Resonant Damping of Prominence Thread Oscillations: Effect of Partial Ionization

Roberto Soler[1]

in collaboration with
J. Andries[1], J. L. Ballester[2], M. Goossens[1], R. Oliver[2]

[1]Centre for Plasma Astrophysics
Katholieke Universiteit Leuven (Belgium)

[2]Solar Physics Group
Universitat de les Illes Balears (Spain)

Workshop on Partially Ionized Plasmas in Astrophysics
Tenerife, 19 – 22 June 2012

Outline

Solar Prominences

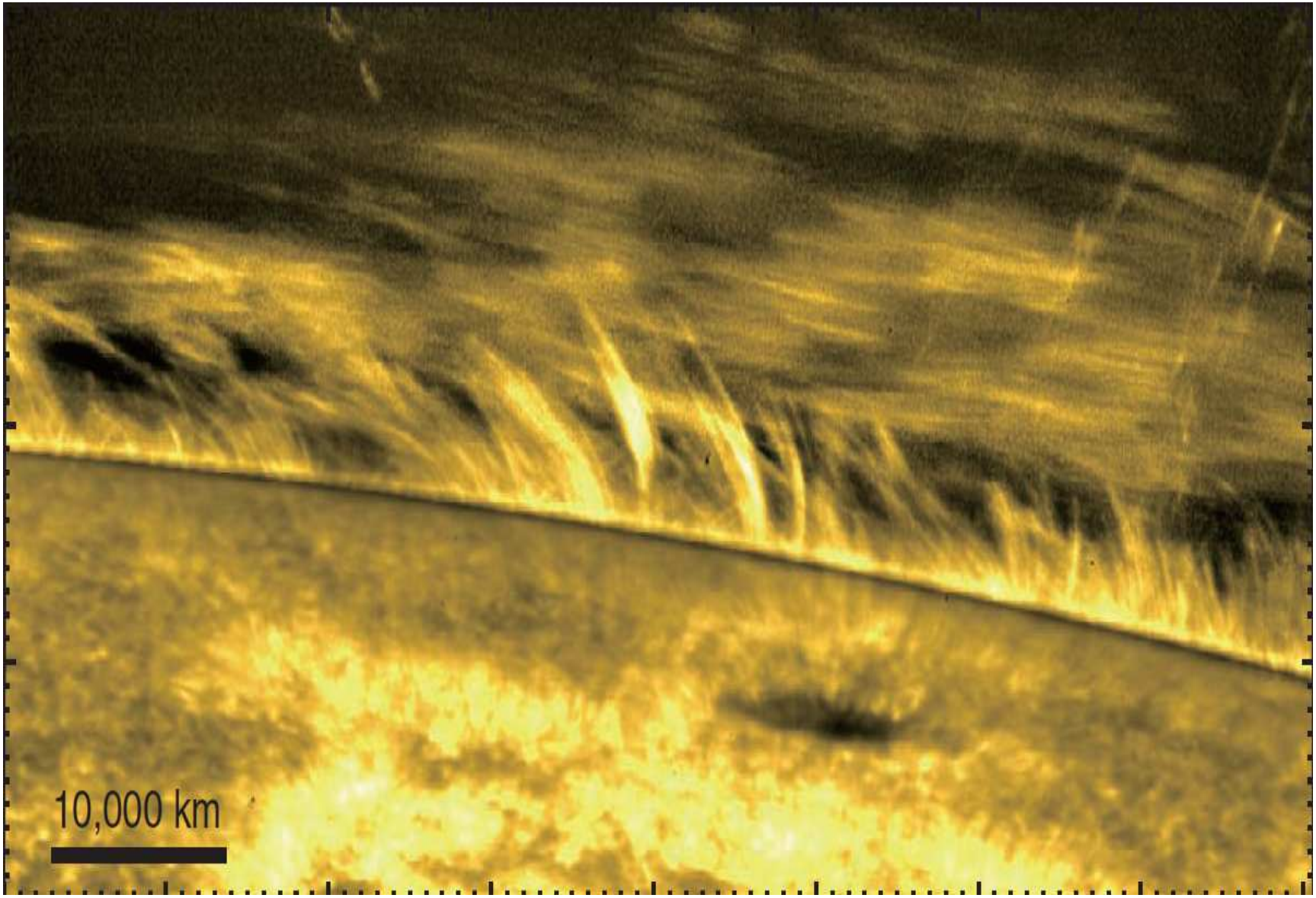


Image credit: Okamoto et al. (2007) / Ca II-H, SOT Hinode

Thin Threads of Solar Prominences

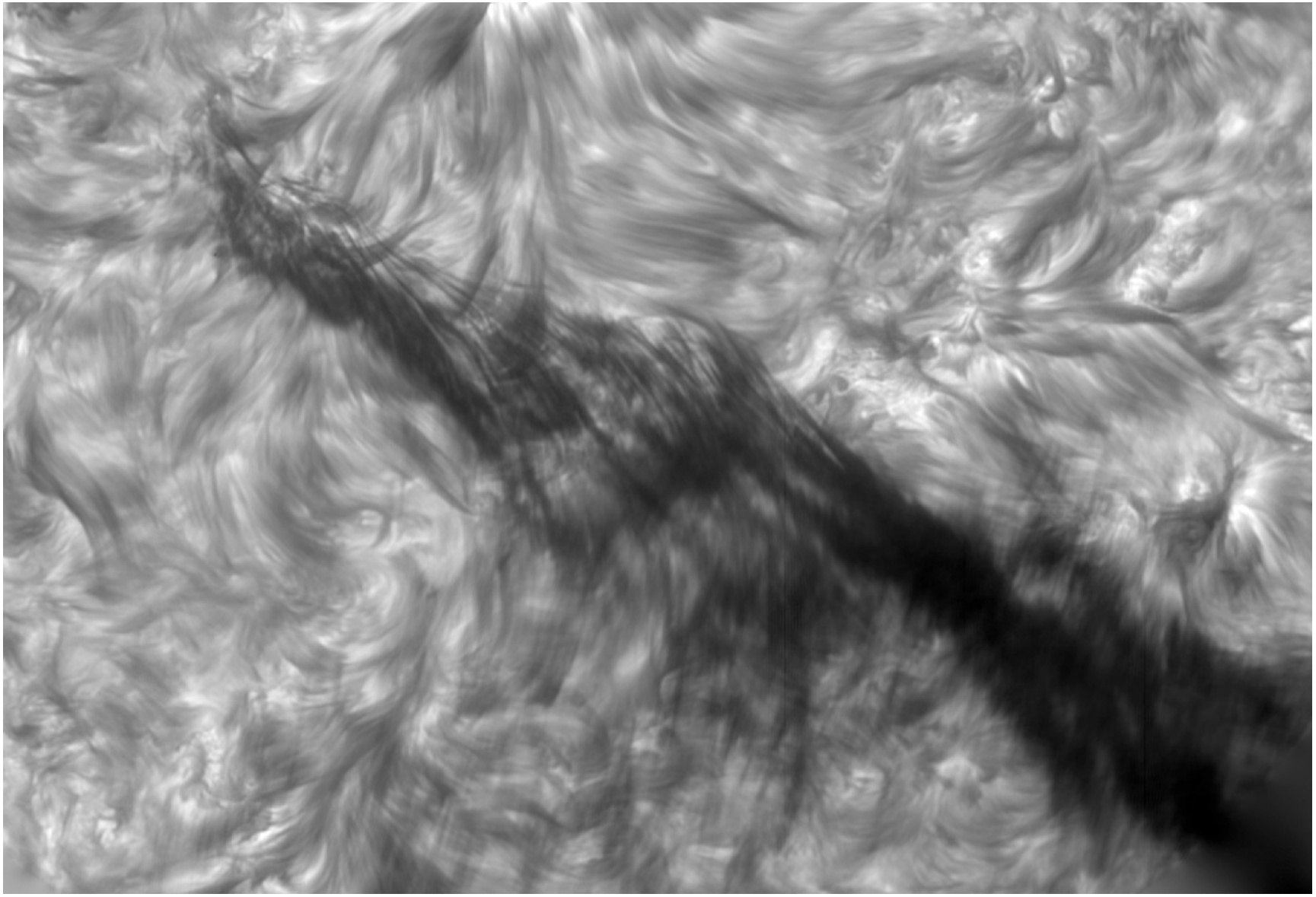
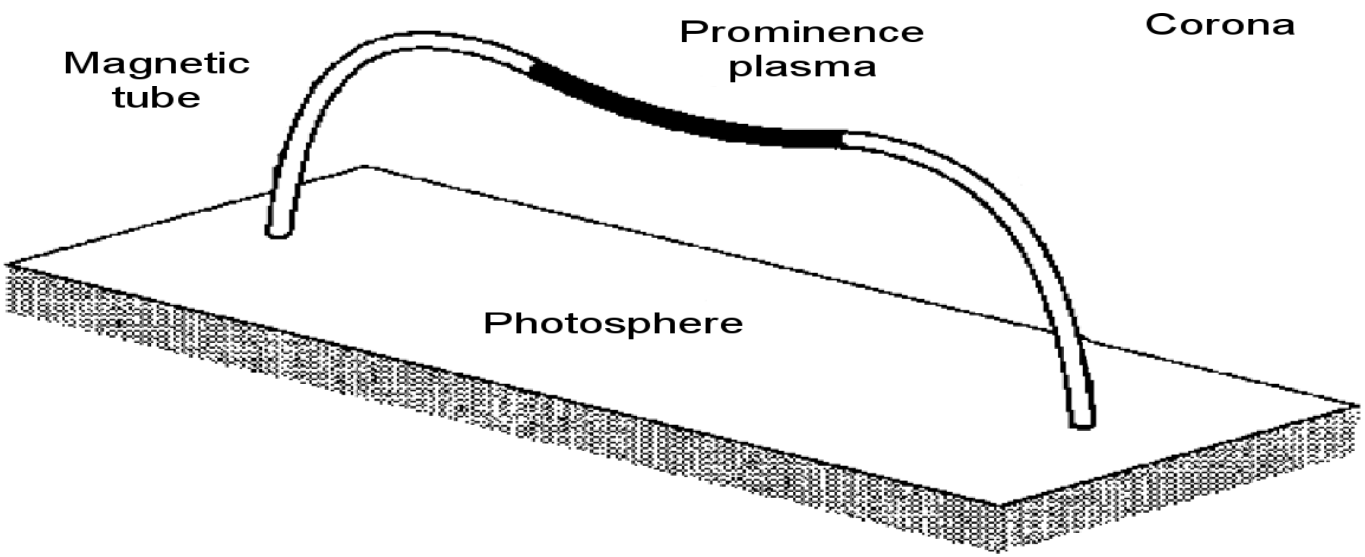


Image credit: Yong Lin / Hα, SST

Thin Threads of Solar Prominences

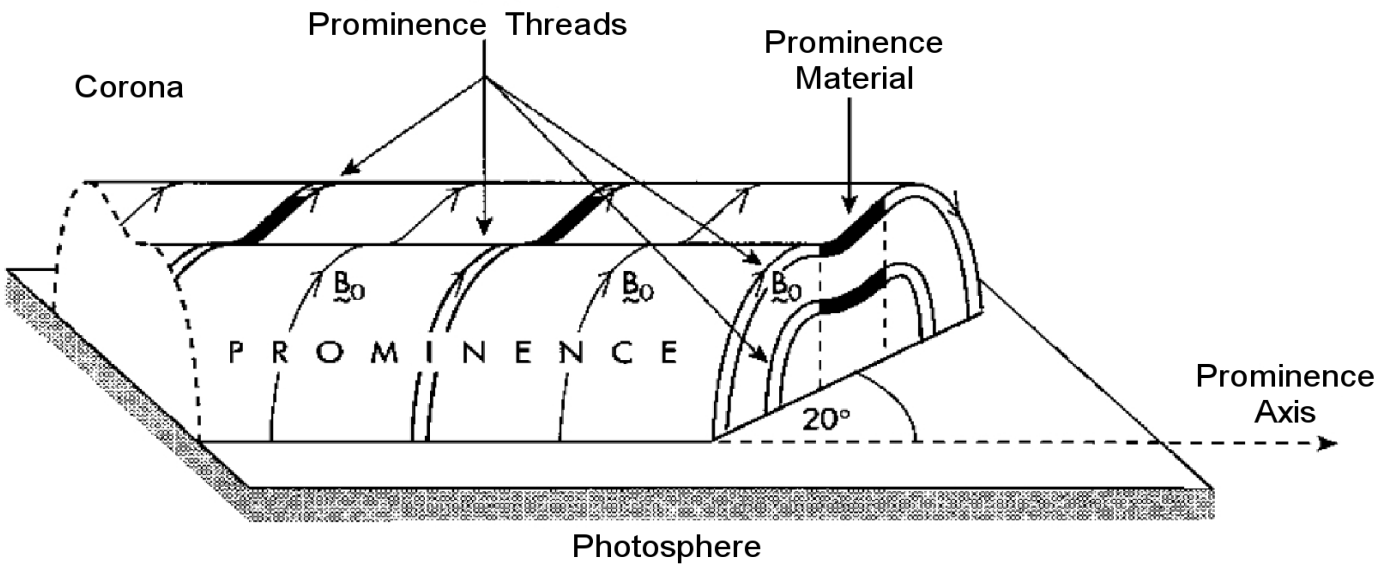
- Threads are the building blocks of prominences (Lin 2004)
- Widths: 100 – 500 km, Lengths: 3,500 – 15,000 km
- Threads are orientated along magnetic field lines
- Observed threads are only a part of larger magnetic flux tubes
- The prominence body is formed by many piled threads



Sketch adapted from Joarder et al. (1997)

Thin Threads of Solar Prominences

- Threads are the building blocks of prominences (Lin 2004)
- Widths: 100 – 500 km, Lengths: 3,500 – 15,000 km
- Threads are orientated along magnetic field lines
- Observed threads are only a part of larger magnetic flux tubes
- The prominence body is formed by many piled threads

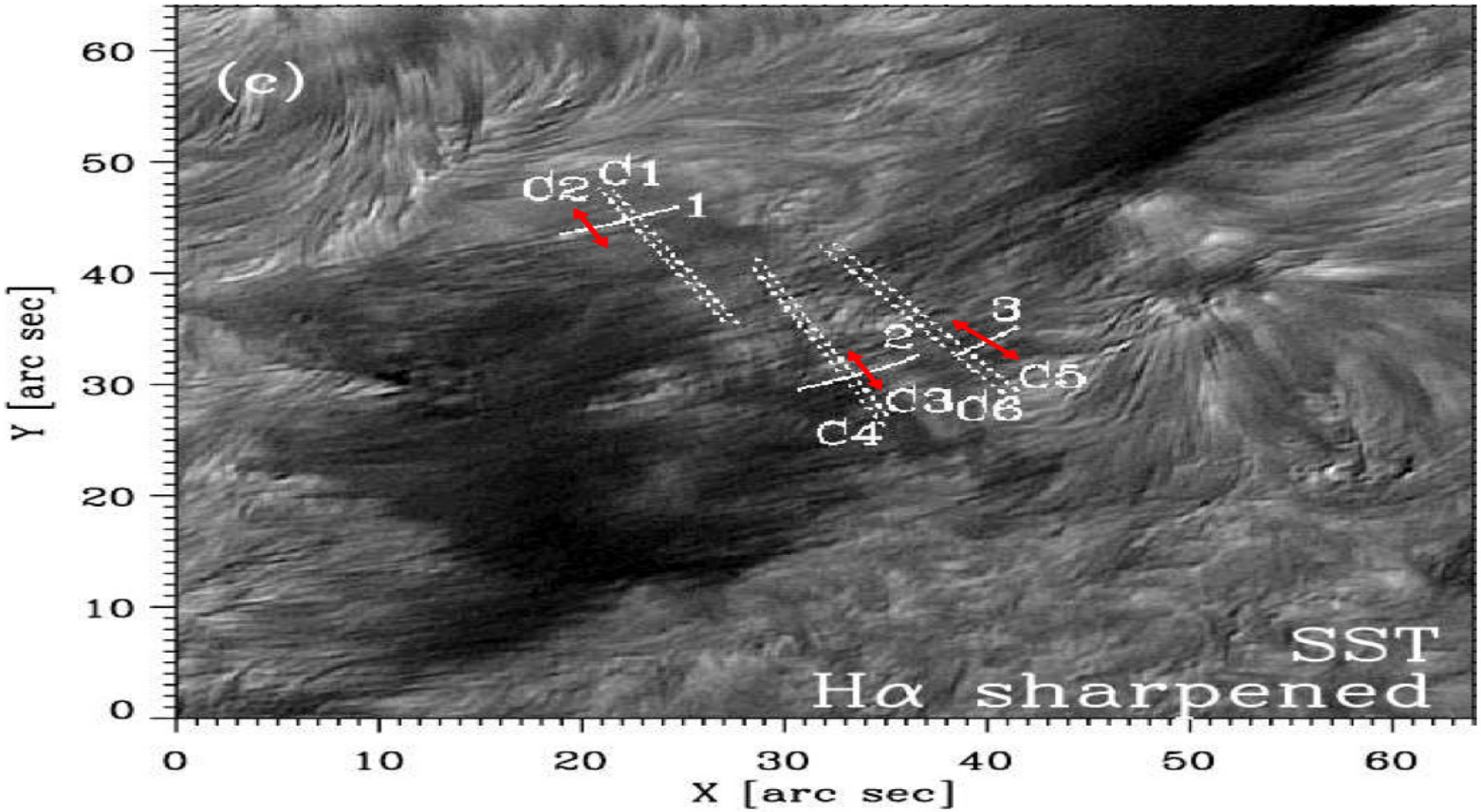


Sketch adapted from Joarder et al. (1997)

Transverse Waves in Prominence Threads

Example: Lin et al. (2009)

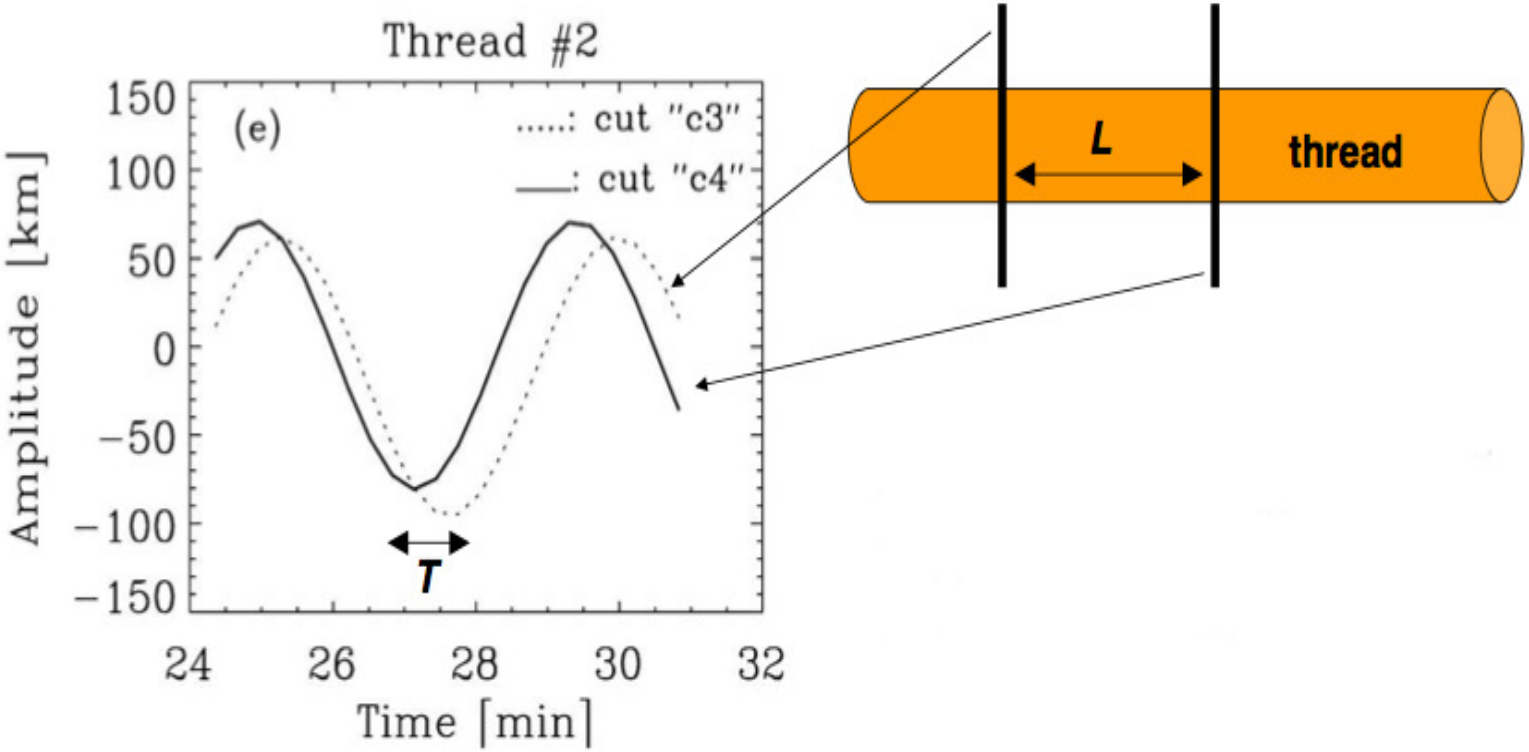
- High-resolution Hα observations of a quiescent prominence (SST)
- Running waves along different threads were observed:
  - $v_{\mathrm{ph}} \sim 30$ km/s
  - $P \sim 4$ min
- Theoretical interpretation: Alfvénic kink waves



Transverse Waves in Prominence Threads

Example: Lin et al. (2009)

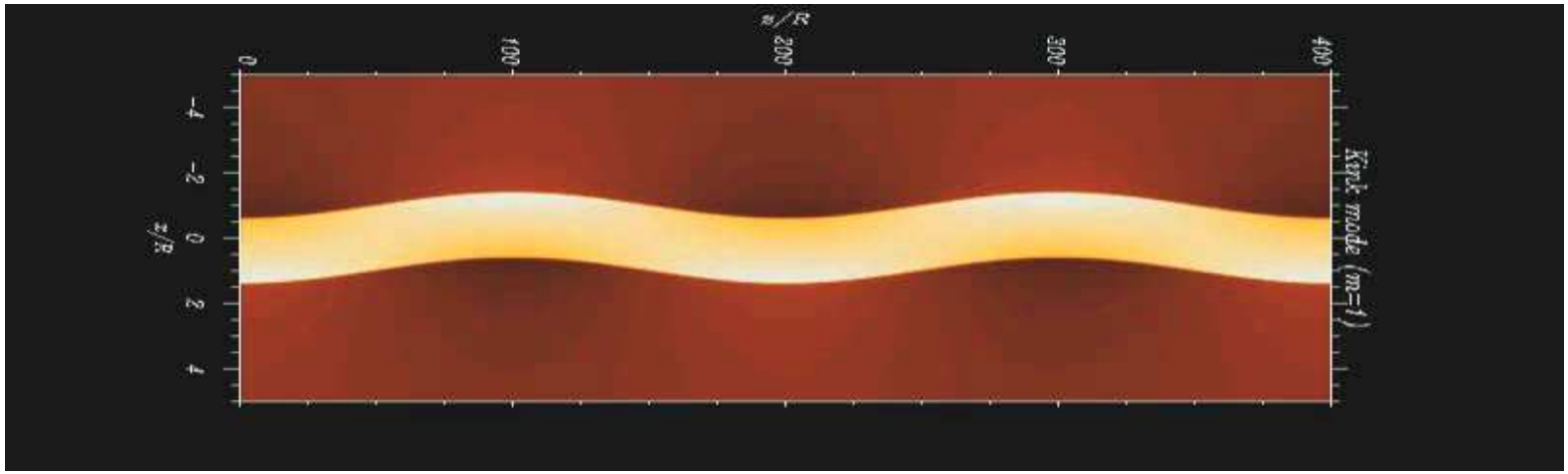
- High-resolution Hα observations of a quiescent prominence (SST)
- Running waves along different threads were observed:
  - $v_{\mathrm{ph}} \sim 30$ km/s
  - $P \sim 4$ min
- Theoretical interpretation: Alfvénic kink waves



Transverse Waves in Prominence Threads

Example: Lin et al. (2009)

- High-resolution Hα observations of a quiescent prominence (SST)
- Running waves along different threads were observed:
  - $v_{\mathrm{ph}} \sim 30$ km/s
  - $P \sim 4$ min
- Theoretical interpretation: Alfvénic kink waves



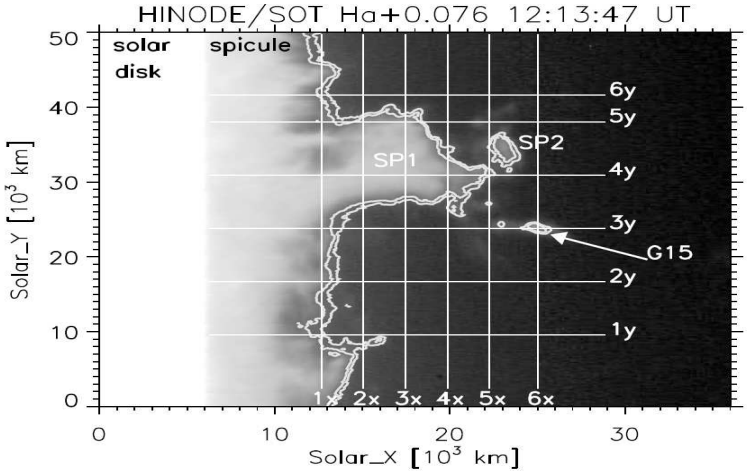
Animation credit: Jaume Terradas

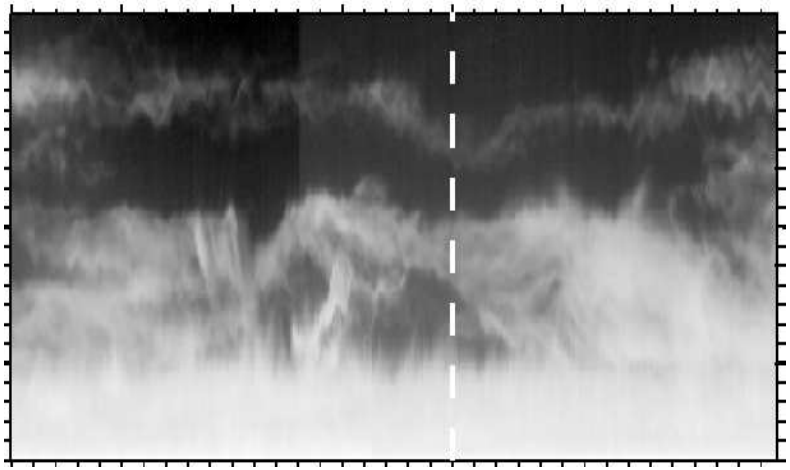
- Dominant restoring force is magnetic tension

Evidences of Wave Damping

Example: Ning et al. (2009)

- High-resolution Hα images of a quiescent prominence (HINODE/SOT)
- Strongly damped transverse oscillations (kink waves)



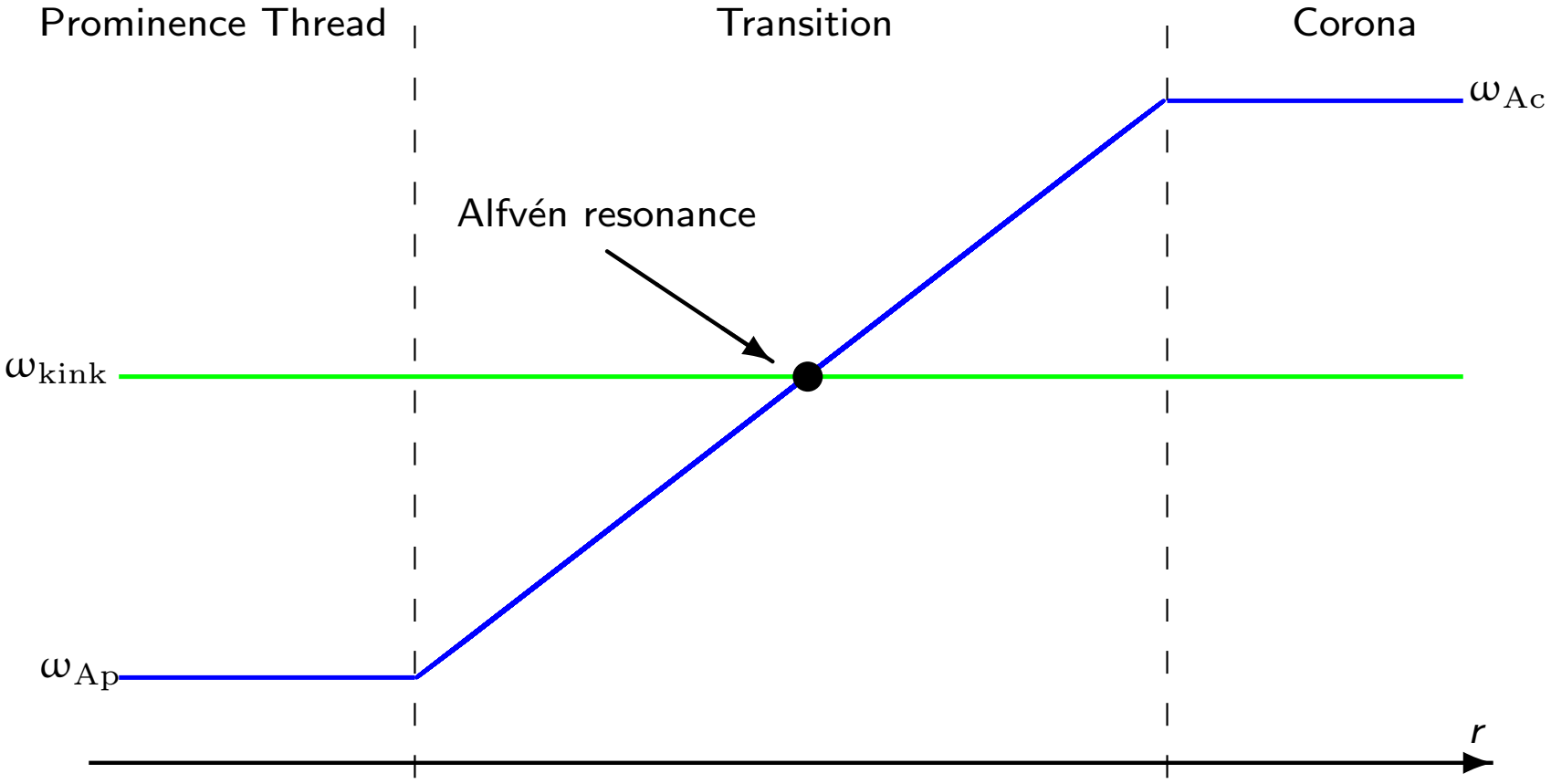


	Number of observed periods	Period (s)	Oscillation amplitude (km)	Phase velocity (km s^{-1})	Drifting velocity (km s^{-1})
G1	3	255	1080	8.5	–
G2	5	292	960	6.6	1.0
G3	3	210	720	6.9	–
G4	6	210	960	9.1	4.0
G5	3	315	840	5.3	–
G6	2	240	1080	9.0	–
G7	3	525	1320	5.0	3.6
G8	8	278	860	6.9	–
G9	–	–	–	–	9.2
G10	–	–	–	–	7.5
G11	–	–	–	–	3.2
G12	5	278	1080	7.8	8.1
G13	6	276	840	6.1	4.8
G14	3	360	1320	7.3	2.7
G15	4	240	1080	9.0	1.9
G16	2	390	1440	7.4	–

Mean number of periods ≈ 4

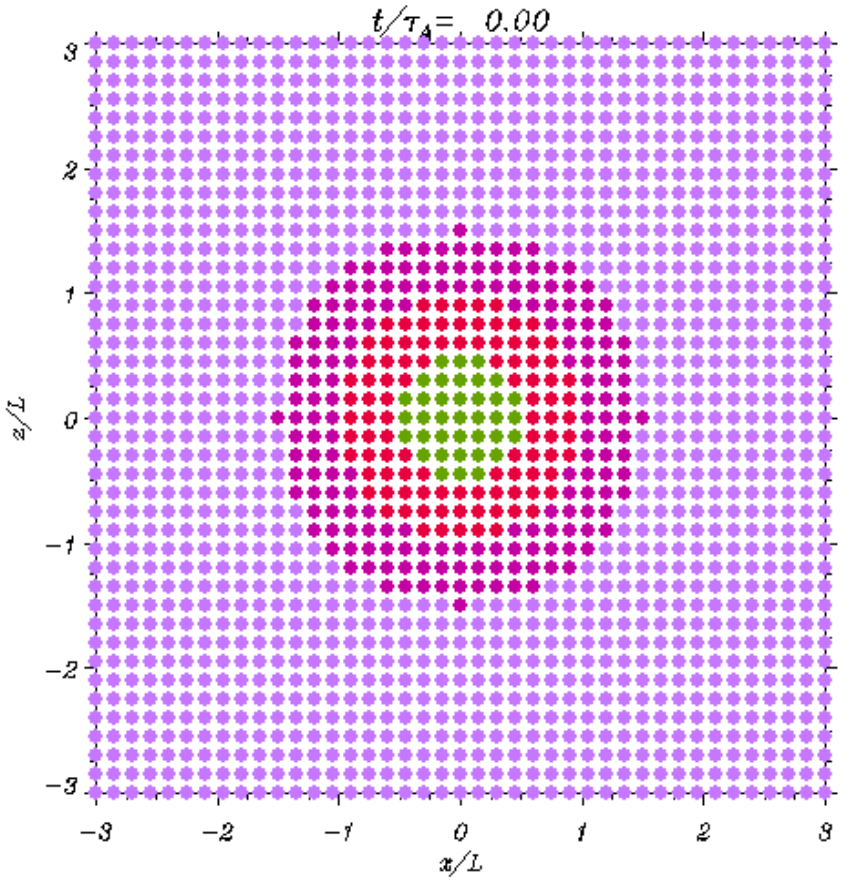
Resonant Absorption as Damping Mechanism

- Due to plasma inhomogeneity the kink mode is a resonant wave



Resonant Absorption as Damping Mechanism

- Energy transfer from transverse to small-scale torsional motions



Animation credit: Jaume Terradas

- Damping length: $L_D \sim \omega^{-1}$ (Terradas, Goossens, & Verth 2010)

Aims

Motivation

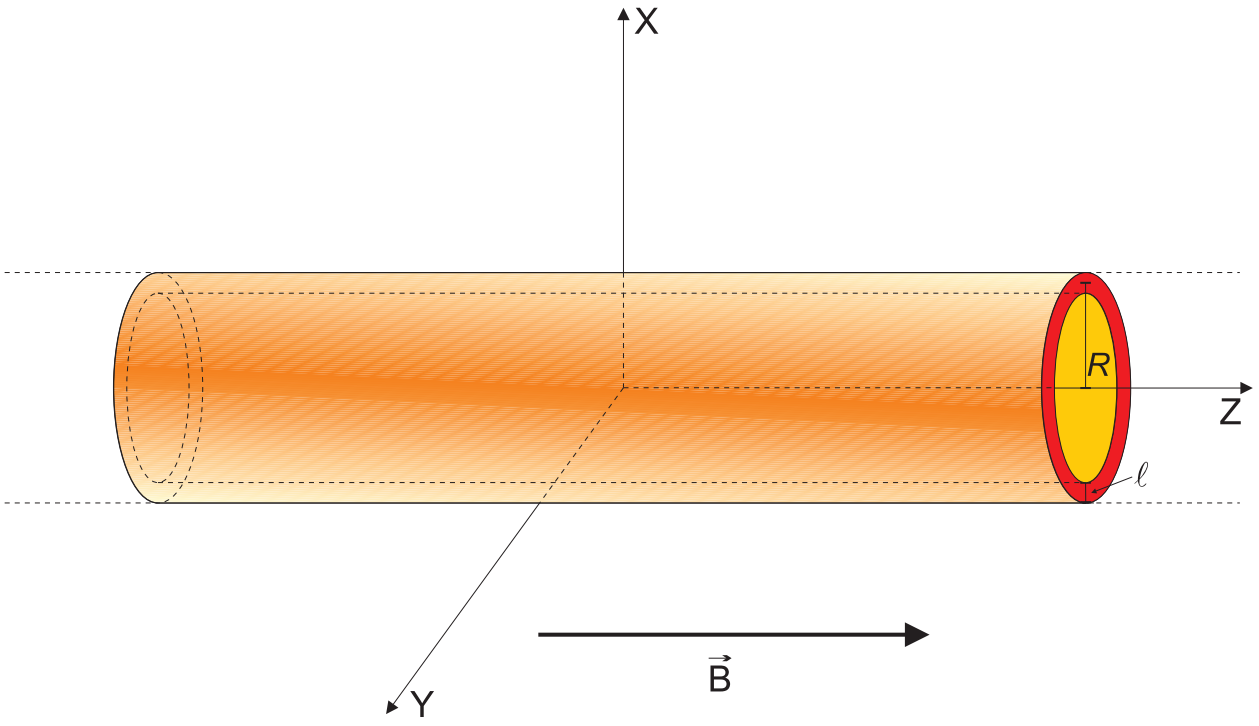
- Resonant absorption can explain the damping of kink waves in fully ionized coronal flux tubes, but...
- ...prominence plasmas are partially ionized!
- Partial ionization may affect the resonant absorption process
- Small length scales are generated at the resonance position

Purpose

- **To investigate the resonant damping of kink modes in partially ionized threads**

Presentation based on results from
Soler, Oliver, & Ballester 2011, ApJ, 726, 102
Soler, Andries, & Goossens 2012, A&A, 537, A84

Model



- Inhomogeneity length scale: $0 \leq l/R \leq 2$
- Arbitrary ionization degree: $0 \leq \alpha = \rho_{\mathrm{n}}/\rho_{\mathrm{i}} < \infty$
- Density contrast: $\zeta = \rho_{\mathrm{p}}/\rho_{\mathrm{c}} = 200$

Single-Fluid Approximation

Soler, Oliver, & Ballester (2011)

- We use the single-fluid approximation (e.g., Braginskii 1965)
- Hydrogen plasma
- Ideal MHD equations + generalized induction equation with Cowling's (Pedersen's) term

Momentum equation + Generalized induction equation

$$\rho \frac{\mathrm{D}\mathbf{v}}{\mathrm{D}t} = \frac{1}{\mu}(\nabla \times \mathbf{B}) \times \mathbf{B},$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \nabla \times \left\{ \left[\frac{\eta_C}{\mathbf{B}^2} (\nabla \times \mathbf{B}) \times \mathbf{B} \right] \times \mathbf{B} \right\}$$

- Cowling's Diffusion $\rightarrow$ ion-neutral collisions

Approximate Analytic Theory

- Fourier analysis of linear perturbations, $\exp(i\frac{2\pi}{\lambda}z + i\varphi - i\omega t)$
- Thin Tube Approximation, $\lambda/R \gg 1$
- Thin Boundary Approximation, $l/R \ll 1$
- Exponential damping length: $A(z) \sim A_0 \exp(-z/L_{\mathrm{D}})$

$$\frac{1}{L_{\mathrm{D}}} \approx \frac{1}{L_{\mathrm{D,RA}}} + \frac{1}{L_{\mathrm{D,C}}}$$

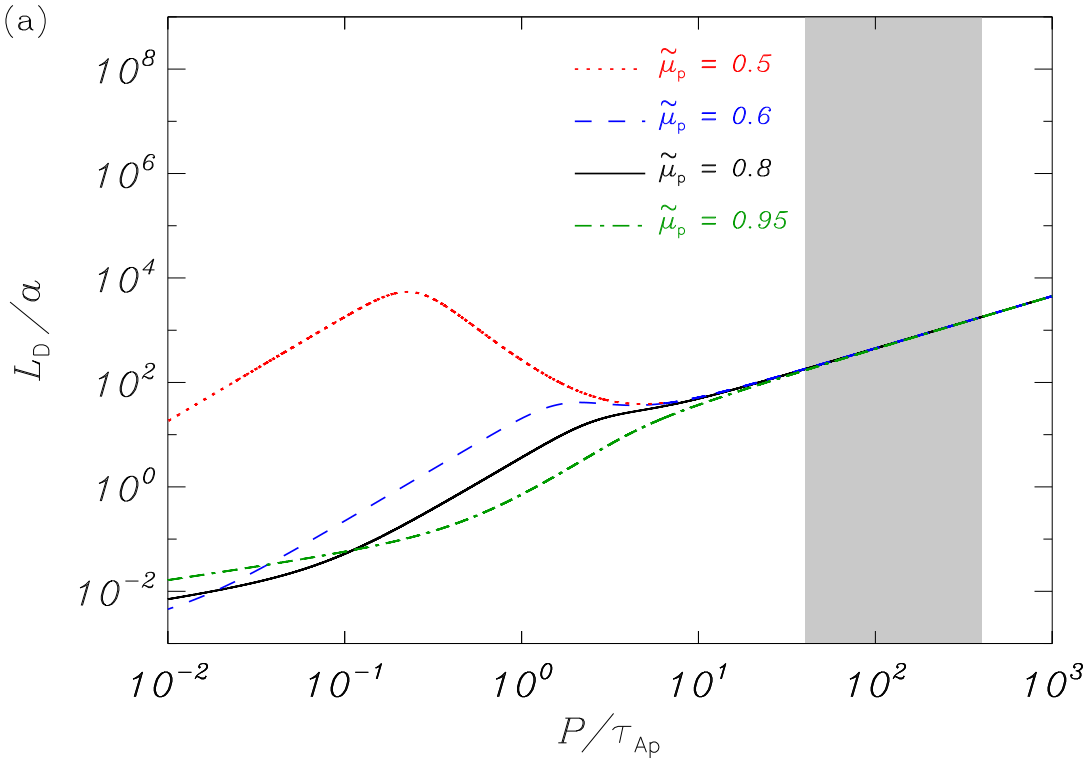
- Resonant Absorption
- Cowling's Diffusion

$$L_{\mathrm{D,RA}} = 2\pi\mathcal{F}\frac{R}{l}\frac{\zeta+1}{\zeta-1}\frac{v_{\mathrm{ph}}}{\sqrt{1+\alpha}}\frac{1}{\omega}$$

$$L_{\mathrm{D,C}} = 2\frac{\zeta}{\zeta-1}\frac{v_{\mathrm{ph}}^3}{(1+\alpha)^{3/2}}\frac{1}{\eta_{\mathrm{C}}}\frac{1}{\omega^2}$$

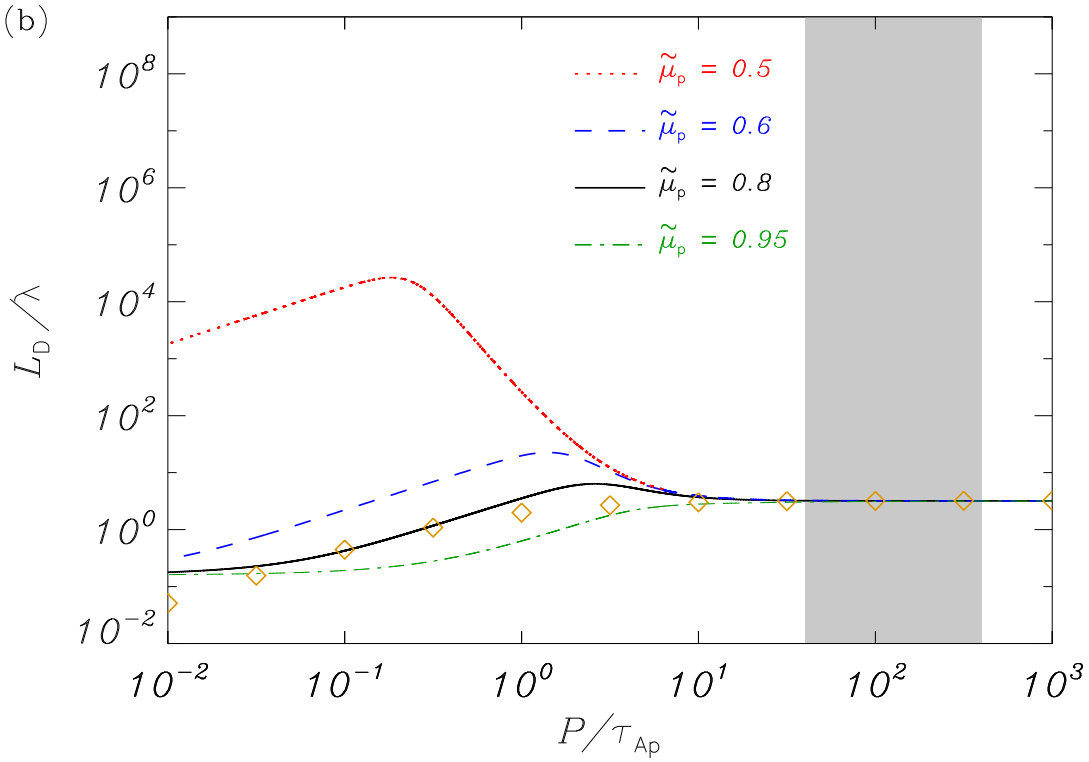
$L_{\mathrm{D,RA}} \ll L_{\mathrm{D,C}}$ for observed frequencies!

Checking the Analytic Results



- L_D obtained by numerically solving the full eigenvalue problem
- The two different behaviors of L_D depending on the frequency range are consistent with the analytic theory
- For observed frequencies resonant absorption dominates: result independent of ionization degree

Checking the Analytic Results



- L_D obtained by numerically solving the full eigenvalue problem
- The two different behaviors of L_D depending on the frequency range are consistent with the analytic theory
- For observed frequencies resonant absorption dominates: result independent of ionization degree

Two-fluid Theory

Soler, Andries, & Goossens (2012)

- The single-fluid approximation is valid only when $\nu_{\rm in}/\omega \gg 1$
- This is OK for realistic frequencies, but...
- ...we look for a general result valid for arbitrary $\nu_{\rm in}/\omega$
- We use the two-fluid theory

$$
\begin{aligned}
\rho_{\rm i}\frac{{\rm D}\mathbf{v}_{\rm i}}{{\rm D}t} &= \frac{1}{\mu}\left(\nabla\times\mathbf{B}\right)\times\mathbf{B} - \rho_{\rm n}\nu_{\rm in}\left(\mathbf{v}_{\rm i}-\mathbf{v}_{\rm n}\right)\\
\rho_{\rm n}\frac{{\rm D}\mathbf{v}_{\rm n}}{{\rm D}t} &= -\rho_{\rm n}\nu_{\rm in}\left(\mathbf{v}_{\rm n}-\mathbf{v}_{\rm i}\right)\\
\frac{\partial\mathbf{B}}{\partial t} &= \nabla\times\left(\mathbf{v}_{\rm i}\times\mathbf{B}\right)
\end{aligned}
$$

Approximate Analytic Theory (again)

- Fourier analysis of linear perturbations, $\exp(i\frac{2\pi}{\lambda}z + i\varphi - i\omega t)$
- Thin Tube Approximation, $\lambda/R \gg 1$
- Thin Boundary Approximation, $l/R \ll 1$
- Exponential damping length: $A(z) \sim A_0 \exp\left(-z/L_{\mathrm{D}}\right)$

$$\frac{1}{L_{\mathrm{D}}} \approx \frac{1}{L_{\mathrm{D,RA}}} + \frac{1}{L_{\mathrm{D,IN}}}$$

- Resonant Absorption
- Ion-neutral Collisions

$$L_{\mathrm{D,RA}} = 2\pi\mathcal{F}\frac{R}{l}\frac{\zeta+1}{\zeta-1}\frac{v_{\mathrm{ph}}}{\omega}\left(\frac{\omega^2+\nu_{\mathrm{in}}^2}{\omega^2+(1+\alpha)\nu_{\mathrm{in}}^2}\right)^{1/2}$$

$$L_{\mathrm{D,IN}} = 2v_{\mathrm{ph}}\frac{\omega^2+\nu_{\mathrm{in}}^2}{\alpha\omega^2\nu_{\mathrm{in}}}\left(\frac{\omega^2+(1+\alpha)\nu_{\mathrm{in}}^2}{\omega^2+\nu_{\mathrm{in}}^2}\right)^{1/2}$$

Recovering the Single-fluid Results

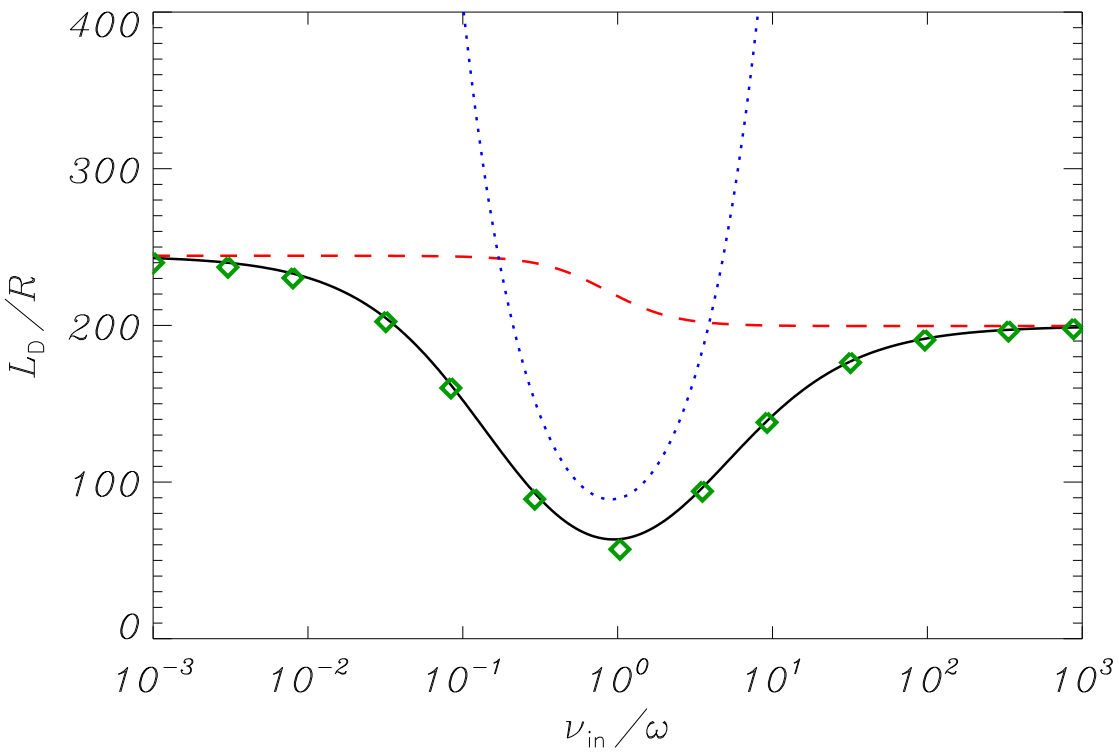
- We perform the limit $\nu_{\rm in}/\omega \gg 1$

$$
\begin{aligned}
L_{\rm D,RA} &= 2\pi\mathcal{F}\frac{R}{l}\frac{\zeta+1}{\zeta-1}\frac{v_{\rm ph}}{\omega}\left(\frac{\omega^2+\nu_{\rm in}^2}{\omega^2+(1+\alpha)\nu_{\rm in}^2}\right)^{1/2} \\
&\approx 2\pi\mathcal{F}\frac{R}{l}\frac{\zeta+1}{\zeta-1}\frac{v_{\rm ph}}{\sqrt{1+\alpha}}\frac{1}{\omega} \longrightarrow \text{OK!}
\end{aligned}
$$

$$
\begin{aligned}
L_{\rm D,IN} &= 2v_{\rm ph}\frac{\omega^2+\nu_{\rm in}^2}{\alpha\omega^2\nu_{\rm in}}\left(\frac{\omega^2+(1+\alpha)\nu_{\rm in}^2}{\omega^2+\nu_{\rm in}^2}\right)^{1/2} \\
&\approx 2v_{\rm ph}\frac{(1+\alpha)^{1/2}\nu_{\rm in}}{\alpha}\frac{1}{\omega^2} = L_{\rm D,C} \longrightarrow \text{OK!}
\end{aligned}
$$

Single-fluid results are consistently recovered!

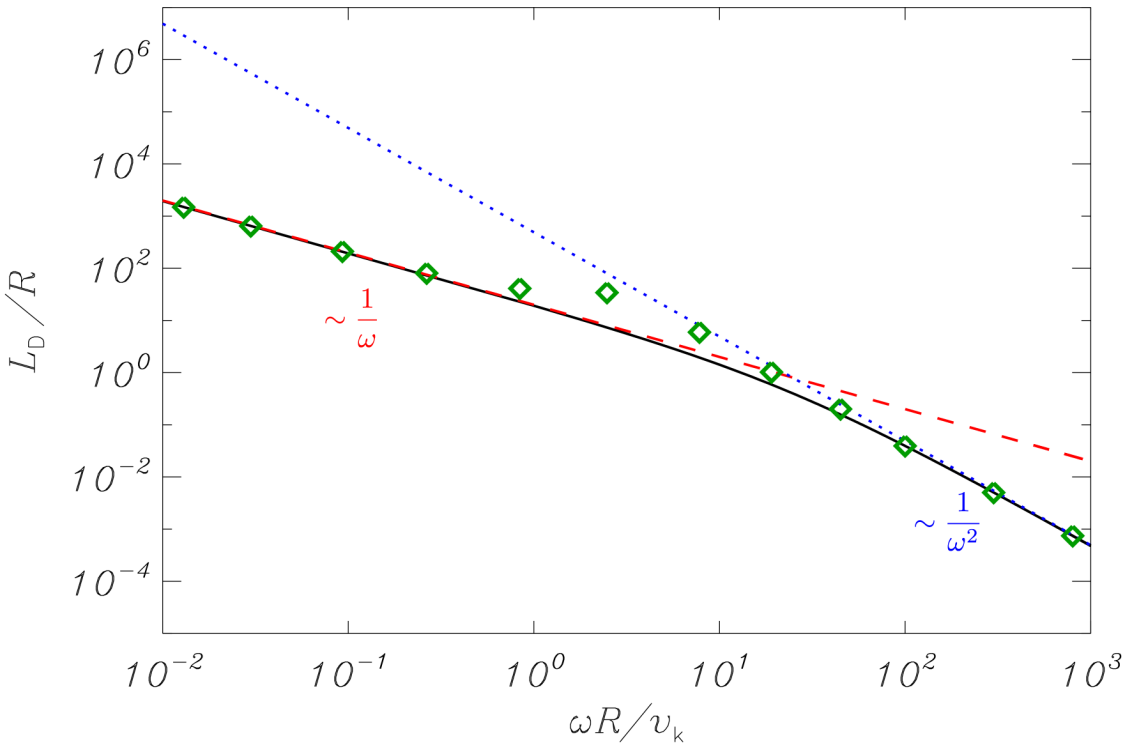
Dependence on $\nu_{\rm in}/\omega$



— Full result (analytic)
◇ Full result (numeric)
— — Resonant damping
· · · Ion-neutral collisions

Dependence on ω

- We fix $\nu_{\rm in} = 100$



— Full result (analytic)
◇ Full result (numeric)
— — Resonant damping
· · · Ion-neutral collisions

Conclusions

- Partial ionization does not affect the resonant damping of kink modes
- Single-fluid results are recovered from the two-fluid case in the limit of high collision frequencies (as expected!)
- Ion-neutral collisions are less efficient than resonant damping unless the wave frequency and the collision frequency are of the same order
- When $\nu_{\rm in} \gg \omega \rightarrow L_{\rm D,RA} \sim \frac{1}{\omega}$, $L_{\rm D,IN} \sim \frac{1}{\omega^2}$
- For realistic wave frequencies the effect of resonant absorption dominates and provides efficient damping

References:
Soler, Oliver, & Ballester 2011, ApJ, 726, 102
Soler, Andries, & Goossens 2012, A&A, 537, A84