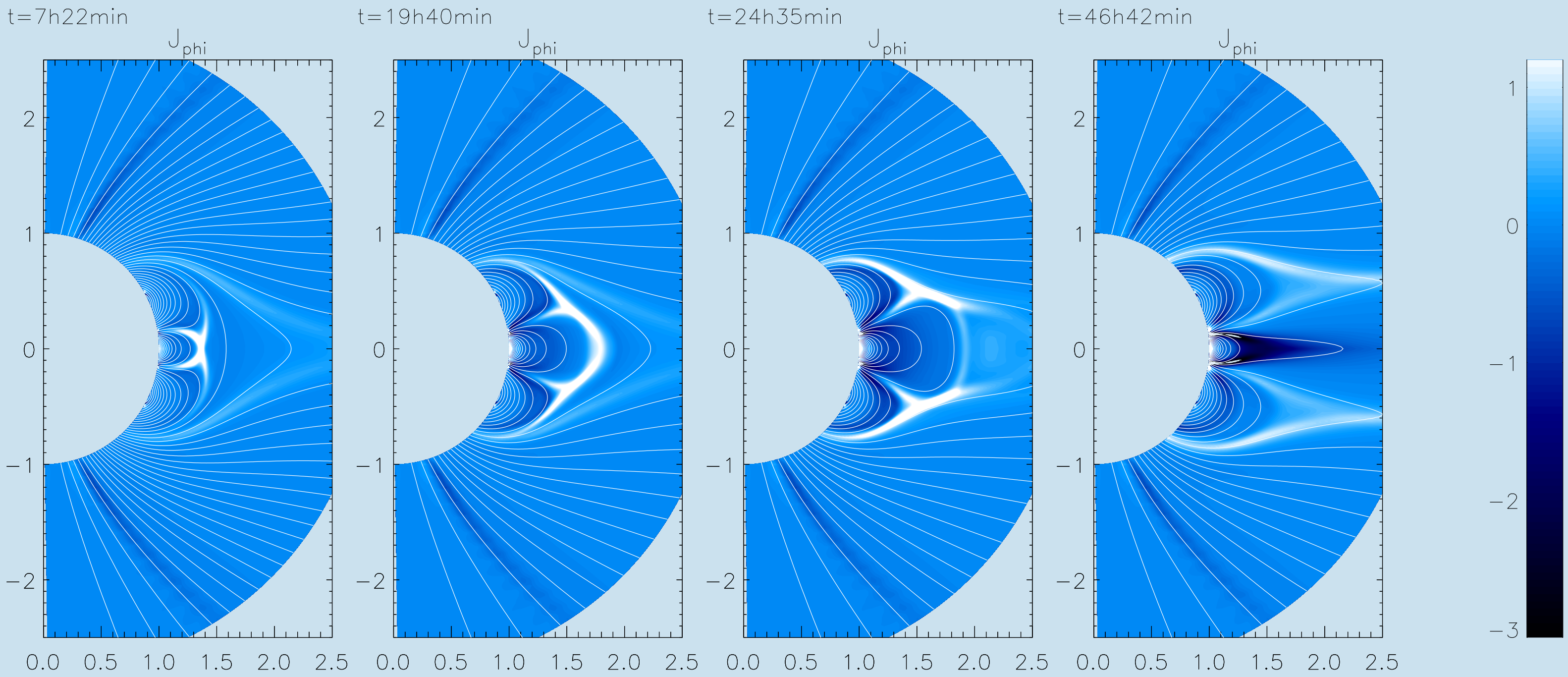


- Study the effect of flux emergence in the setup of the breakout model.
- Simulation domain: lower corona - $30R_{\odot}$. Including the effect of the solar wind.
- Bipolar active region, embedded in global dipole field.

Zuccarello et al. 2009, A&A

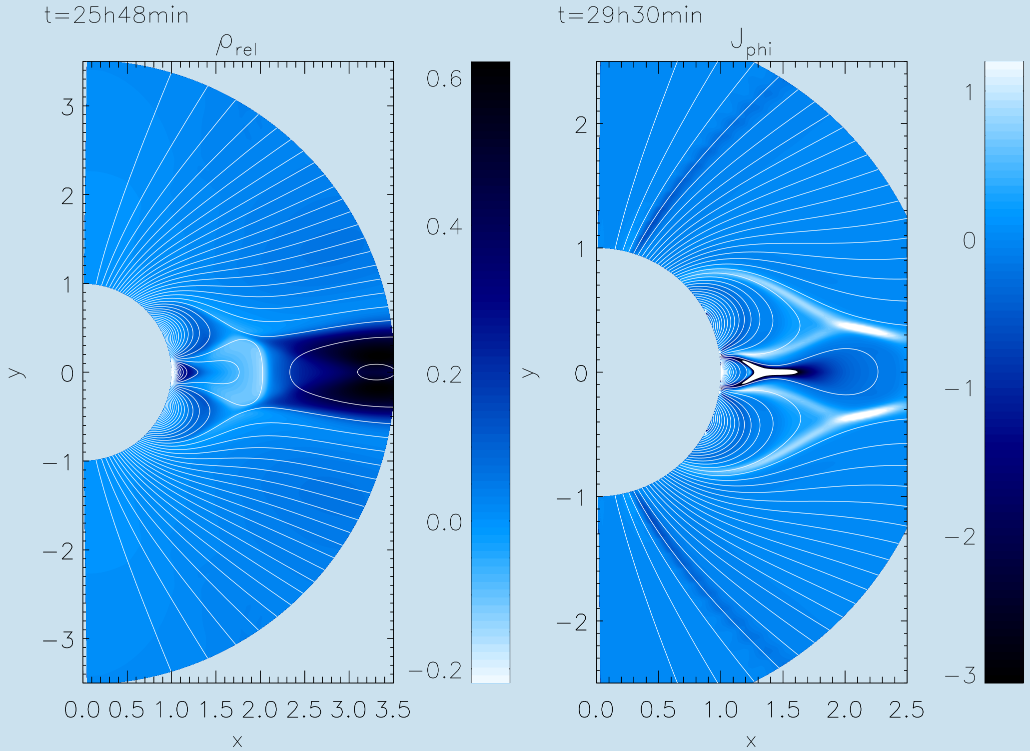


- Flux emergence by time dependent boundary condition on vector potential $\mathbf{A} \Rightarrow$ active region flux increases linearly in time.
- $\Delta t = 24$h.
- $|\Phi_E| = 2\pi |c_e| = 1.97 \times 10^{22}$Mx.



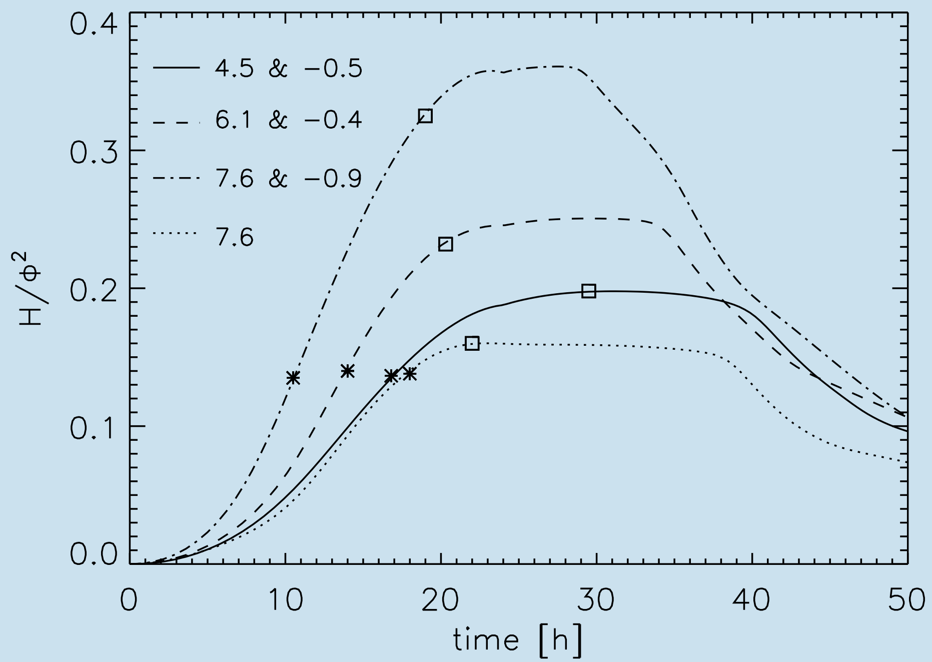
- Central arcade expands upward. • *Breakout* reconnection removes overlying field towards the side arcades. • Reconnection eventually detaches the helmet streamer. • No flare reconnection. • No injection of helicity. • CME is result from specific topology.

Combining flux emergence and shearing motions: emergence of sheared arcade in pre-existing active region.



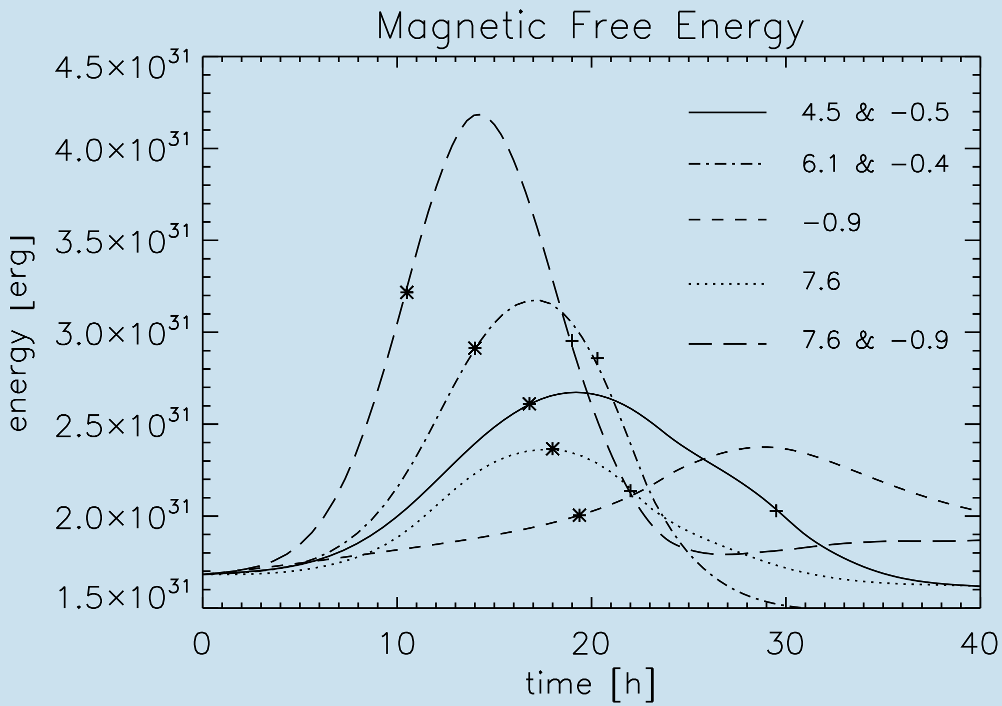
- Similar dynamic evolution as in the previous case.
- Due to injection of azimuthal magnetic field: flare reconnection at the bottom of the expanding central arcade.
- Threshold in helicity seems to exist (≈ 0.14).
- No clear threshold for the magnetic energy.
- Depending on the driving mechanism, same magnetic configuration can undergo different evolution.
- In all simulations: actual CME is detached helmet streamer $\rightarrow$ importance of the background wind.

Combining flux emergence and shearing motions: emergence of sheared arcade in pre-existing active region.



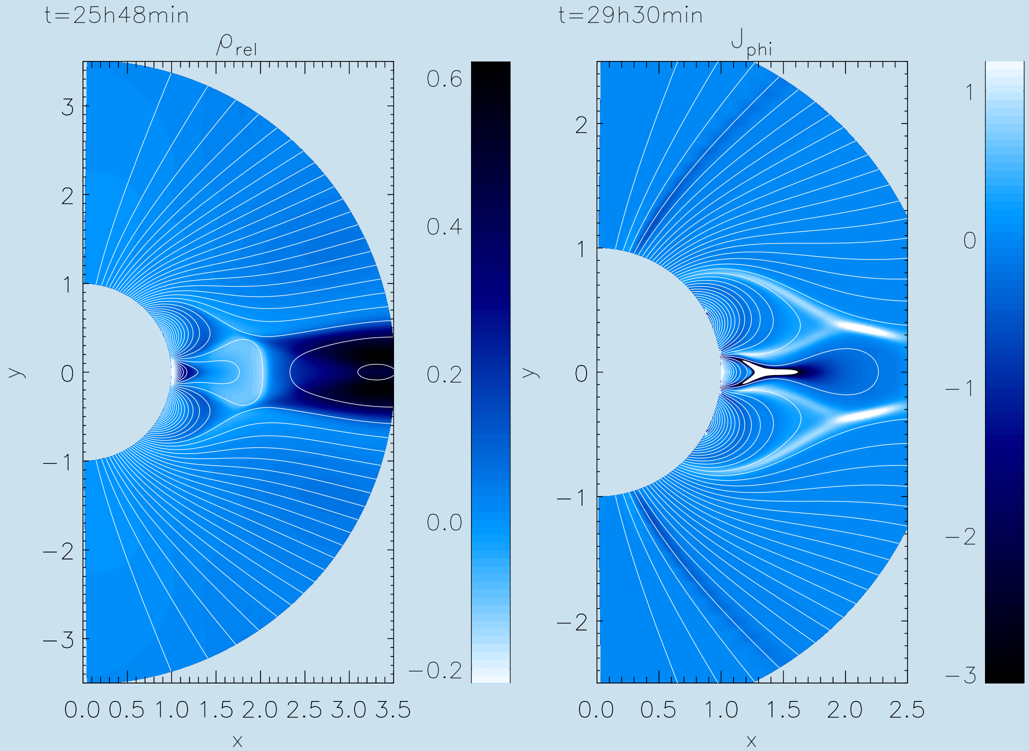
- Similar dynamic evolution as in the previous case.
- Due to injection of azimuthal magnetic field: flare reconnection at the bottom of the expanding central arcade.
- Threshold in helicity seems to exist (≈ 0.14).
- No clear threshold for the magnetic energy.
- Depending on the driving mechanism, same magnetic configuration can undergo different evolution.
- In all simulations: actual CME is detached helmet streamer $\rightarrow$ importance of the background wind.

Combining flux emergence and shearing motions: emergence of sheared arcade in pre-existing active region.



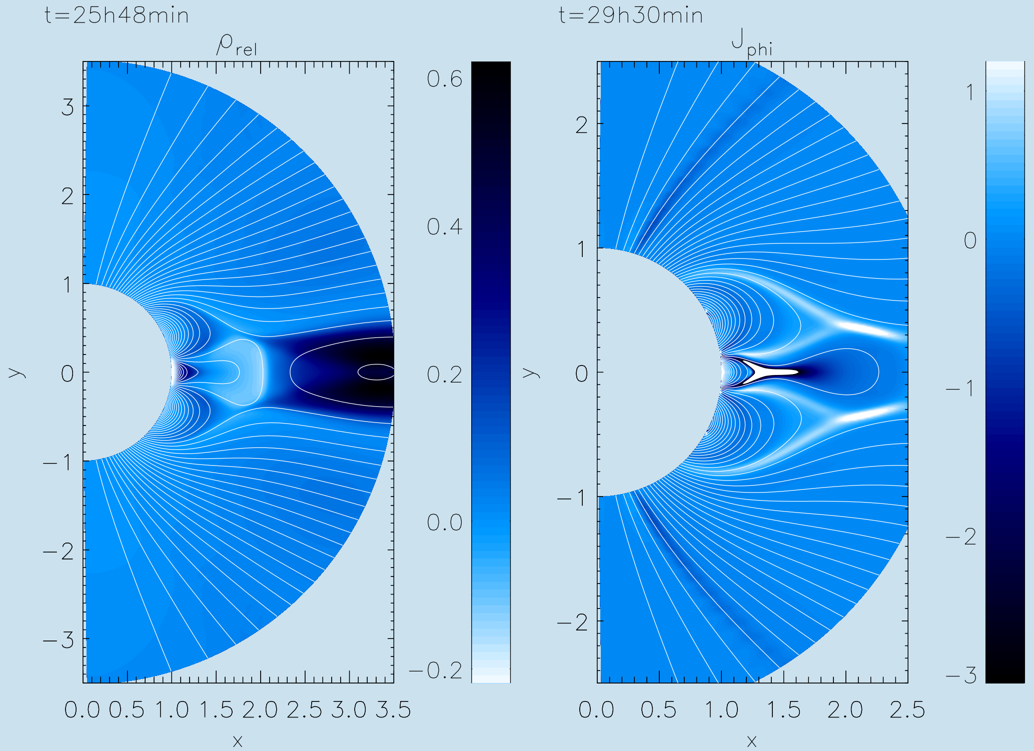
- Similar dynamic evolution as in the previous case.
- Due to injection of azimuthal magnetic field: flare reconnection at the bottom of the expanding central arcade.
- Threshold in helicity seems to exist (≈ 0.14).
- No clear threshold for the magnetic energy.
- Depending on the driving mechanism, same magnetic configuration can undergo different evolution.
- In all simulations: actual CME is detached helmet streamer $\rightarrow$ importance of the background wind.

Combining flux emergence and shearing motions: emergence of sheared arcade in pre-existing active region.



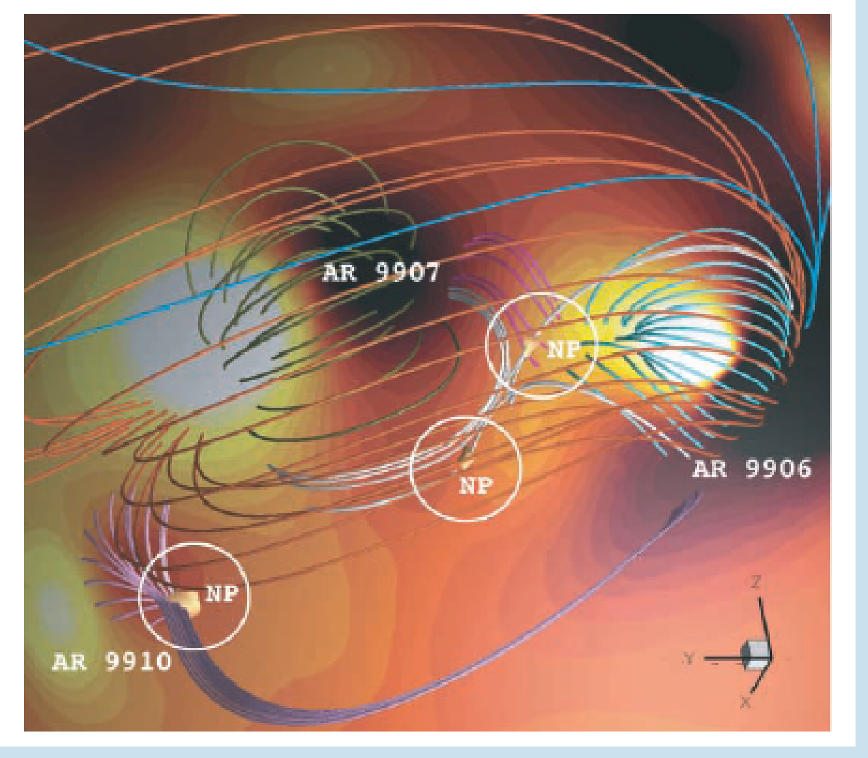
- Similar dynamic evolution as in the previous case.
- Due to injection of azimuthal magnetic field: flare reconnection at the bottom of the expanding central arcade.
- Threshold in helicity seems to exist (≈ 0.14).
- No clear threshold for the magnetic energy.
- Depending on the driving mechanism, same magnetic configuration can undergo different evolution.
- In all simulations: actual CME is detached helmet streamer $\rightarrow$ importance of the background wind.

Combining flux emergence and shearing motions: emergence of sheared arcade in pre-existing active region.



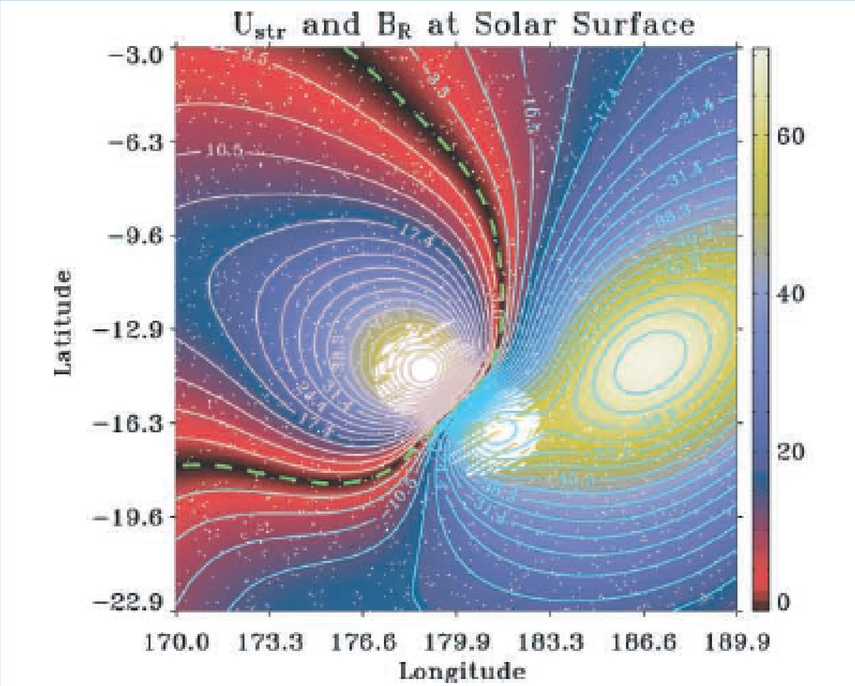
- Similar dynamic evolution as in the previous case.
- Due to injection of azimuthal magnetic field: flare reconnection at the bottom of the expanding central arcade.
- Threshold in helicity seems to exist (≈ 0.14).
- No clear threshold for the magnetic energy.
- Depending on the driving mechanism, same magnetic configuration can undergo different evolution.
- In all simulations: actual CME is detached helmet streamer → importance of the background wind.

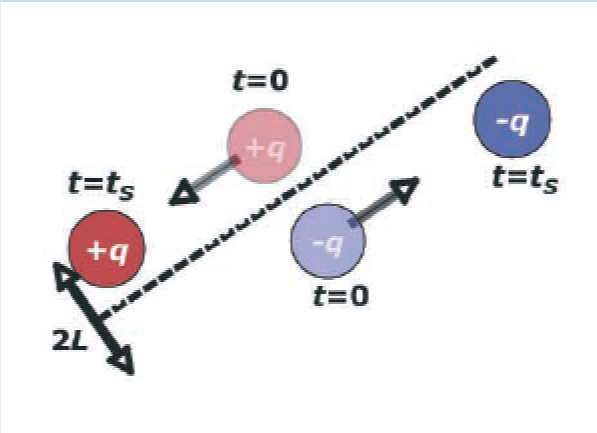
[Roussev et al. 2007, ApJ]



- CME event studies of April 21 and August 24 2002.
- 3D MHD, starting from magnetogram observations, including background solar wind.
- Loss of equilibrium of the coronal magnetic field and subsequent eruption achieved by stretching the opposite polarity feet of a newly emerged magnetic dipole.
- The stressed magnetic field reconnects through null points.
- Jumplike change in the location of one footprint of the erupting magnetic field.

[Roussev et al. 2007, ApJ]

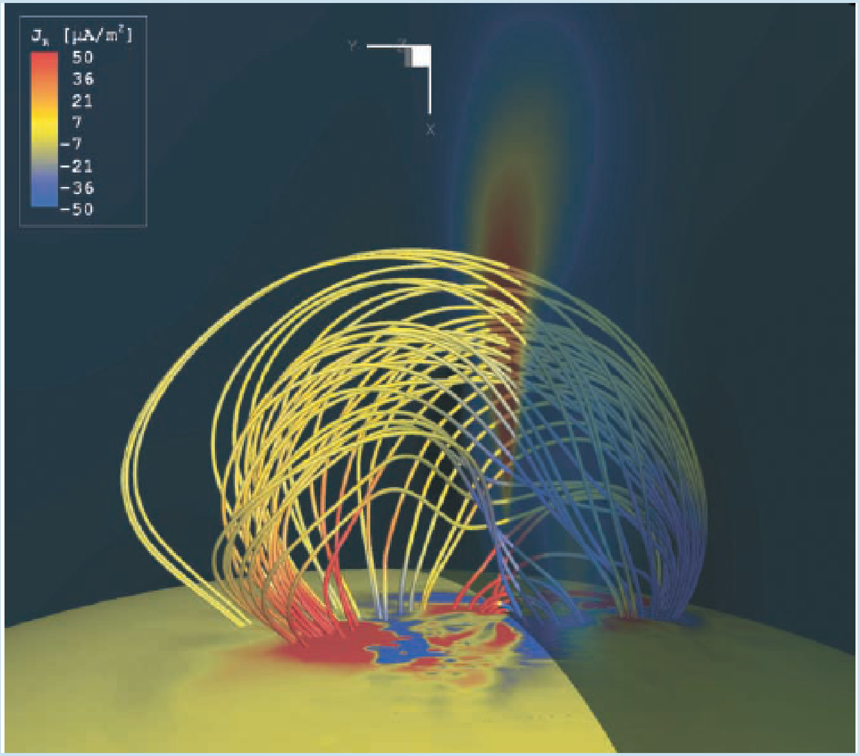




$|B_R| \sim qd/R^3$ (d is depth of charges below photosphere).

- CME event studies of April 21 and August 24 2002.
- 3D MHD, starting from magnetogram observations, including background solar wind.
- Loss of equilibrium of the coronal magnetic field and subsequent eruption achieved by stretching the opposite polarity feet of a newly emerged magnetic dipole.
- The stressed magnetic field reconnects through null points.
- Jumplike change in the location of one footprint of the erupting magnetic field.

[Roussev et al. 2007, ApJ]



- CME event studies of April 21 and August 24 2002.
- 3D MHD, starting from magnetogram observations, including background solar wind.
- Loss of equilibrium of the coronal magnetic field and subsequent eruption achieved by stretching the opposite polarity feet of a newly emerged magnetic dipole.
- The stressed magnetic field reconnects through null points.
- Jumplike change in the location of one footprint of the erupting magnetic field.

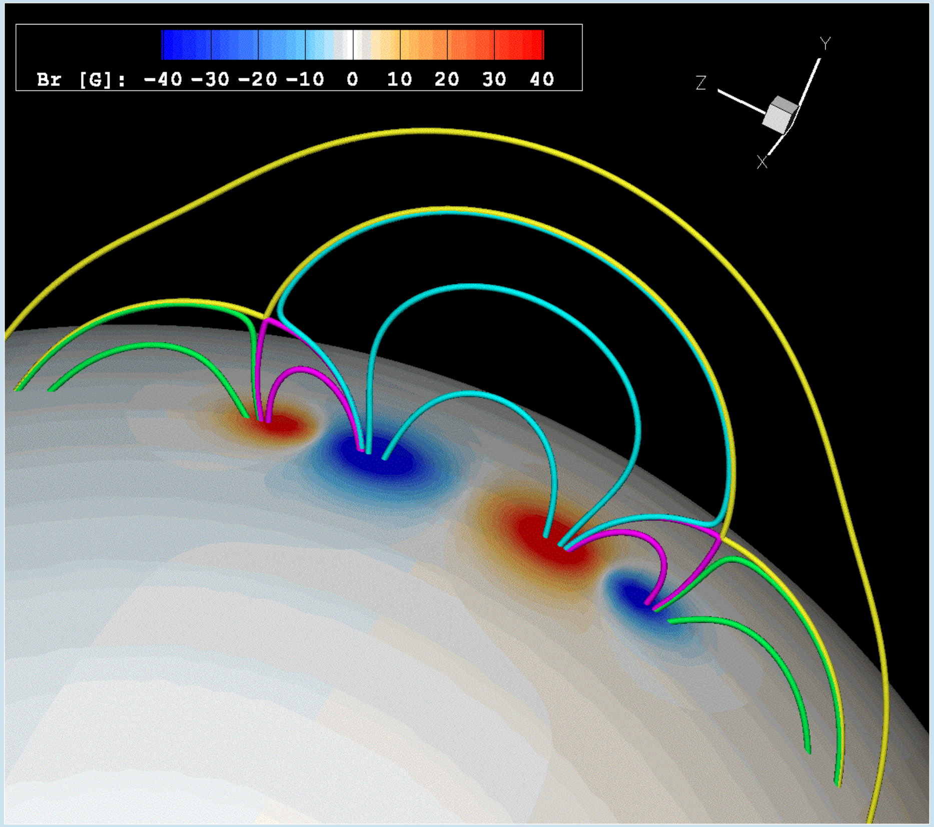
Outline

Study the initiation of a CME in idealized settings

Model features Jacobs et al. 2009

Steady state solar corona and solar wind achieved using model of Roussev et al. (2003).
Multi-polar magnetic field is produced by:

- Dipole field ⇝ solar minimum.
- Pre-existing active region (outer spots with BR ≈ 50 G).
- Newly emerged active region (inner spots with BR ≈ 70 G).
- "quadrupolar" active region with two null points.

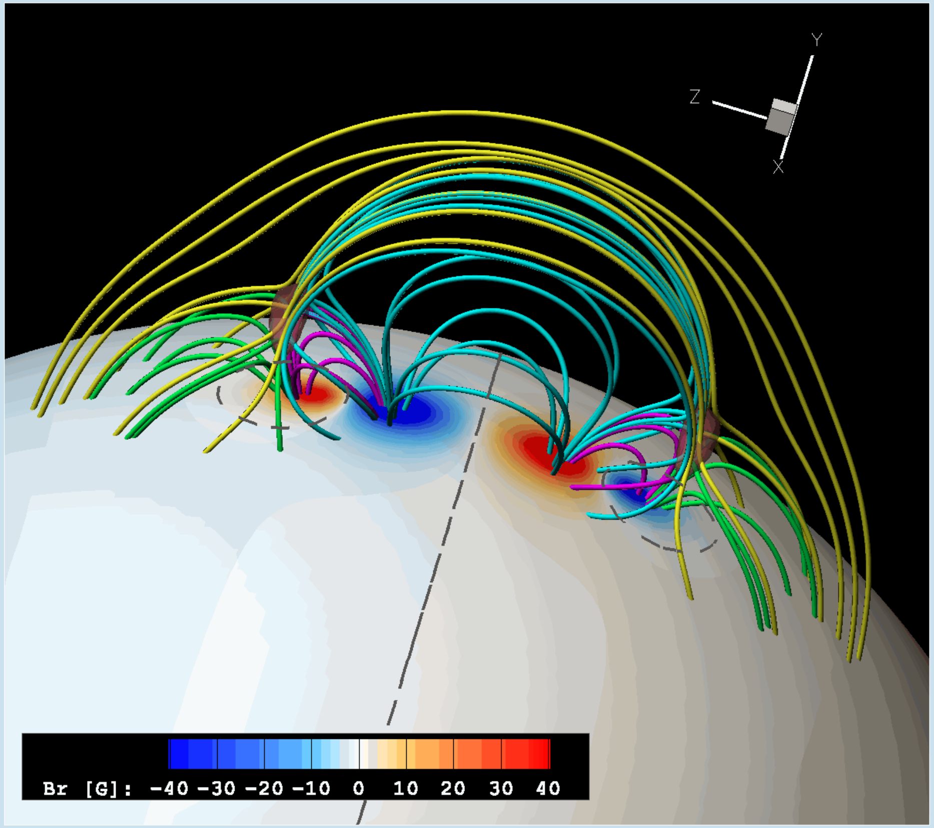


Study the initiation of a CME in idealized settings

Model features Jacobs et al. 2009

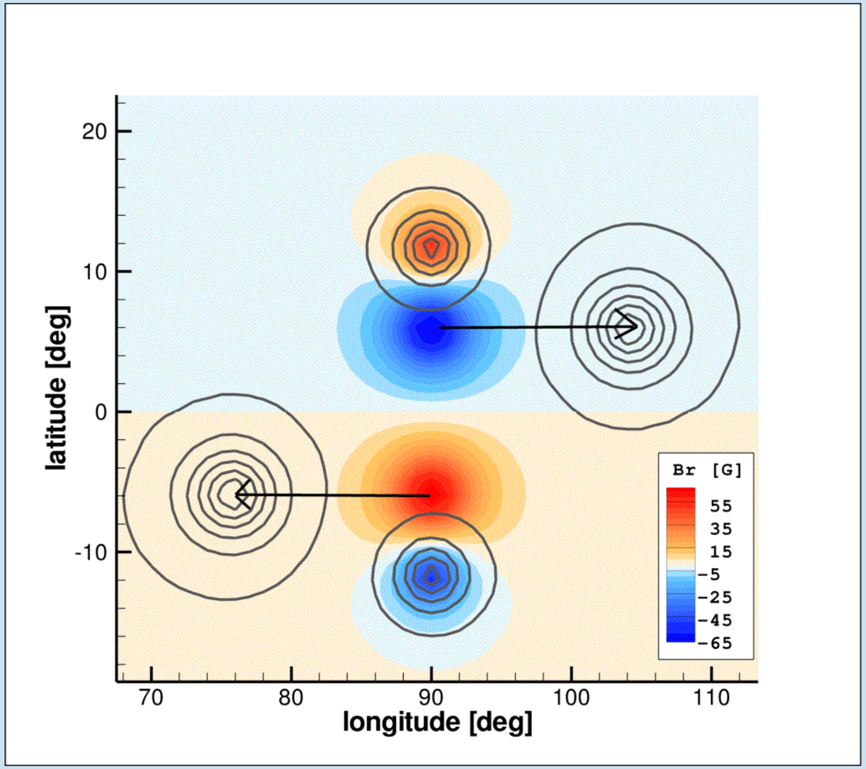
Steady state solar corona and solar wind achieved using model of Roussev et al. (2003).
Multi-polar magnetic field is produced by:

- Dipole field $\rightsquigarrow$ solar minimum.
- Pre-existing active region
  (outer spots with BR $\approx$ 50 G).
- Newly emerged active region
  (inner spots with BR $\approx$ 70 G).
- "quadrupolar" active region with two null points.



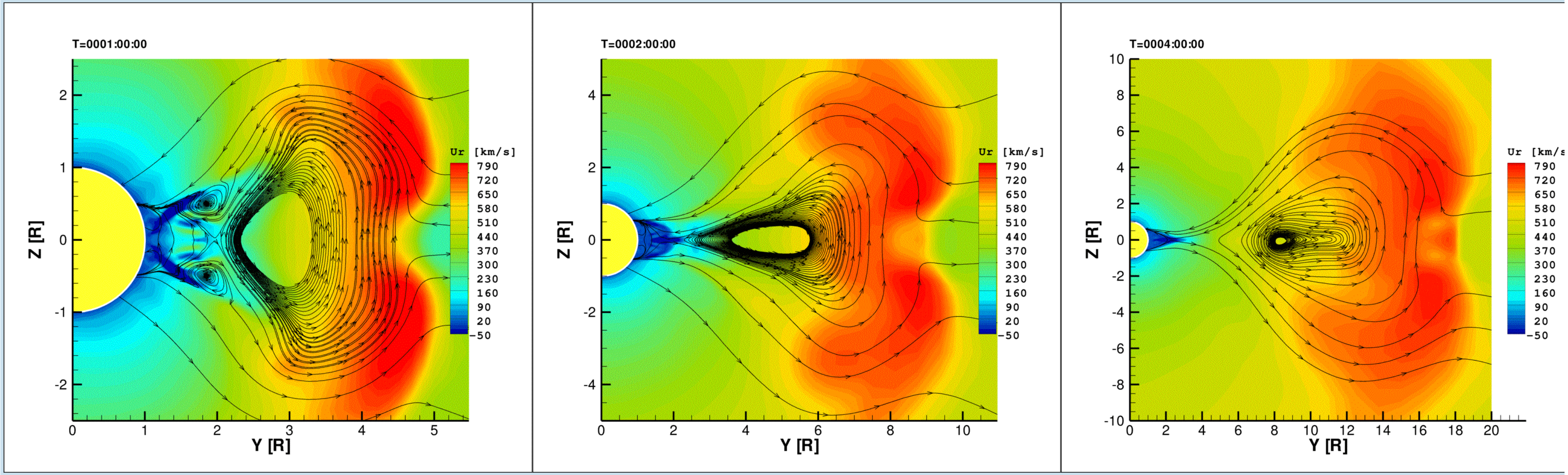
CME driver: shearing & flux emergence

- Inner spots are moved apart in finite time (30 min) with speed of 90 km/s ($< 3\%$ of local V_A).
- These shearing motions energize the magnetic field.
- Total separation of the charges is about 30°.



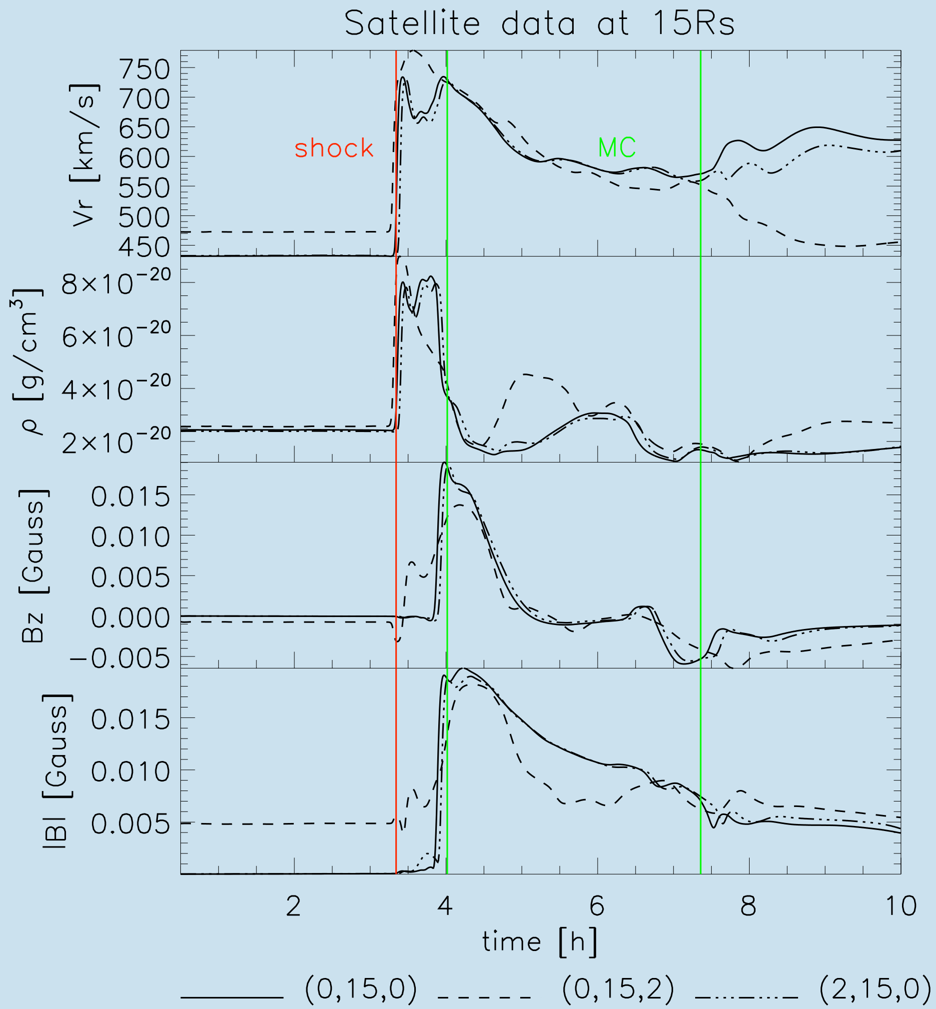
CME structure in meridional plane

quadrupolar case



This appears to be the cross-section of a magnetic flux rope.
Fast CME! ($< v >= 850$km/s)

3D structure of the CME



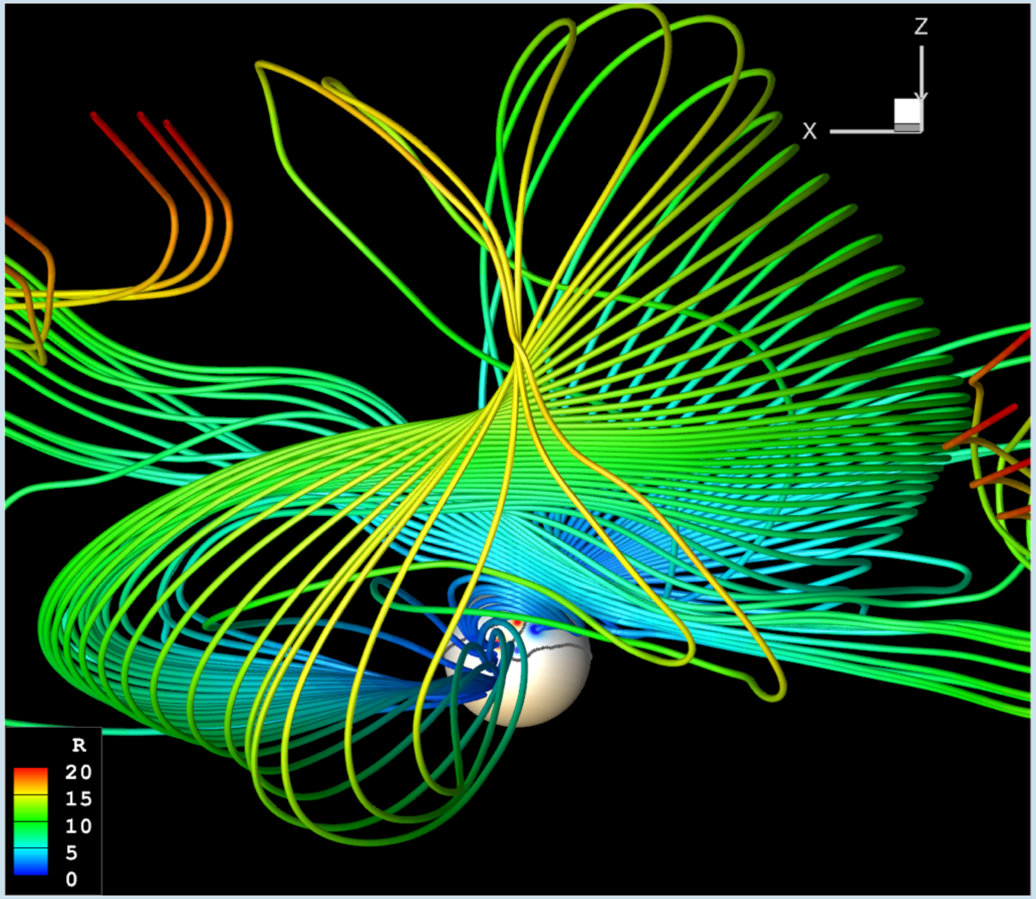
CME possesses:

- High magnetic field strength.
- Low-density interior with higher-density core.
- Smooth rotation of Bz.

These properties are usually associated with **magnetic clouds** → twisted magnetic flux ropes.

BUT...

3D structure of the CME

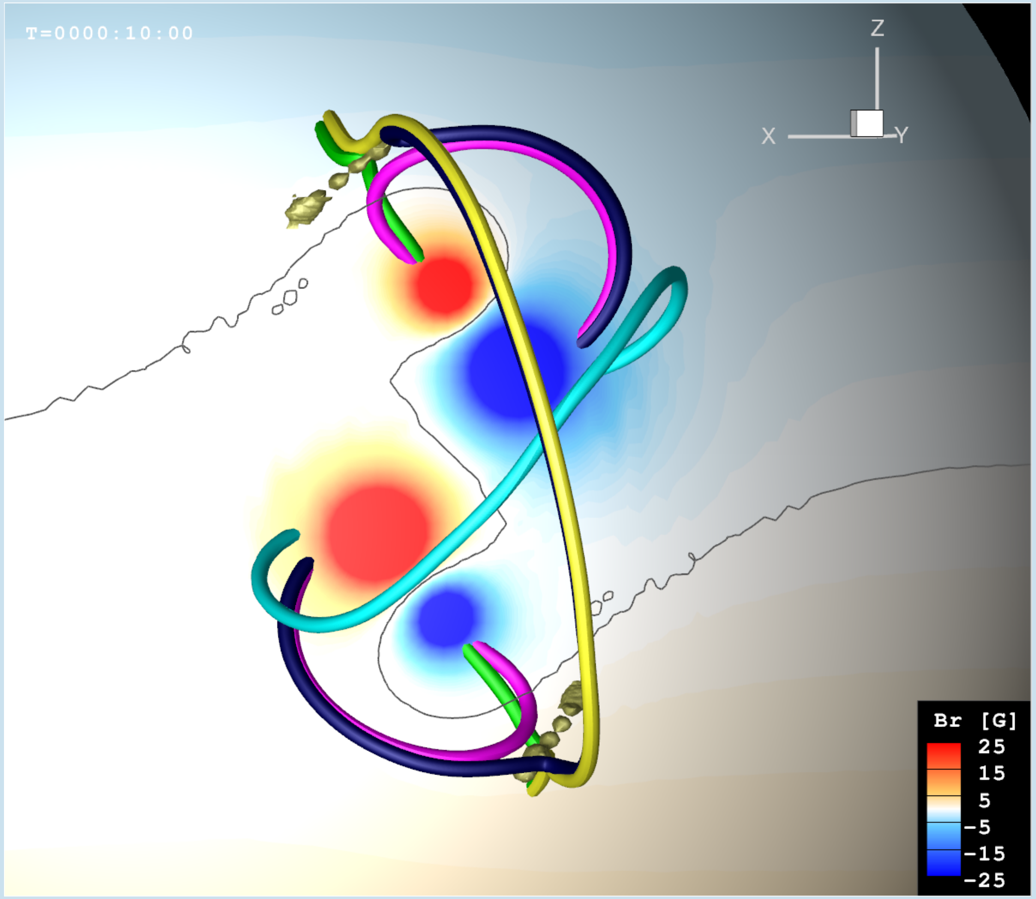


This is not "standard" flux-rope type CME

- Magnetic field of CME shows significant writhe.
- Footprints of the erupting field are not localized on the solar surface.
- There are jumps in field line mapping on solar surface as a satellite flies through CME.

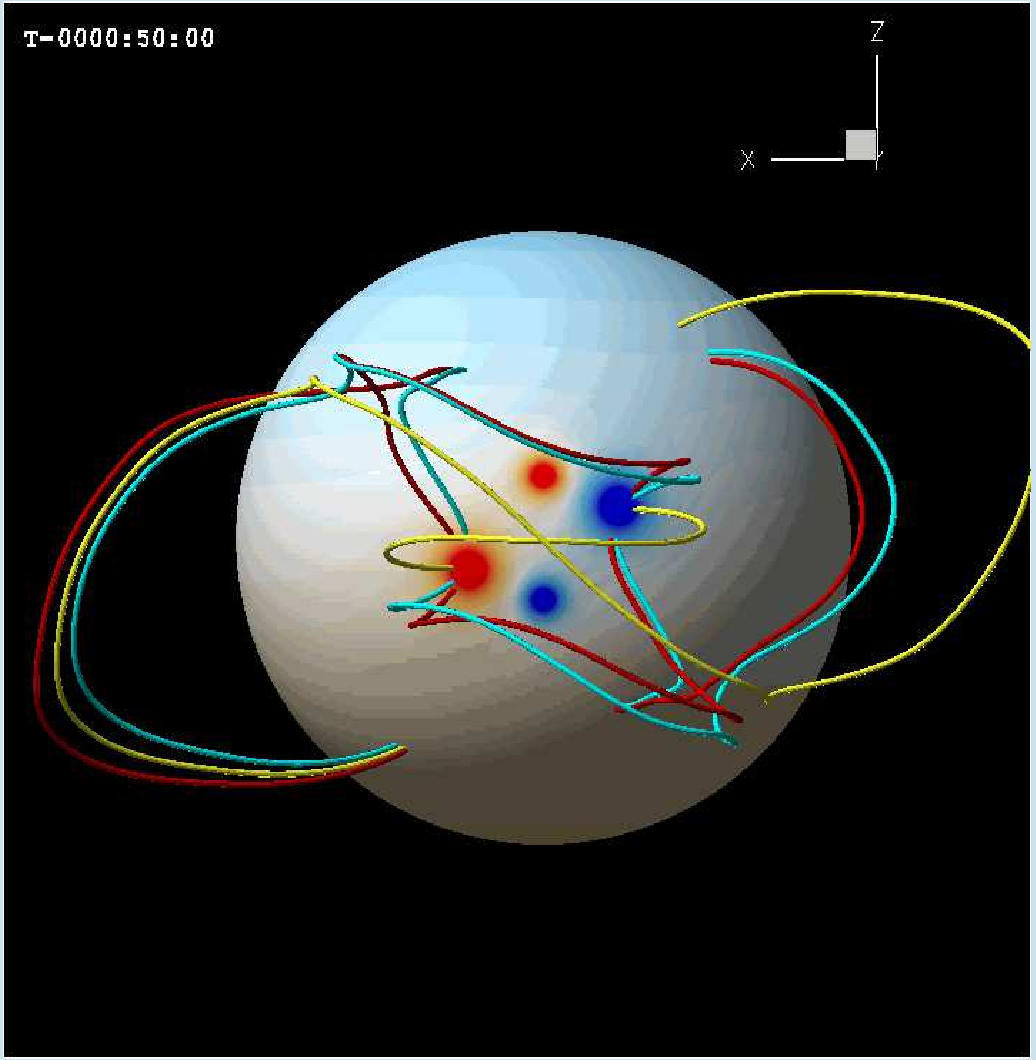
Large scale reconnection between global and erupting magnetic field.

3D structure of the CME



Magnetic reconnection occurs at the two null points: Purple field lines reconnect with yellow field line (of overlying field) through current sheets formed at two pre-existing null points: result of reconnection is S-shaped dark blue field line.

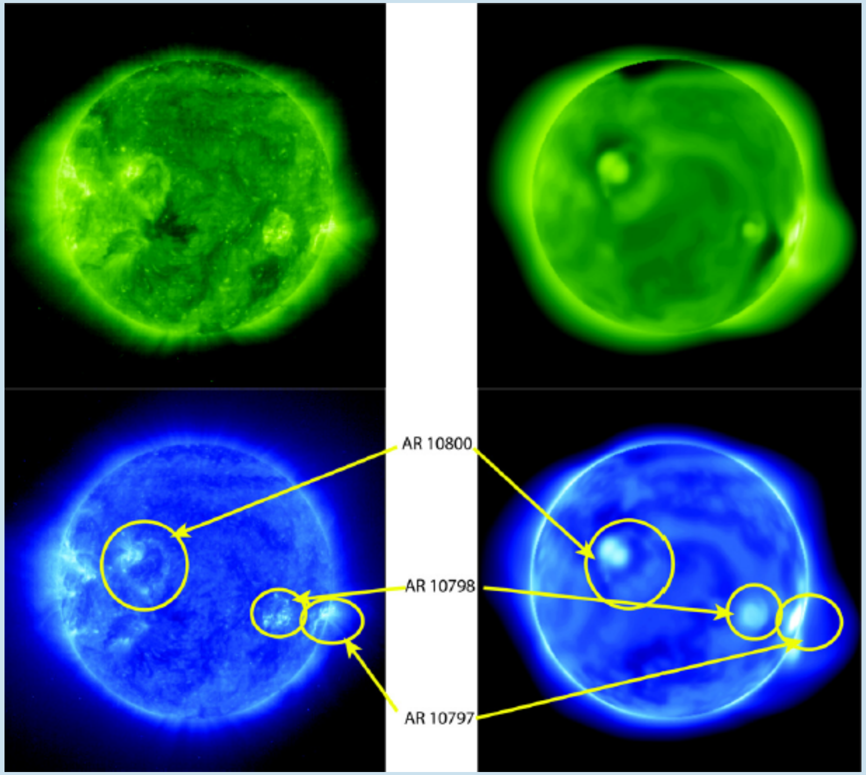
3D structure of the CME



- Reconnection between the erupting field and the global field causes highly writhed field lines.
- Two systems of flare loops connecting the active region with the quiet Sun.
- Magnetic connection between very remote regions on the Sun.

Event study: the 2005 August 22 event

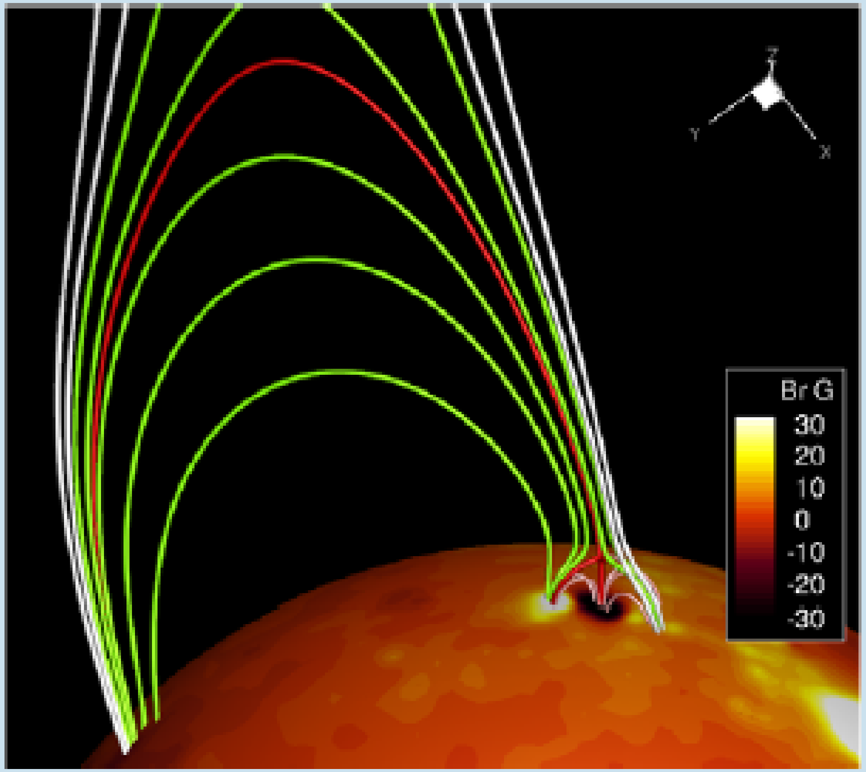
[Lugaz et al., ApJ (2011)]



- 3D MHD model Downs et al. 2010).
- **Anemone AR** emerging in coronal hole.
- CME initiated by out-of-equilibrium FR (Roussev et al. 2003).
- Negative foot point of erupting FR reconnects with helmet streamer and with open field.
- Reproduction of coronal dimmings: footprint of erupting field.

Event study: the 2005 August 22 event

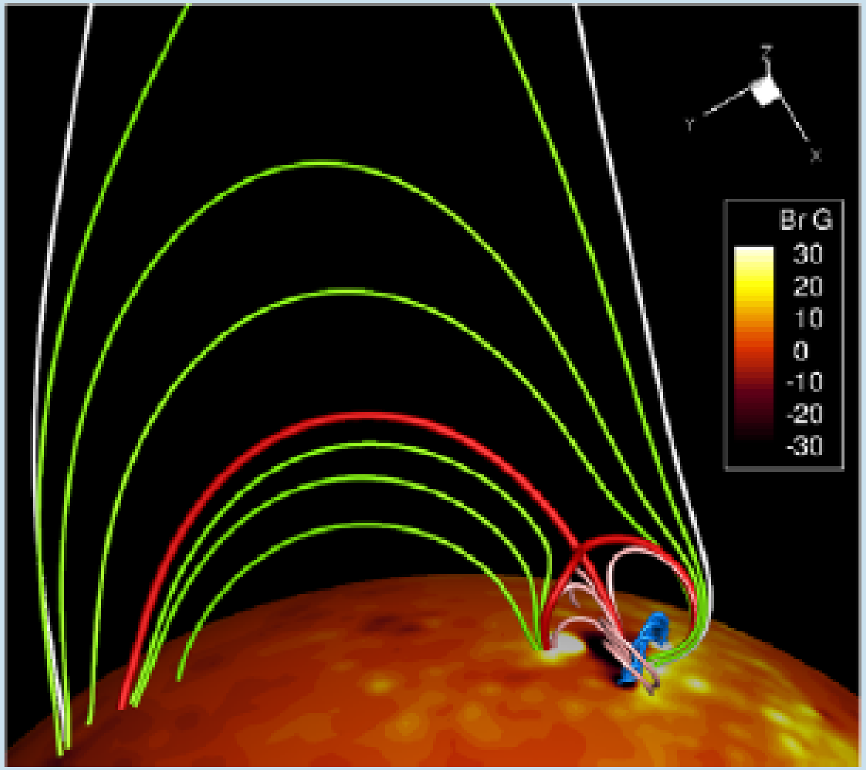
[Lugaz et al., ApJ (2011)]



- 3D MHD model Downs et al. 2010).
- **Anemone AR** emerging in coronal hole.
- CME initiated by out-of-equilibrium FR (Roussev et al. 2003).
- Negative foot point of erupting FR reconnects with helmet streamer and with open field.
- Reproduction of coronal dimmings: footprint of erupting field.

Event study: the 2005 August 22 event

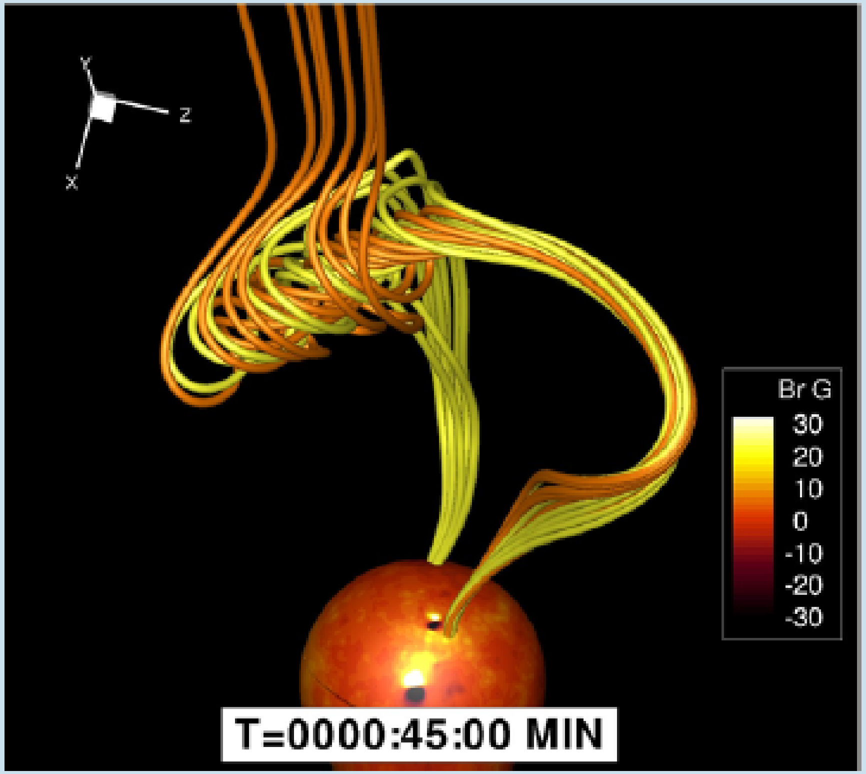
[Lugaz et al., ApJ (2011)]



- 3D MHD model Downs et al. 2010).
- **Anemone AR** emerging in coronal hole.
- CME initiated by out-of-equilibrium FR (Roussev et al. 2003).
- Negative foot point of erupting FR reconnects with helmet streamer and with open field.
- Reproduction of coronal dimmings: footprint of erupting field.

Event study: the 2005 August 22 event

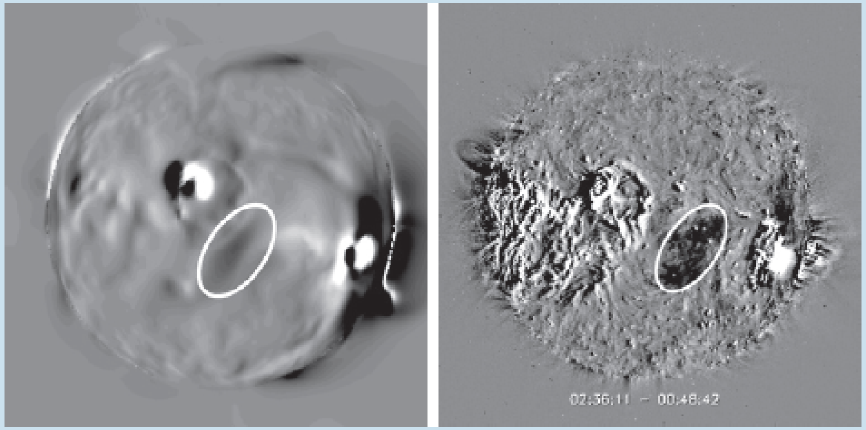
[Lugaz et al., ApJ (2011)]



- 3D MHD model Downs et al. 2010).
- **Anemone AR** emerging in coronal hole.
- CME initiated by out-of-equilibrium FR (Roussev et al. 2003).
- Negative foot point of erupting FR reconnects with helmet streamer and with open field.
- Reproduction of coronal dimmings: footprint of erupting field.

Event study: the 2005 August 22 event

[Lugaz et al., ApJ (2011)]



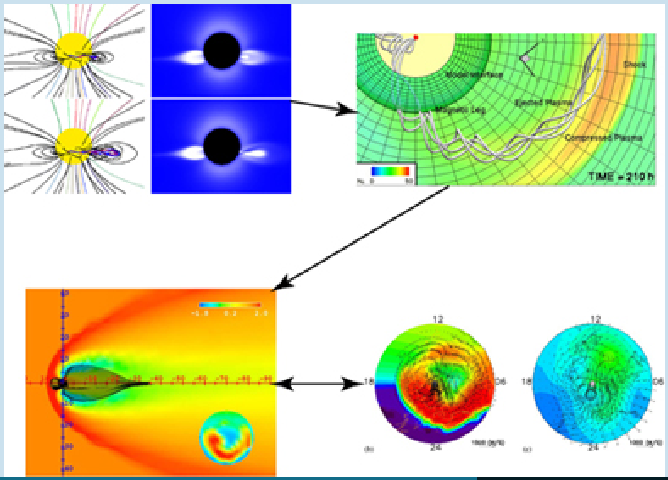
- 3D MHD model Downs et al. 2010).
- **Anemone AR** emerging in coronal hole.
- CME initiated by out-of-equilibrium FR (Roussev et al. 2003).
- Negative foot point of erupting FR reconnects with helmet streamer and with open field.
- Reproduction of coronal dimmings: footprint of erupting field.

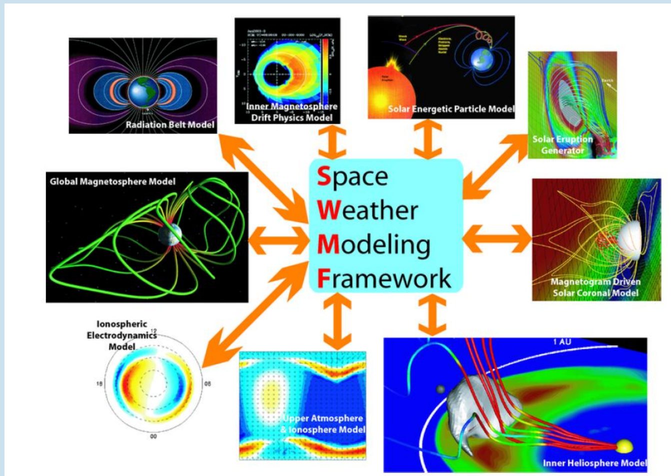
Outline

Conclusions

Numerical simulations provide deeper inside in the onset and evolution of CMEs. **Simulations are complementary to observations**.

- The present numerical simulations of CME initiation and evolution are able to reproduce many of the observed features.
- Simulations of CMEs focus either on the photosphere/low corona, or on the low/high corona ⇒ there exists a large gap between the two.
- Advanced coupled 3D MHD models for the simulation of a CME from its initiation up to the interaction with the Earth are being developed (CISM (Luhmann 2004), SWMF (Toth 2005))





Conclusions

Numerical simulations provide deeper inside in the onset and evolution of CMEs. **Simulations are complementary to observations**.

- The present numerical simulations of CME initiation and evolution are able to reproduce many of the observed features.
- Simulations of CMEs focus either on the photosphere/low corona, or on the low/high corona ⇒ there exists a large gap between the two.
- Advanced coupled 3D MHD models for the simulation of a CME from its initiation up to the interaction with the Earth are being developed (CISM (Luhmann 2004), SWMF (Toth 2005))
- Cannot predict the onset, size, velocity, direction, magnetic field,...of CMEs.

The End

Questions?