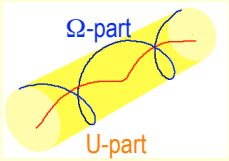
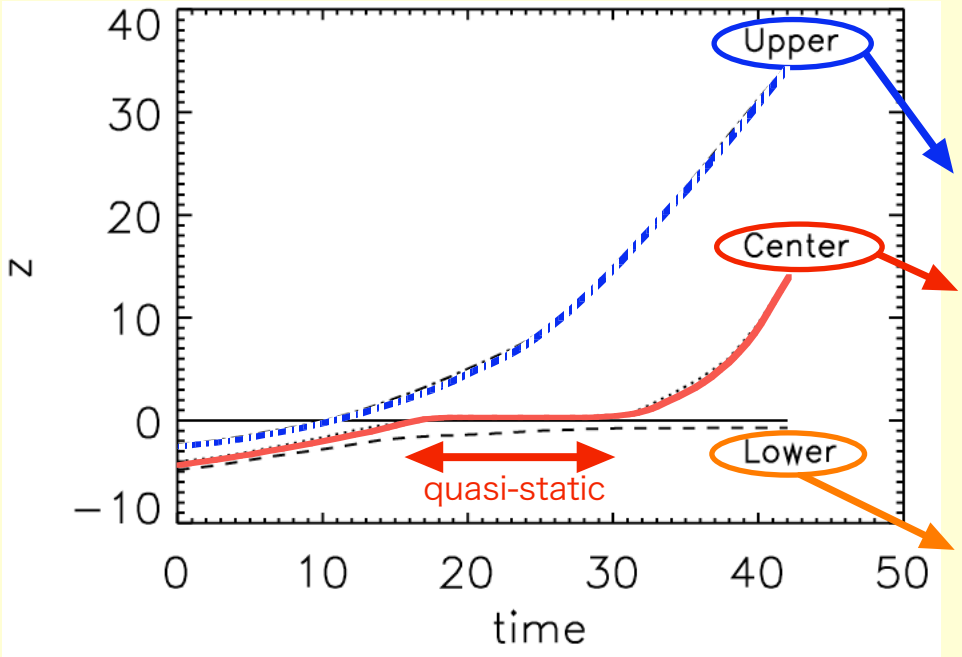
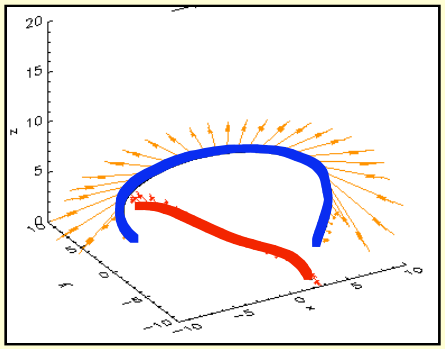
Key features of emerging field lines

(**Evolutionary characteristics**)

Height-time relation of **outer** & **inner (axis)** field lines:







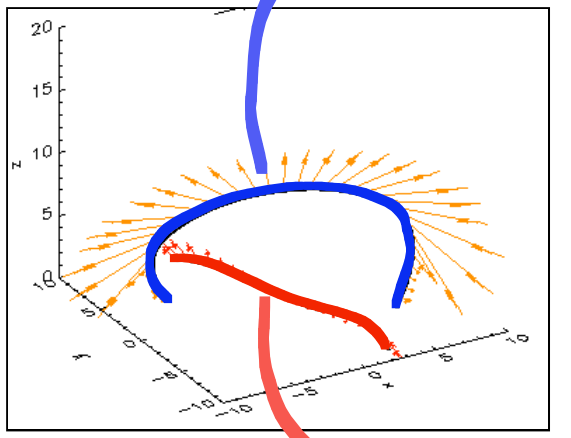
Ω-part of outer field line **continuously expands.**

axis field line **shows quasi-static evolution.**

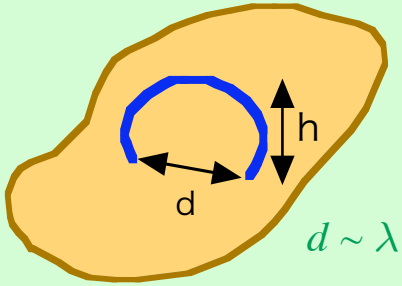
U-part of outer field line **does not emerge.**

Key features of emerging field lines

(Shape characteristics)



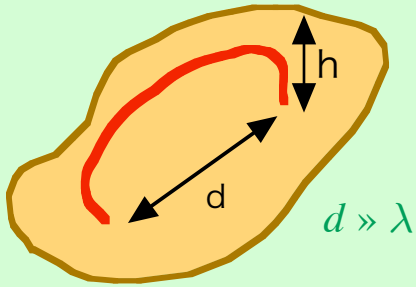
Outer field line... short footpoint distance



$d \sim \lambda_c$

aspect ratio h/d: large

Inner field line... long footpoint distance

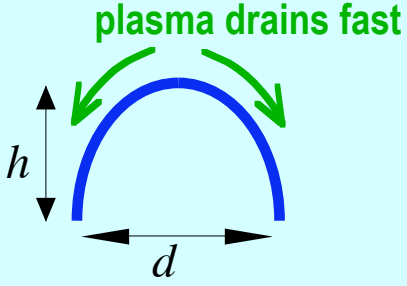


$d \gg \lambda_c$

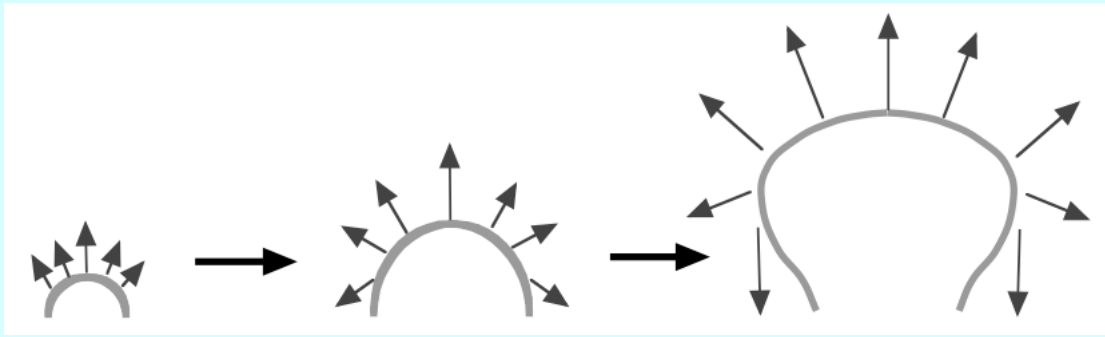
aspect ratio h/d: small

Relation between the evolution and shape of emerging field line

Outer field line

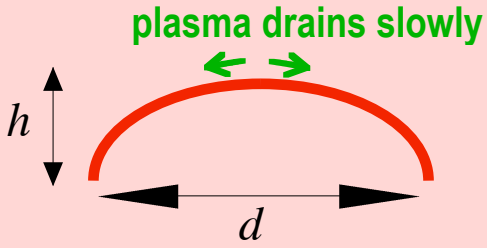


large aspect ratio h/d

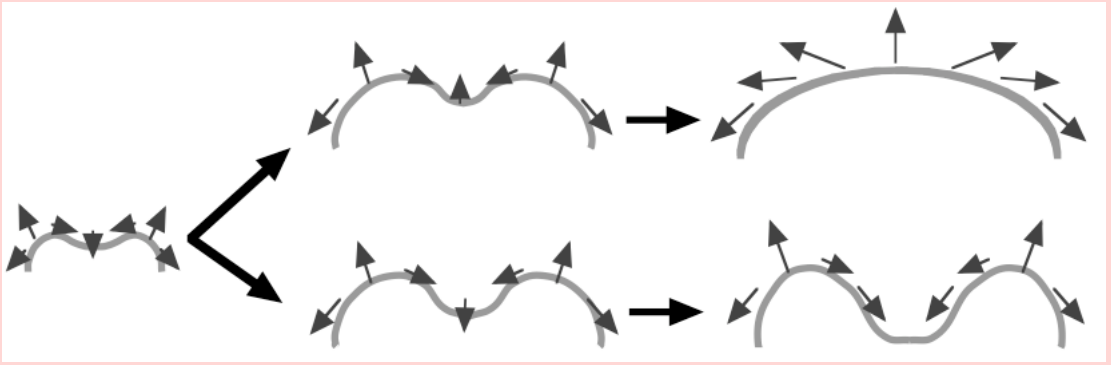


Continuous expansion

Inner field line



small aspect ratio h/d

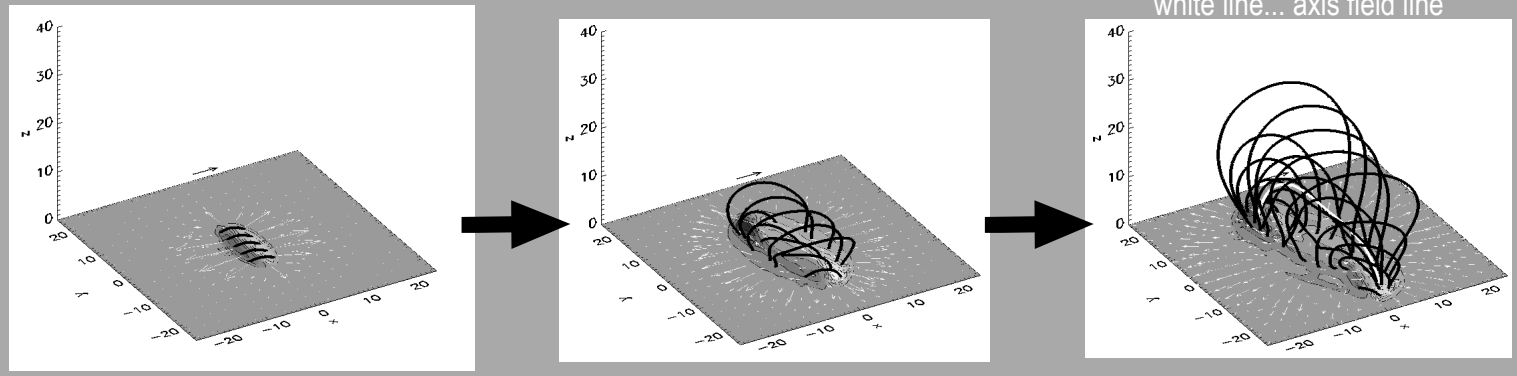


Slow evolution with dip formation

Evolution of magnetic structure and flows produced by emerging twisted flux tube

3D view of magnetic structure (black lines) & **flows** (white arrows)

white line... axis field line



Early state ***Developing state*** ***Developed state***

Top view (magnetic polarity regions & flow patterns at a solar surface)

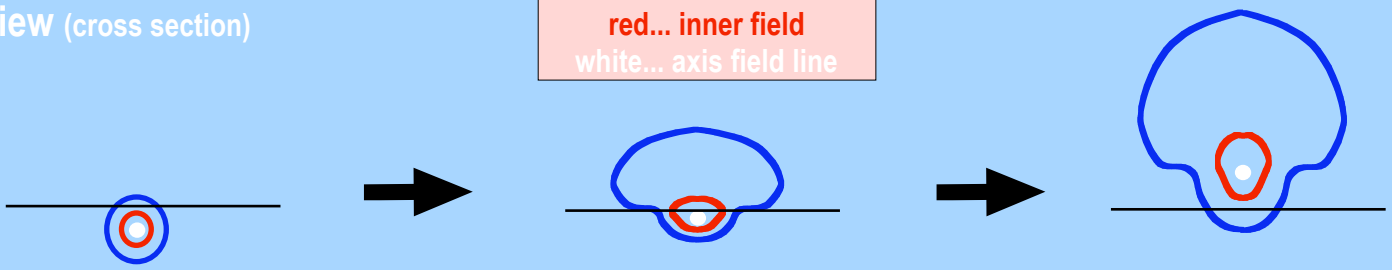
diverging flow

shear flow (strong)

shear (weak) & rotational flow

blue... outer field
red... inner field
white... axis field line

Side view (cross section)



Structurization in the emerging twisted flux tube (developed state):

expanding shearless arcade (outer part) + **quasi-static sheared arcade** (inner part)

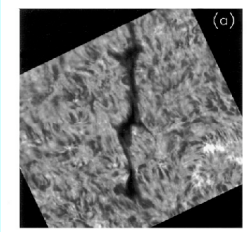
Shearless arcade (outer field lines)

continuously expanding, curved shape

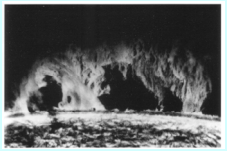
helmet streamer

Sheared arcade/flux rope (inner field lines)

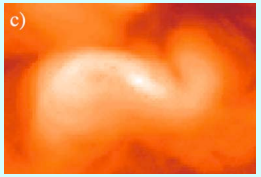
quasi-static, relatively flat shape



filament



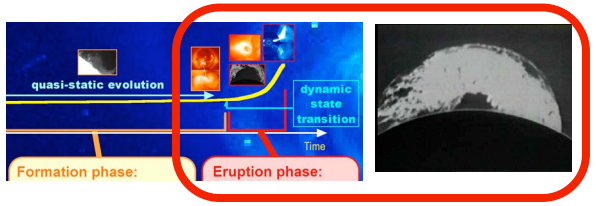
prominence



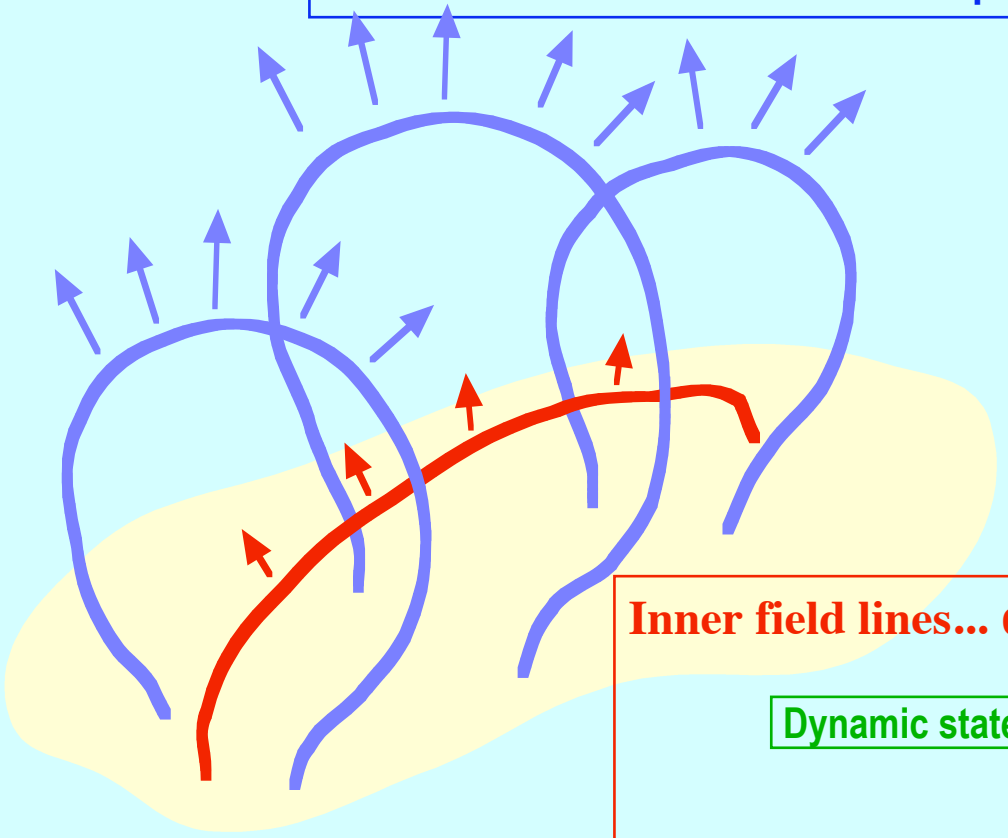
sigmoid

Toward eruption phase...

Dynamic state transition of inner field lines



Outer field lines... continuous expansion



Inner field lines... quasi-static evolution

Dynamic state transition

eruption

Transition of dynamic states from quasi-static state to eruptive state

Magara (2013)

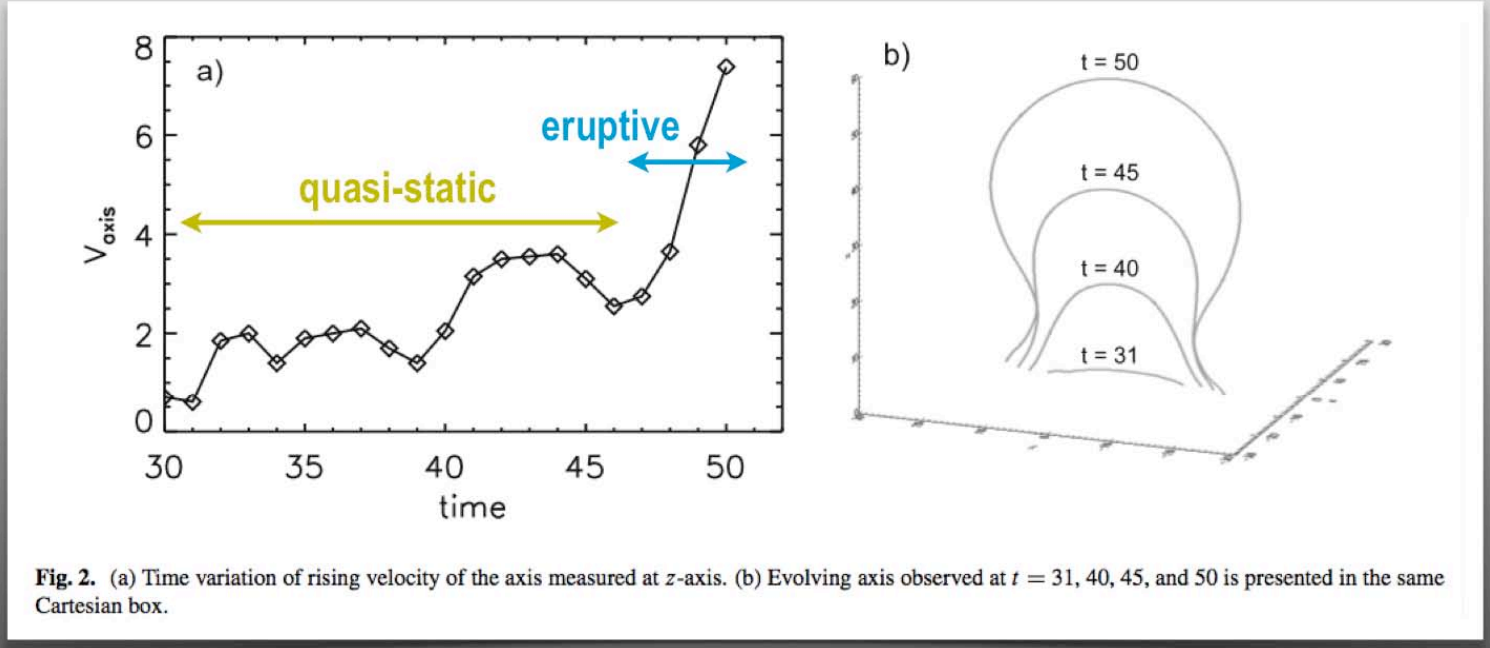
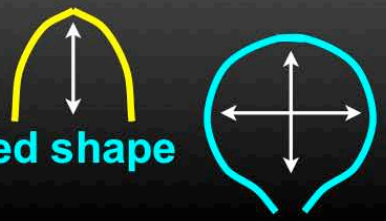


Fig. 2. (a) Time variation of rising velocity of the axis measured at z-axis. (b) Evolving axis observed at $t = 31$, 40, 45, and 50 is presented in the same Cartesian box.

A key to understanding the **dynamic state transition**... **Change of field-line shape**

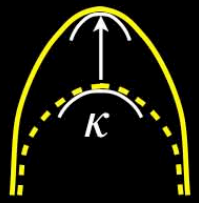
Quasi-static phase... Vertically expanded shape

Eruptive phase... Vertically and Laterally expanded shape



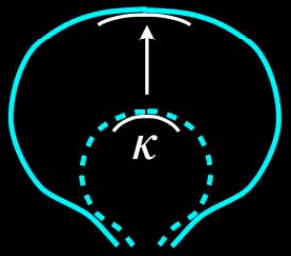
Quasi-static phase... expands vertically

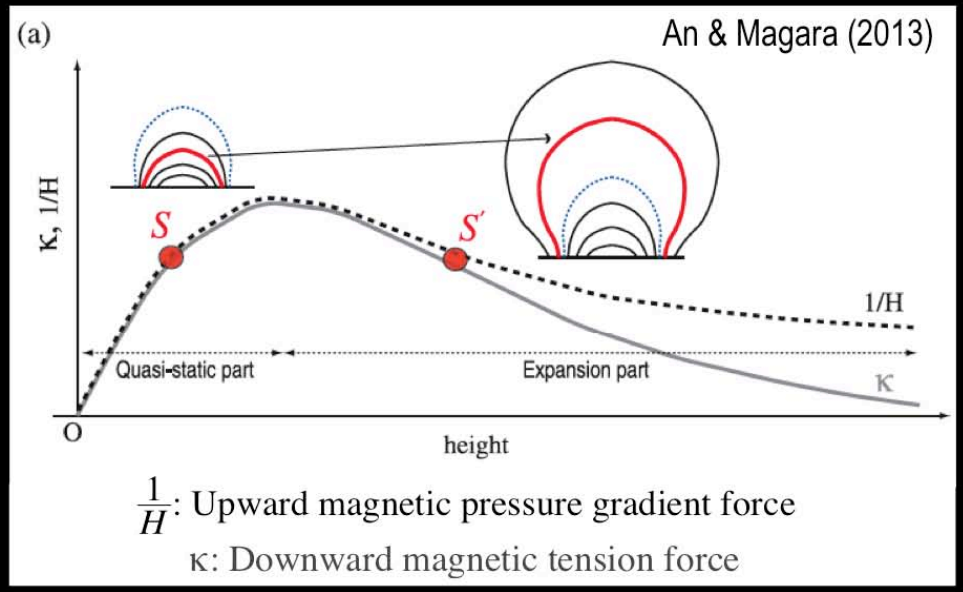
κ (curvature) increases => downward tension becomes effective



Eruptive phase... expands vertically and laterally

κ (curvature) decreases => downward tension becomes less effective





$\frac{1}{H}$: Upward magnetic pressure gradient force

κ: Downward magnetic tension force

There is a **critical height** over which an emerging field line changes its **expansion style**.

Dynamic state transition from **quasi-static state** to **eruptive state**

(Lee & Magara 2018)