12th European Solar Physics Meeting
8 - 12 September 2008
Freiburg, Germany

Electronic proceedings

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Thursday 11:15-11:30

Modelling CMEs Close to the Sun

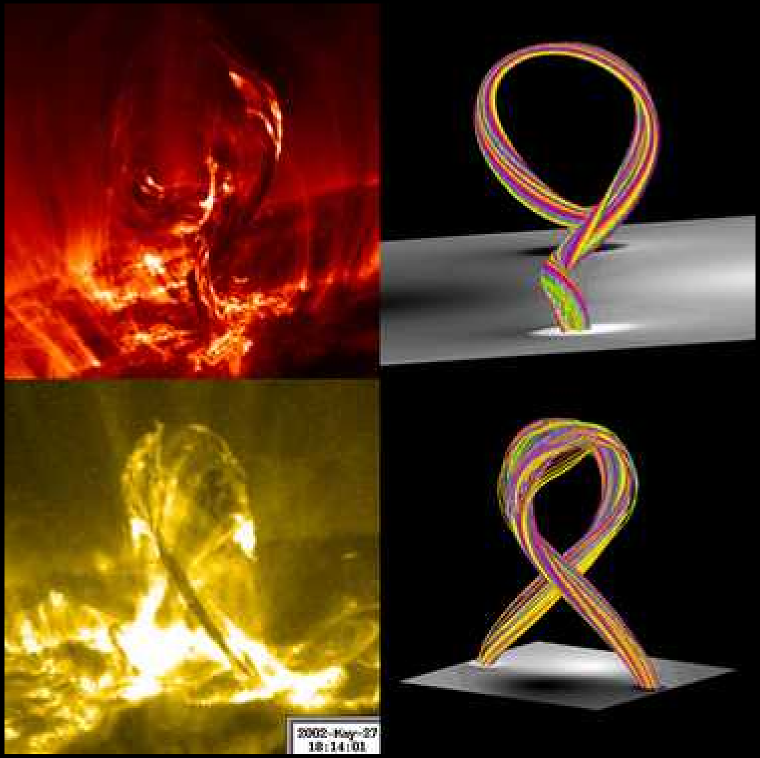
Török, T.
Paris Observatory

It is now widely accepted that large-scale solar eruptive phenomena like flares, eruptive prominences or filaments, and coronal mass ejections (CMEs) are magnetically driven. They are different observational manifestations of a more general process, namely a large-scale disruption of the coronal magnetic field ("solar eruption" in the following). It is also widely accepted that the energy necessary to drive solar eruptions is stored in the low corona, in form of sheared and twisted magnetic fields which are held in equilibrium prior to eruption by the ambient coronal field. An eruption occurs if this equilibrium is driven or perturbed such that it becomes unstable. In spite of this general understanding, the detailed processes which initiate and drive solar eruptions are not yet well understood. Several mechanisms have been proposed in the last decades. In recent years, the availability of 3D MHD simulations has helped to test the models and has greatly increased our understanding of these processes. In this talk, I will review current theoretical models and corresponding numerical simulations of solar eruptions. I will outline their differences and similarities and briefly discuss how current and future observations can help us to constrain the models. The simulation results indicate a flux rope instability or loss of equilibrium to be the canonical driving mechanism of solar eruptions in their fast acceleration phase close to the Sun, and they point towards a relatively large variety of possible mechanisms that initiate that phase. As an example for such an initiation mechanism, I will present new simulations which show how the eruption of a pre-existing 3D coronal flux rope can be triggered by magnetic flux emergence.

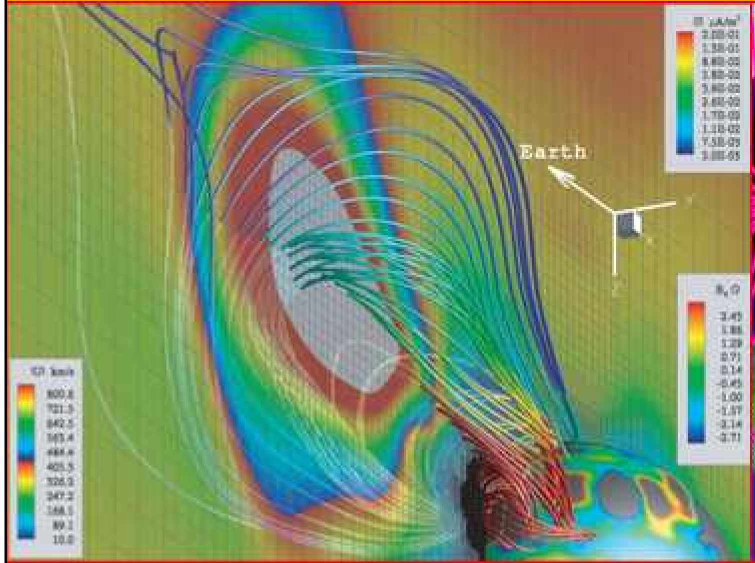
Modeling Solar Eruptions Close To The Sun

Tibor Török

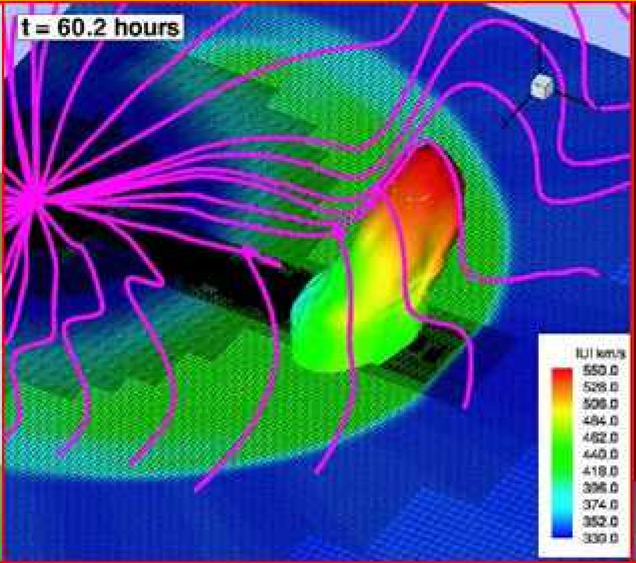
LESIA, Paris Observatory, France



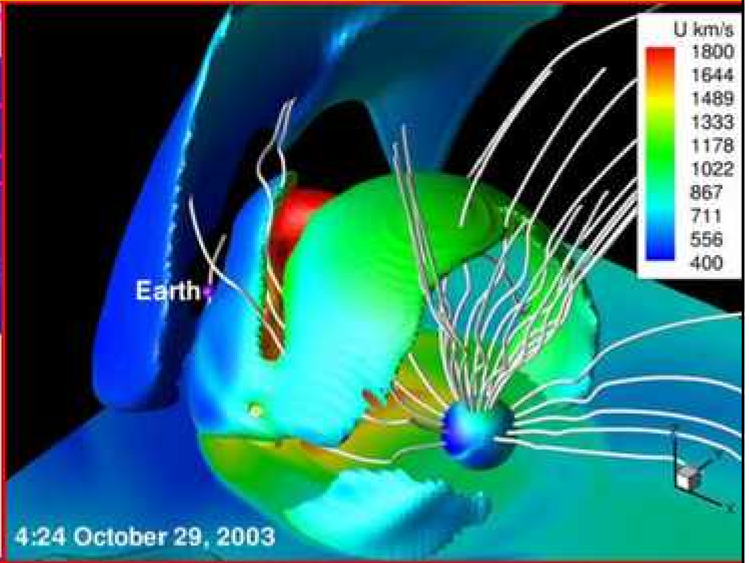
What I will not talk about … "global" CME models



Roussev et al., 2004



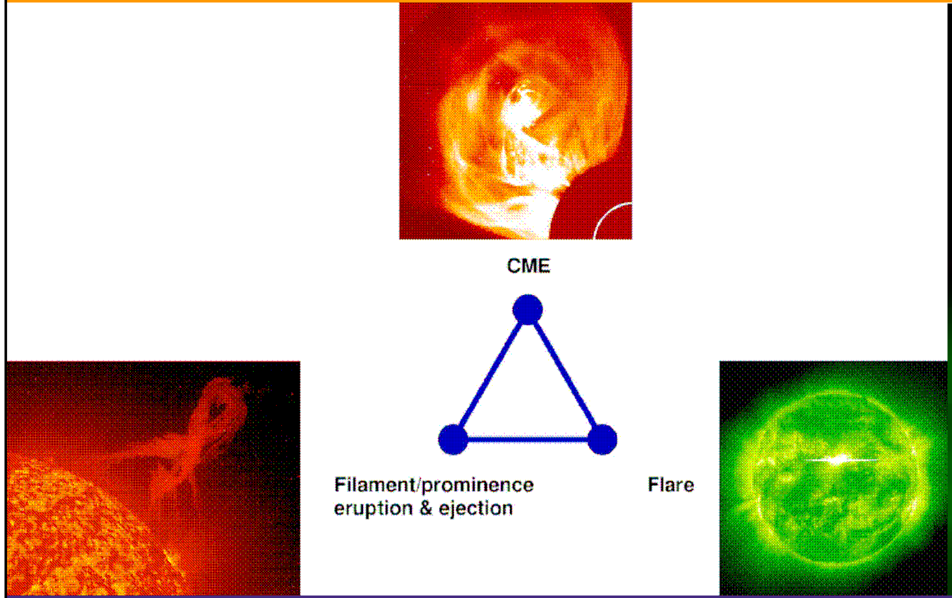
Manchester et al., 2004

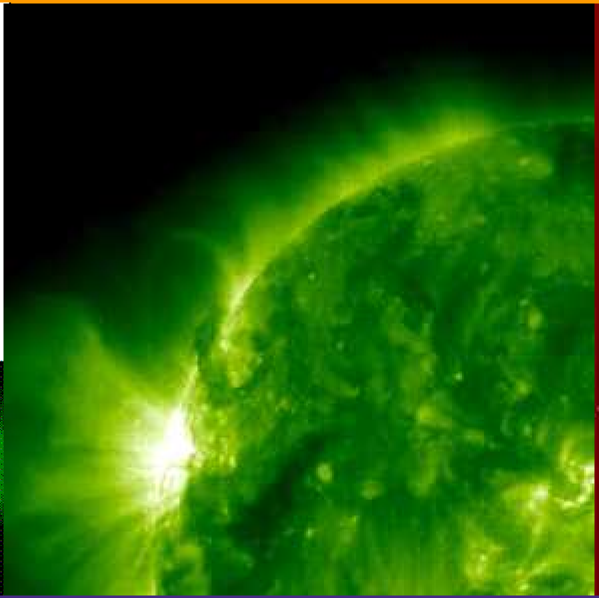


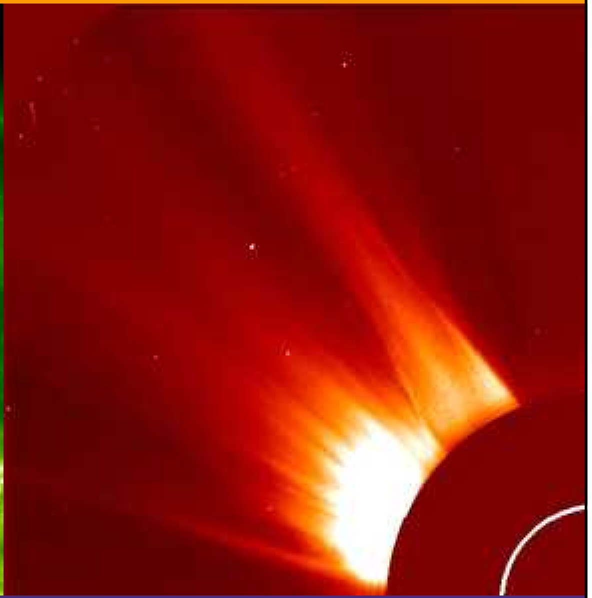
Tóth et al., 2007

- numerical simulation of CME propagation to Earth (and beyond)
- important to understand space weather
- study shocks, interaction with solar wind and magnetosphere, etc.
- long-term aim: real-time simulation of solar eruptions
- however: initiation mechanism(s) not yet treated properly

Solar Eruptions



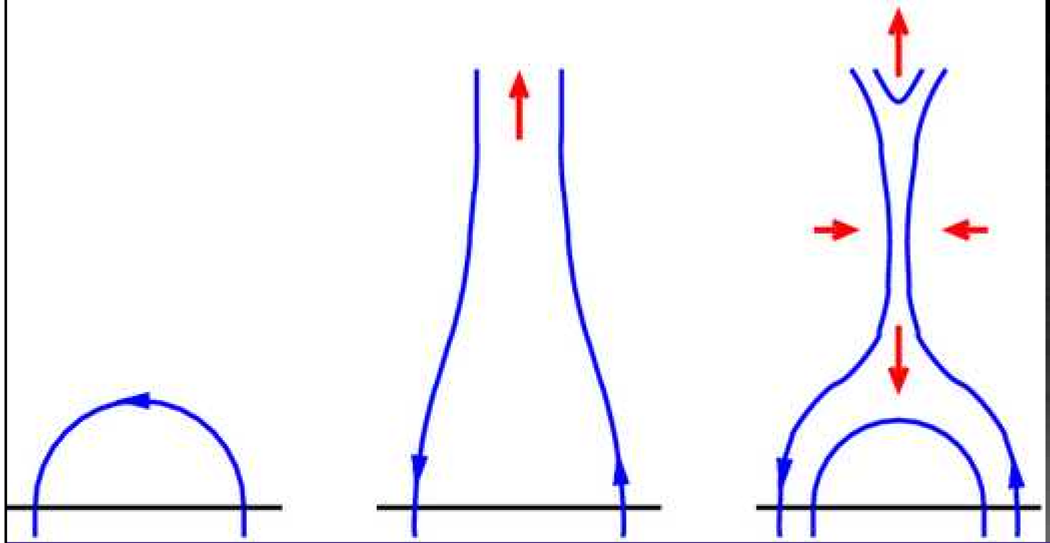




- largest energy release processes in solar system → space weather
- often all three components observed together (“eruptive flares”)
- different observational manifestations of one underlying process:

dynamic reconfiguration of coronal magnetic field

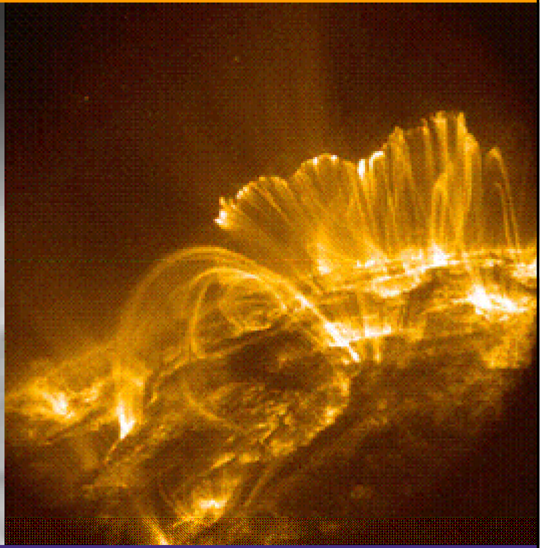
Basic Theoretical Concept



initiation

main phase

Yokoyama et al., 2001



“Standard (CSHKP) Model” of eruptive flares:

phase 1 = initiation and opening (includes “impulsive phase”)

phase 2 = “main phase”:

- formation of large-scale vertical current sheet
- reconnection re-closes active region field
- plasma & flux ejection into interplanetary space

Observational Constraints

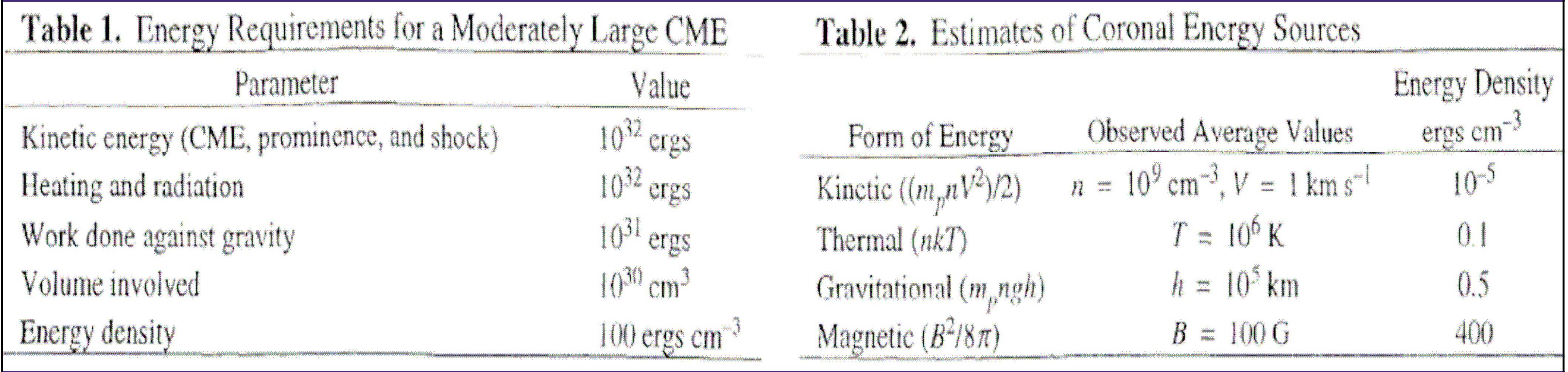


Table 1. Energy Requirements for a Moderately Large CME

Parameter	Value
Kinetic energy (CME, prominence, and shock)	10^{32} ergs
Heating and radiation	10^{32} ergs
Work done against gravity	10^{31} ergs
Volume involved	10^{30} cm^3
Energy density	100 ergs cm^{-3}

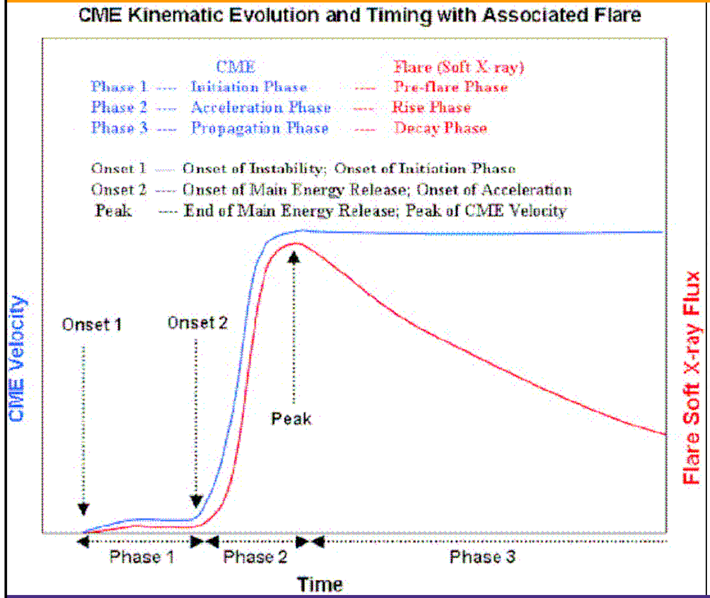
Table 2. Estimates of Coronal Energy Sources

Form of Energy	Observed Average Values	Energy Density ergs cm^{-3}
Kinetic ($(m_p n V^2)/2$)	$n = 10^9$ cm^{-3}, $V = 1$ km s^{-1}	10^{-5}
Thermal (nkT)	$T = 10^6$ K	0.1
Gravitational ($m_p n g h$)	$h = 10^5$ km	0.5
Magnetic ($B^2/8\pi$)	$B = 100$ G	400

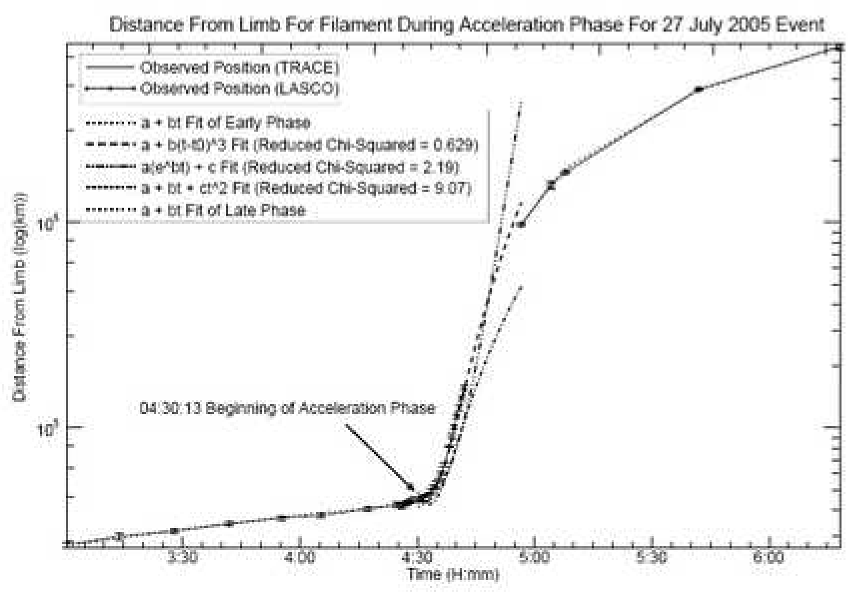
T. Forbes, 2000

- rapid timescale of eruption (~10^{32} ergs released within first few minutes)
- photospheric magnetic field largely unaffected by eruptions
- energy for eruption stored in corona → eruption magnetically driven
- pre-eruptive configuration: stressed core field + stabilizing overlying field

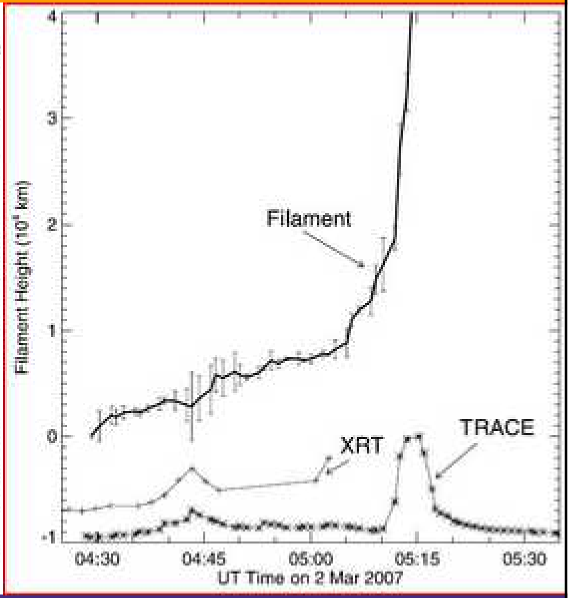
Eruption Phases



Zhang & Dere 2006



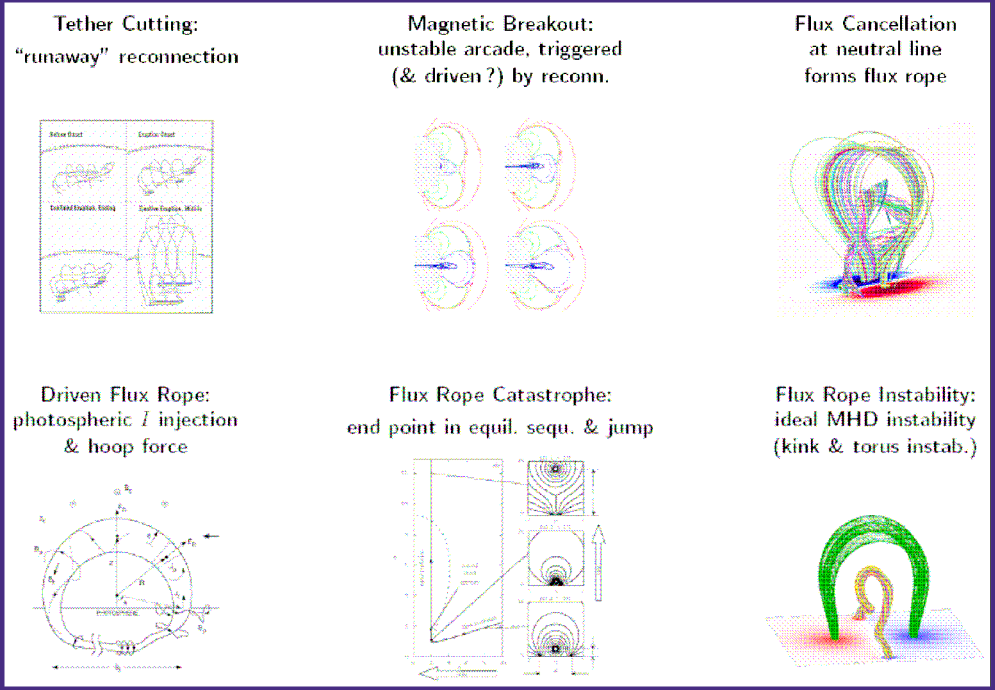
Schrijver et al. 2008



Sterling et al. 2007

- initiation phase: slow filament rise; weak soft X-ray signatures
- acceleration phase: fast filament rise & CME; flare onset
- propagation phase: constant CME velocity; flare decay
- recent careful observations show clear evidence for a linear rise phase prior to exponential-like rise during rapid acceleration phase
  → different physical mechanisms in these two phases

Models & Limitations (see Forbes 2000, 2001)



<u>models comprised of:</u>

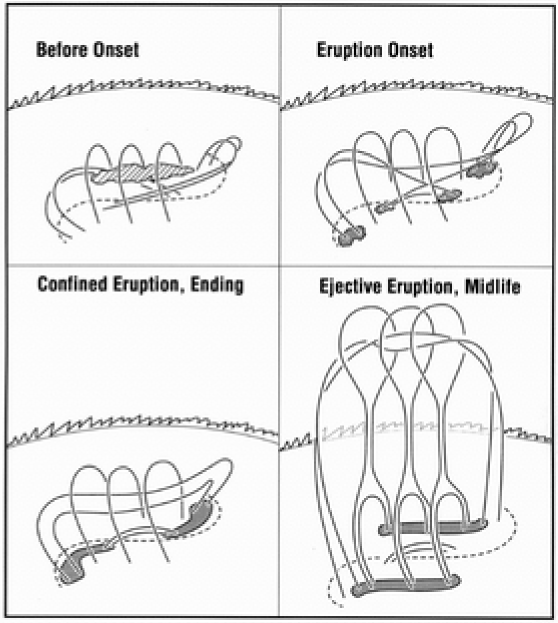
- system of differential equations (mostly MHD approximation)
- set of physical boundary conditions (well constrained by observations)
- initial state (poorly constrained by observations)

- coronal field not known → initial states idealized & complexity removed
- equations difficult to solve → numerical simulations required
- computer power limited → cannot cover full equations & length scale range

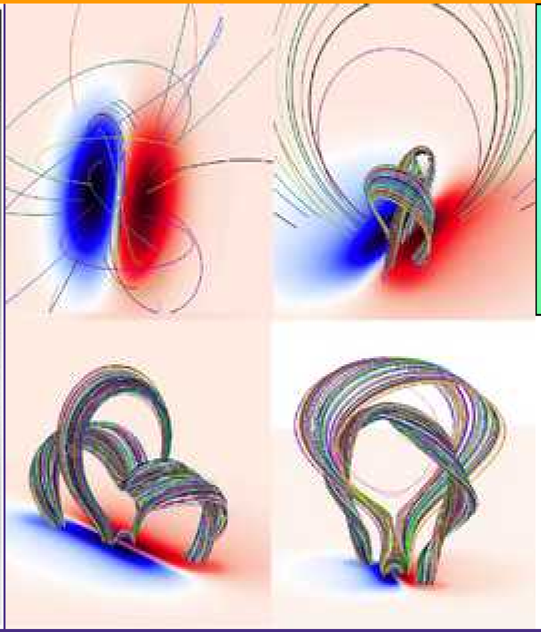
models still valuable to test proposed physical mechanisms

- "storage and release": initial arcade or flux rope + boundary driven evolution

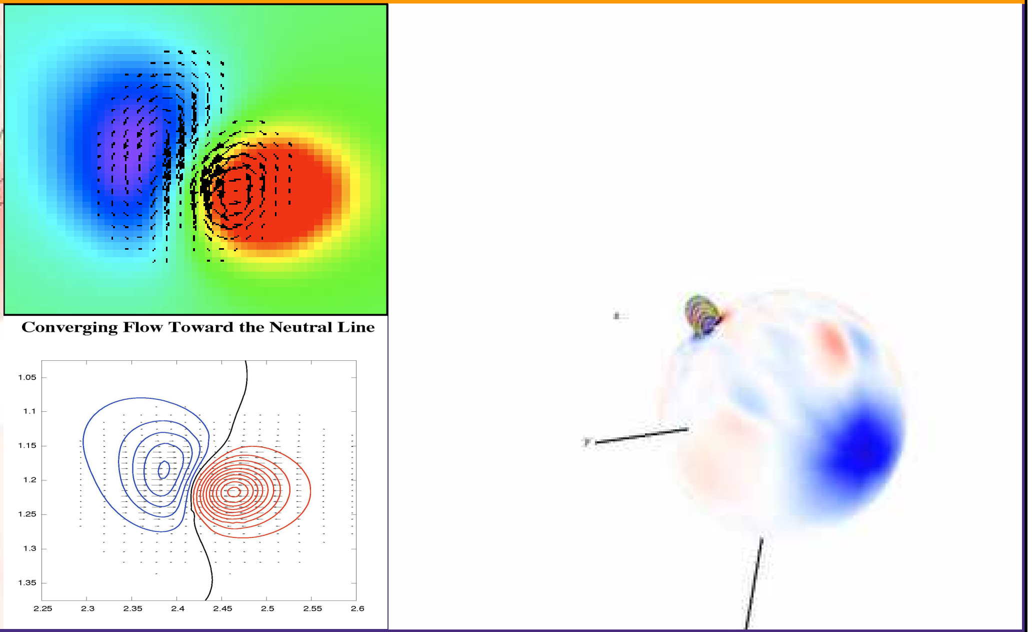
Tether Cutting / Flux Cancellation



Moore et al., 2001



Amari et al. 2003

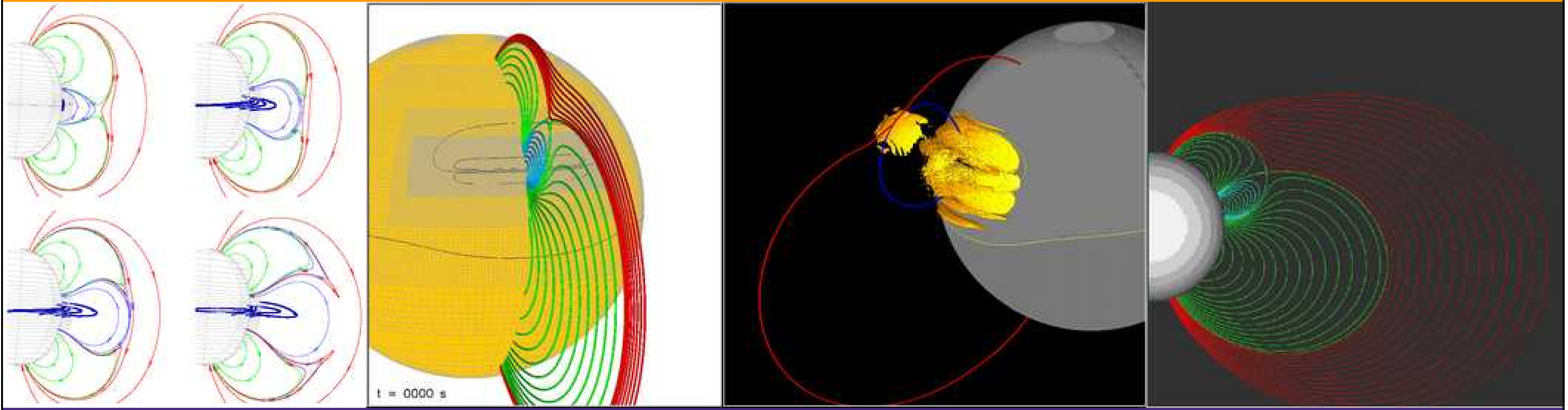


simulation 1997 May 12 event (SAIC)

- initial slow reconnection within sheared arcade (flux rope formation)
- fast reconnection follows (flare)
- flux rope ejection if overlying tension is weak; otherwise compact flare

- provides model for initiation phase & flux rope formation
- does not clearly address flux rope ejection mechanism

Magnetic Breakout



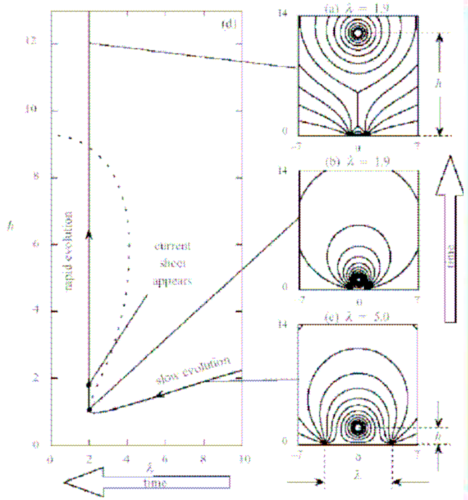
Antiochos et al., 1999

3D model, courtesy Ben Lynch

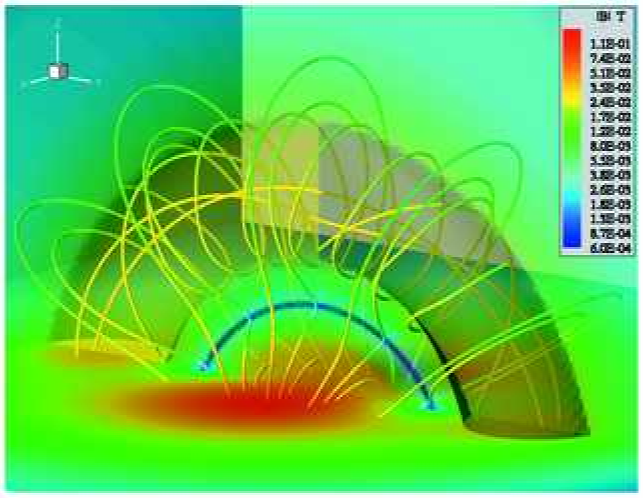
- (central) magnetic arcade is sheared and expands
- “feedback” between expansion and breakout reconnection is initial driver
- flare reconnection (pos. feedback) drives eruption in main phase
- most large eruptions originate in multipolar source regions
- cannot work in bipolar active regions

(note: other models work in quadrupolar configuration as well)

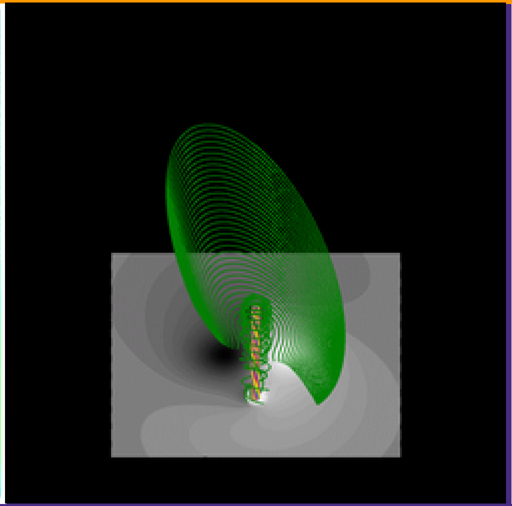
Ideal MHD Catastrophe / Instability



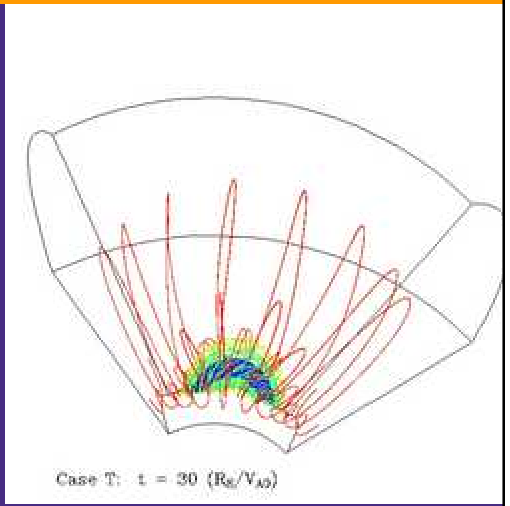
Forbes, Lin, Isenberg, Priest, Démoulin, et al.



Roussev et al. 2003, Titov & Démoulin 1999



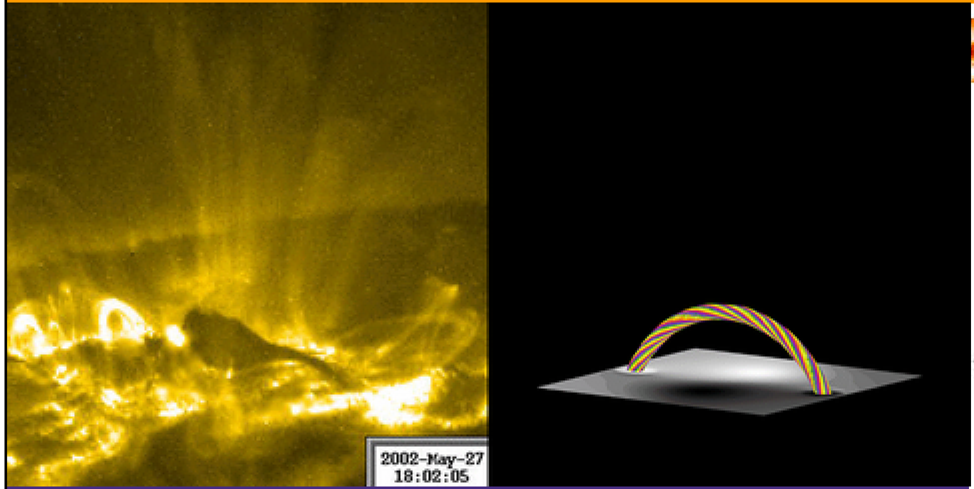
Török & Kliem 2005



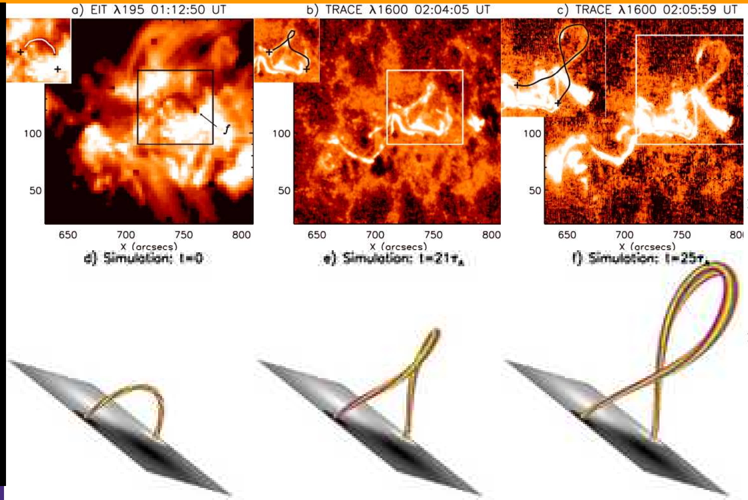
Fan & Gibson 2007

- <u>catastrophe:</u> no neighbouring equilibrium in sequence of stable equilibria
- <u>kink instability:</u> occurs for supercritical flux rope twist
- <u>torus instability:</u> occurs for sufficient drop of overlying field (Kliem & Török 2006)
- instability and catastrophe closely related; not yet understood in 3D

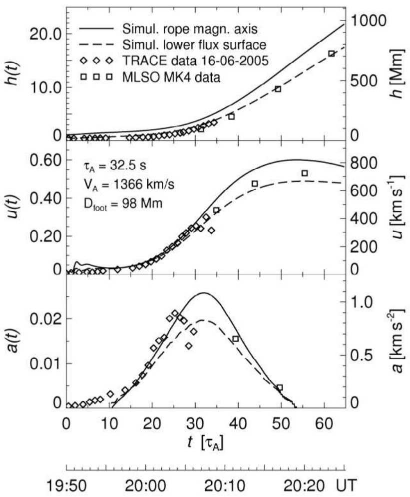
Ideal MHD Instability



Török & Kliem 2005



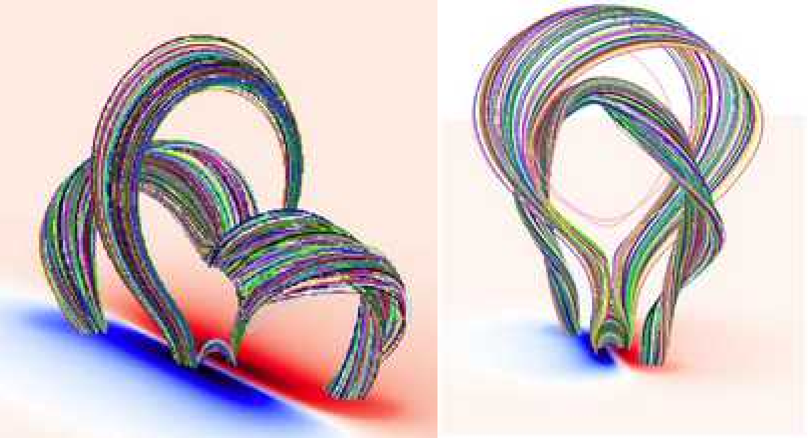
Williams et al. 2005



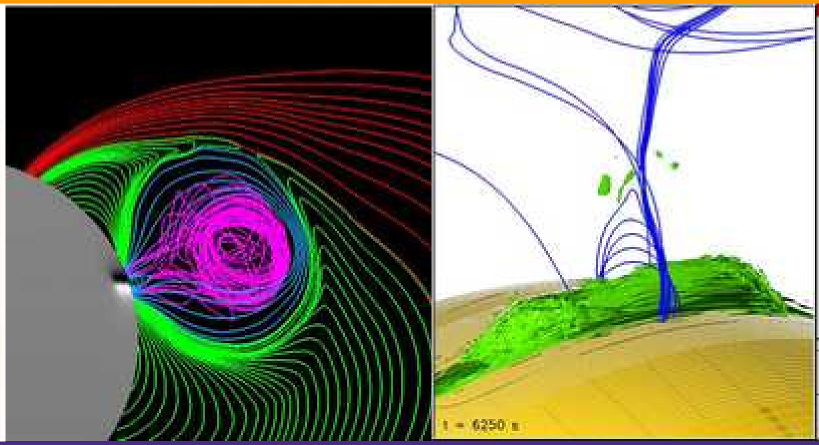
Schrijver et al.
2008

- good quantitative match with certain eruption properties
- predict thresholds for eruption onset (twist & external field slope)
- does not include pre-eruptive evolution (TK)
- not well correlated with CME occurrence (FG)

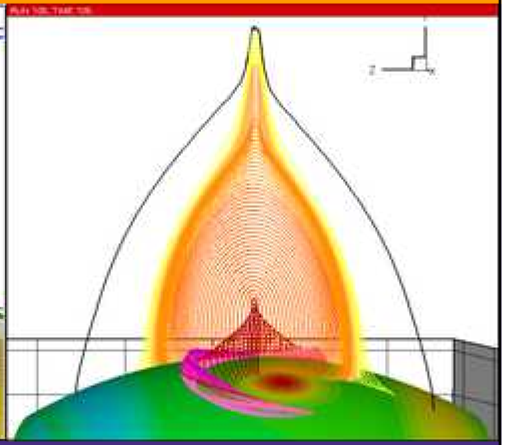
Similarities & Differences



tether cutting / flux cancellation



magnetic breakout



MHD instability

- all models include a twisted flux rope at relatively early stage of eruption
- all models produce a vertical CS below flux rope → flare reconnection
- models differ in trigger mechanism, otherwise evolution similar

Warning: be careful when interpreting observations with simulation results:

- models are very sensitive to parameter choices (Schrijver et al. 2008)
  (but published simulations mostly consider only a very limited parameter set)

Trigger & Driver

pre-eruptive configuration: stressed core field + stabilizing overlying field

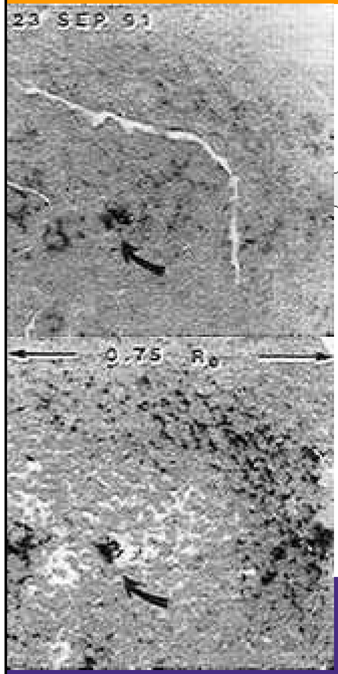
TRIGGER: any mechanism which slowly drives or dynamically perturbes the pre-eruptive configuration such that the core field erupts:

- tether cutting, breakout, kink instability
- converging, shearing, twisting flows
- flux emergence

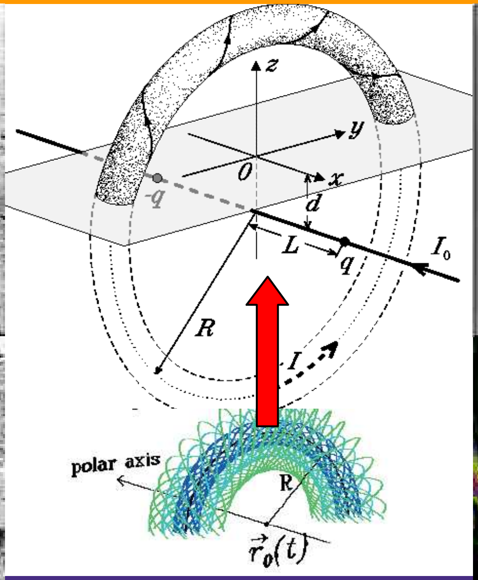
DRIVER: any mechanism which can account for rapid (exp.) acceleration and huge expansion of the core field / flux rope:

- flux rope (torus) instability / catastrophe
- flare-reconnection (pos. feedback with rope expansion)

Example: Flux Emergence & Torus Instability

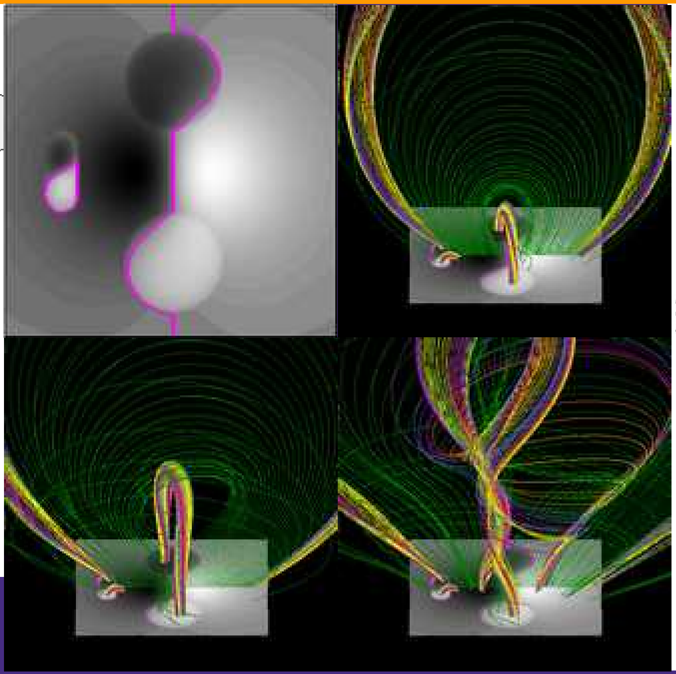


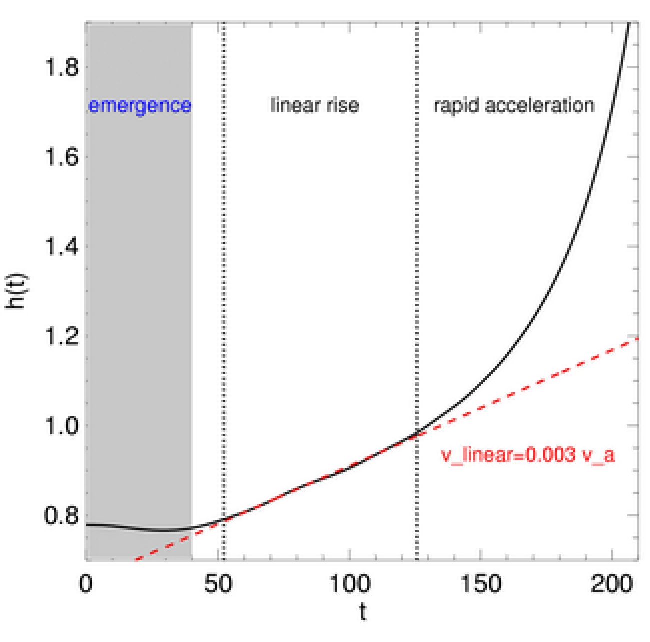
Feynman & Martin 1995



Titov & Démoulin (TD)

Fan & Gibson (FG)





Török, *in preparation*

- FG flux rope emerges “kinematically” into TD equilibrium
- reconnects with TD ambient field → TD rope starts to rise linearly
- when onset criteria for torus instability are met → TD rope erupts

trigger: flux emergence & driver: flux rope instability

Summary

a canonical model of CME initiation is emerging, it will include:

- ideal flux rope dynamics (instability / catastrophe)
- reconnection, probably in two stages:
  - slow reconnection (trigger): e.g. breakout; flux rope formation
  - fast reconnection in vertical current sheet → flare;
    can support eruption by pos. feedback with rising flux rope
- path to formation of unstable / catastrophic flux rope equilibrium:
  (e.g.: flux emergence, flux cancellation, photospheric motions)
- probably elements of most current models

What About Forecast?

so far mostly statistical studies:
try to find correlations between observable quantities and eruption occurence

Mark Rast: "… we can say where the sandpiles are, but we cannot say where and when we will get the next avalanche …"

consider example flux emergence (trigger) + torus instability (driver):

eruption onset depends on:

- "distance" from instability: flux rope has to be lifted to a height where the overlying field drops fast enough for torus instability to occur
- "effectivity" of trigger: how effective is the reconnection between the emerging flux and overlying field in weakening the tension of the latter?

What About Forecast?

theory has to provide:

- instability threshold(s) → parametric studies!
- quantitative (parametric) studies of trigger effectivity

observers have to:

- measure related quantities (profile of overlying field; position of flux rope; amount of emerging flux, etc.)
- consider pre-eruptive evolution

how realistic is it in practice?

- we still cannot measure important quantities
- eruption source regions can be very complex
- several trigger mechanisms might be at work
- conditions can change rapidly (e.g. new flux emergence)
- etc.

but: we should think about it …