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Resonance Heating of Solar Coronal Loops: Advanced Models

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Resonance heating of solar coronal loops: advanced models

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Motivation

MHD model

⇒ equations / waves and time-scales

Side-ways and footpoint excitation of coronal loops

⇒ linear MHD results / 2D and 3D nonlinear dynamics of resonant layer

New self-organizing model

⇒ automatic tuning / consistent with Yohkoh observations

Conclusions and perspective

Introduction / Motivation

- corona: highly inhomogeneous

  in space and time (Yohkoh, Soho)
- structure dominated by magnetic field
- hot material concentrated in loops

  (loops outline magnetic field)
- average temperature $2 - 3 \times 10^6$ K

$\Rightarrow$ heating mechanism(s)?

$\Rightarrow$ efficiency / time scales ?

- magnetohydrodynamics (MHD): simplest $\Rightarrow$ most popular

MHD wave dissipation in coronal loops

- heating model requires:

  energy source + transport device + dissipation mechanism

- *source of MHD waves*?

  1) originally: convective motions $\Rightarrow$ FMWs, SMWs, and AWs

  only AWs reach corona (Hollweg '84)

  $\rightarrow$ when 'slow': twisting & braiding $\Rightarrow$ reconnection (Parker '72)

  $\rightarrow$ when 'fast': MHD waves

$$\left.\begin{array}{l} v_A = B/\sqrt{\mu\rho} \approx \text{ a few } 10^6 \text{ m/s} \\ 40 \times 10^6 \leq L \leq 400 \times 10^6 \text{ m} \end{array}\right\} \Rightarrow \tau_A = \frac{L}{v_A} \approx \text{ sec to min}$$

  2) recently: *generated in corona itself* (reconnection, wave transformations)

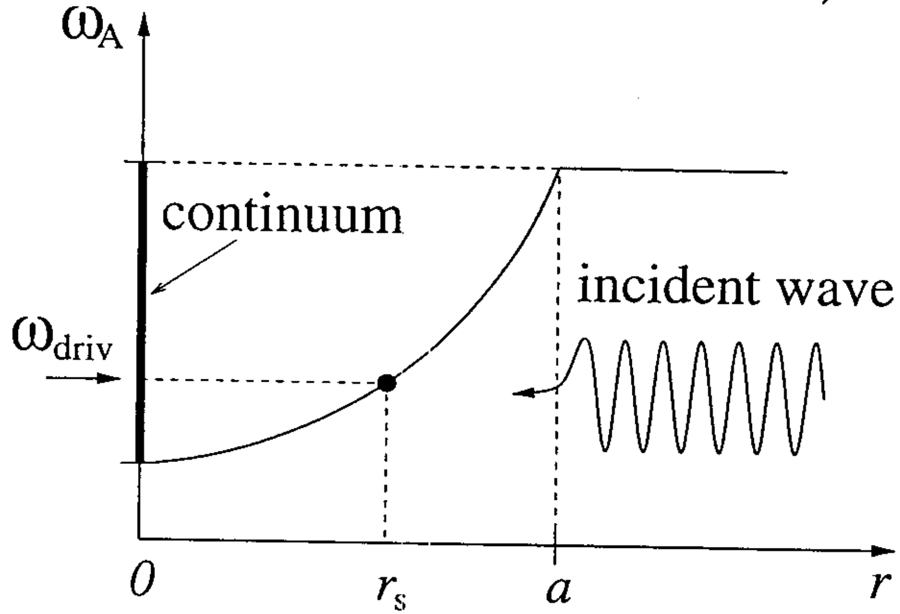
- dissipation AWs? $\boxed{\tau_D = \mu l^2/\eta}$

  $\Rightarrow$ extremely long in solar corona

  $\Rightarrow$ small l required

  $\Rightarrow$ resonances!

$$\omega_A(r_s) \equiv \frac{1}{\sqrt{\mu\rho}} \left(\frac{m}{r_s} B_\theta(r_s) + \frac{2\pi n}{L} B_z(r_s)\right)$$



- width $\Delta \sim \left(\frac{\eta + \nu}{\omega'_A}\right)^{\frac{1}{3}}$

$\Rightarrow \boxed{\tau_{RD} \sim \mu(\eta + \nu)^{-\frac{1}{3}} {\omega'_A}^{-\frac{2}{3}}}$

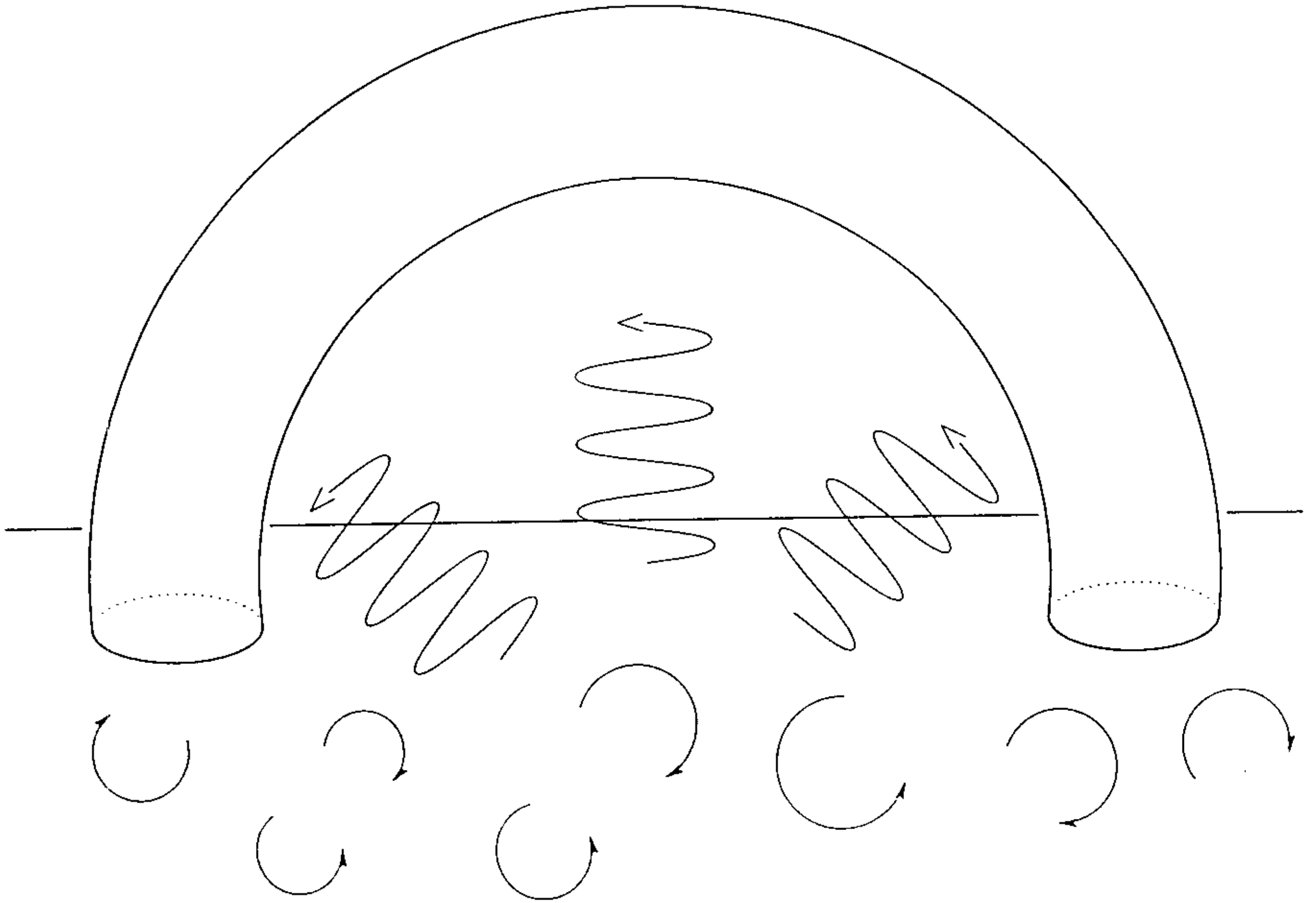
$\Rightarrow \tau_{RD} \sim \mu(\eta + \nu)^{-\frac{1}{3}}$ $\Rightarrow$ much shorter in solar corona ($R_m, R_e \gg 1$)

$\Rightarrow$ acceptable?, i.e. $\tau_{RD} \ll 1$ day (= typical life time loops)?

$\Rightarrow$ answer requires *time-dependent*, *high-resolution 3D*, *nonlinear* computer simulations!

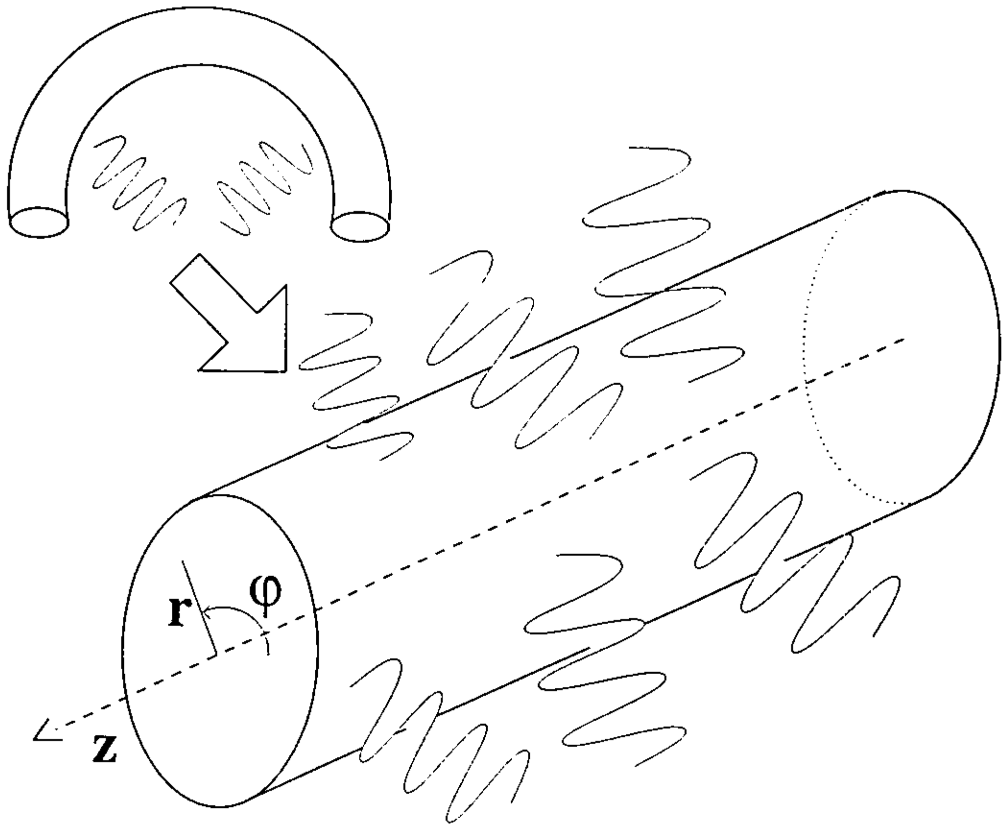
Side-ways excitation of coronal loops

Physical situation



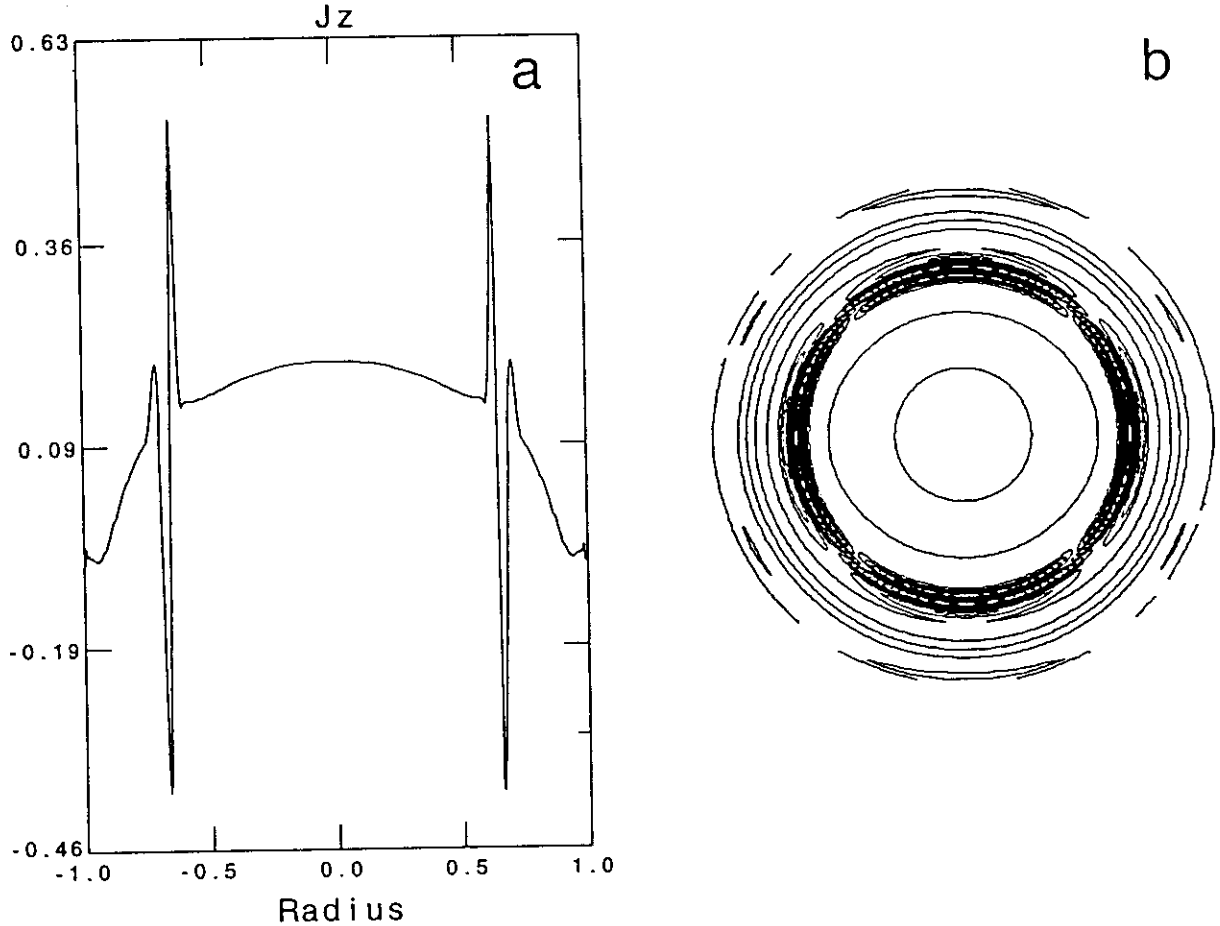
Configuration

- cylindrical model, excited *externally* by incident waves



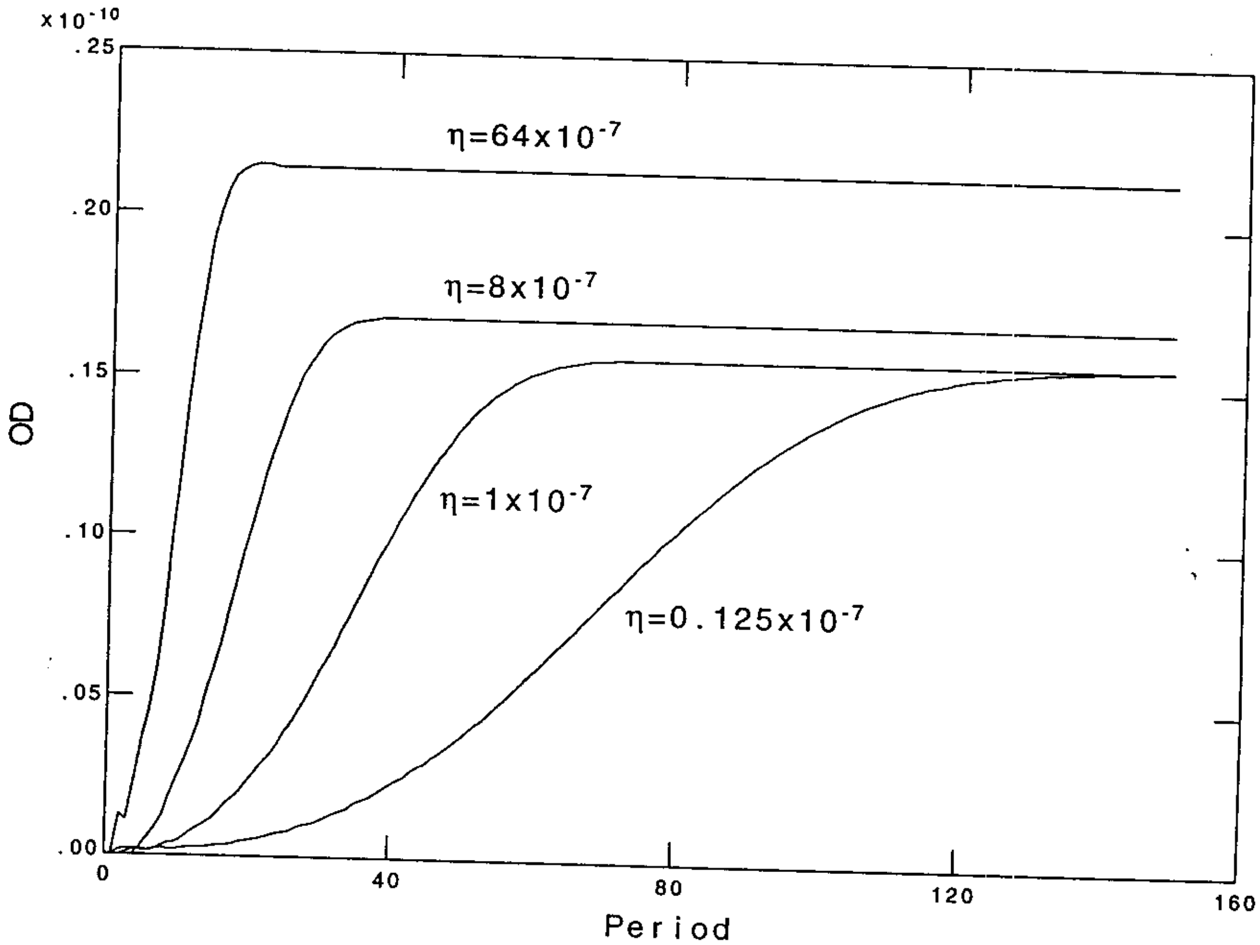
⇒ video of linear MHD simulation (Poedts et al., '92)

$\Rightarrow$ *strongly localized AC currents* in resonant layer $\Rightarrow$ *heating*



$A = 0.001\, V_A,\ R_m = 1.25 \times 10^6,\ t = 2500\tau_A$

- heating rate independent of dissipation mechanism! for $\eta, \nu \rightarrow 0$



Average Ohmic dissipation rate versus time

Main linear MHD results

- very good plasma-driver coupling: *fractional absorption* often $> 90\%$!
- 'bad quality' resonances: good for heating efficiency !
- acceptable time scales:

loop density	*loop radius* 10^6 m	*loop radius* 5×10^6 m
10^{15} m^{-3}	20 s - 1 h	2 m - 5 h
10^{16} m^{-3}	1 m - 3 h	5 m - 14 h

$\Rightarrow$ viable heating mechanism ?

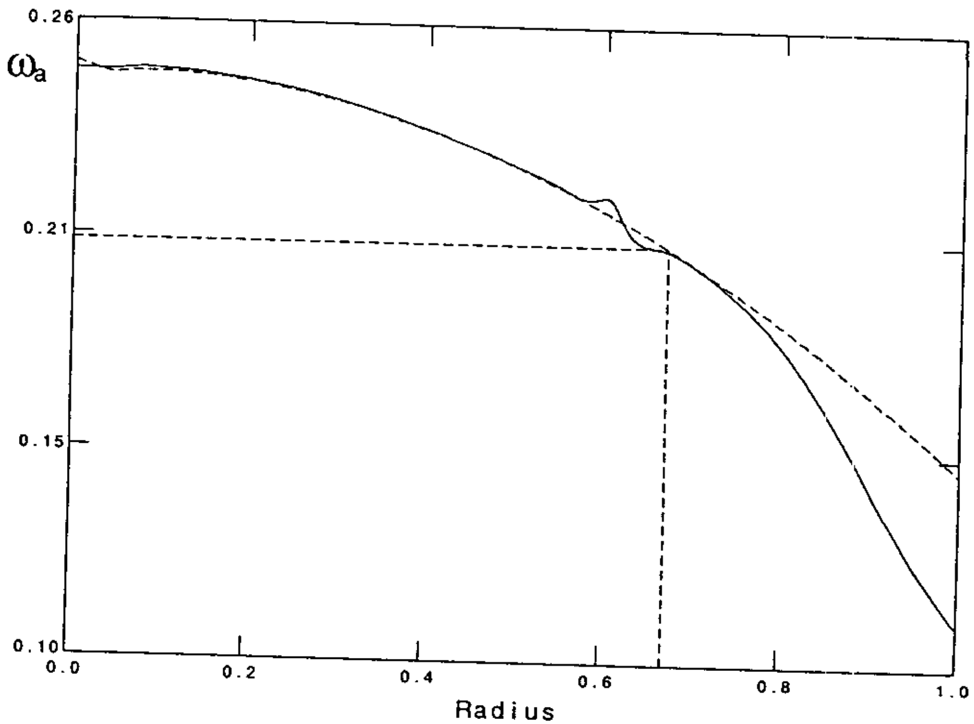
$\Rightarrow$ answer requires simulations including, e.g.

- nonlinearity
- line-tying

Variation of the background 'equilibrium'

1) diffusion of background field $\Rightarrow$ $\tau_{diff} \sim \eta^{-1}$ $\Rightarrow$ long

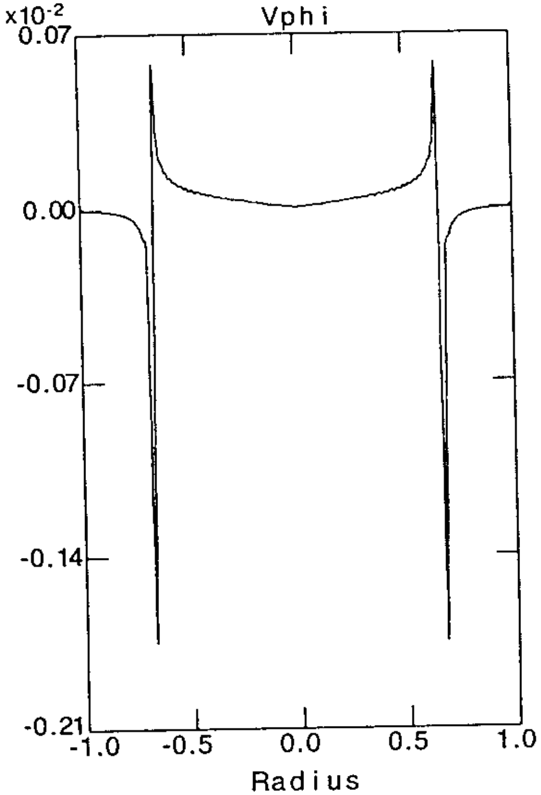
2) heating at resonant layer $\Rightarrow$ $\tau_{RA} \sim \eta^{-1/3}$ $\Rightarrow$ shorter

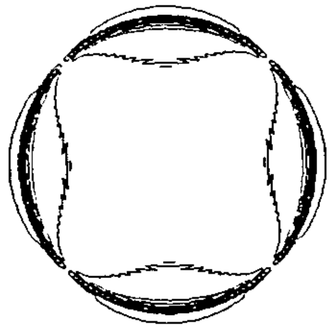


$\omega_A(r)$ *for* $A = 0.001\,V_A$, $R_m = 1.25 \times 10^6$ *at t=0 and average*

Stability resonant layer

- wave motions produce shear flow $\Rightarrow$ two narrow counterstreams ($\sim \sin(\omega t)$)





$\Rightarrow$ potentially susceptable to Kelvin-Helmholtz instability (Heyvaerts & Priest '83)!

Nonlinear effects on resonant heating

variation of background $\Rightarrow$ *resonance location shifts in time*

- good: larger portion of loop heated
- bad: can resonance fully develop ?

nonlinear mode coupling $\Rightarrow$ Δ_{res} *wider*

- good: larger portion of loop heated
- bad: longer l $\Rightarrow$ longer time-scales

Kelvin-Helmholtz instability resonant layer

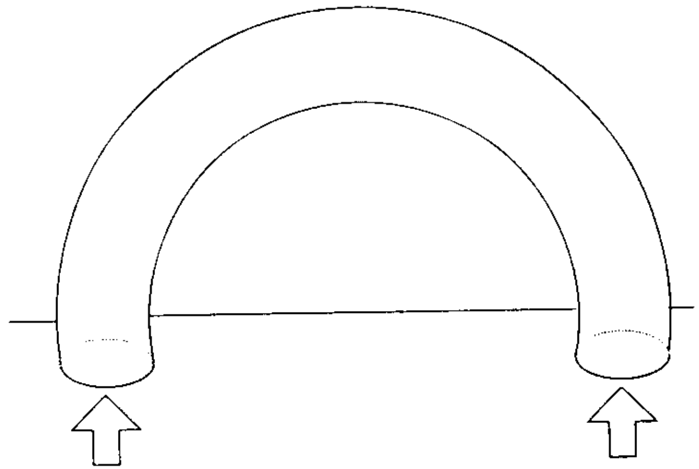
- good: shorter l created (vortex splitting)
- bad: resonant layer may be destroyed

Footpoint excitation of coronal loops

- *Strauss & Lawson ('89)*: effect of 'anchoring' ('line-tying') and foot point excitation

- *Goedbloed & Halberstadt ('94, '95)*:

  - AWs and FMWs are coupled!
  - AW continuum: $\omega_A(r) = \frac{n\pi}{L}\frac{B_z(r)}{\sqrt{\mu\rho(r)}}$

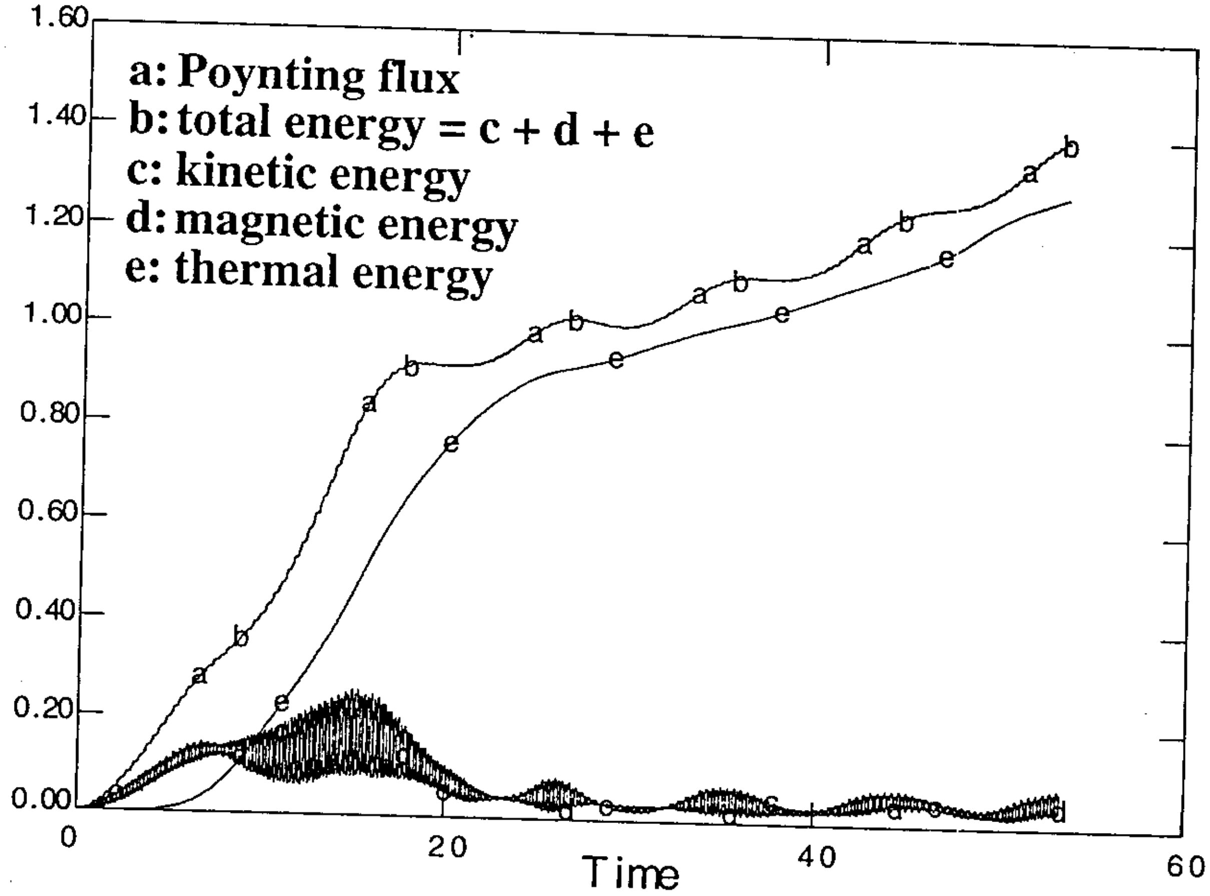


⇒ studied <u>*rigorously*</u>: linear and nonlinear studies, numerical and analytical, steady state approach, eigenvalue approach and time evolution (*Poedts et al. '89-'96; Ofman et al. '95, '96; Berghmans & Tirry '96, '97, etc.*)

- *Beliën et al. '97*: effect of variation density and magnetic field strength *along* the loops

⇒ *resonant dissipation is a viable heating mechanism!*

Energetics



- 2D nonlinear MHD simulation (Poedts & Boynton '94)

- HOWEVER: coupling to chromosphere important

  ⇒ leakage *(Berghmans & De Bruyne '96)*

  ⇒ evaporation ⇒ tuning/detuning

  Ofman et al. '98: 1D scaling laws to update density

- *Beliën, Martens, Keppens '99*: thermal structure *along* loops included

  ⇒ efficient generation of SMWs

  ⇒ input energy does not reach corona (only 30% AWs)

  ⇒ heating much less efficient (but: unrealistic monoperiodic driver)

- *Kano & Tsuneta '96*: detailed analysis of Yohkoh data

  ⇒ loop tops emit more and are hotter!

  ⇒ 2 types of T profiles: peaked and with 'plateau'

⇒ can be compatible with the wave heating model!

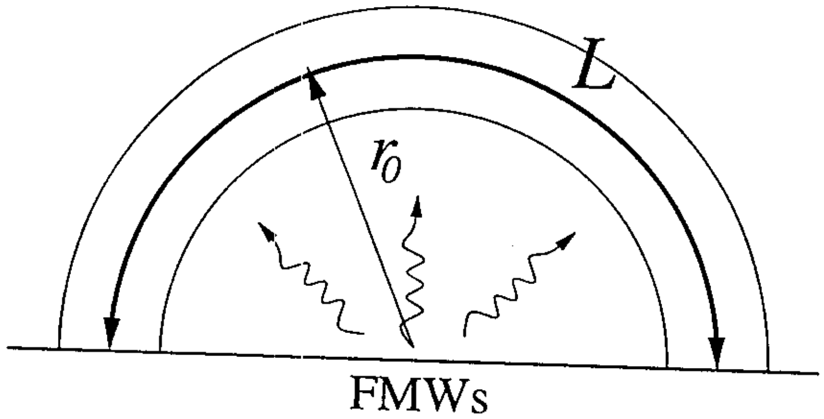
A self-organizing mechanism

(Voitenko & Poedts '99)

- line-tied loop, excited by FMWs generated by convection or *in the corona itself*

- basic ($n = 1$) resonance occurs at

$$\omega = \frac{v_A(r_0)}{r_0}$$



$\Rightarrow$ *Chen & Hasegawa '74*: $$\boxed{\frac{dW}{dt} = \frac{2\pi}{\mu_0} L_y L_z \omega |C|^2 l}$$ with $l = \left(\frac{1}{\rho}\frac{\partial \rho}{\partial r}\right)^{-1}$

- $|C|^2 = |C_0|^2 \, P(\omega)$

- simplification: $l \approx \Delta r$ ('sharp nonuniformity')

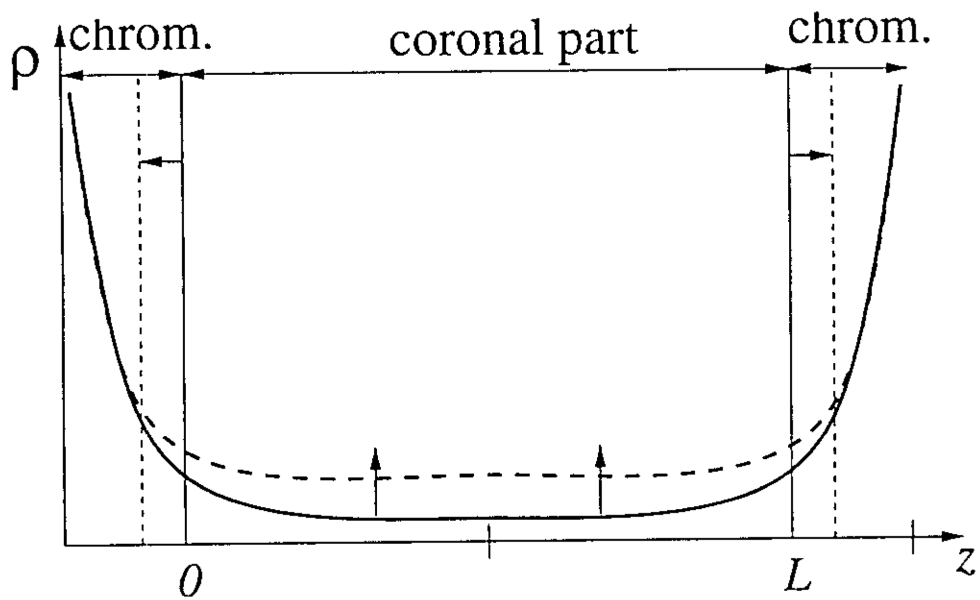
⇒ volumetric heating rate (devide by $L_y L_z \Delta r$)

$$Q(\omega) = \frac{2\pi}{\mu_0}\omega |C_0|^2 \; P(\omega) = A\omega \; P(\omega)$$

⇒ <u>repetitive scenario</u>:

- *thermal conduction* ⇒ T spreads over entire loop

⇒ *chromospheric evaporation* ⇒ density coronal part loop rises:



⇒ loop *tunes to lower frequency* (more power!)

⇒ more heating takes place ⇒ more evoporation, etc.

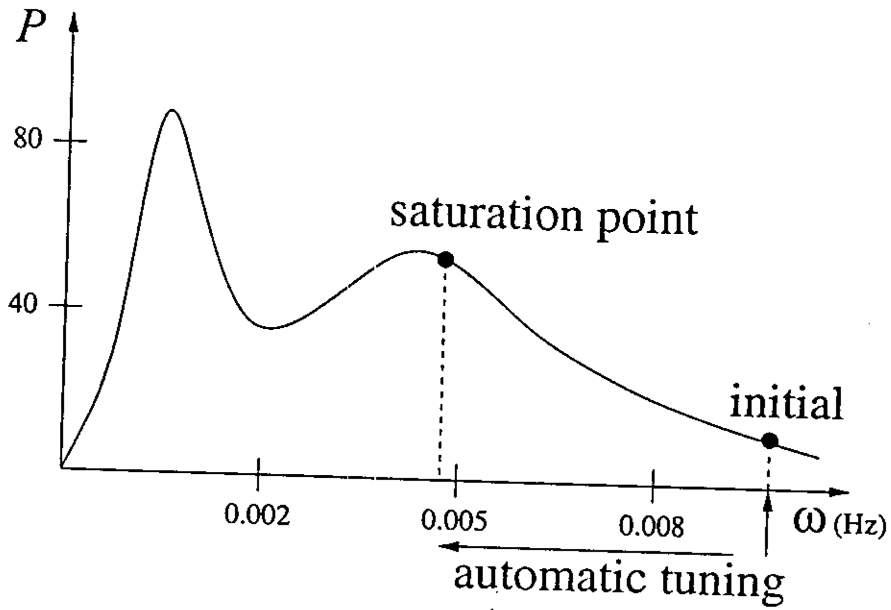
- density gradients at loop ends determine cavity in which waves are trapped, i.e. the part of the loop that is heated directly by resonant dissipation

⇒ *saturation* occurs when

$$\frac{\partial Q}{\partial \rho} = \frac{\partial Q}{\partial \omega}\frac{\partial \omega}{\partial \rho} = 0$$

$$\Rightarrow \frac{\partial Q}{\partial \omega} = A\ P(\omega) + A\omega\ P'(\omega) = 0$$

$$\Rightarrow \boxed{\omega = -\frac{P(\omega)}{P'(\omega)}}$$



Conclusions

- *coronal loop heating*: very advanced models

⇒ effects of

- nonlinearity
- leakage (side-ways and at foot points)
- geometry (.g. flaring out of loops at foot points)
- flows (Doppler shift & wave transformations)
- chromospheric evaporation (density affected), . . .

need to be combined in one model

⇒ wave heating occurs, depends on input power spectrum & loop structure

- self-organizing mechanism with automatic tuning
- would explain observed hot, emitting loop tops