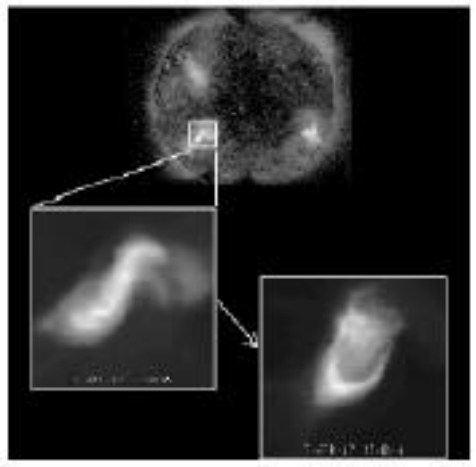
3-dimensional Evolution of an Emerging Flux Tube in the Sun

T. Magara

(Montana State University)

February 6, 2002

- Introduction of the study
- Dynamical evolution of emerging field lines
- Physical process working on emerging field lines
- *Some implications based on the result*
- Summary



Rust and Kumar (1996)
Canfield, Hudson, Pevtsov (2000), etc.

Emerging magnetic field...

sometimes related to energetic events on the sun, such as

Sigmoids, Prominence eruptions, CMEs, etc.

About this study...

We have done 3-dimensional MHD numerical simulations of a magnetic flux tube emerging through the solar atmosphere with a special attention paid to the dynamics of emerging field lines.

About the simulation...

Simulation model

background atmosphere:

4 layers (convection zone, photosphere, chromosphere, and corona)

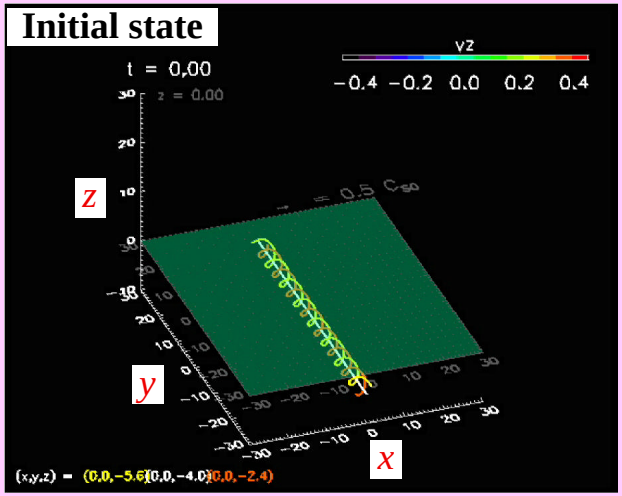
magnetic flux tube:

Gold-Hoyle type magnetic field
($r = 2$, $L_w = 2\pi$)

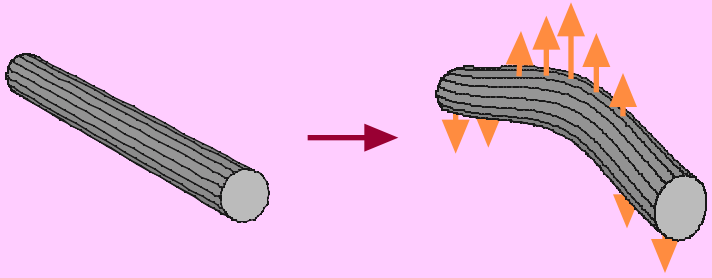
simulation box: $(n_x, n_y, n_z) = (149, 167, 168)$

$-100 \le x \le 100$, $-100 \le y \le 100$, $-10 \le z \le 100$
Δx: 0.4 → 4.0, Δy: 0.4 → 4.0, Δz: 0.2 → 4.0
(Nonuniform mesh system)

Initial state

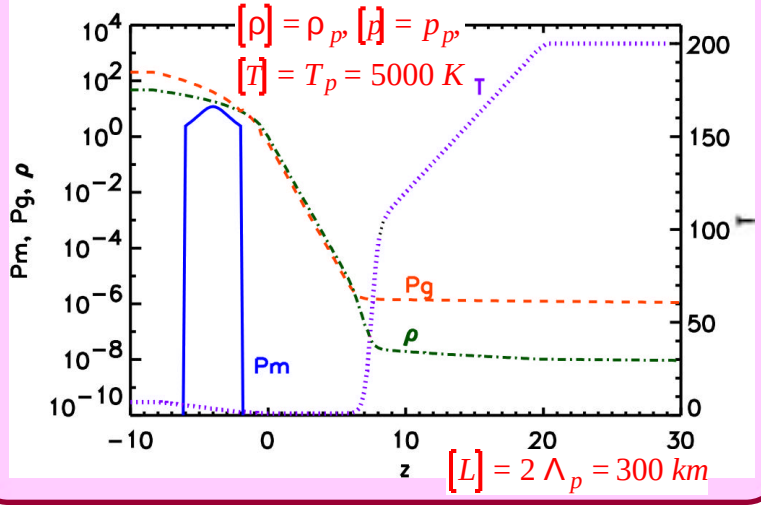


Initial perturbation

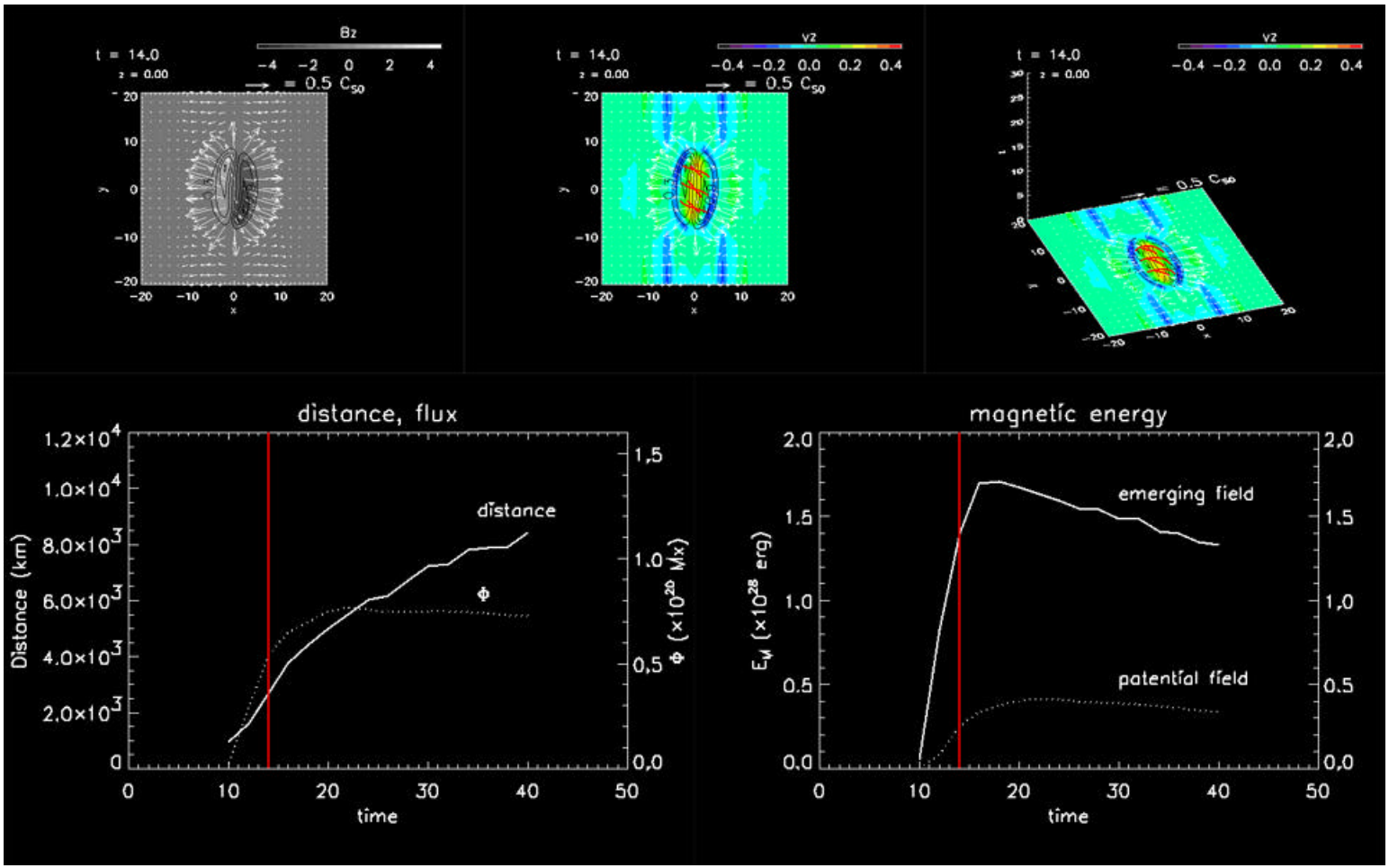


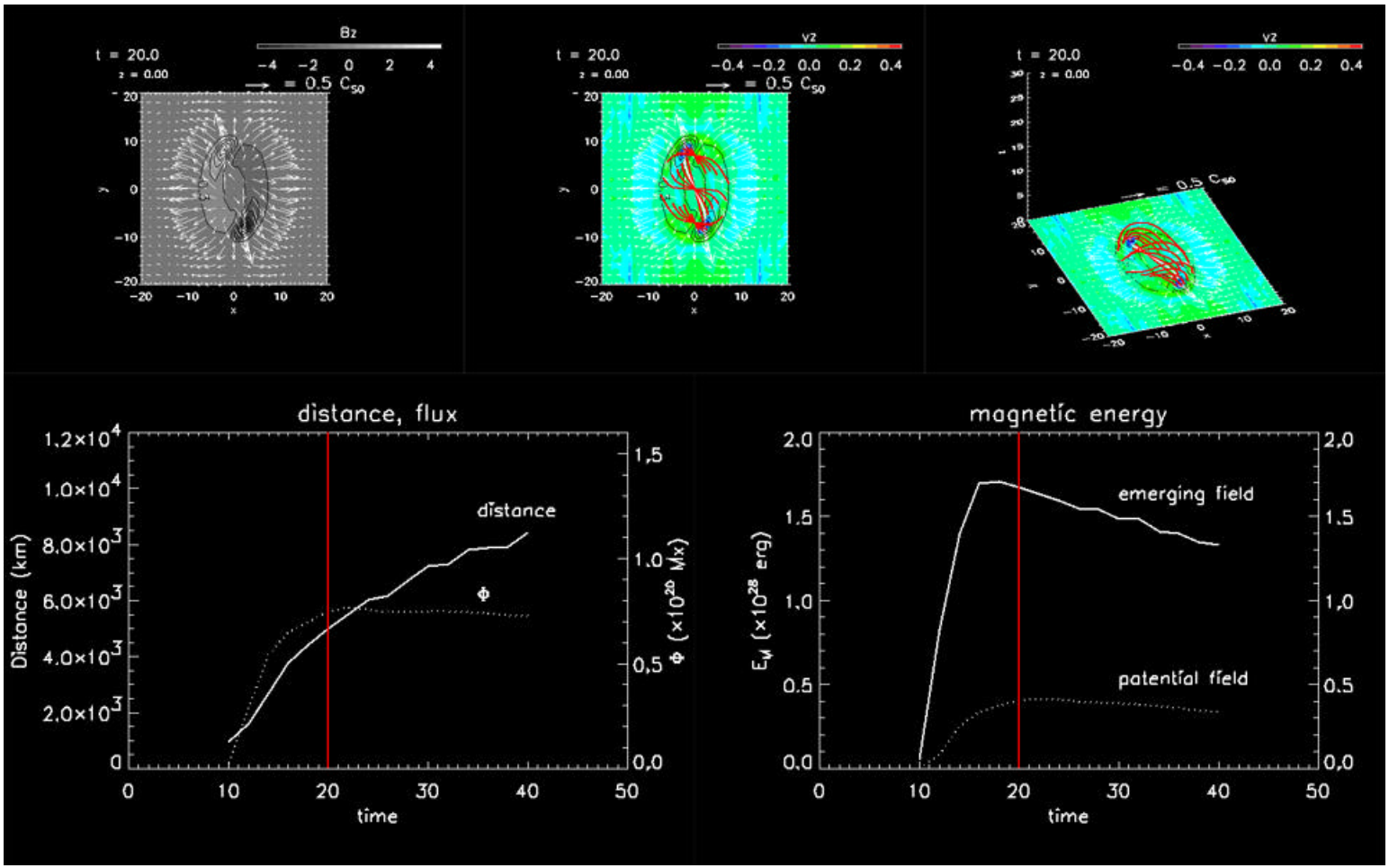
We impose an upward motion in the middle of flux tube and a downward motion at both ends of tube during the initial phase ($0 \le t \le 5$).

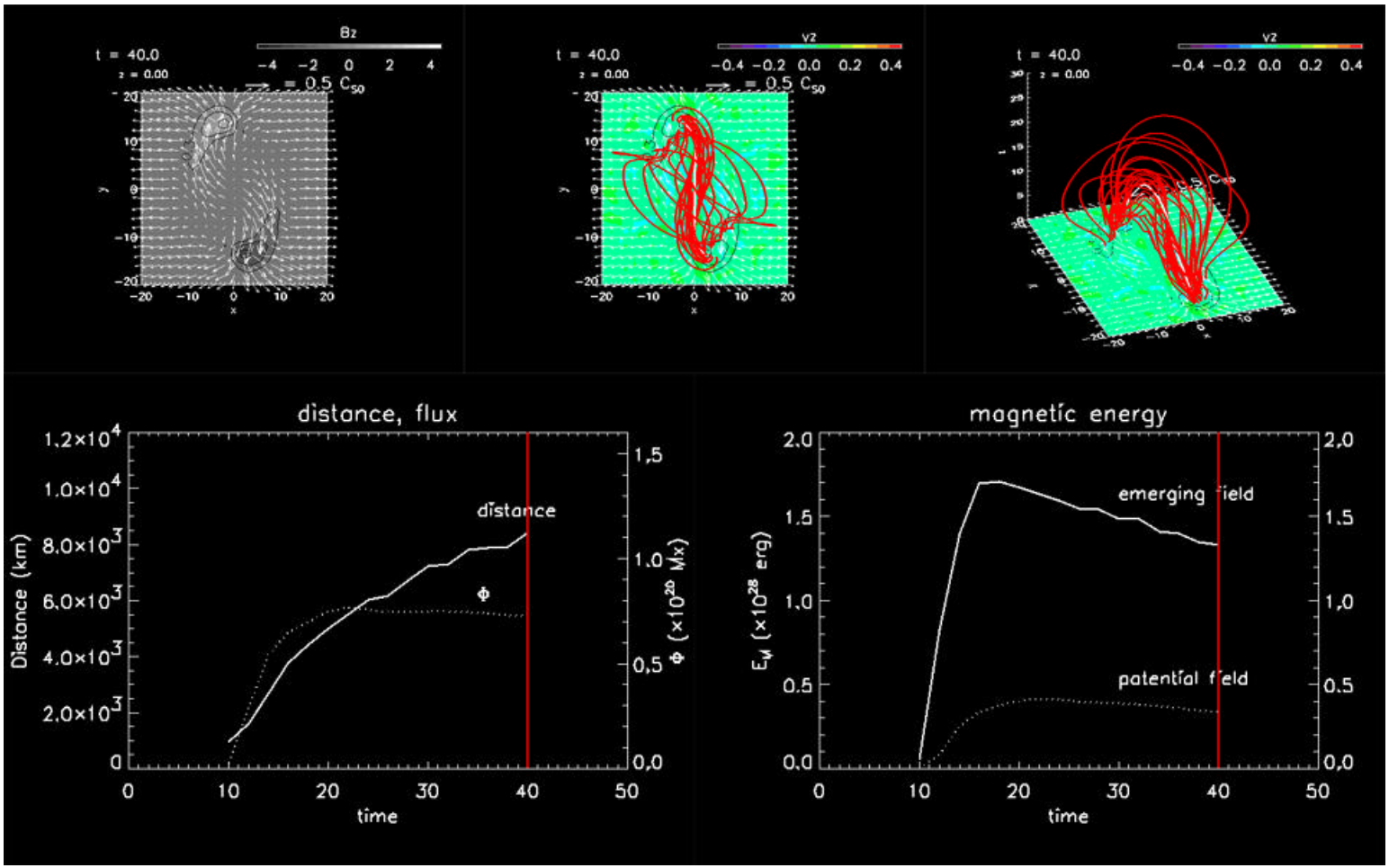
Vertical distribution



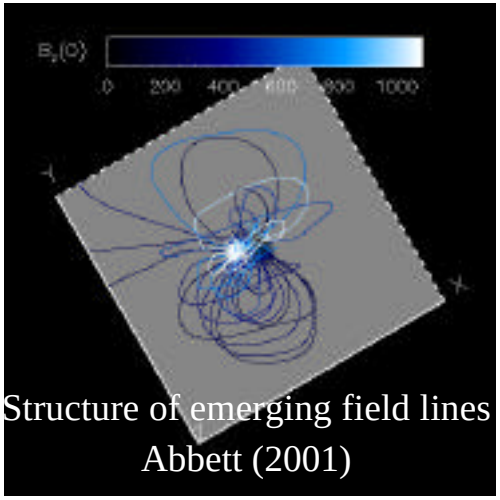
Evolution of an emerging flux tube



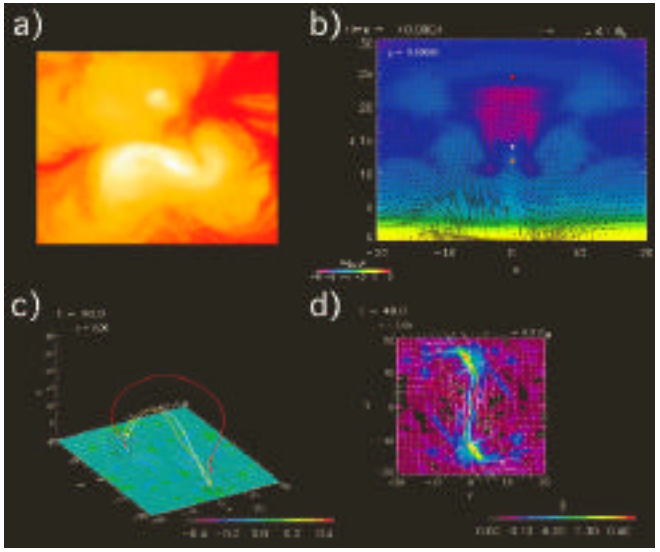

Bz
t = 20.0
z = 0.00
0.5 C_S0
vz
t = 20.0
z = 0.00
0.5 C_S0
vz
t = 20.0
z = 0.00
0.5 C_S0
distance, flux
Distance (km)
distance
Φ
Φ (×10^20 Mx)
time
magnetic energy
E_M (×10^28 erg)
emerging field
potential field
time


Bz
t = 40.0
z = 0.00
= 0.5 C_{s0}
vz
t = 40.0
z = 0.00
= 0.5 C_{s0}
vz
t = 40.0
z = 0.00
distance, flux
distance
Φ
Distance (km)
Φ ($\times 10^{20}$ Mx)
time
magnetic energy
emerging field
potential field
E_M ($\times 10^{28}$ erg)
time

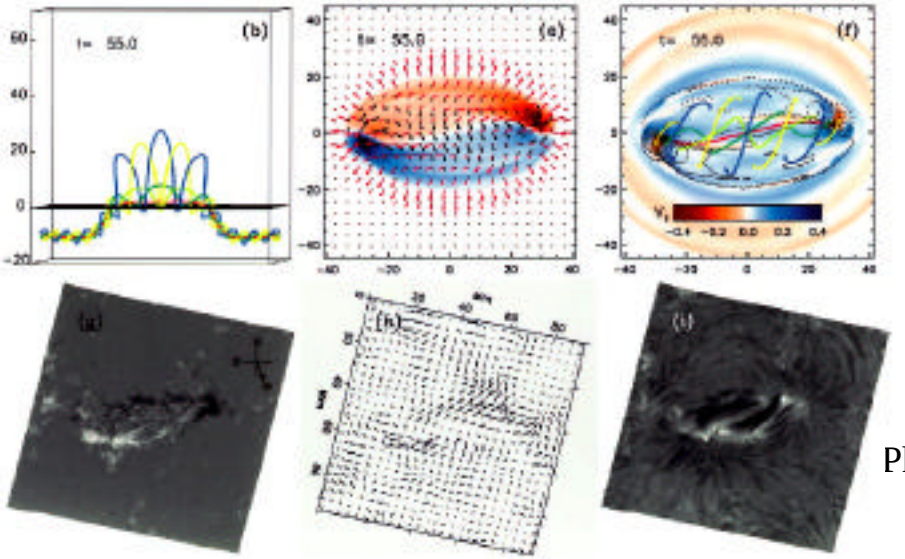
So far, we obtained...



Structure of emerging field lines
Abbett (2001)



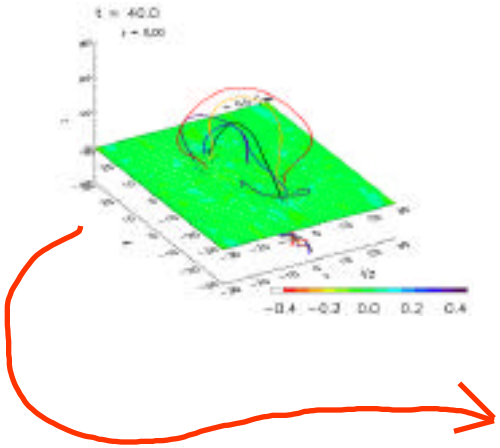
Sigmoids
Magara & Longcope (2001)



Photospheric velocity field & magnetic field
Fan (2001)

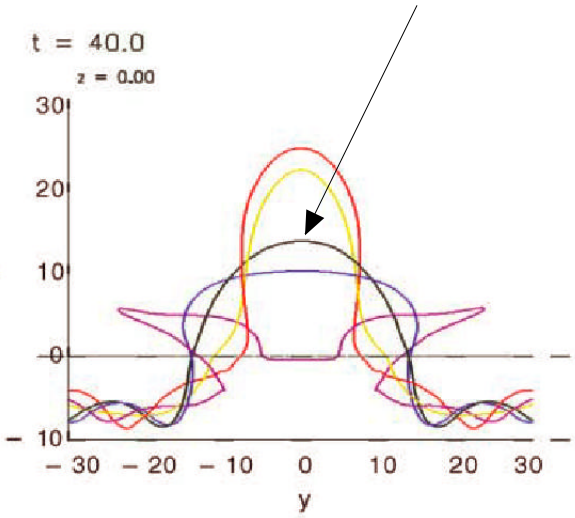
Today's main topic is

the dynamical behavior of emerging magnetic field in the solar atmosphere with a focus on the axis field of flux tube.



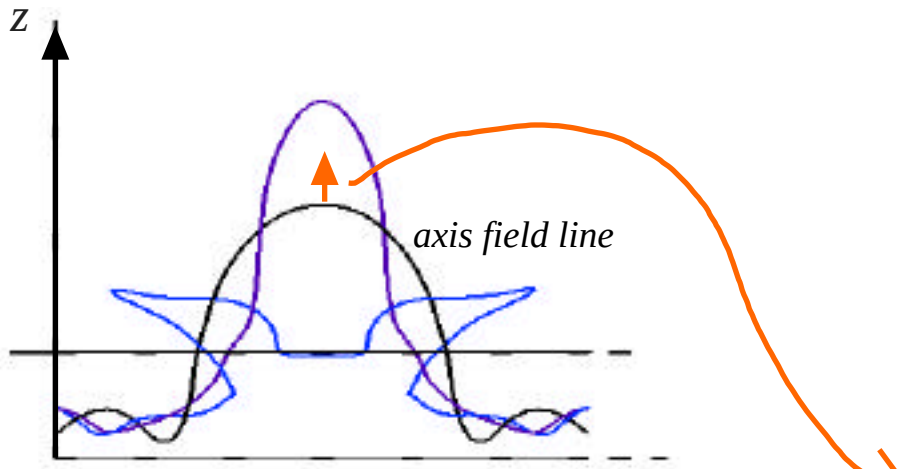
Side view

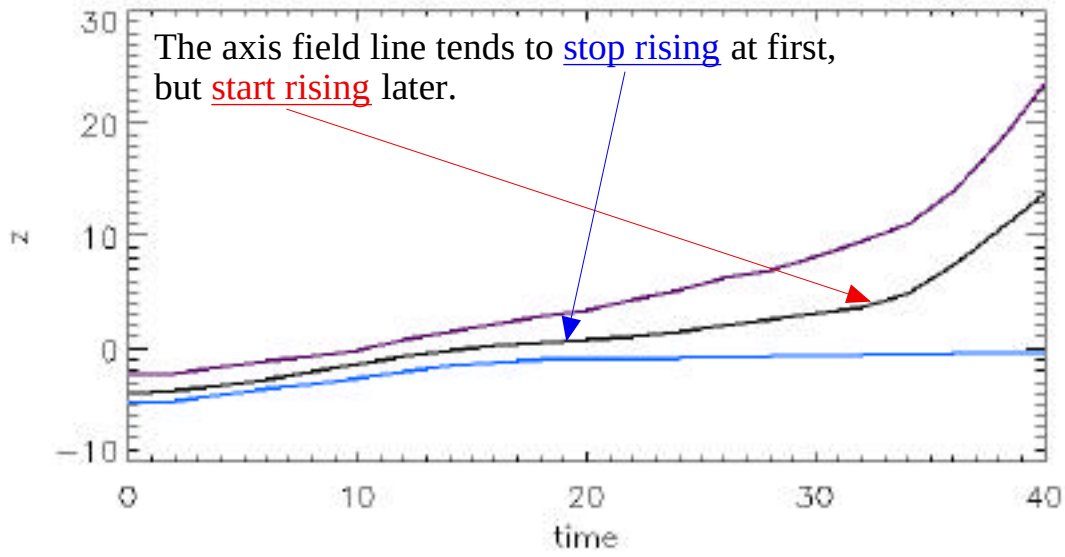
Black line: axis field line



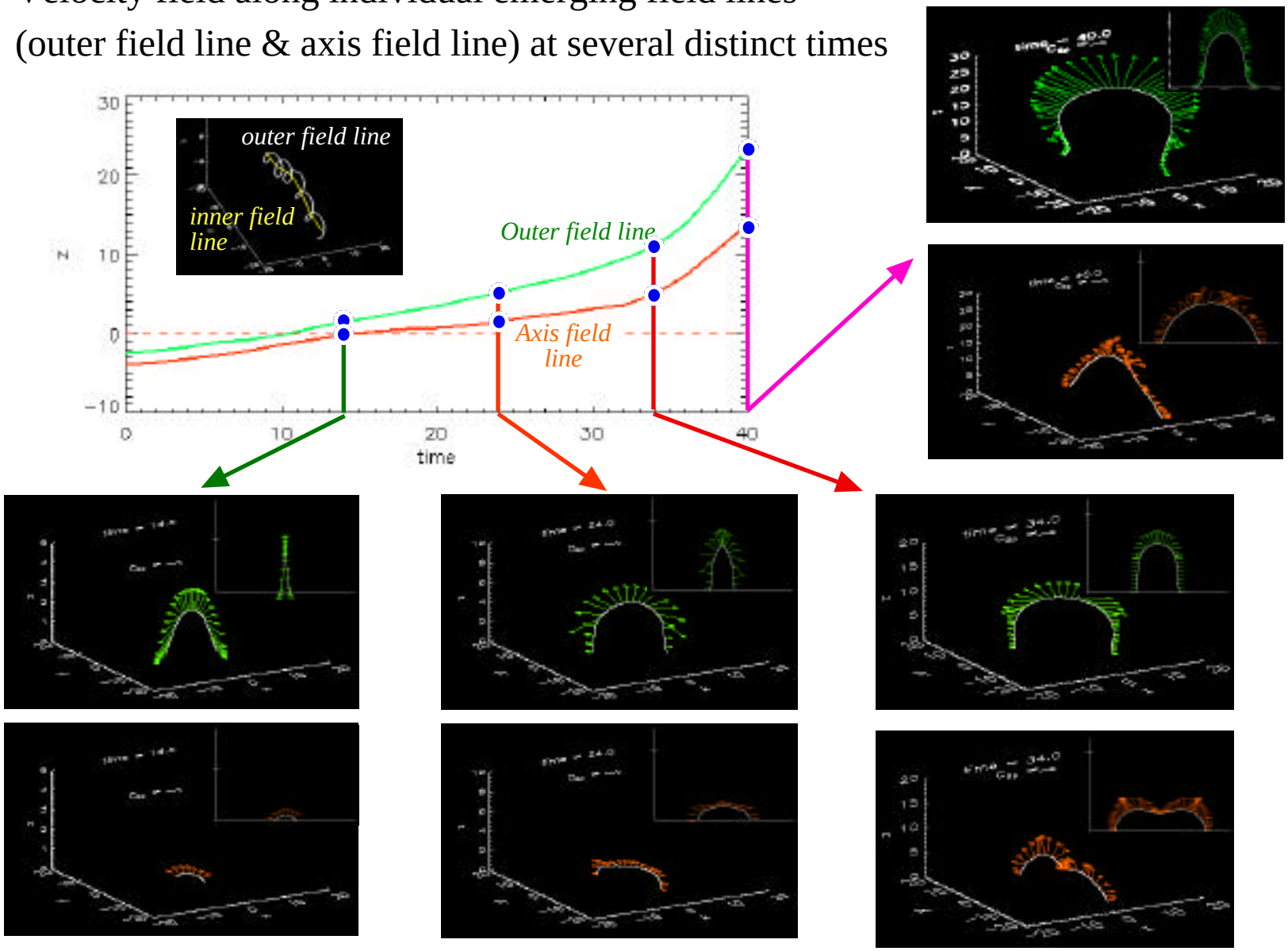
Magara & Longcope (2001)

Let us start to see the time variation of the height of axis field line.

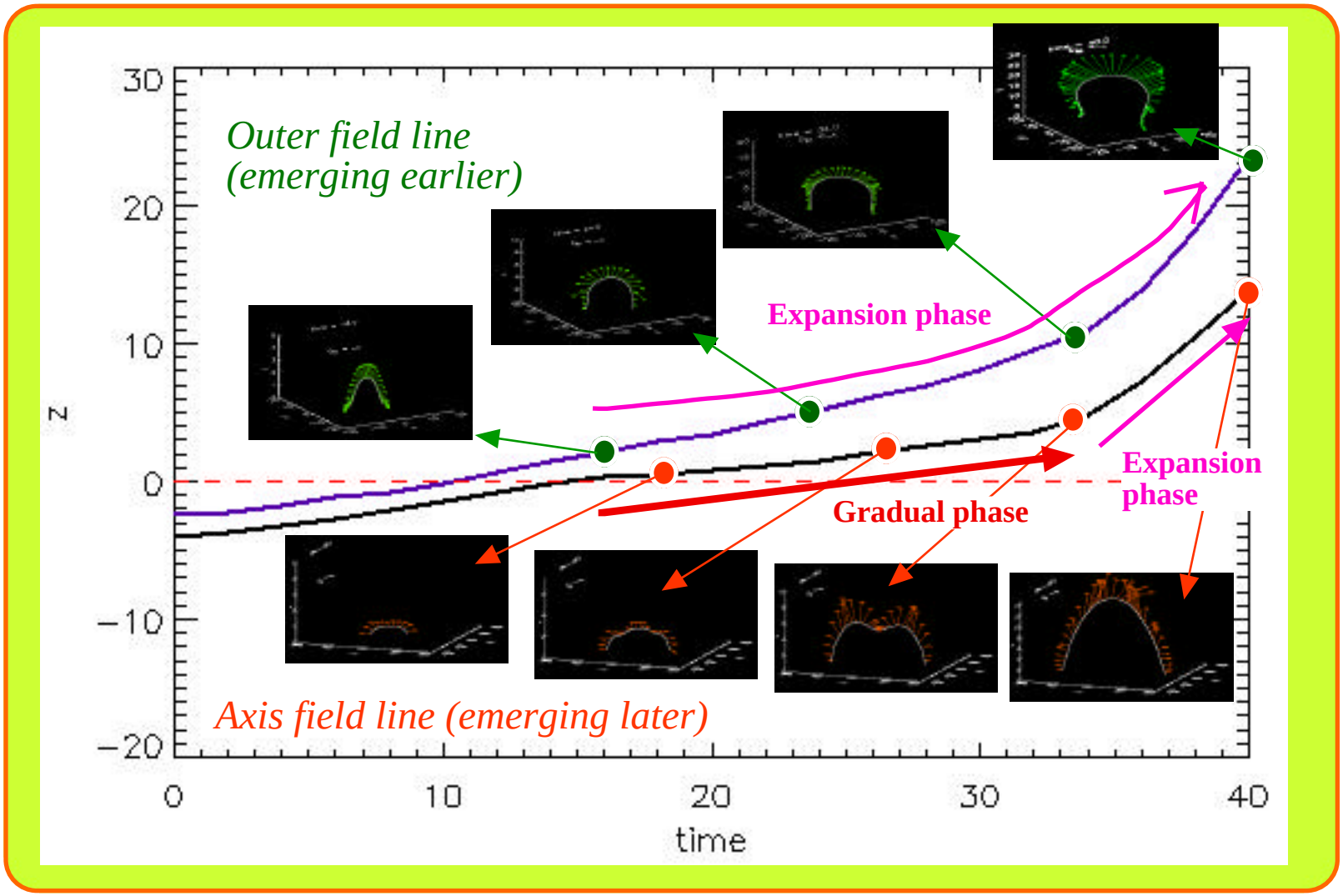




Velocity field along individual emerging field lines
(outer field line & axis field line) at several distinct times

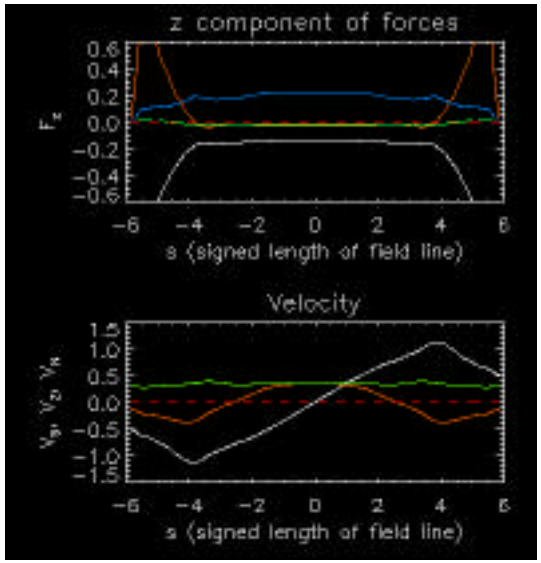


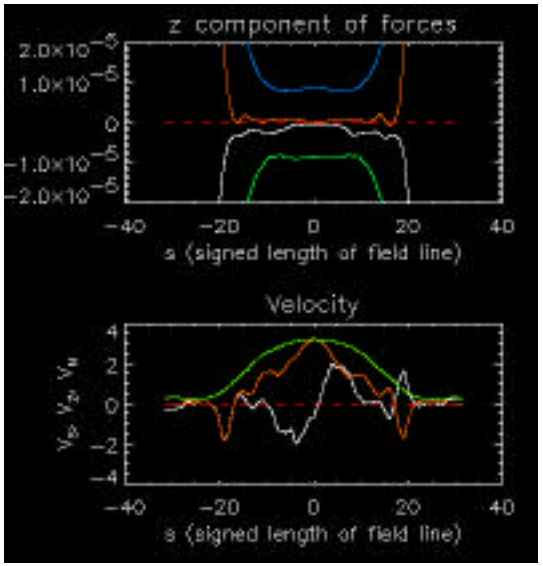
Each field line (outer field line & axis field line) has a distinct evolutionary character.

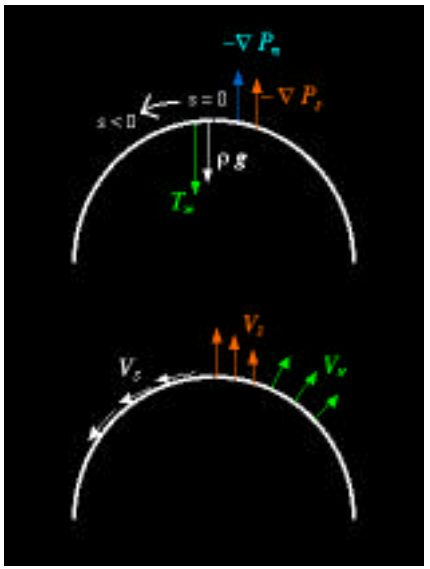


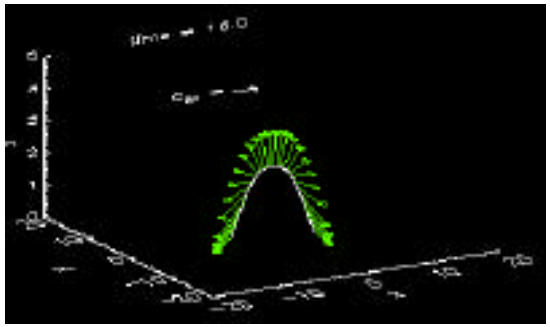
We find two kinds of phases: 'expansion phase' and 'gradual phase'.
Next, let us investigate how forces (– P_g, – P_m, T_m, ρ $\boldsymbol{g}$) work at these phases.

Outer field line

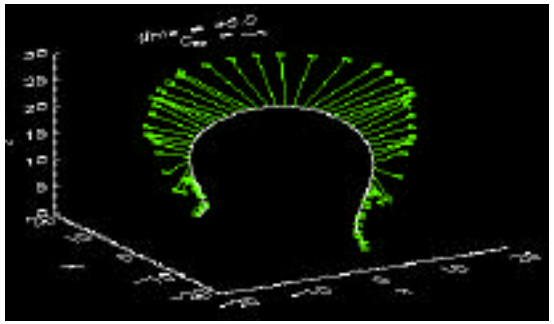








time = 16.0



time = 40.0

Expansion phase

Upward force: – P_m

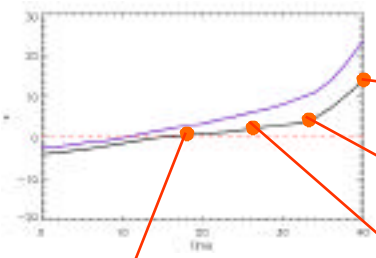
Downward force:

ρ $\boldsymbol{g}$ **(early phase)**

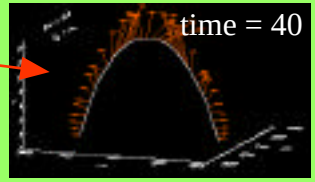
↓

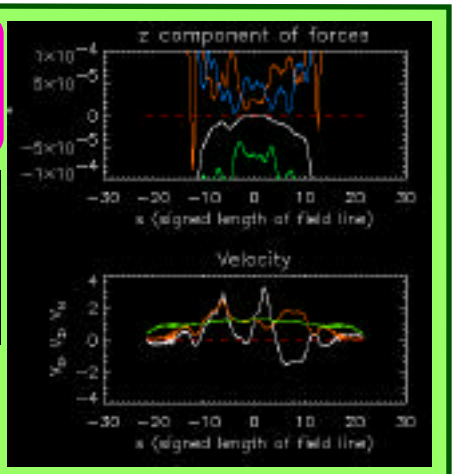
T_m **(late phase)**

Axis field line

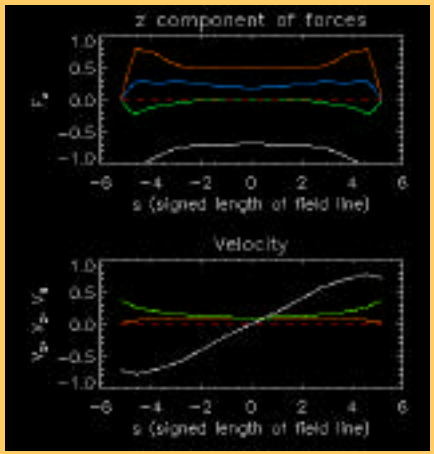


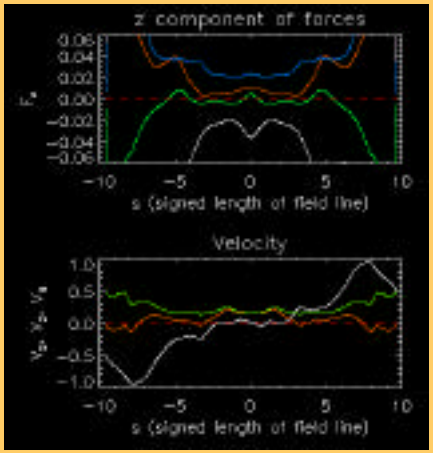
Expansion phase:
upward force: – P_m, downward force: T_m

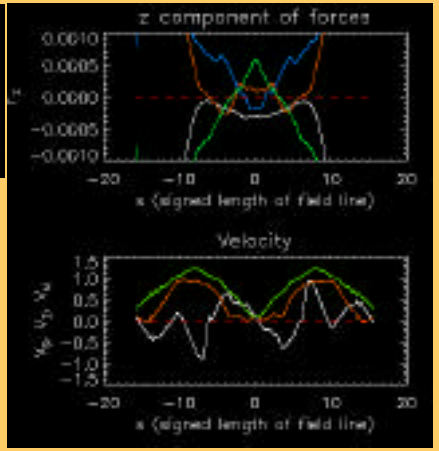




Gradual phase... undulation







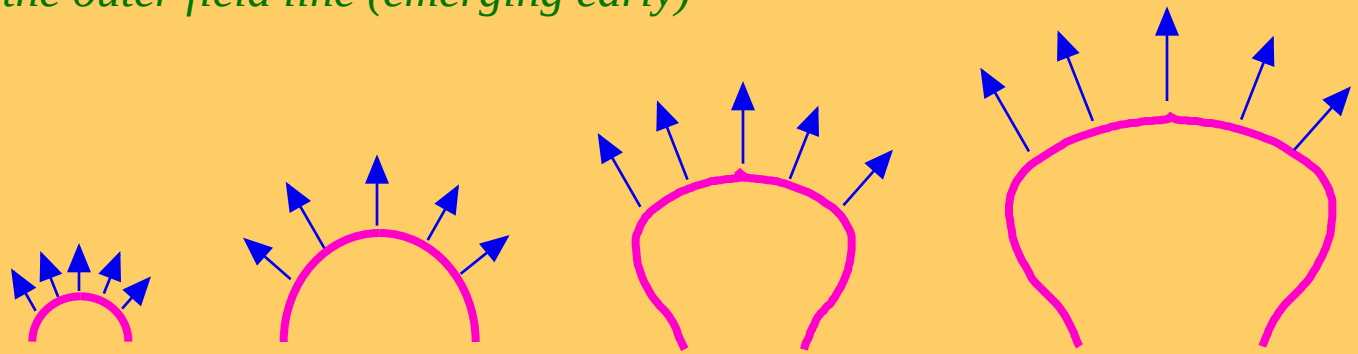
Quasi-static stage:
– $P_g \approx \rho g$

Expansion stage:
upward force: – P_m
downward force: ρg

Regression stage:
upward force: T_m
downward force: ρg

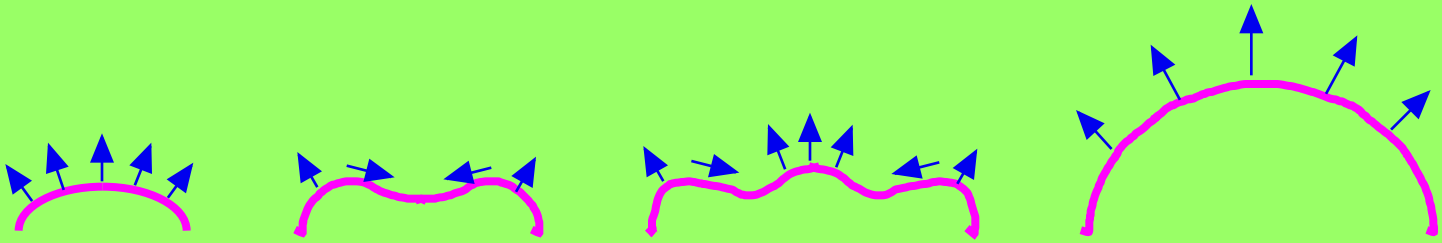
From the simulation result, we found

for the outer field line (emerging early)



a magnetic loop simply continues to expand

for the axis field line (emerging late)

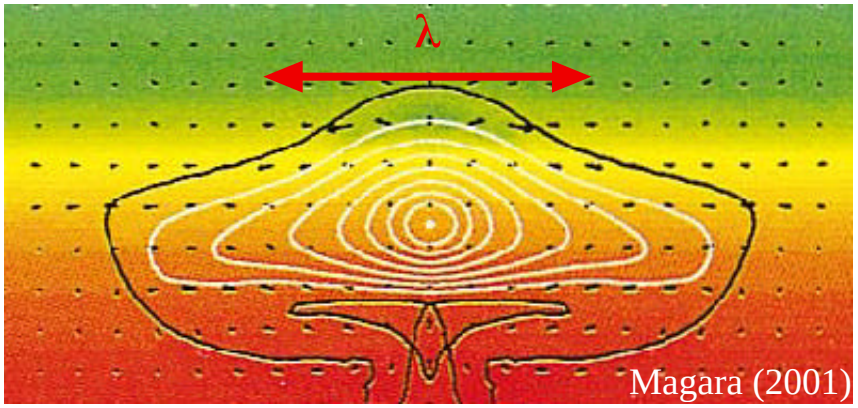


a magnetic loop is in gradual phase at first, and then enters a expansion phase later

Now let us consider the physical process working on the individual field lines.

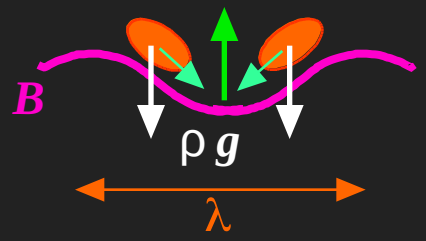
In order to come out to the atmosphere, field lines must satisfy the emergence condition.

$$\lambda > \lambda_{RT} \equiv \frac{B^2}{2 \rho g}$$



λ_{RT}: critical wavelength for magnetic Rayleigh-Taylor instability

$$T_m = \frac{B^2}{4\pi}\frac{1}{R_c} \sim \frac{B^2}{4\pi}\frac{1}{\lambda}$$

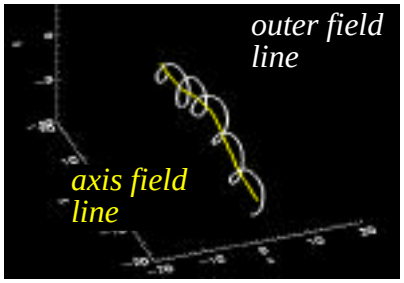


for instability

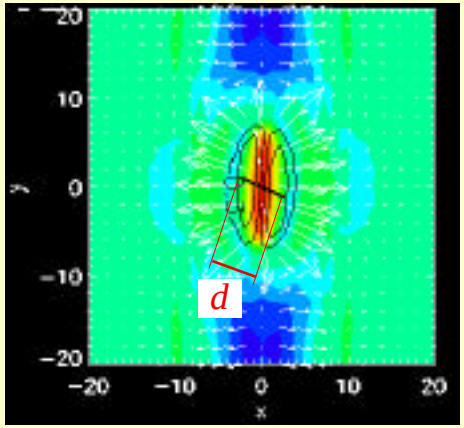
$$T_m < \rho g$$

$$\downarrow$$

$$\lambda > \lambda_{RT} \sim \frac{B^2}{\rho g}$$

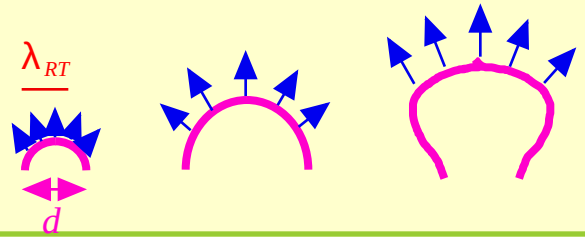


The difference in evolution between outer field line and axis field line comes from the fact that they have a different distance between footpoints when they emerge.

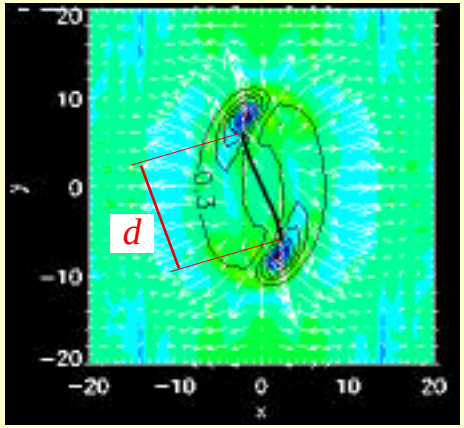


For the outer field line, the emergence distance between footpoints is

$$\lambda_{RT} \leq d < 2\,\lambda_{RT}$$

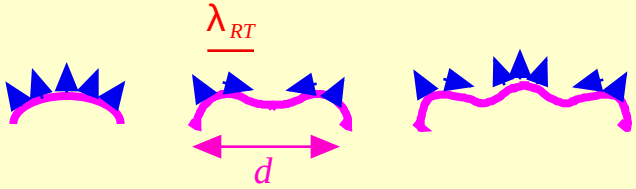


In this case, the emerged field line can expand without waving.



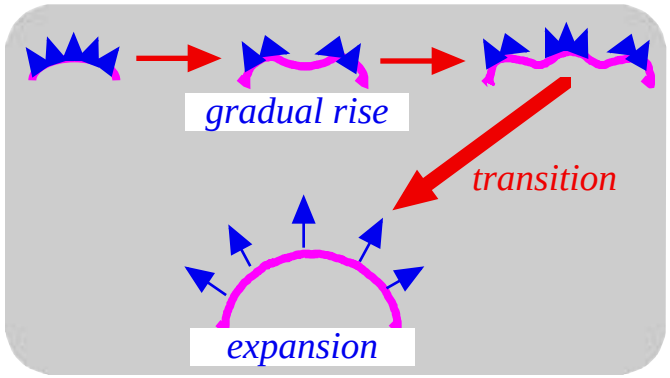
For the axis field line, the emergence distance between footpoints is

$$2\,\lambda_{RT} < d$$



In this case, the emerged field line is subject to undulation.

The field line does not make a simple expansion but takes a waving behavior with gradual rise.

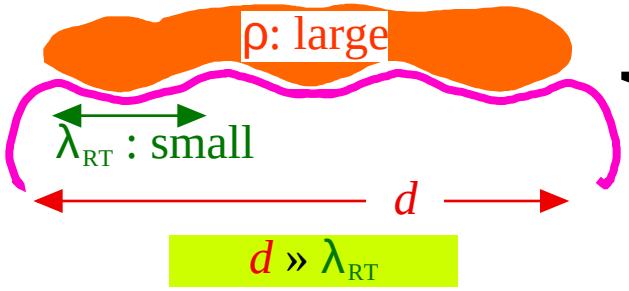


What causes the transition from the gradual phase to the expansion phase?

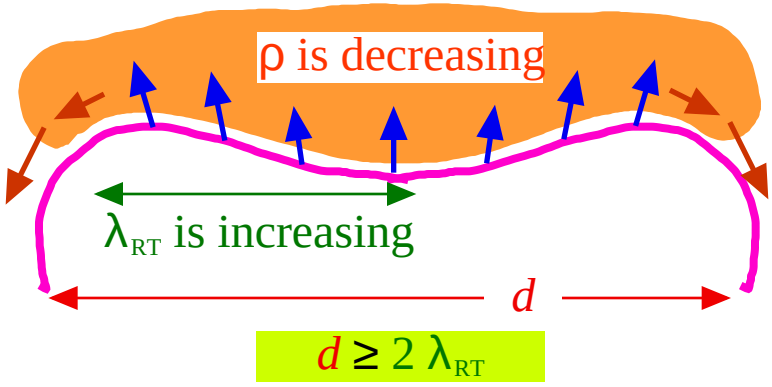
↓

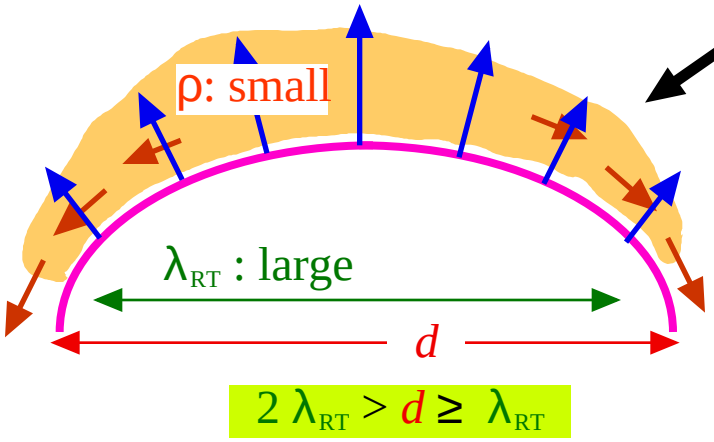
The point is that the critical wavelength for the R-T instability changes inversely with the gas density.

$$\lambda_{RT} = \frac{B^2}{2\,\rho\,g} \qquad \rho^{-1}$$

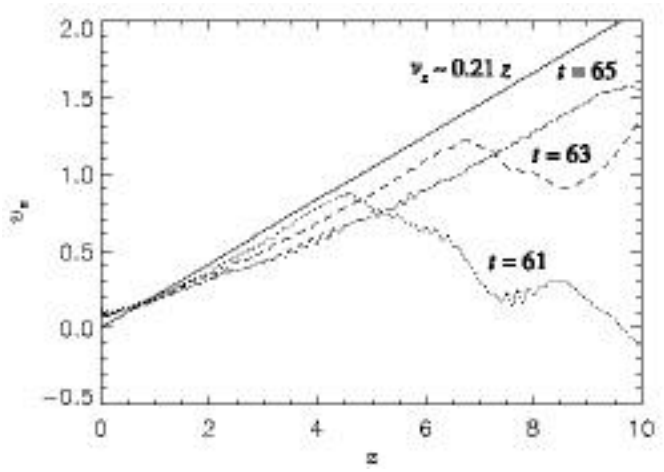


As a magnetic loop gradually rises,





When λ_{RT} becomes comparable to d, then the loop can keep a convex shape and starts expanding continuously.



Shibata's self-similar solution (1989, 1990)

In the nonlinear phase of Parker instability,

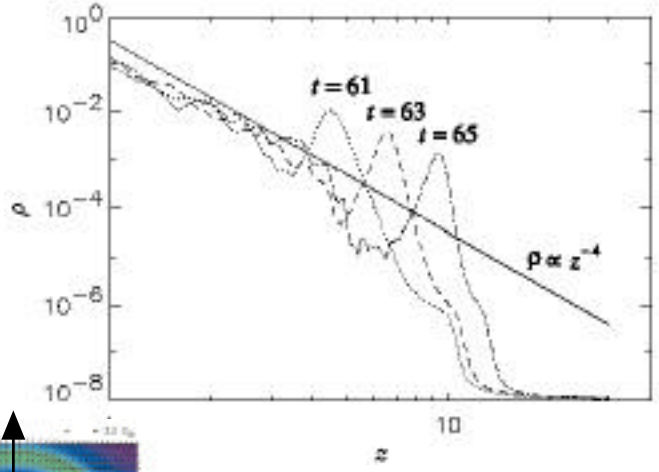
$v_z \sim (\omega_I / 2)\, z$,

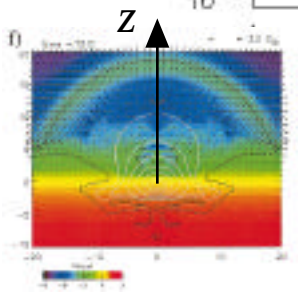
$\rho \quad z^{-4}$,

and $\rightarrow \quad \lambda_{RT} = \dfrac{B^2}{2\,\rho\, g} \quad z^2$

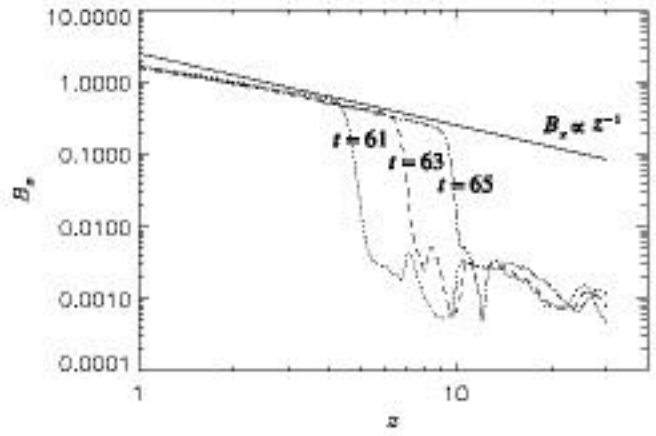
$B_z \quad z^{-1}$.

ω_I: *linear growth rate*



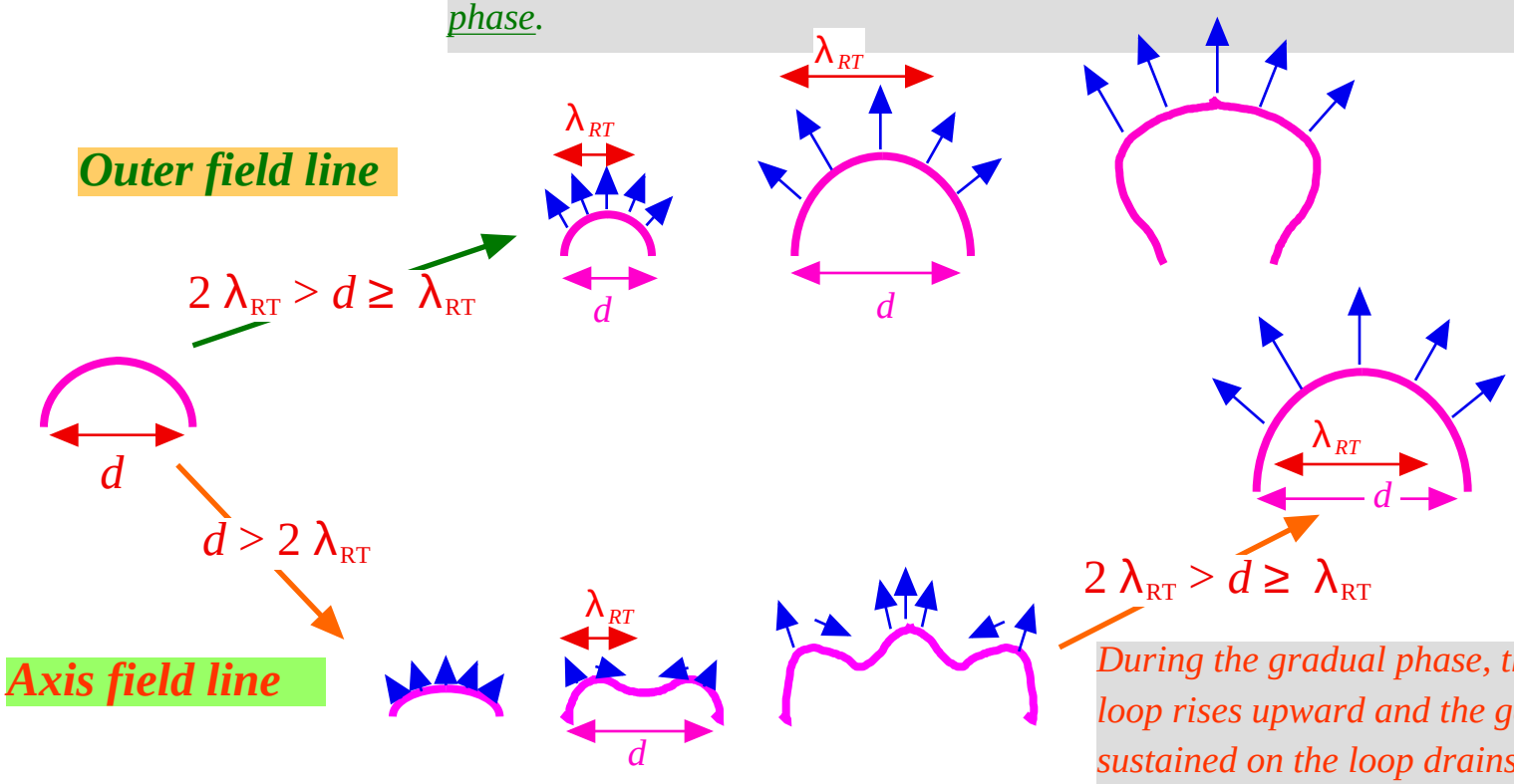


Magara (2001)



Evolution of emerging field lines

When the distance between footpoints of a magnetic loop is comparable to λ_{RT} at the appearance stage, the loop simply follows an expansion phase.



When the distance between footpoints of a magnetic loop is much larger than λ_{RT} at the appearance stage, the loop becomes undulated and takes a gradual phase.

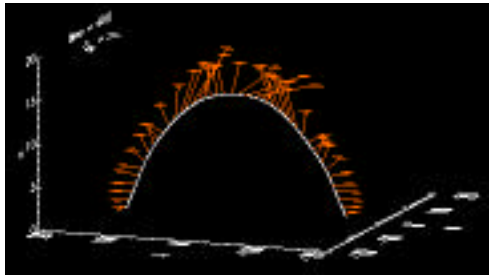
During the gradual phase, the loop rises upward and the gas sustained on the loop drains downwards. This makes the local value of λ_{RT} larger and finally λ_{RT} becomes comparable to d, leading to the expansion phase.

Some implications from the simulation result...

Prominence Eruption

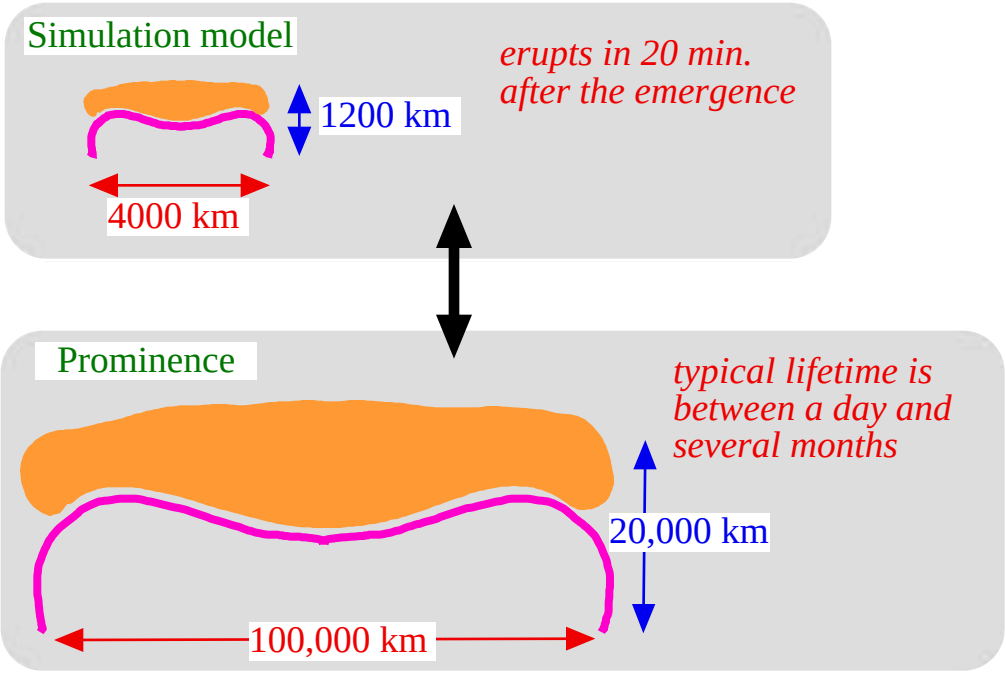
Gradual phase

Expansion phase



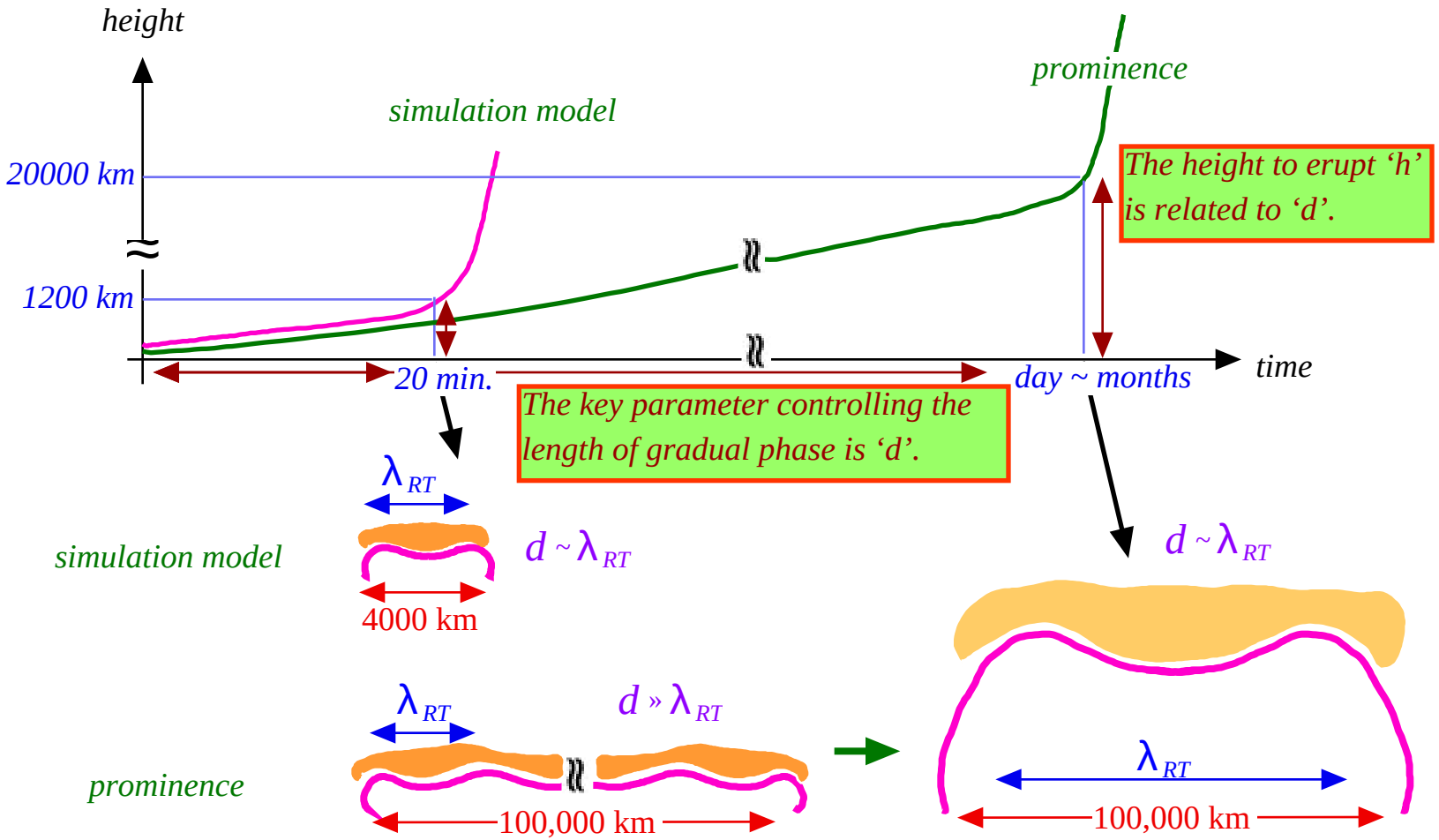
The problem is

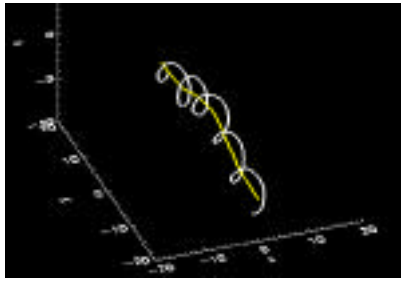
there is a huge gap in scale (time & space)
between the simulation model
and the actual prominence.



How can we overcome this gap?

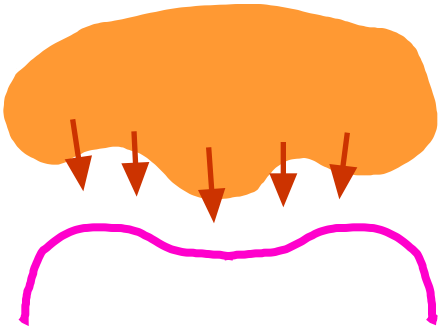
→ *Here we focus on the distance between footpoints and compare this with the critical wavelength of R-T instability.*





Simple emergence

Evaporation

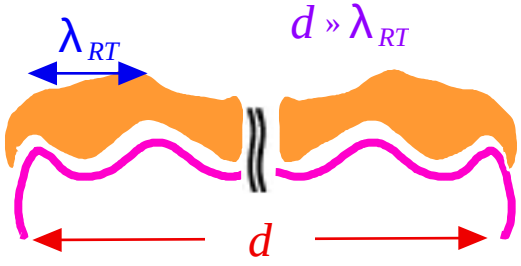


Condensation

?

?

?

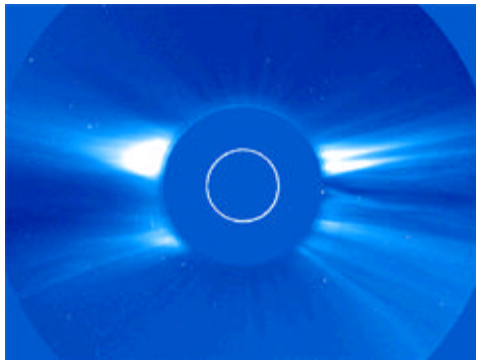


Gradual phase

We have not yet known the precise mechanism of prominence formation, but the lifetime of them (the length of gradual phase) could be related to parameter 'd', that is, the ratio of 'd' to 'λ_{RT}' may control the evolution of prominences.

CMEs

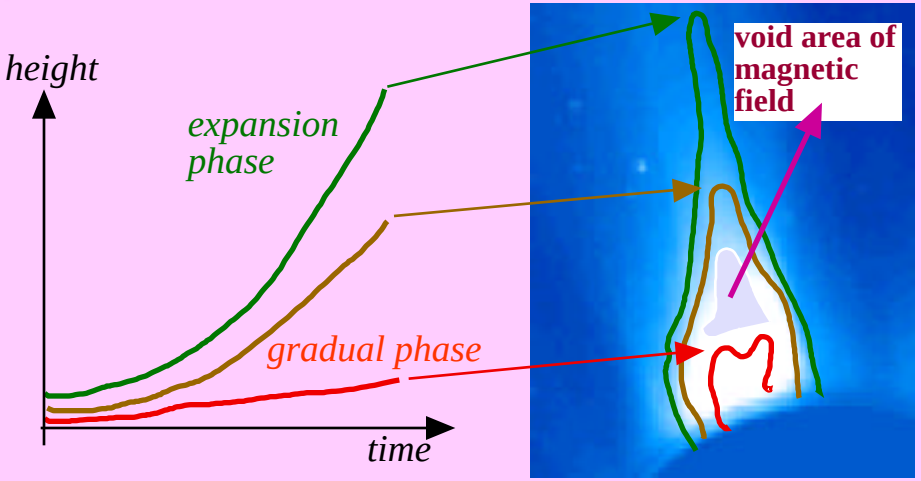
... a manifestation of the dynamical evolution of magnetic loops that have a distinct evolutionary character



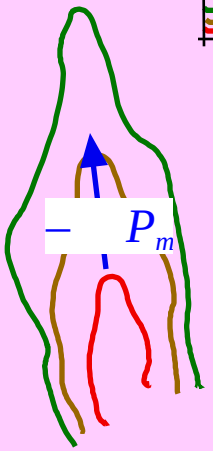
Outer field lines... expansion phase

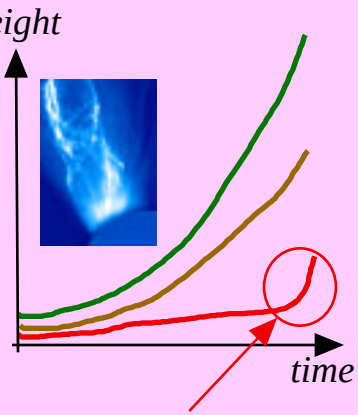
Inner field lines... gradual phase → expansion phase

→ *Stratified structure*
outer layer... helmet streamer
inner layer... compact, dense structure (prominence)



Pre-eruption stage





When the inner field line enters an expansion phase, they are ejected by a strong magnetic pressure gradient force and show a CME.

Eruption stage

Summary

- Objective of the study

  to investigate the dynamics of emerging magnetic field

- Dynamical evolution of emerging field lines

  expansion phase and gradual phase

- Physical process working on emerging field lines

  the relation between the footpoint distance and λ_{RT}

- *Some implications from the result*

  prominence eruption and CMEs