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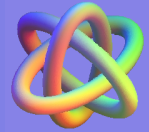
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Equilibrium and structure of twisted configurations in sigmoidal flares

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Ruhr-Universität-Bochum

October 25, 2001

Collaborators: Pascal Démoulin



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2. The model of magnetic configuration.
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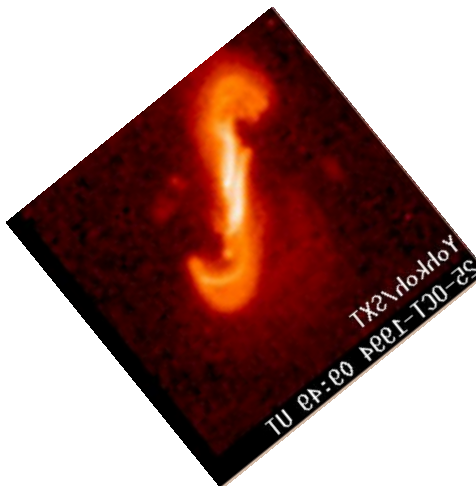
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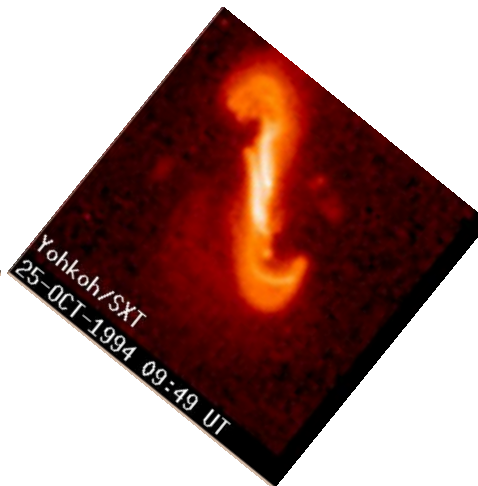
1. Introduction: sigmoidal flares

Soft X-ray images of sigmoids

S-shaped



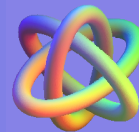
inverse-S-shaped



(positive current helicity)

(negative current helicity)

Short bright and long faint systems of the loops!?



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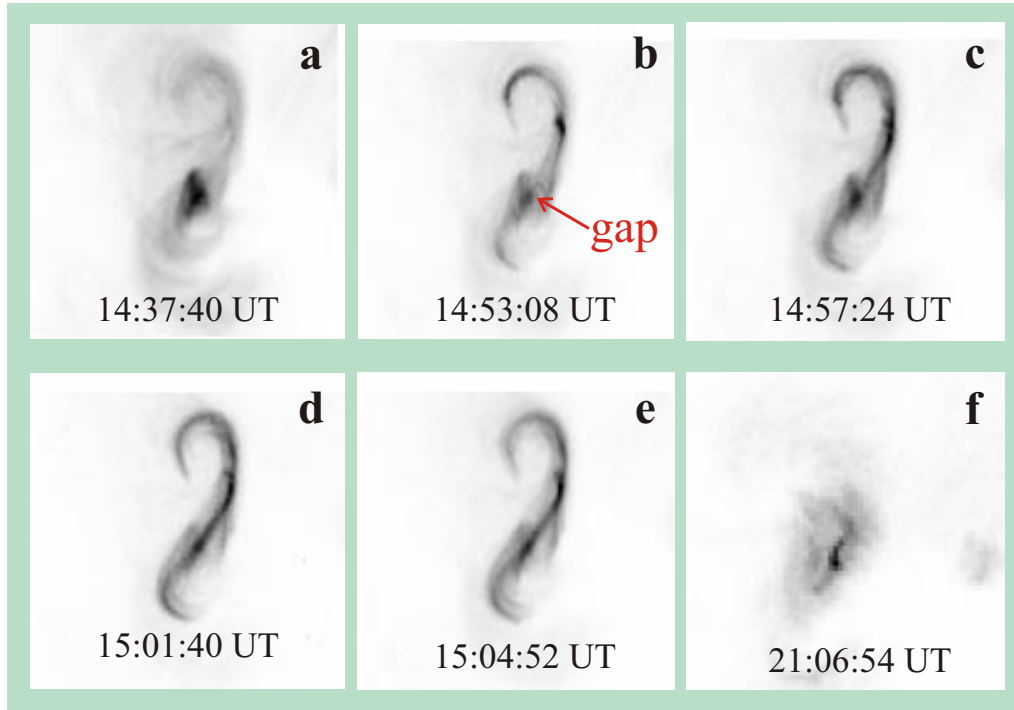
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Evolution of sigmoids (Pevtsov et al., 1996):

Yohkoh SXT images before (a-e) the flare of 1992 May 8 15:12 UT and after (f) the flare on May 9 21:06:54



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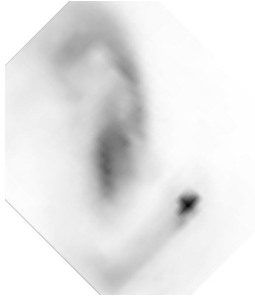
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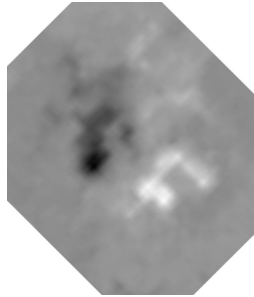
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Sigmoid lies **between two polarities** (AR 7154 on 1992 May 6):

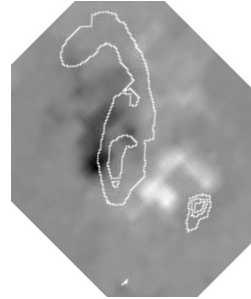
X-ray image
(23:31 UT)



Magnetogram
(19:09 UT)

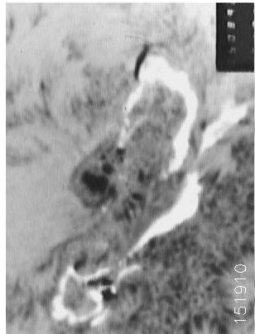


Superposition



Filament eruption and **flare** of 1992 May 8:

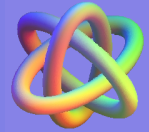
$H_{\alpha} - 0.6A$
(15:20:23 UT)



$H_{\alpha} + 0.6A$
(15:19:10 UT)



How one can
explain all these
features?



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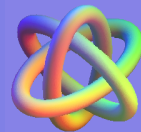
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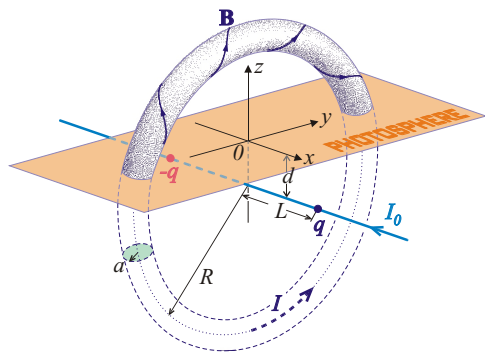
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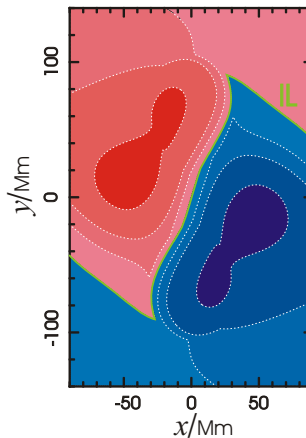
2. The model of magnetic configuration - a force-free tube embedded into a potential field



Construction of the model:
(Titov & Démoulin, 1999)



Effective magnetogram:



Basic assumptions: $a/R \ll 1$ and $a/L \ll 1$.

Outside the tube the field is $\mathbf{B} = \mathbf{B}_q + \mathbf{B}_I + \mathbf{B}_{I_0}$.

Inside the tube it is approximately the field of a straight flux tube.

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Equilibrium current

Matching condition is $\mathbf{B}_q + \mathbf{B}_I \approx 0$ in the vicinity of the tube or the force balance:

$$\mathbf{F}_q + \mathbf{F}_I \approx 0, \quad (1)$$

where

$$\mathbf{F}_q = -\frac{2qLI}{(R^2 + L^2)^{3/2}} \hat{\mathbf{R}} \quad (2)$$

is due to \mathbf{B}_q and

$$\mathbf{F}_I = \frac{\mu_0 I^2}{4\pi R} \left(\ln \frac{R}{a} + \ln 8 - 3/2 + l_i/2 \right) \hat{\mathbf{R}} \quad (3)$$

is due to *curvature* of the tube.

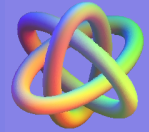
$l_i \sim 1$ is the internal *self-inductance* per unit length of the tube.

(1)–(3) \Rightarrow total **equilibrium current**

$$I = \frac{8\pi qLR(R^2 + L^2)^{-3/2}}{\mu_0 [\ln(8R/a) - 3/2 + l_i/2]}. \quad (4)$$

Minor radius a changes with R according to

$$\frac{a}{L} \approx 2 \left\{ \frac{2\pi q (R/L)^3 [(R/L)^2 + 1]^{-3/2}}{\mu_0 N_t |I_0| L [\ln(8R/a) - 3/2 + l_i/2]} \right\}^{1/2}, \quad (5)$$



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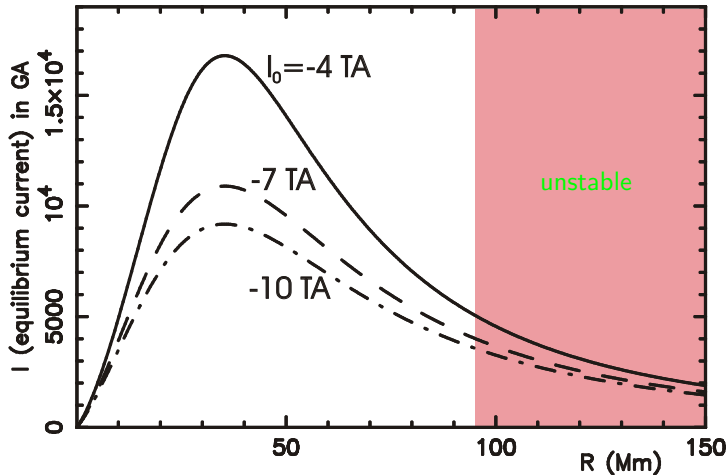
which follows from that the number of field-line turns

$$N_t \approx \frac{\mu_0 I R}{2\pi a^2 |B_{I_0}|}, \quad (6)$$

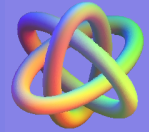
$$B_{I_0} \approx \frac{\mu_0 I_0}{2\pi R} \quad (7)$$

must be constant.

Equilibrium current I versus the radius R :



Stability criterion:
 $\delta(F_q + F_I)|_{N_{\text{cor}}} \leq 0$



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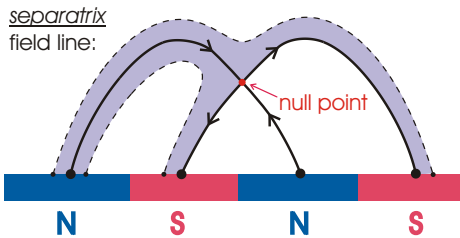
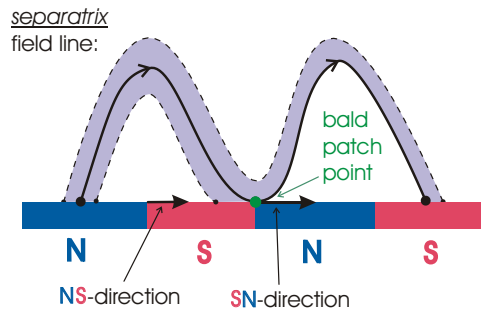
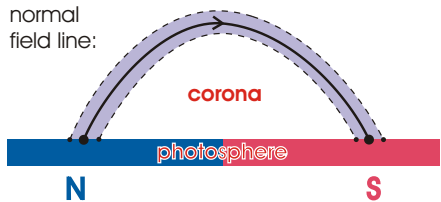
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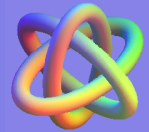
3. Topological structure of the field

2D case

field-line connectivity → topology



- Flux tubes enclosing separatrices **split** at null and “bald patch” points.
- **Current sheets** are formed along the separatrices by the suitable photospheric motions (2D and $2\frac{1}{2}$ D cases).



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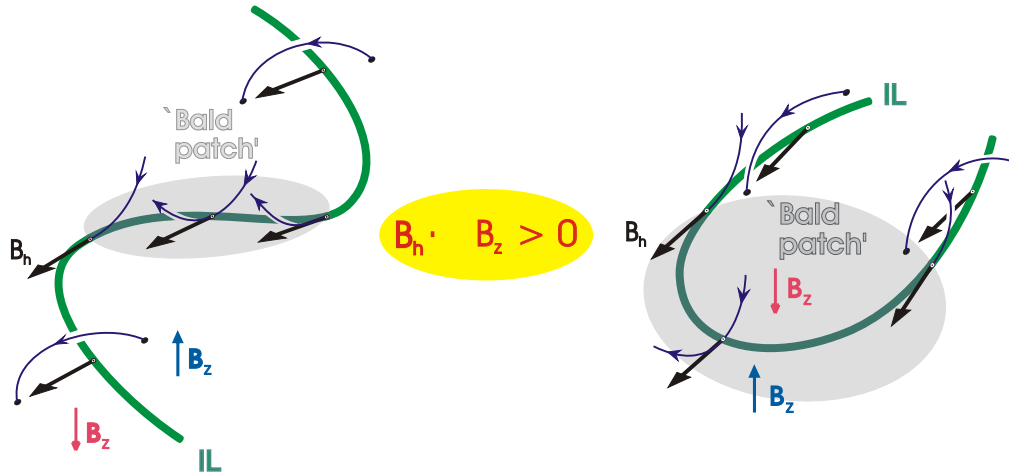
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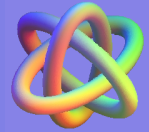
3D case

In the absence of the nulls the magnetic topology in the corona may be nontrivial due the “bald patches” (BP, Seehafer, 1985; Titov et al., 1993).

Local structure of field lines at the photospheric inversion line (IL)



BPs and the associated **separatrices** are **structurally stable!**



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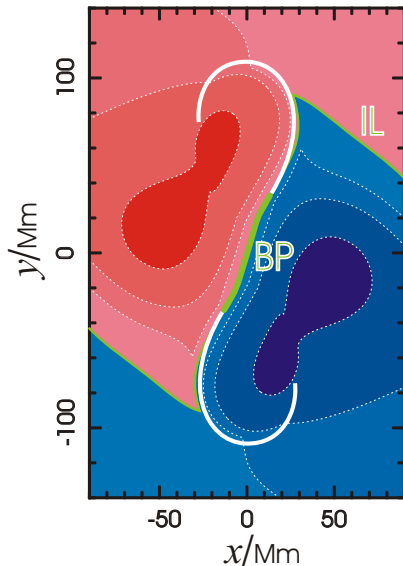
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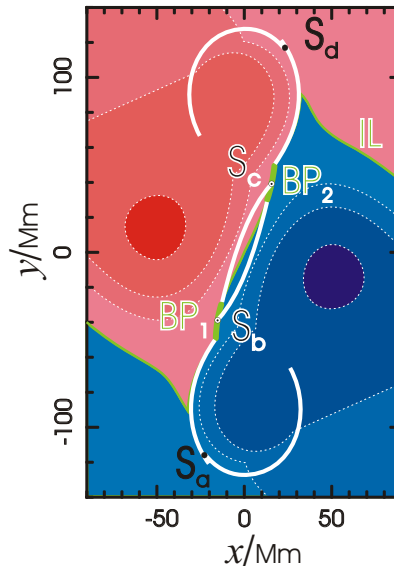
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Topological complex states in the model

BP appeared ($R = 85$ Mm):



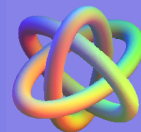
BP bifurcated ($R = 98$ Mm):



Fixed parameters: $L = 50$ Mm, $d = 50$ Mm, $q = 100$ T · Mm⁻², $N_t = 5$, $I_0 = -7$ TA. Contours of $B_z = \pm 100, \pm 200, \pm 400$ G.

Thick white lines are photospheric *intersections* of the separatrix surfaces.

Generalized separator: footpoints S_a and S_d , contact points S_b and S_c .



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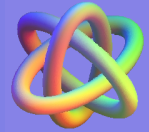
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Top view on the topological skeleton of the configuration in the bifurcated state



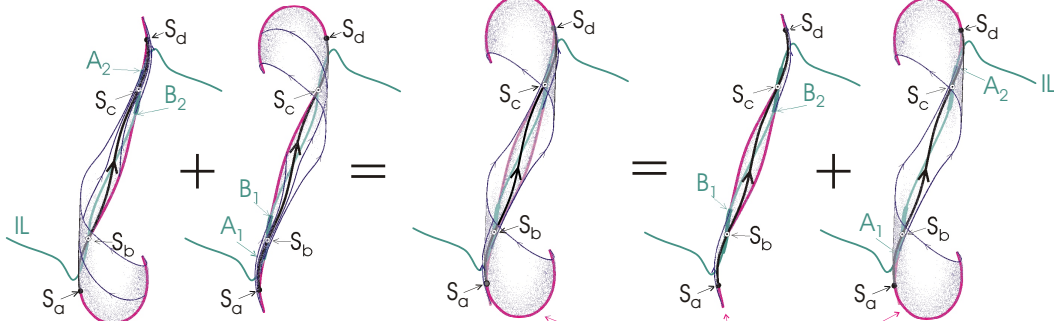
due to A_2B_2

... A_1B_1

total skeleton

... S_bB_1 & S_cB_2

... S_bA_1 & S_cA_2



IL is photospheric inversion line

A_1B_1, A_2B_2 are bald patches

separatrix intersections with the photosphere

$S_aS_bS_cS_d$ is generalized separator field line

Strong **current layers** have to develop at the skeleton
when the configuration evolves.

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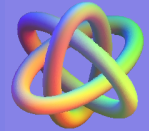
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4. Implications and comparison with numerics

Model \Rightarrow scenario for sigmoidal two-ribbon flares:

1. **Emerging** of the flux tube \Rightarrow appearance of the BP \Rightarrow **lift** of the dense plasma in the corona (prominence).
2. **Line-tying** effect \Rightarrow **stretching** of the field lines \Rightarrow locally **strong** current density \Rightarrow **support & heating** of the dense plasma.
3. Further emergence \Rightarrow toroidal field dominates the poloidal one \Rightarrow the BP **bifurcates** \Rightarrow the **separator** appears.
4. Reconnection \Rightarrow heating of plasma near separatrices \Rightarrow **illumination of sigmoidal structure**.
5. **Evaporation** \Rightarrow **short bright** and **long faint** loops.
6. When $R \sim L$ the equilibrium has to be **unstable** \Rightarrow **eruption** of the flux tube \Rightarrow **flare** \Rightarrow **CME**.
7. Fish-hook-shaped H_α -ribbons (=intersection of separatrix surfaces with the photosphere).



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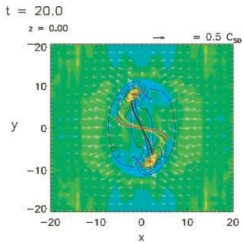
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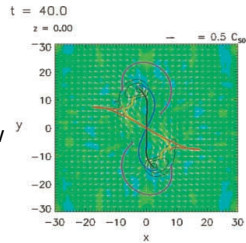
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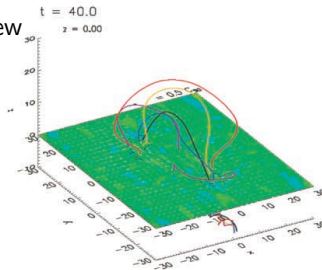
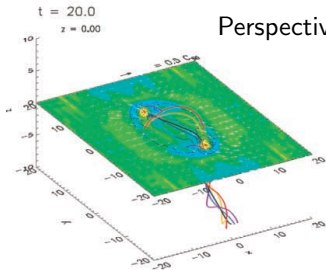
Numerics – an emerging flux tube (Magara & Longcope, 2001):



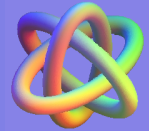
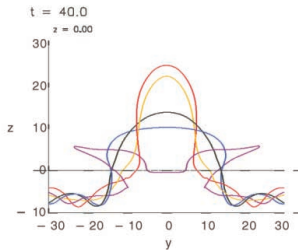
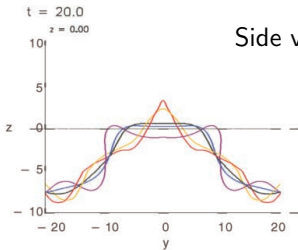
Top view



Perspective view



Side view



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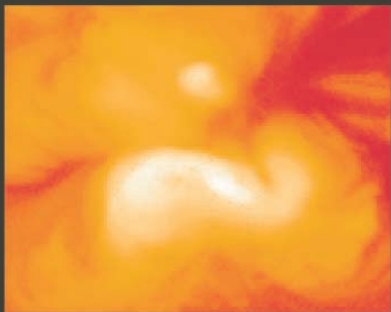
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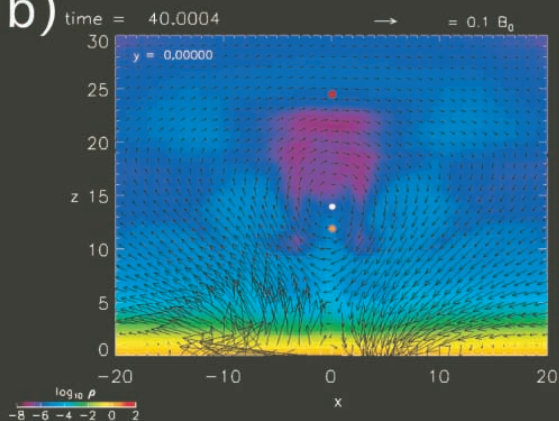
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- Ideal, compressible MHD.
- Appearance of the BP.
- Current concentrations at the BP ends.
- + resistivity \Rightarrow Magnetic reconnection!

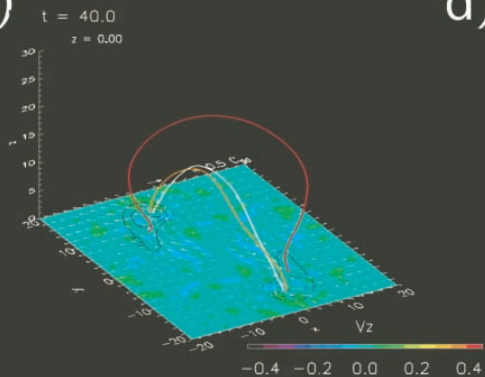
a)



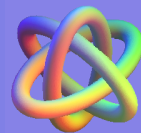
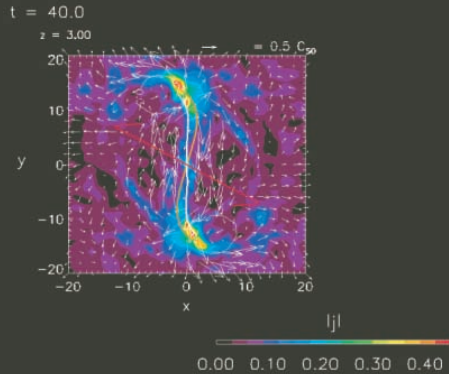
b)



c)



d)



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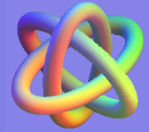
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5. Summary

- An analytical model for twisted magnetic configuration is developed.
- It has a complex topological structure due to “bald patches” in a wide range of parameters.
- The scenario with emerging magnetic flux tube can explain several observed features of sigmoidal flares.
- Numeric simulations of Magara & Longcope (2001) confirmed the main predictions of the model for the initial stage of the emergence.



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