

Russian–British Seminar of Young Scientists
“Dynamical plasma processes in the heliosphere:
from the Sun to the Earth”, Irkutsk, 18th Sept 2017

Nonlinear transverse oscillations of prominences in a magnetic field dip

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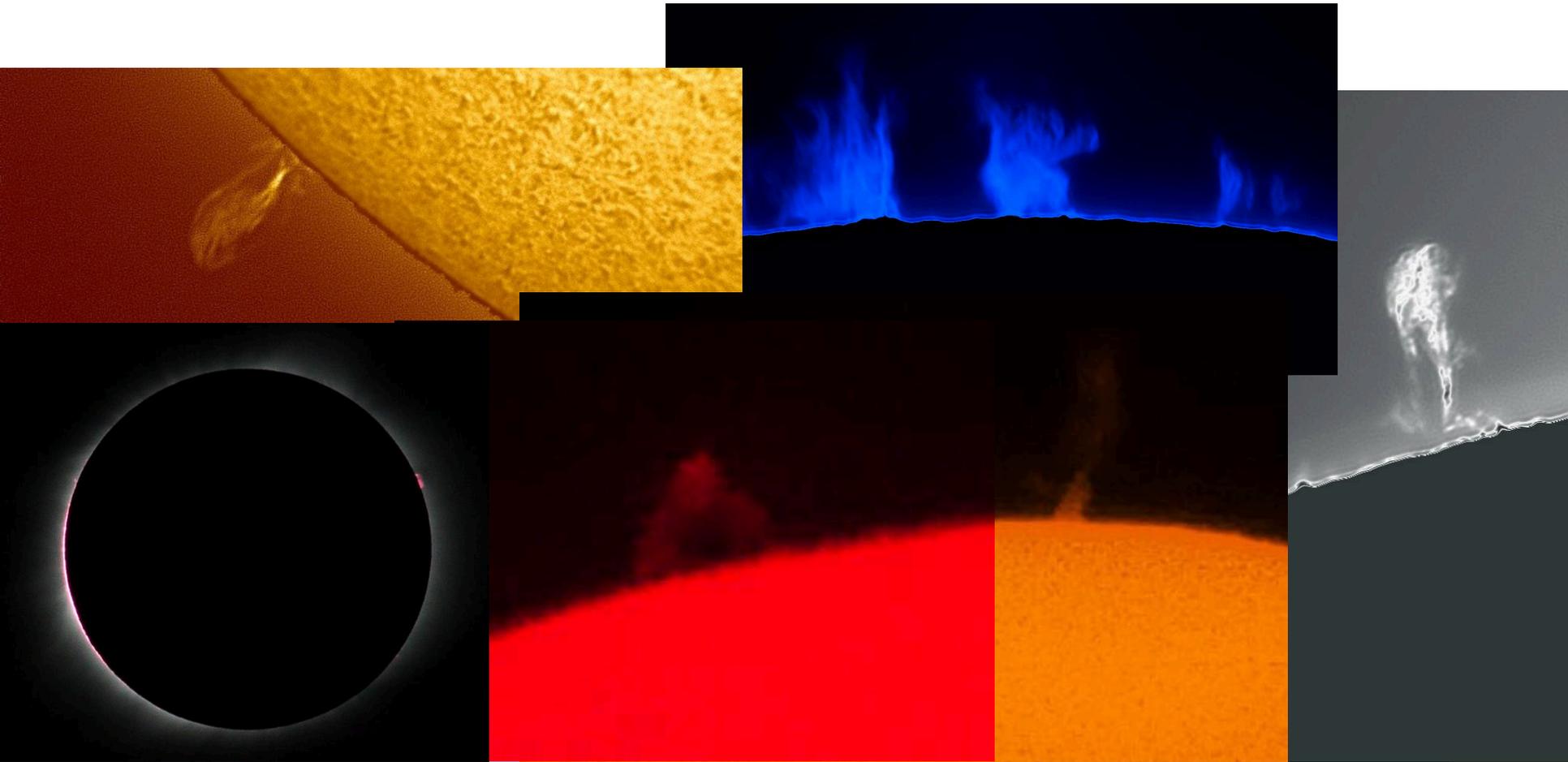
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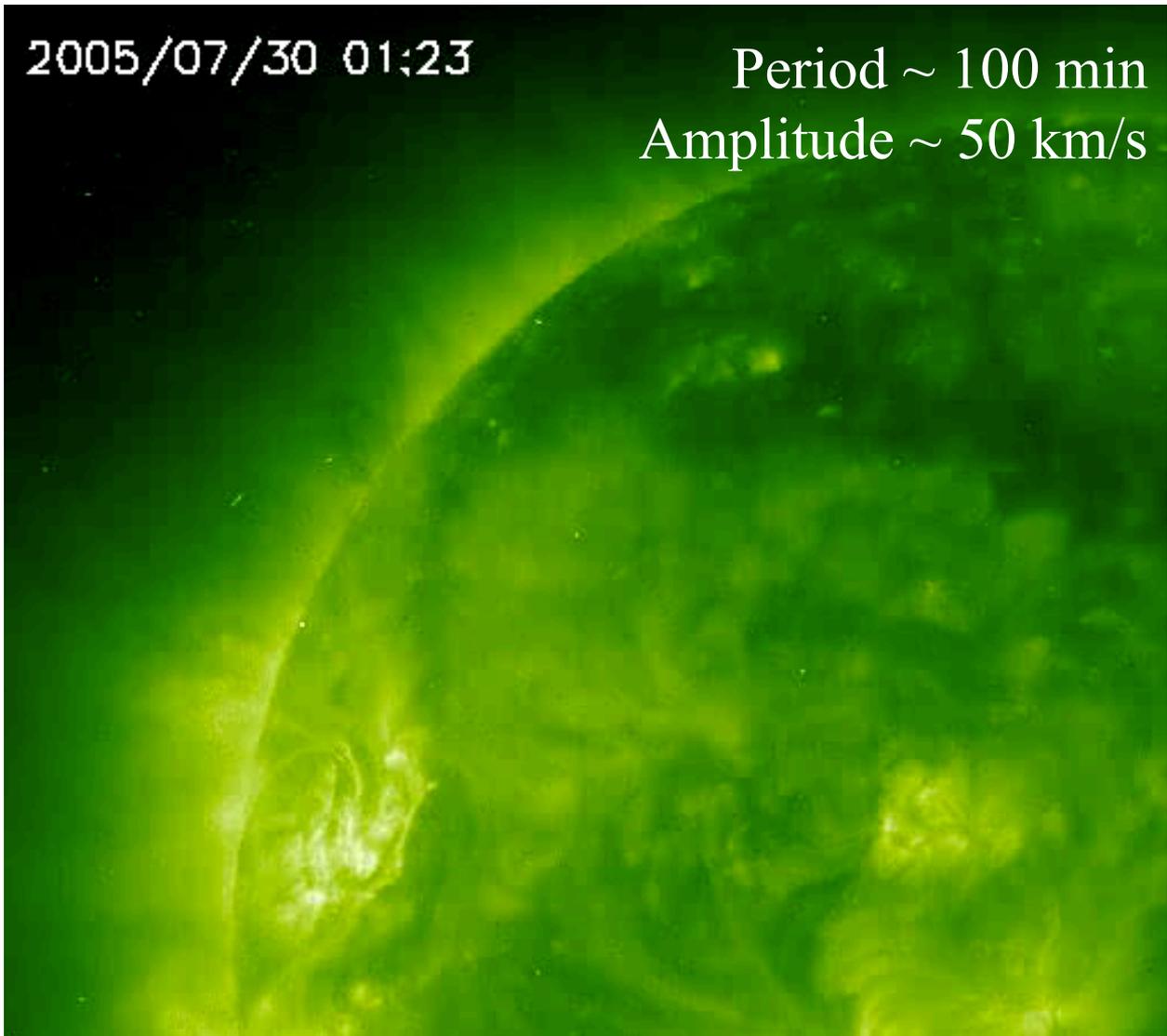
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Solar prominences...

"...are made of dense cool chromospheric material immersed into the 1 MK corona." (Parenti, 2014)



Oscillations of prominences



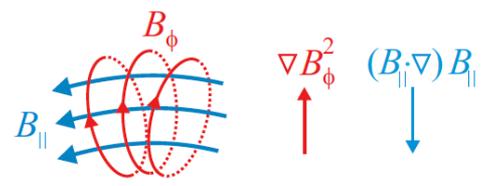
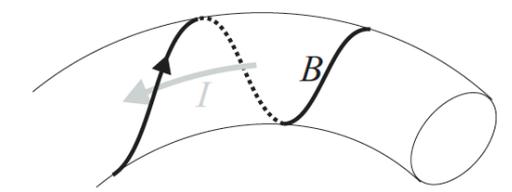
Hershaw et al., 2011

Observational evidences of oscillations in prominences

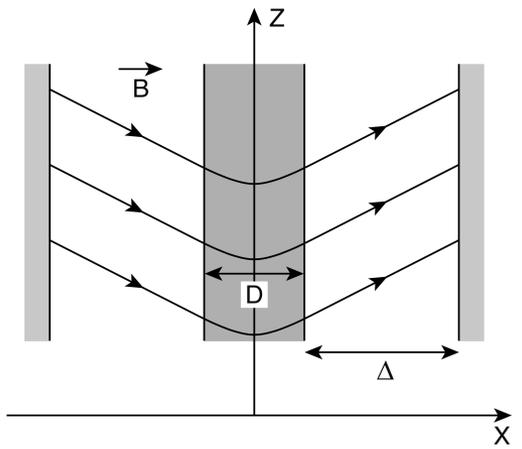
- ...can be transverse (vertical and/or horizontal) or longitudinal.
- ...usually seen in the Doppler velocity, with amplitudes 2–3 km/s and periods from a few tens of minutes to several hours.
- ...exponentially decay, with the quality factor of 1–4.
- The coherence spatial scales grow with the oscillation period.
- Such small amplitude oscillations are not related to flaring activity.
- Oscillations with amplitudes > 10 km/s (local Alfvén or sound speed) are usually referred to as large amplitude.
- These are always associated with active regions located nearby.
- The oscillation amplitude and period may depend on the prominence height.
- Lack of a simple, elliptically polarised regime.
- Presence of metastable equilibria.

Analytical modelling of transverse oscillations in prominences

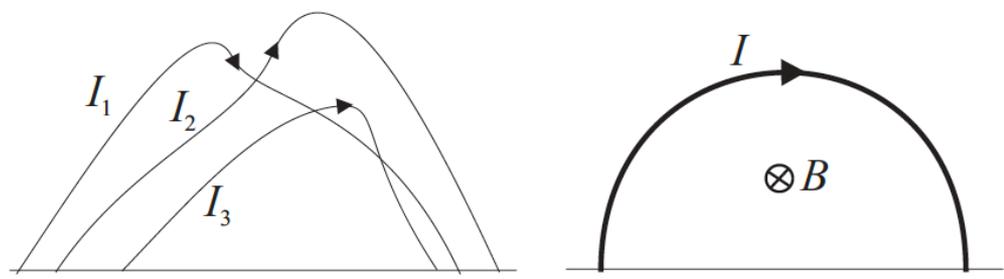
Toroidal currents with an aerodynamic-like drag force (Vrsnak et al., 1990; Cargill et al., 1994; Farrugia et al., 1997; Joarder et al., 1997)



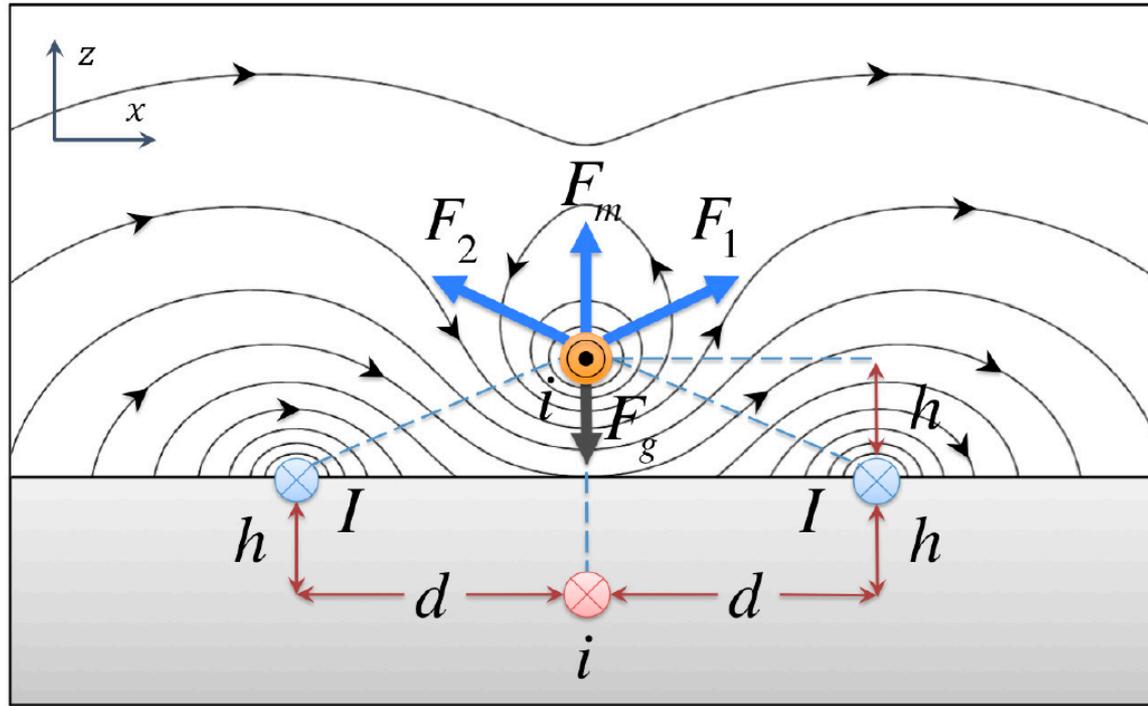
Plasma slab in a magnetic dip (Kippenhahn–Schluter equilibrium, Oliver et al., 1993; Joarder and Roberts, 1993; Anzer, 2009)



Line currents with the magnetic “mirror” force effect (KR model, Kuperus and Raadu, 1974; van den Oord et al., 1998)



Quiescent prominence as a line current in a magnetic dip



$$F_x = \frac{2k_1 x [(h+z)^2 + x^2 - d^2]}{(d^2 - x^2)^2 + 2(d^2 + x^2)(h+z)^2 + (h+z)^4}$$

$$F_z = \frac{2k_1 (h+z) [d^2 + x^2 + (h+z)^2]}{(d^2 - x^2)^2 + 2(d^2 + x^2)(h+z)^2 + (h+z)^4} + \frac{k_2}{2h+z} - \rho g$$

Prominence as a line current in a dip. Linear theory (< 5 km/s)

Assume $x, z \ll h, d$:

$$F_z \approx \left[\frac{2k_1(d^2 - h^2)}{(d^2 + h^2)^2} - \frac{k_2}{4h^2} \right] z \quad \Rightarrow \quad \ddot{z} + (2\pi/P_z)^2 z = 0$$

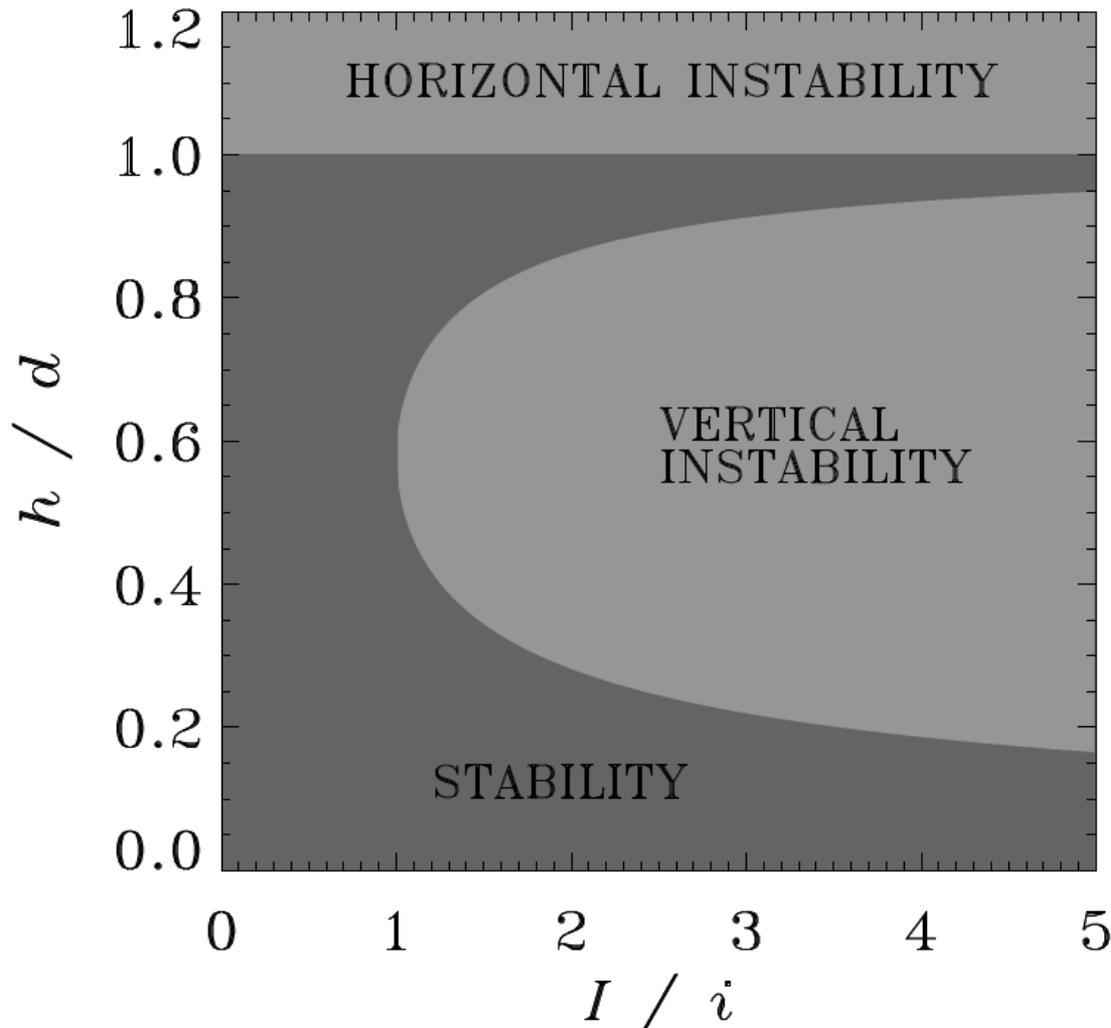
$$P_z = P_{\text{KR}} \left[1 + 8 \frac{k_1}{k_2} \frac{h^2(h^2 - d^2)}{(d^2 + h^2)^2} \right]^{-1/2}, \quad \text{where } P_{\text{KR}} = 2\pi \sqrt{4\rho h^2/k_2} \quad \text{KR limit,} \\ \sim 20 \text{ min.}$$

$$F_x \approx \frac{2k_1(h^2 - d^2)}{(d^2 + h^2)^2} x \quad \Rightarrow \quad \ddot{x} + (2\pi/P_x)^2 x = 0$$

$$P_x = P_{\text{KR}} \sqrt{\frac{k_2}{8k_1} \frac{(d^2 + h^2)^2}{h^2(d^2 - h^2)}}$$



Linear theory. Mechanical stability



$h < d$ and $i > I$ – full stability

$i < I$ – vertical instability

$h > d$ – horizontal instability

Nonlinear theory (10–100 km/s). Potential energy analysis

Writing $F_x = -\partial U/\partial x$ and $F_z = -\partial U/\partial z$,

potential energy of the prominence:

$$U(x, z) = -\frac{k_1}{2} \ln D - k_2 \ln(2h + z) + \rho g z + C,$$

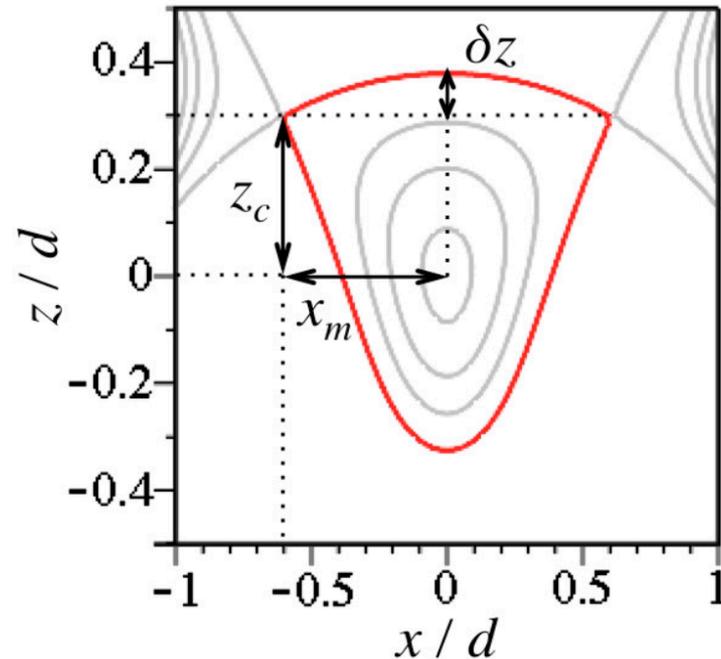
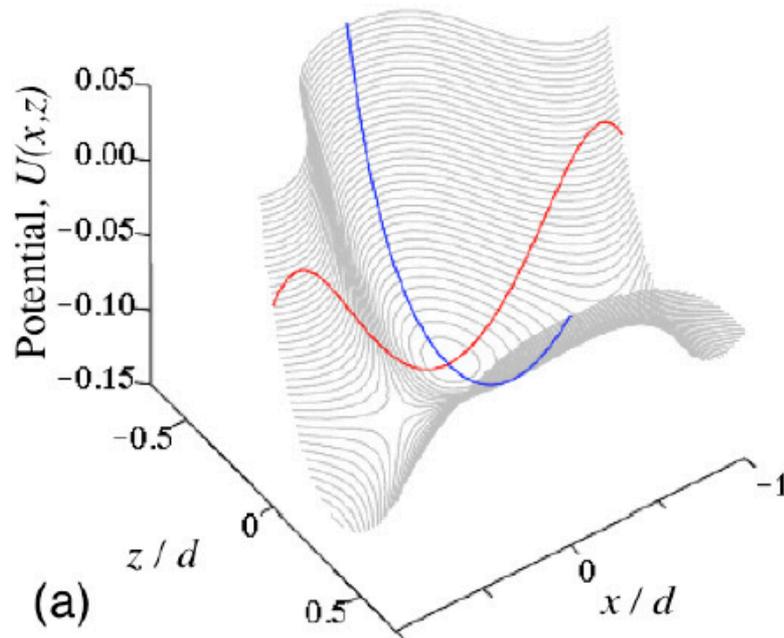
where $D \equiv (d^2 - x^2)^2 + 2(h + z)^2(d^2 + x^2) + (h + z)^4$.

Nonlinear theory. A metastable equilibrium

Potential energy in the region of a full linear stability, $h < d$ and $i > I$:

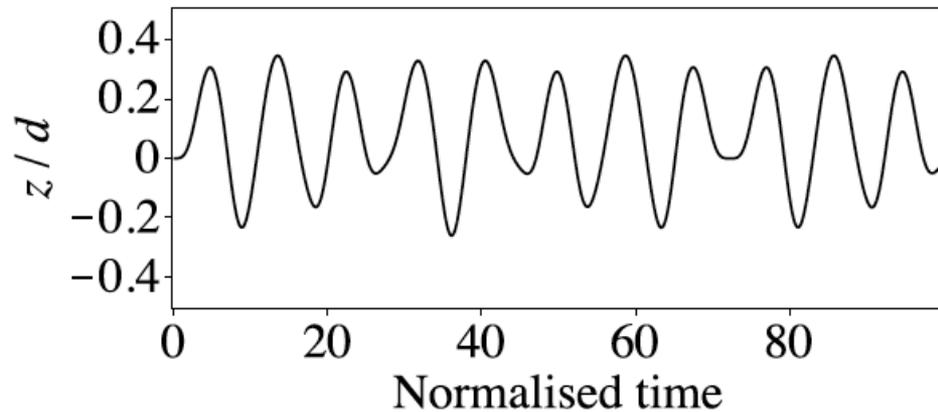
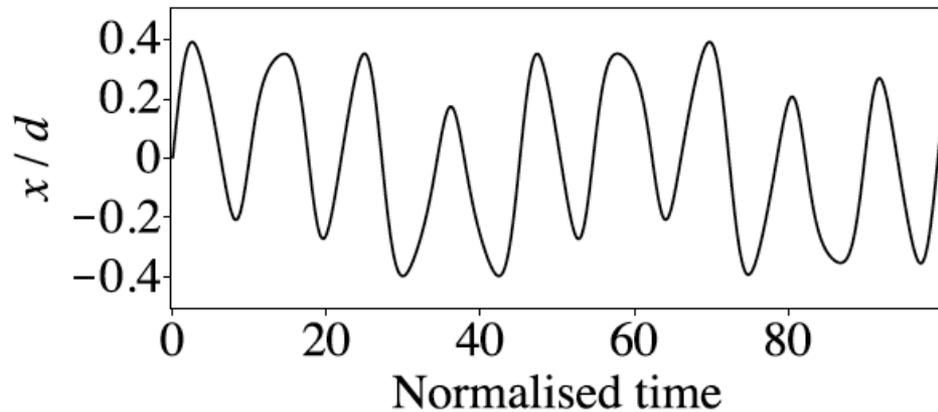
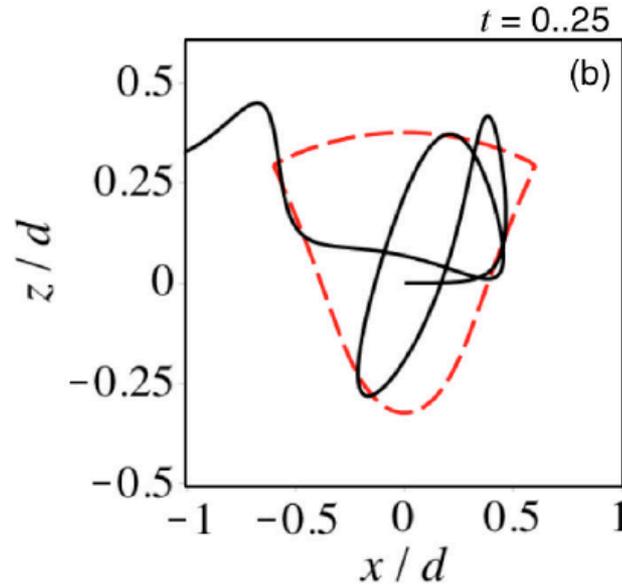
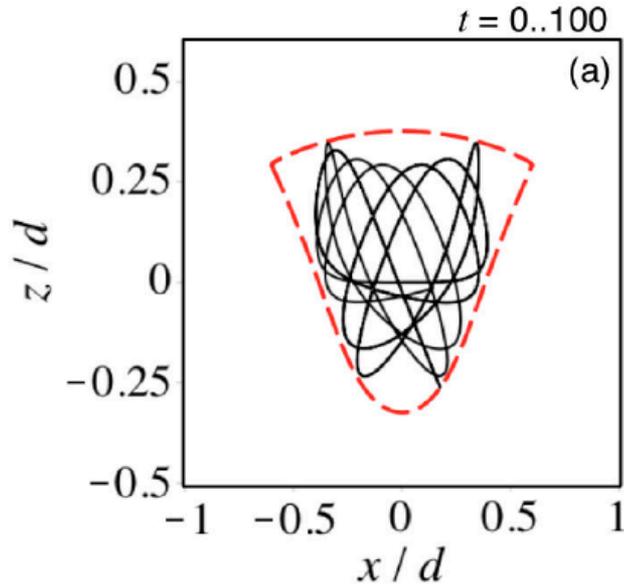
Side view:

Top view:



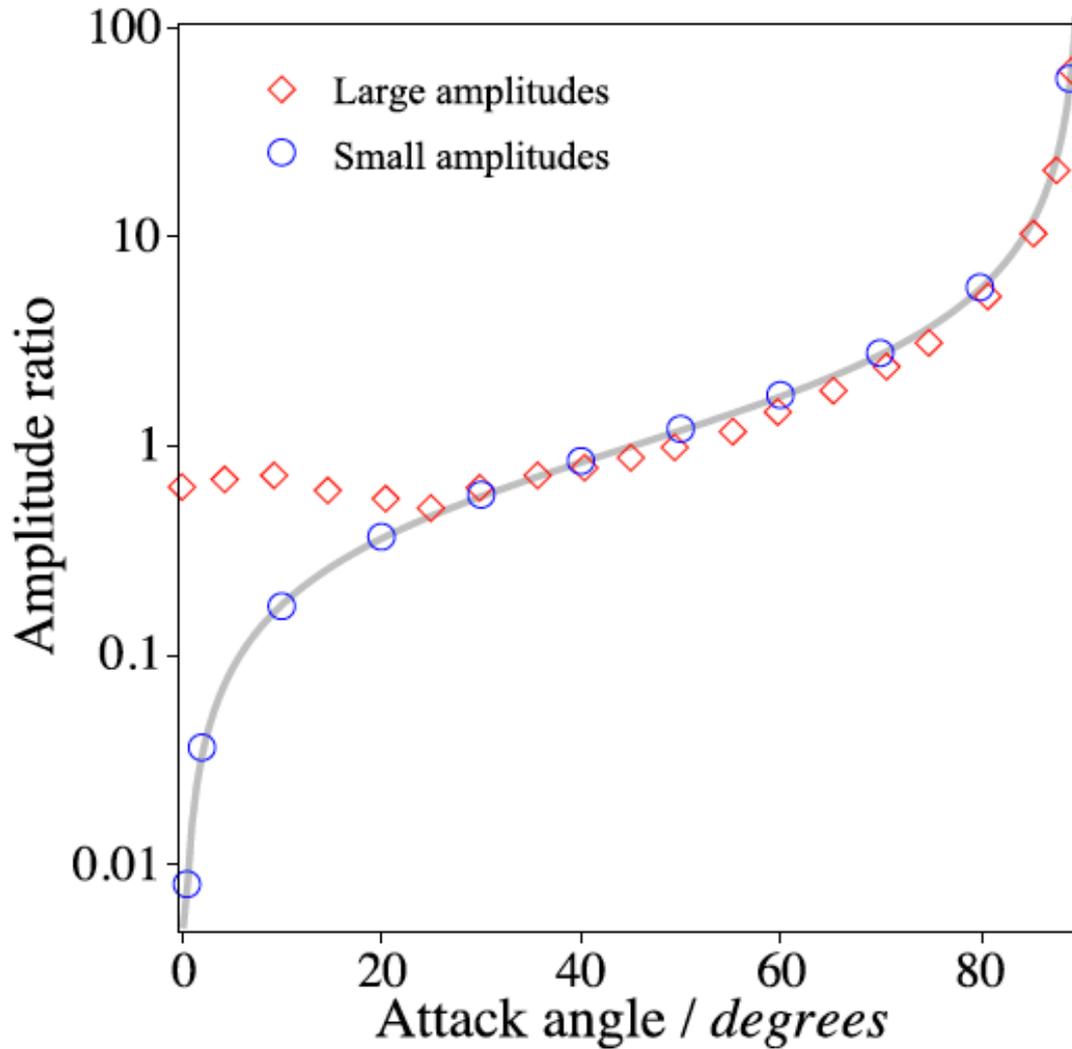
Nonlinear theory. Finite amplitude solutions

Initial conditions: $z(0) = 0, x(0) = 0, v_z(0) = 0, v_x(0) \neq 0$.



cf. Isobe and Tripathi, 2006; Hershaw et al. , 2011; Pant et al. , 2015

Efficiency of a nonlinear mode coupling

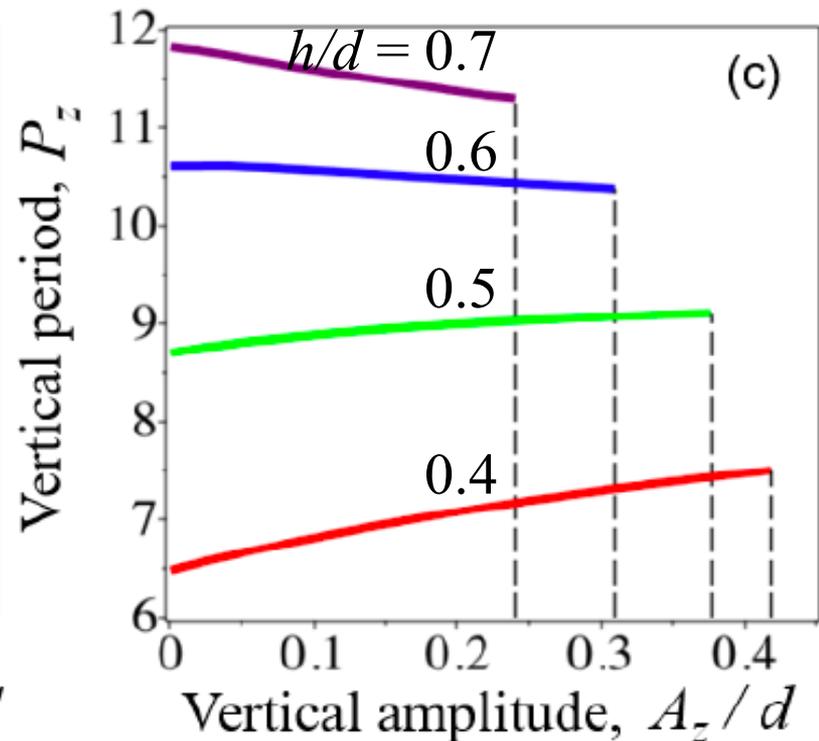
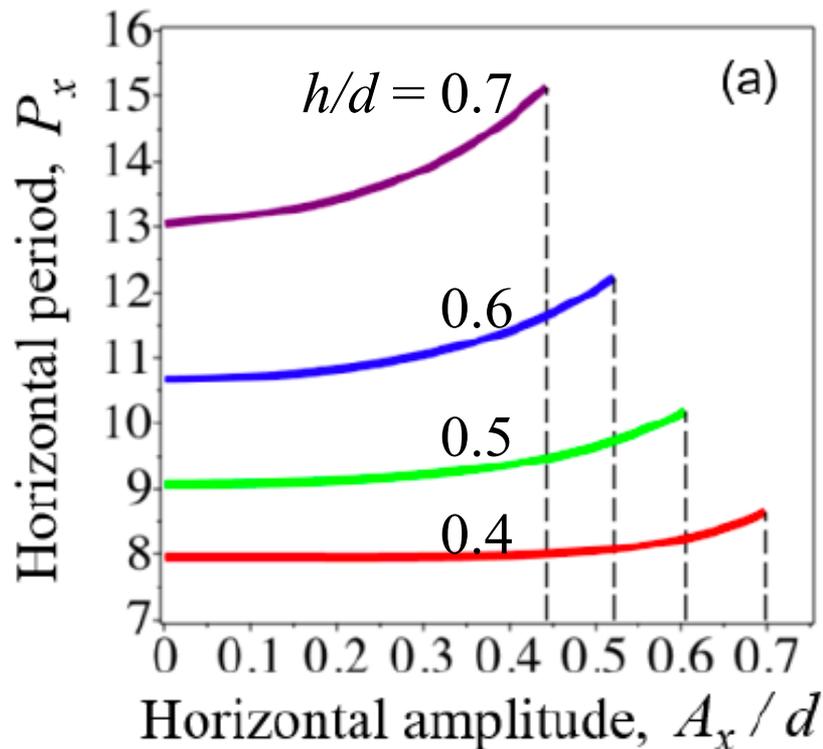


cf. Berger et al. , 2008; Shen et al. , 2014

Nonlinear oscillation periods...

...are determined by the oscillation amplitude, prominence current, its mass and position above the photosphere, and the parameters of the magnetic dip.

For example, for the prominence current $\sim 2 \times 10^{10}$ A, $h = 26$ Mm (Parenti, 2014), $h/d = 0.4$, and $I/i = 0.5$, P_x and P_z would be equal to 86 and 75 min, respectively.



Possible seismological applications. Prominence current.

Input parameters: mass density $\sim 10^{-10} \text{ kg m}^{-3}$; diameter $\sim 10 \text{ Mm}$.

Output value of the prominence current: $1.5 \times 10^{10} - 10^{11} \text{ A}$.

Related publication	Method	Prominence/flux rope current value, A
Sachdeva et al., Sol. Phys., 2017	seismology	$0.31 \times 10^{10} - 1.16 \times 10^{11}$
Sharykin et al., ApJ Lett., 2014	indirect observation	4×10^{10}
Zaitsev et al., Astr. Lett., 2013	seismology	$3 \times 10^{10} - 10^{11}$
Canou and Amari, ApJ, 2010	seismology	$\sim 4 \times 10^{12}$
Zaitsev et al., A&A, 1998	seismology	$6 \times 10^{10} - 1.4 \times 10^{12}$
Wu et al., Chin. Astr. Astrophys., 1994	seismology	$\sim 10^{10} - 10^{11}$
Severny, Space Sci. Rev., 1964	indirect observation	$\sim 10^{11}$



Instead of summary

- ✓ Coupling between horizontal and vertical motions of the prominence, hence the lack of a simple elliptical polarisation;
- ✓ Presence of a metastable equilibria with a threshold energy above which the prominence can get destabilised;
- ✓ Dependence of oscillation periods upon the oscillation amplitude and parameters of the initial equilibrium;
- ✓ Seismological estimation of electric currents in prominences.

"Save yourselves, everybody! A piece of the sun is falling!" "A piece of what?" "Of the sun! Hurry up! It'll strike any minute, and that'll be the end of us! You don't know about the sun! It's bigger than our earth!"

