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# Nonlinear transverse oscillations of prominences in a magnetic field dip

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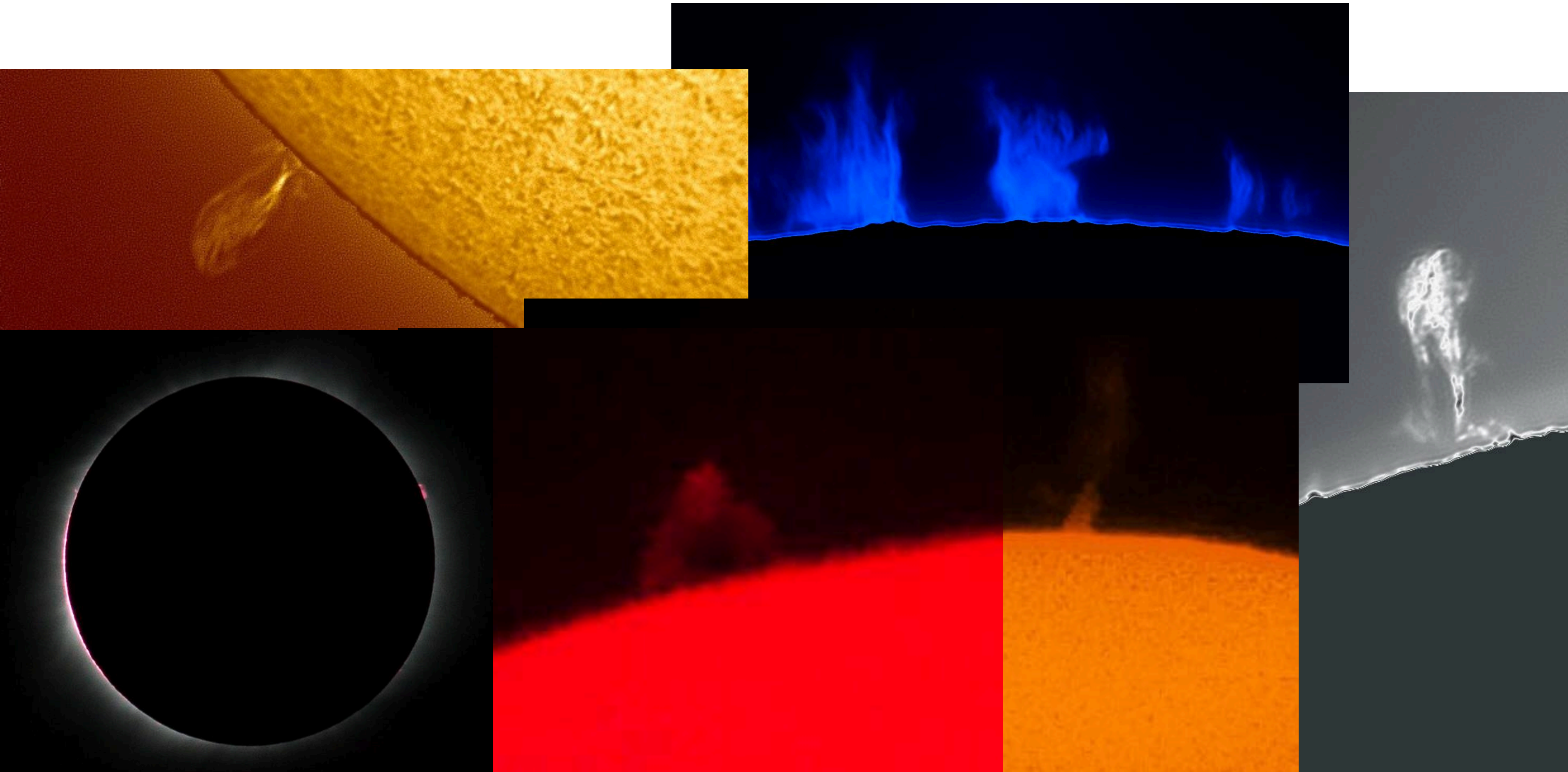
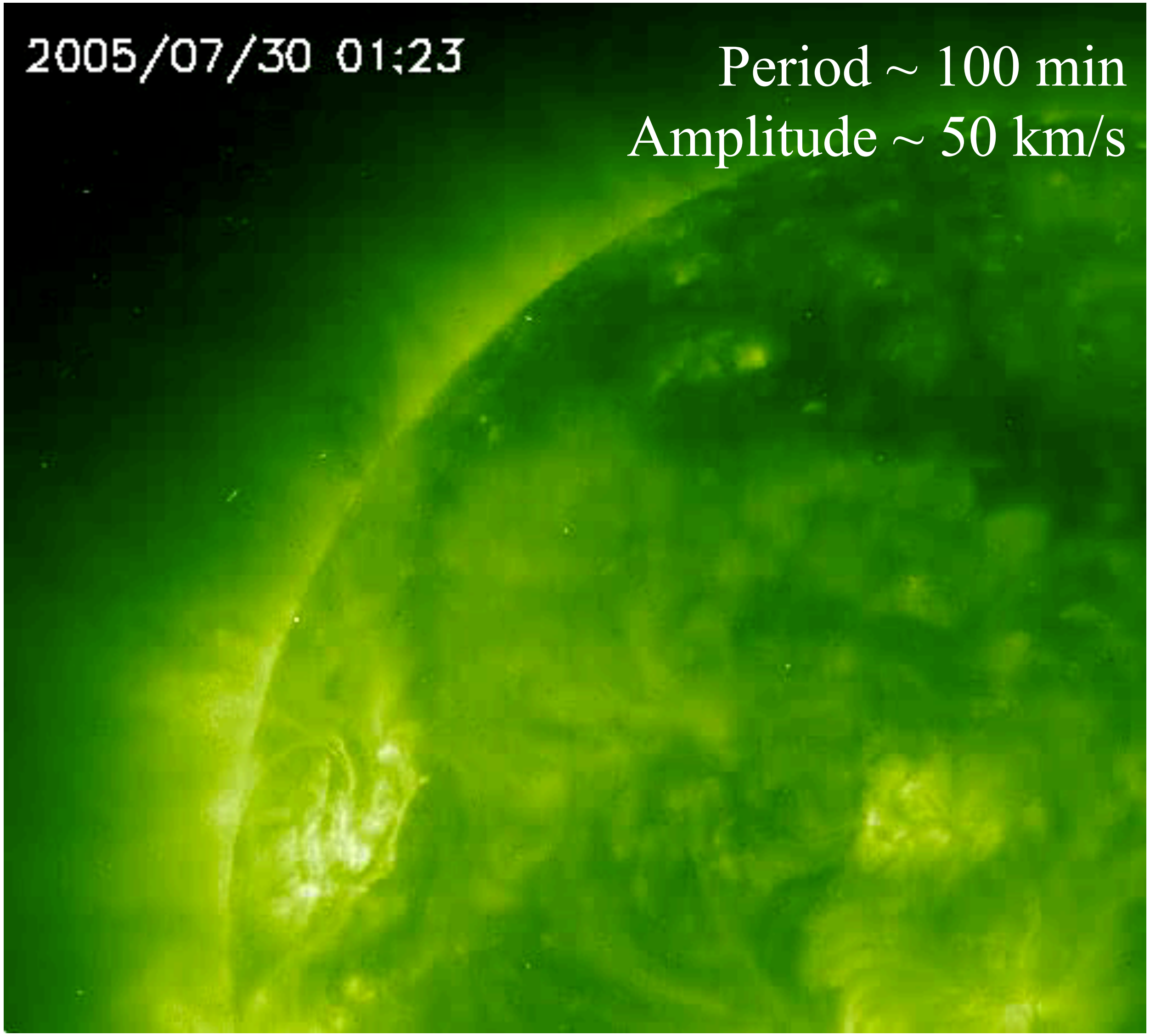
# Solar prominences…

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



P.C. UK Solar Imaging & Observations. Facebook public group

# Oscillations of prominences




Hershaw et al., 2011

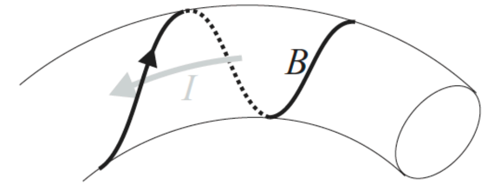
# Observational evidences of oscillations in prominences

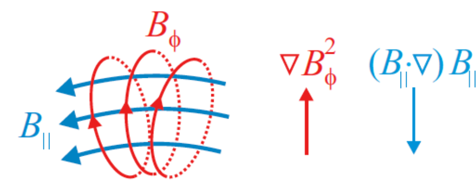
- …can be transverse (vertical and/or horizontal) or longitudinal.
- …usually seen in the Doppler velocity, with amplitudes 2–3 km/s and periods from a few tens of minutes to several hours.
- …exponentially decay, with the quality factor of 1–4.
- The coherence spatial scales grow with the oscillation period.
- Such small amplitude oscillations are not related to flaring activity.
- Oscillations with amplitudes > 10 km/s (local Alfven 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.

Arregui et al., 2012; Tripathi et al., 2009; Vrsnak, 2008

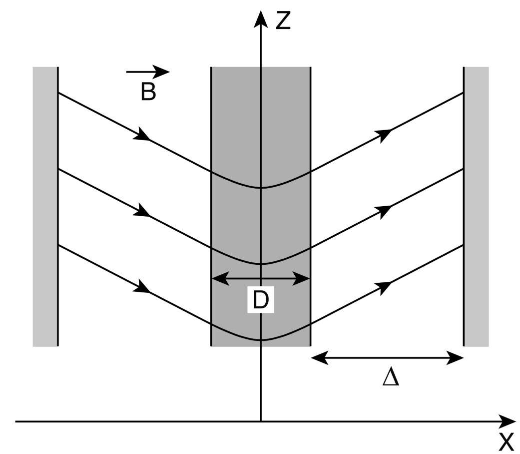
# Analytical modelling of transverse oscillations in prominences

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

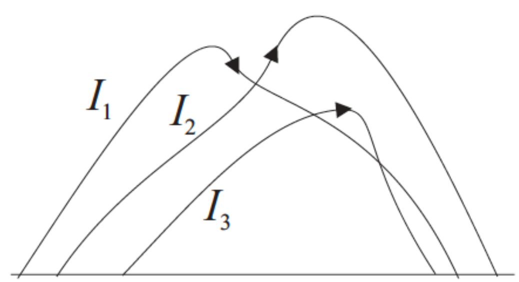


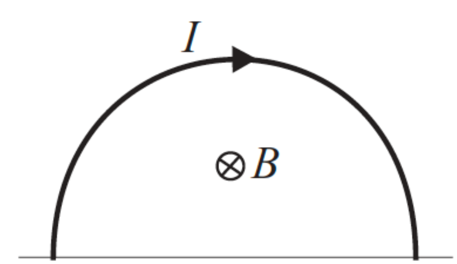




Plasma slab in a magnetic dip (Kippenhahn–Schluter equilibrium, Oliver et al., 1993; Joarder and Roberts, 1993; Anzer, 2009)

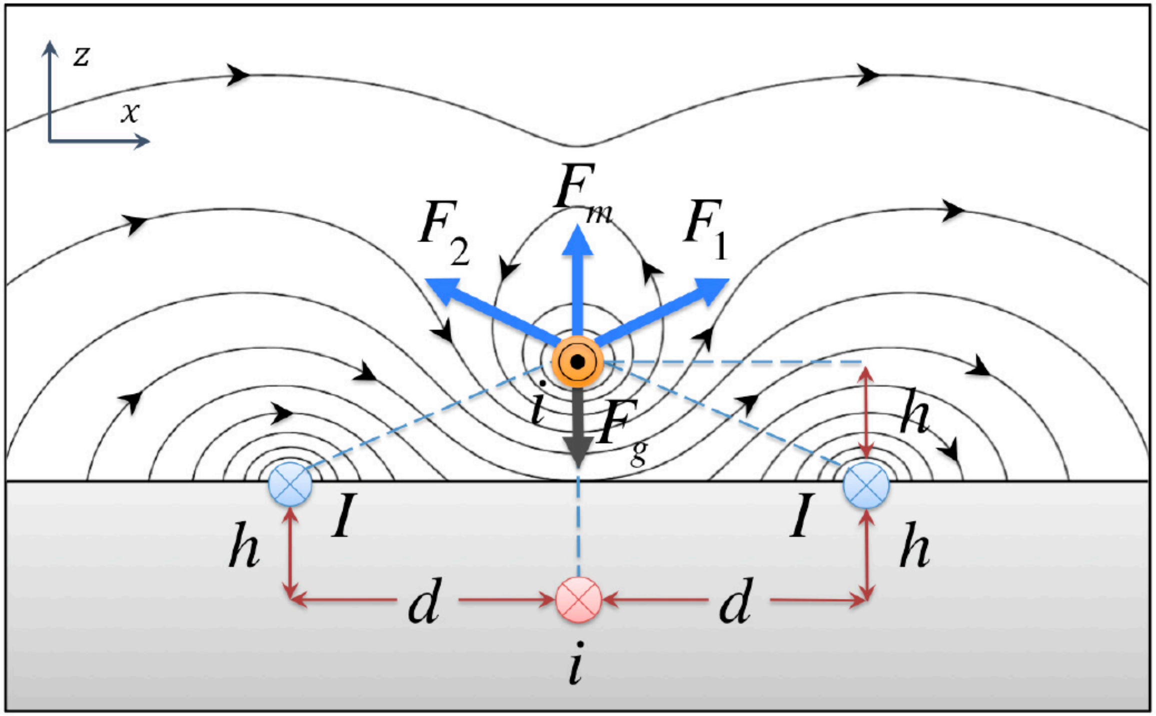



Line currents with the magnetic "mirror" force effect (KR model, Kuperus and Raadu, 1974; van den Oord et al., 1998)



# Quiescent prominence as a line current in a magnetic dip




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

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

Kolotkov et al., 2016

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

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

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

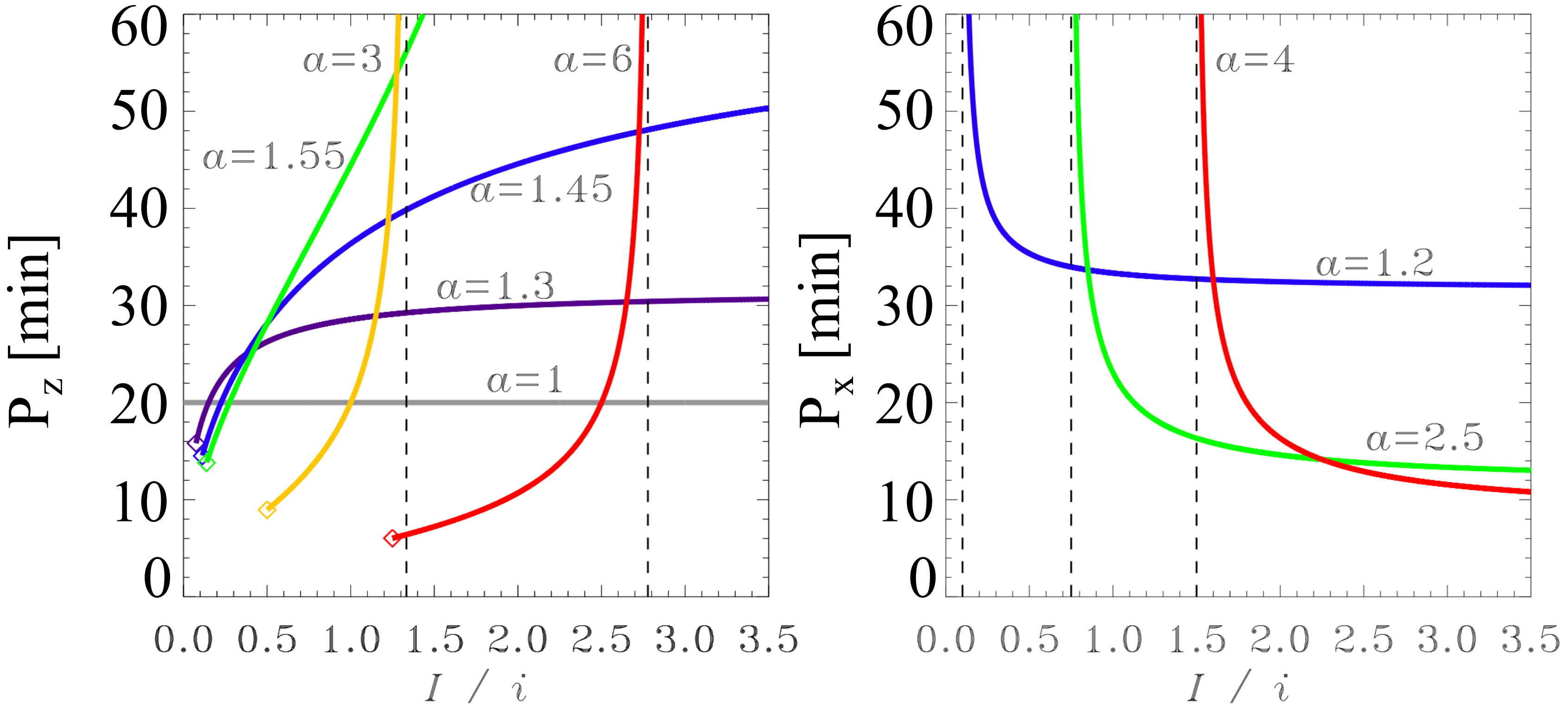
$$P_z = P_{\mathrm{KR}} \left[1 + 8\frac{k_1}{k_2}\frac{h^2(h^2 - d^2)}{(d^2 + h^2)^2}\right]^{-1/2}, \text{ where } P_{\mathrm{KR}} = 2\pi\sqrt{4\rho h^2/k_2}$$

KR limit,
$\sim$ 20 min.

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

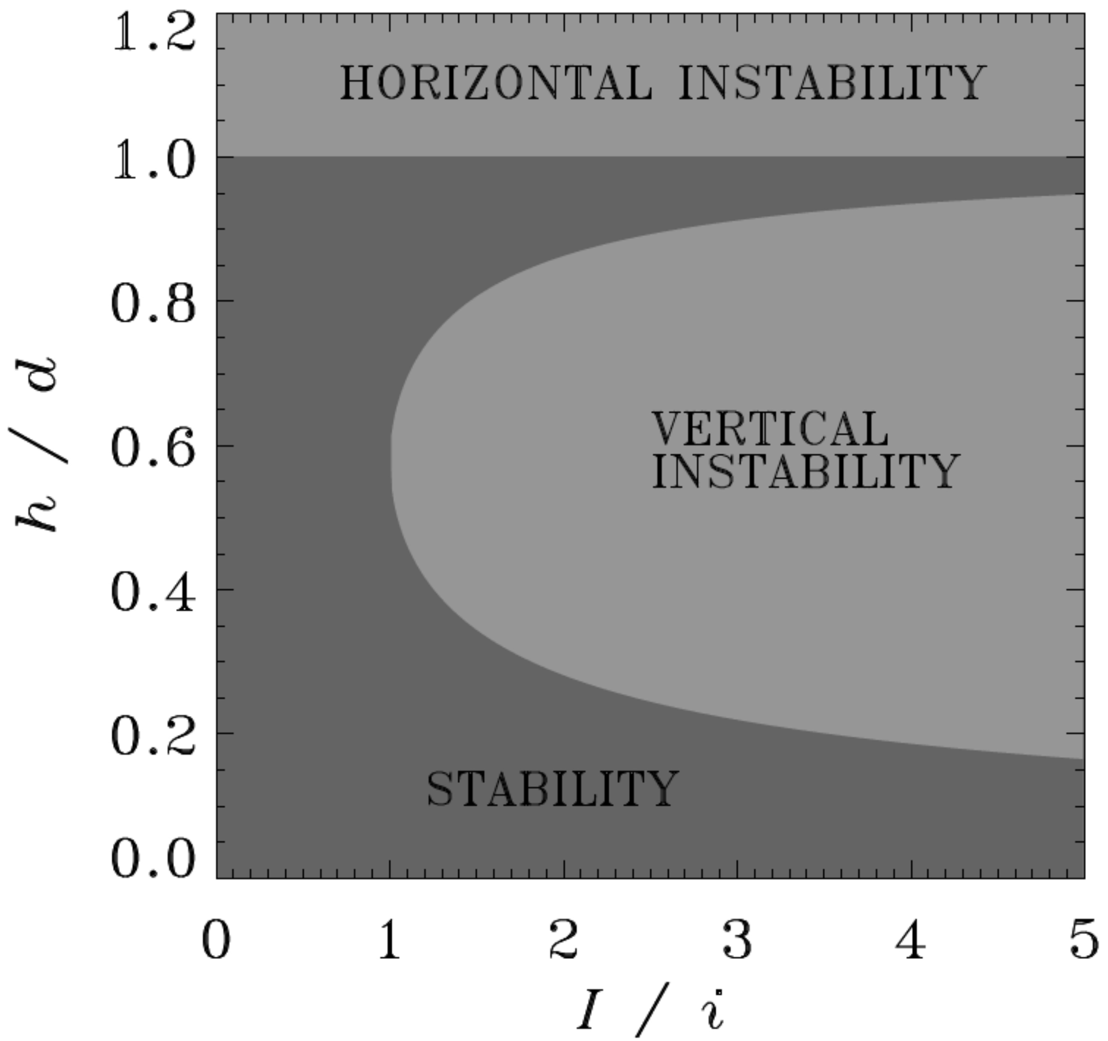
$$P_x = P_{\mathrm{KR}} \sqrt{\frac{k_2}{8k_1}\frac{(d^2 + h^2)^2}{h^2(d^2 - h^2)}}$$

# Periods of small amplitude oscillations (< 5 km/s)




$$a = 2\rho g h / k_2$$

# Linear theory. Mechanical stability




*h*<*d* and *i*>*I* – full stability

*i*<*I* – vertical instability

*h*>*d* – horizontal instability

cf. Vrsnak, 2008

# 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:

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

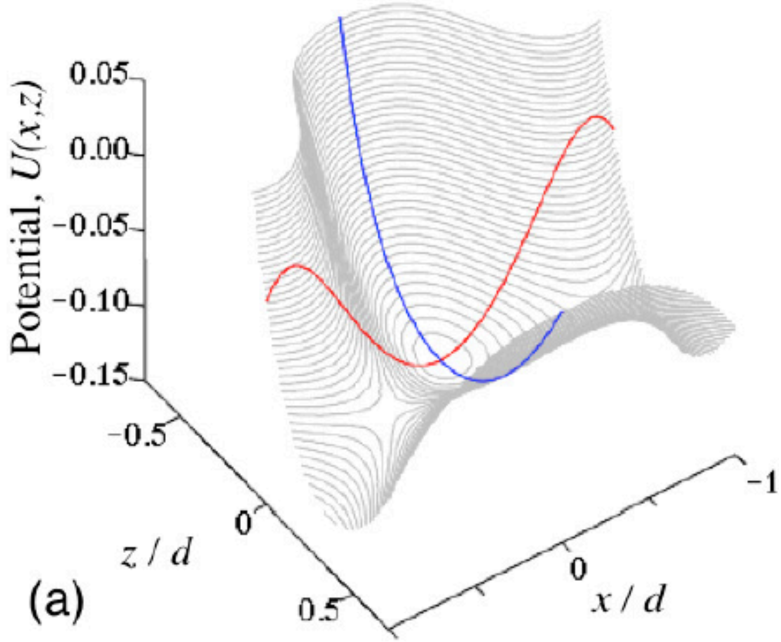
where $D \equiv (d^2 - x^2)^2 + 2(h + z)^2(d^2 + x^2) + (h + z)^4.$

Kolotkov et al., 2017 (submitted)

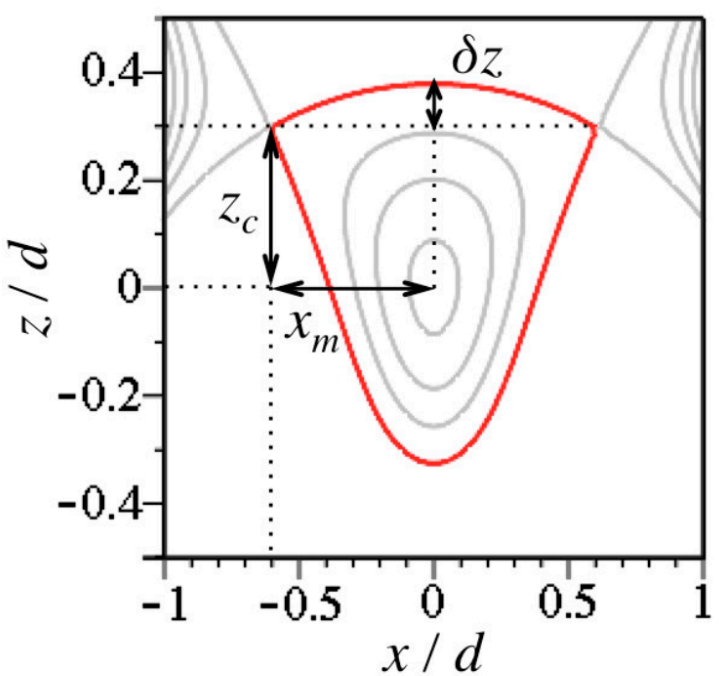
# Nonlinear theory. A metastable equilibrium

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

Side view:

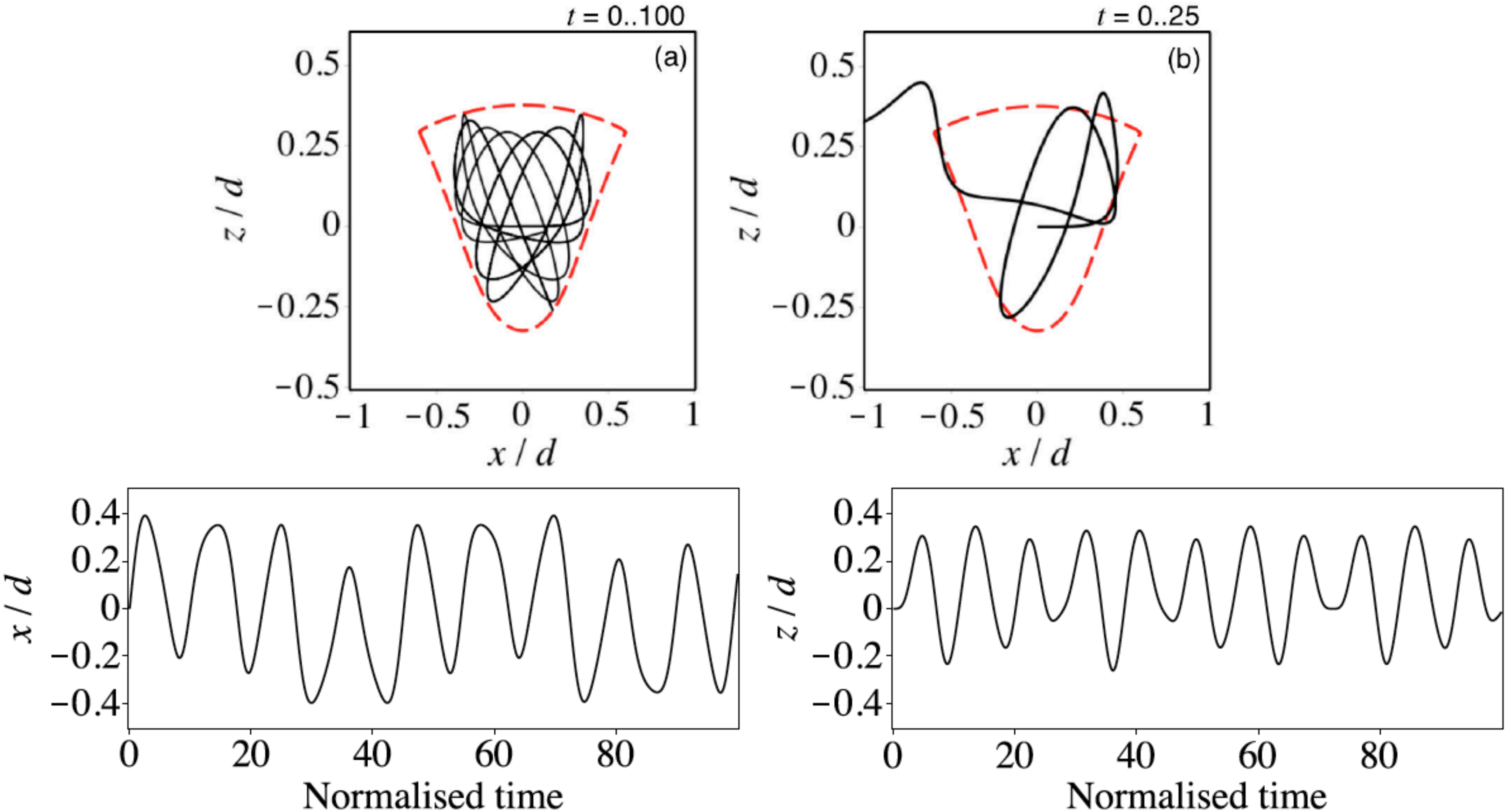



Top view:



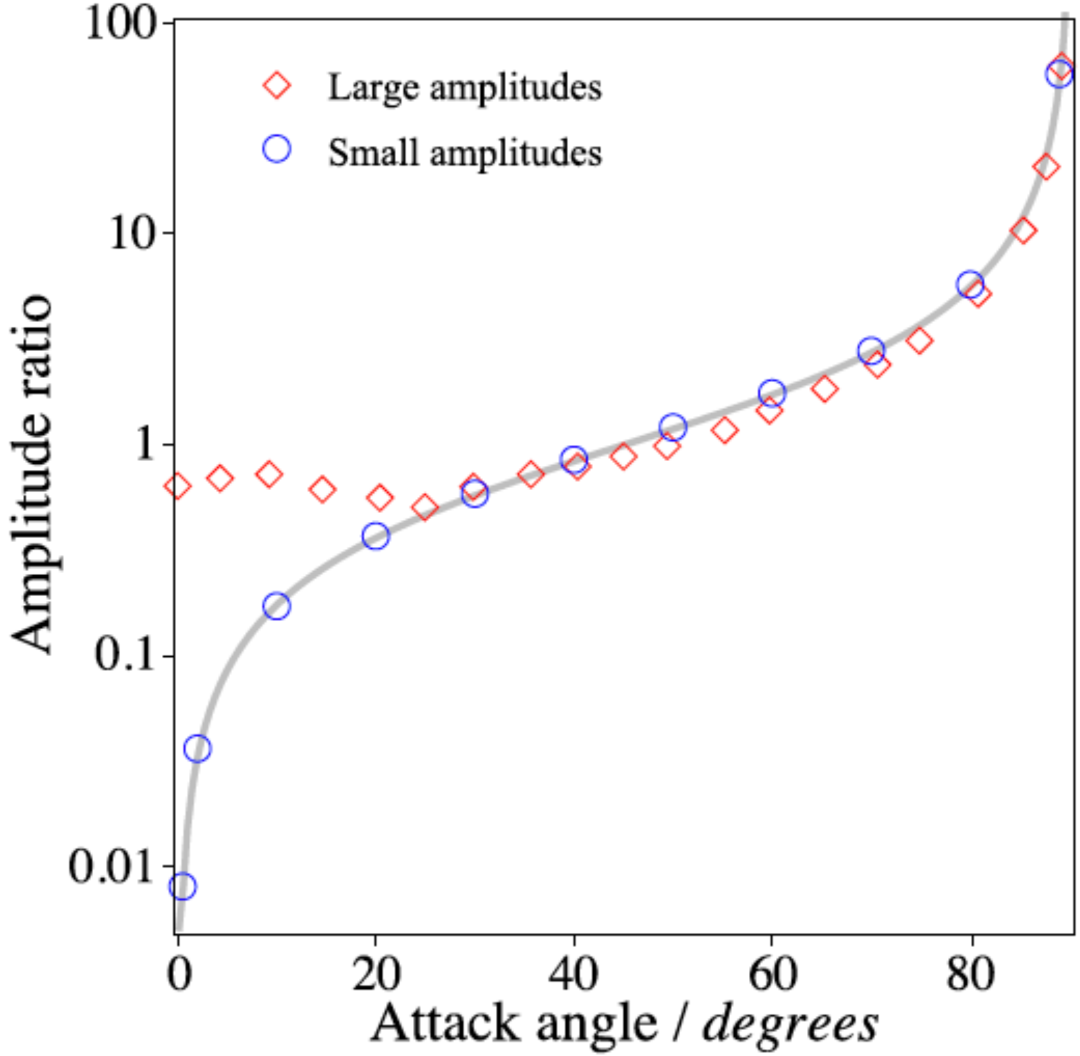
# Nonlinear theory. Finite amplitude solutions

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

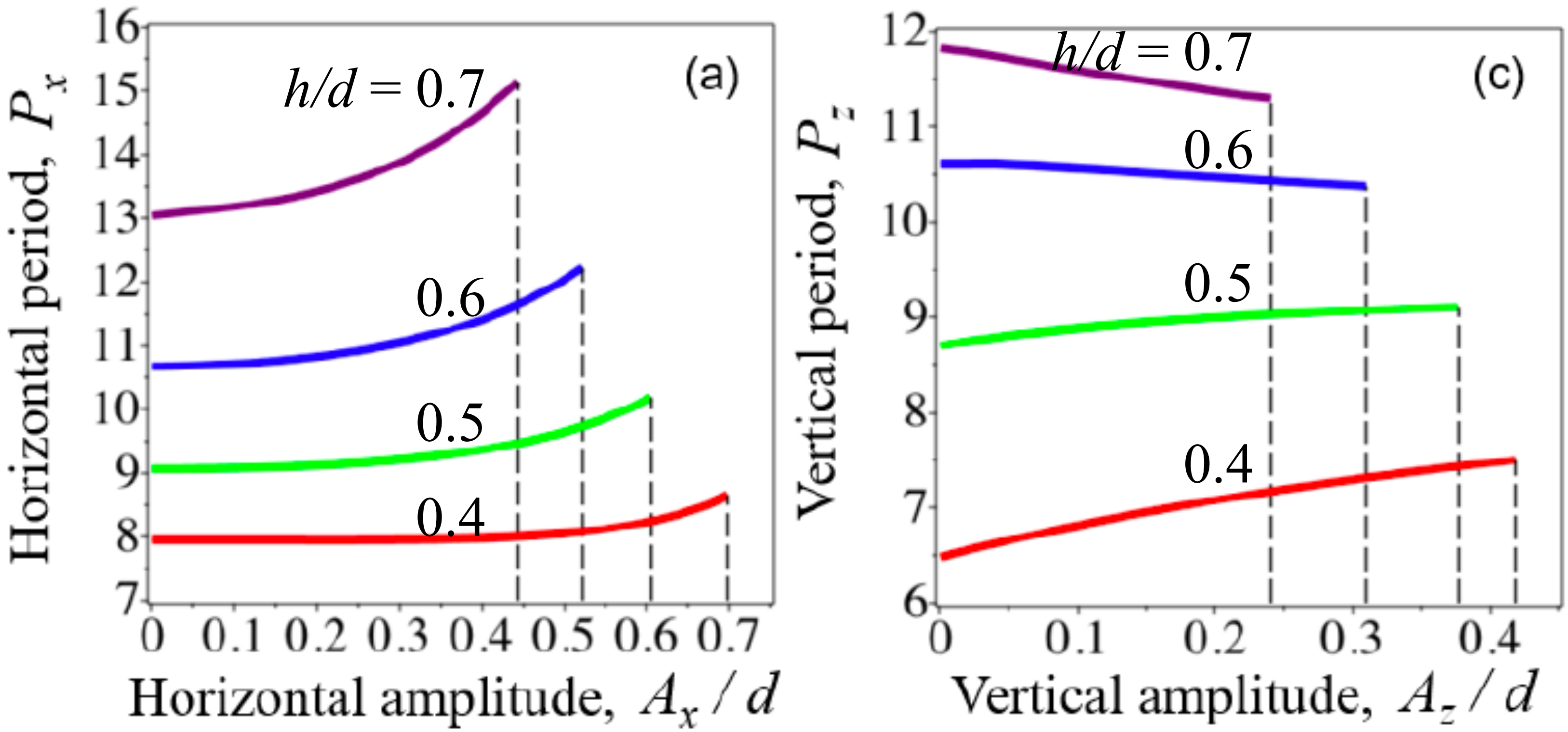



cf. Berger et al. , 2008; Shen et al. , 2014

# 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 ~ $2 \times 10^{10}$ 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.




cf. Bocchialini et al., 2011; Hershaw et al., 2011; Hillier et al., 2013

# Possible seismological applications. Prominence current.

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

Output value of the prominence current: $1.5 \times 10^{10} - 10^{11}$ 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 | $4 \times 10^{10}$ |
| 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 | $\sim 10^{11}$ |

# Summary

- ✓ Coupling between horizontal and vertical motions of the prominence, hence the lack of a simple elliptical polarisation;
- ✓ Presence of 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.