NUMERICAL STUDY OF A 3D PROMINENCE MODEL: TRANSVERSE AND LONGITUDINAL MHD OSCILLATORY MODES

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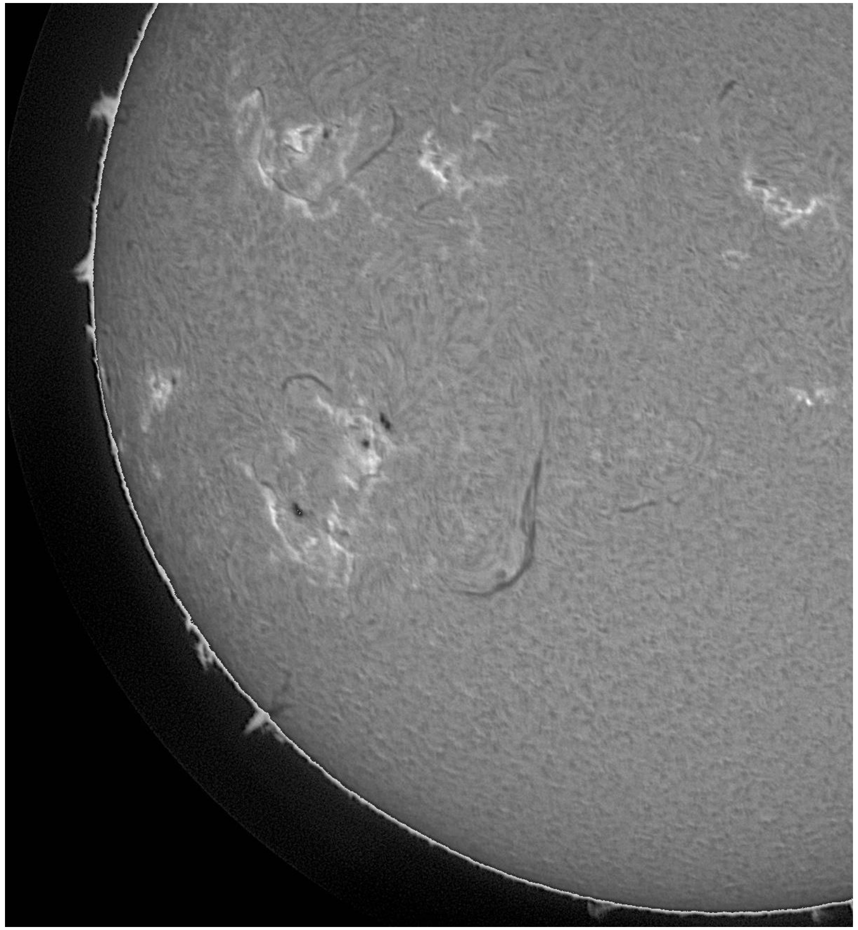
Solar Prominence oscillations



-Prominences:

Relatively cool, dense plasma structures suspended in the solar corona

-**Prominence oscillations:**

Damped oscillations

Small amplitude oscillations: $v < 10$ km s^{-1}
Large amplitude oscillations: $v \approx 10 – 100$ km s^{-1}

Periods ≈ 30 – 110min or short-period oscillations < 10 min

$T_d / P \sim 1\text{-}3$

MHD equations

Magnetohydrodynamics → Ideal MHD equations

$$\frac{Dln\rho}{Dt} = -\nabla \cdot \vec{u}$$

$$\frac{D\vec{u}}{Dt} = -c_s^2\nabla\left(\frac{s}{c_p} + ln\rho\right) - \nabla\Phi_{grav} + \frac{\vec{j}\times\vec{B}}{\rho} + \vec{F}_v$$

$$c_s^2 = \frac{\gamma p}{\rho} = c_{s0}^2 exp\left(\frac{\gamma s}{c_p} + (\gamma - 1)ln\frac{\rho}{\rho_0}\right)$$

$$\frac{\partial\vec{A}}{\partial t} = \vec{u}\times\vec{B} - \mu_0\eta\vec{j}$$

$$\rho T\frac{Ds}{Dt} = 0$$

MHD equations

Magnetohydrodynamics → Ideal MHD equations

$$\frac{\boldsymbol{D ln\rho}}{\boldsymbol{Dt}} = -\boldsymbol{\nabla} \cdot \vec{\boldsymbol{u}}$$

$$\frac{\boldsymbol{D\vec{u}}}{\boldsymbol{Dt}} = -\boldsymbol{c_s^2 \nabla}\left(\frac{\boldsymbol{s}}{\boldsymbol{c_p}} + \boldsymbol{ln\rho}\right) - \boldsymbol{\nabla\Phi_{grav}} + \frac{\vec{\boldsymbol{j}} \times \vec{\boldsymbol{B}}}{\boldsymbol{\rho}} + \vec{\boldsymbol{F}}_{\boldsymbol{v}}$$

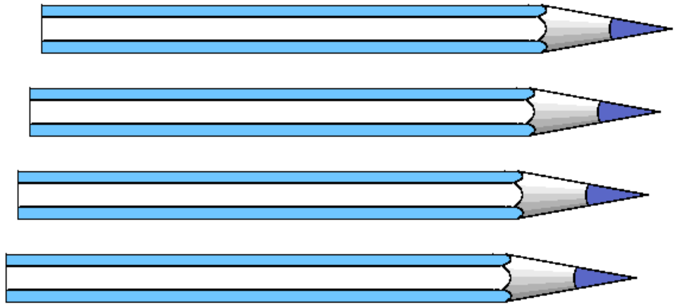
$$\boldsymbol{c_s^2} = \frac{\boldsymbol{\gamma p}}{\boldsymbol{\rho}} = \boldsymbol{c_{s0}^2 exp}\left(\frac{\boldsymbol{\gamma s}}{\boldsymbol{c_p}} + (\boldsymbol{\gamma} - \mathbf{1})\boldsymbol{ln}\frac{\boldsymbol{\rho}}{\boldsymbol{\rho_0}}\right)$$

$$\frac{\boldsymbol{\partial \vec{A}}}{\boldsymbol{\partial t}} = \vec{\boldsymbol{u}} \times \vec{\boldsymbol{B}} \cancel{- \boldsymbol{\mu_0 \eta \vec{j}}}$$

$$\vec{\boldsymbol{F}}_{\boldsymbol{v}}^{\boldsymbol{(hyper)}} = \boldsymbol{\nu_{(hyper)}\nabla^4\vec{u}} + \boldsymbol{\zeta_{shock}}$$

$$\boldsymbol{\rho T}\frac{\boldsymbol{Ds}}{\boldsymbol{Dt}} = \mathbf{0}$$

The Pencil Code



- Publicly available code
- High-order finite-difference code.
- Programming language: Fortran
- Different switchable modules
- The code can use MPI
- Long list of parameters, boundary conditions and some specific initial conditions

Initial Configuration

$$\mathbf{B_x = B_0\cos(k_1x)\exp\big(-k_1(z-z_0)\big) - B_0\cos(k_2x)\exp\big(-k_2(z-z_0)\big)}$$

$$\mathbf{B_z = -B_0\sin(k_1x)\exp\big(-k_1(z-z_0)\big) + B_0\sin(k_2x)\exp\big(-k_2(z-z_0)\big)}$$

$$\rho = \rho_0 \exp\left(\frac{-z}{\Lambda}\right)$$

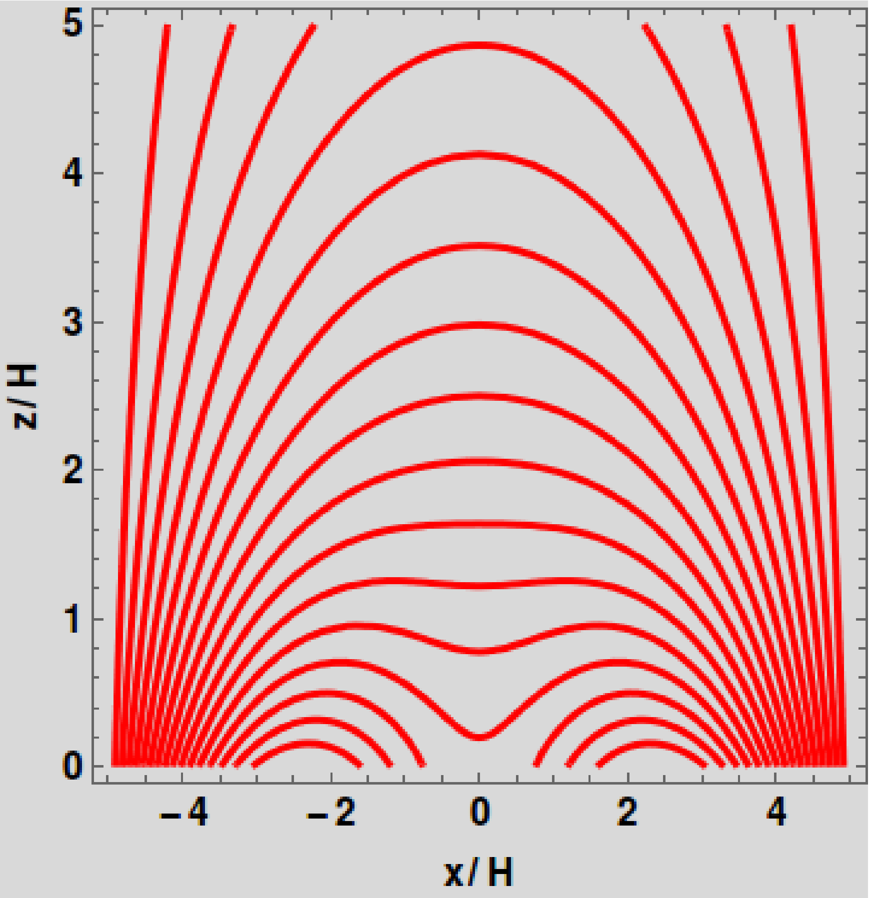
$$\Lambda = c_{s0}^2/\gamma\, g \approx 6\mathrm{H}$$

$$H = 10^4\ km$$

$$\gamma = 5/3$$

$$c_{s0} = 166\ kms^{-1}\ (T = 10^6\ K)$$

$$g = 0.274\ kms^{-2}$$



$$k_1 = \pi/(2L)$$

$$k_2 = 3\,\pi/(2L)$$

$$L = 5H$$

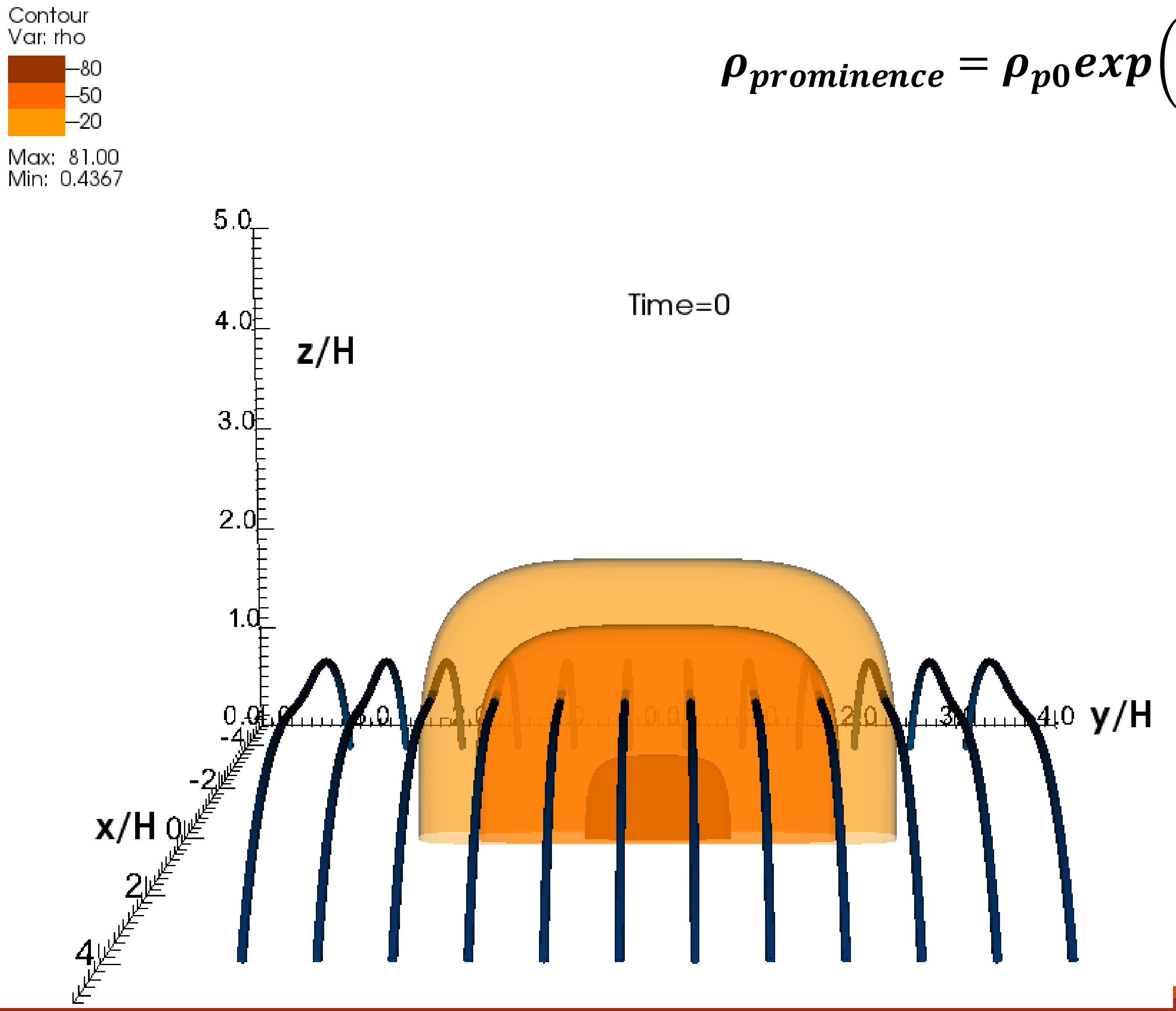
$$B_0 = 10\ G$$

$$v_{A0} \approx 17.1 C_{s0}$$

$$z_0 = -0.2H$$

z0 places the null point of the magnetic field outside the numerical domain

Prominence mass deposition



$$\rho_{prominence} = \rho_{p0} exp\left(-2\left((x/w_x)^n + (y/w_y)^n + (z/w_z)^n\right)\right)$$

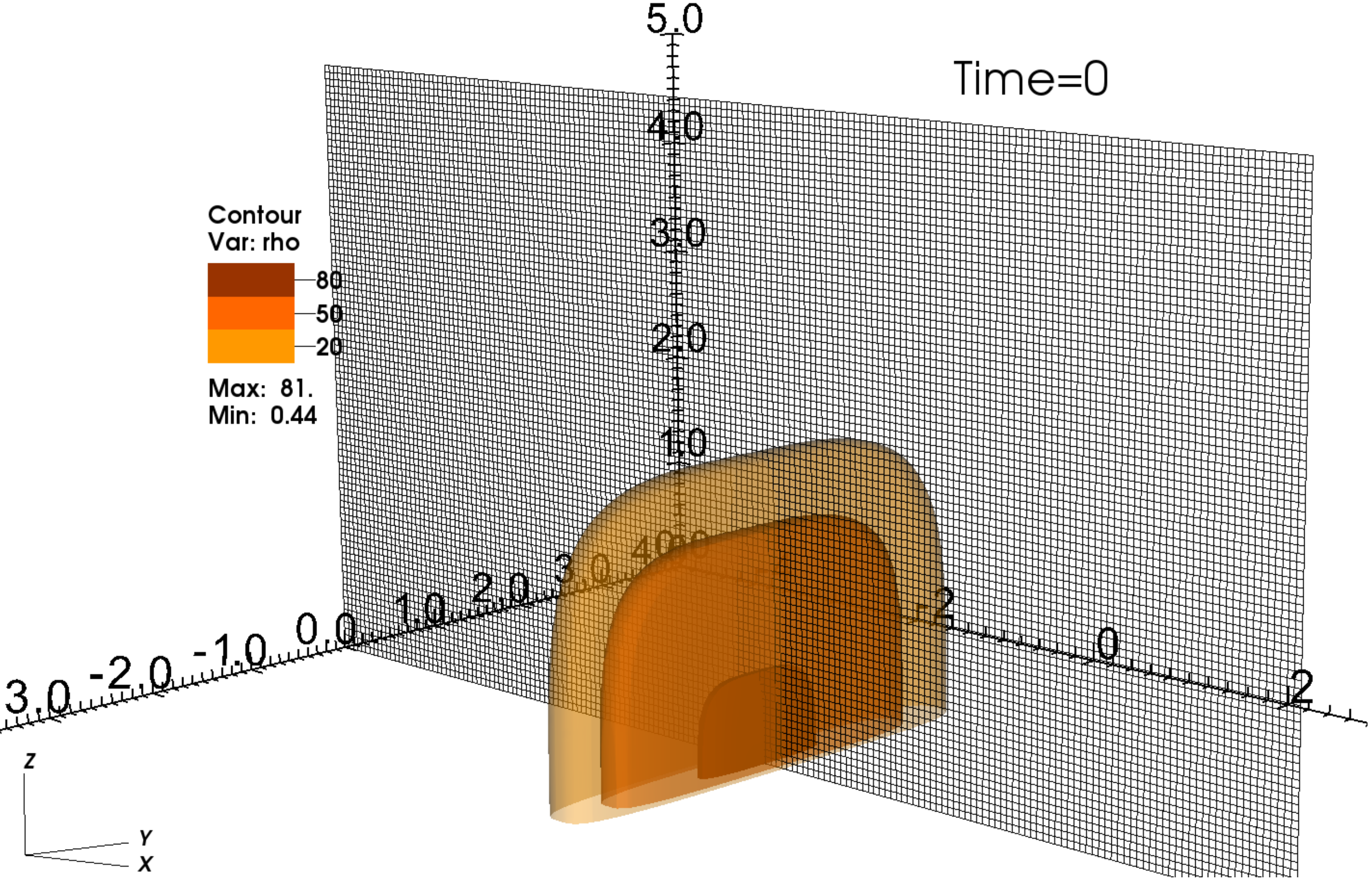
$$\mathbf{n = 4 \;\; \rho_{p0} = 80}$$

$$\mathbf{w_x = 0.3/H}$$

$$\mathbf{w_y = 2.2/H}$$

$$\mathbf{w_z = 2.6/H}$$

Numerical tools



-High-order finite-difference code (6th)

-Equidistant grid

-Resolution:
180x144x90

-Box size:
-5/H>x>5/H -4/H>y>4/H 0/H>z>5/H

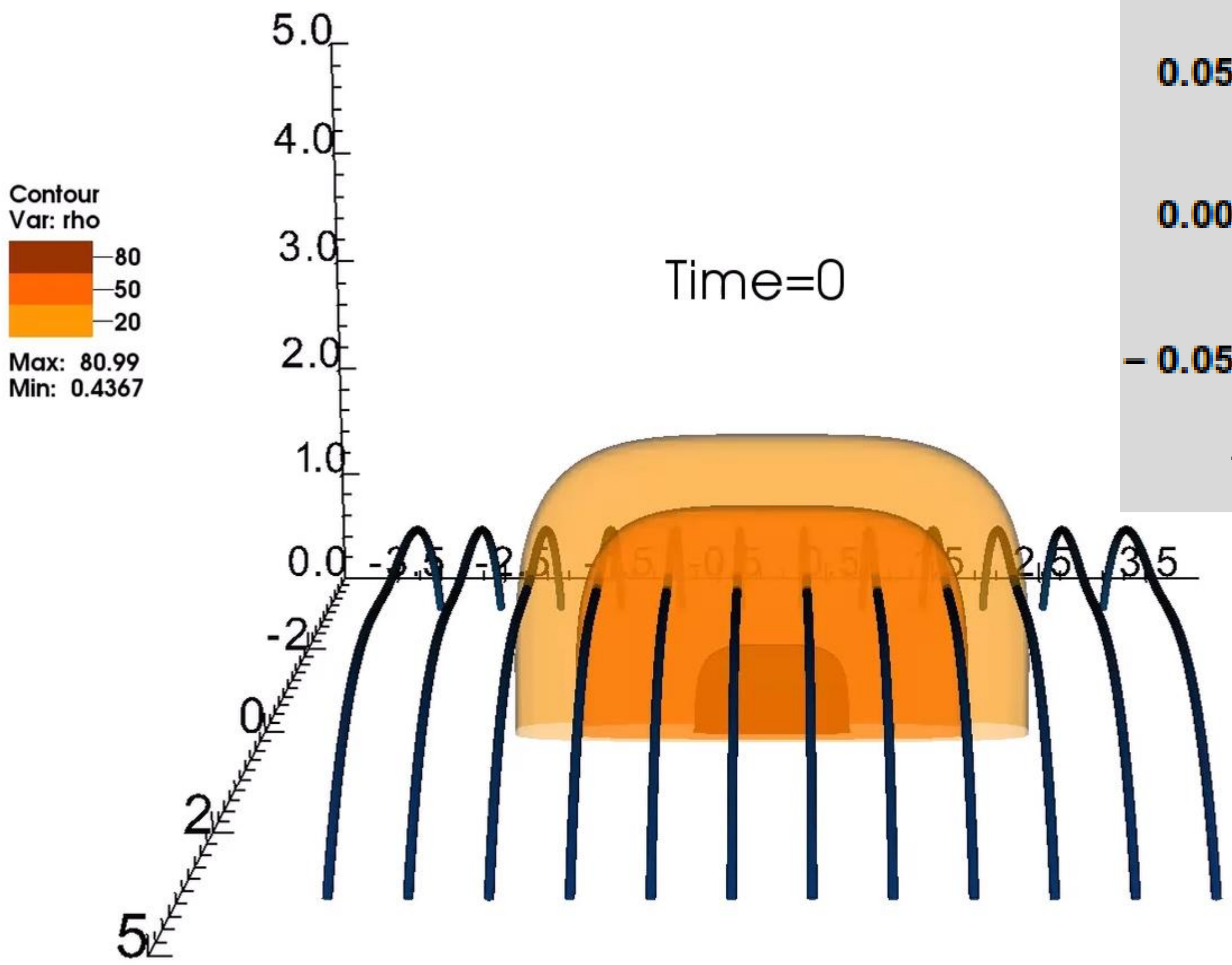
-Line-tying boundary conditions:

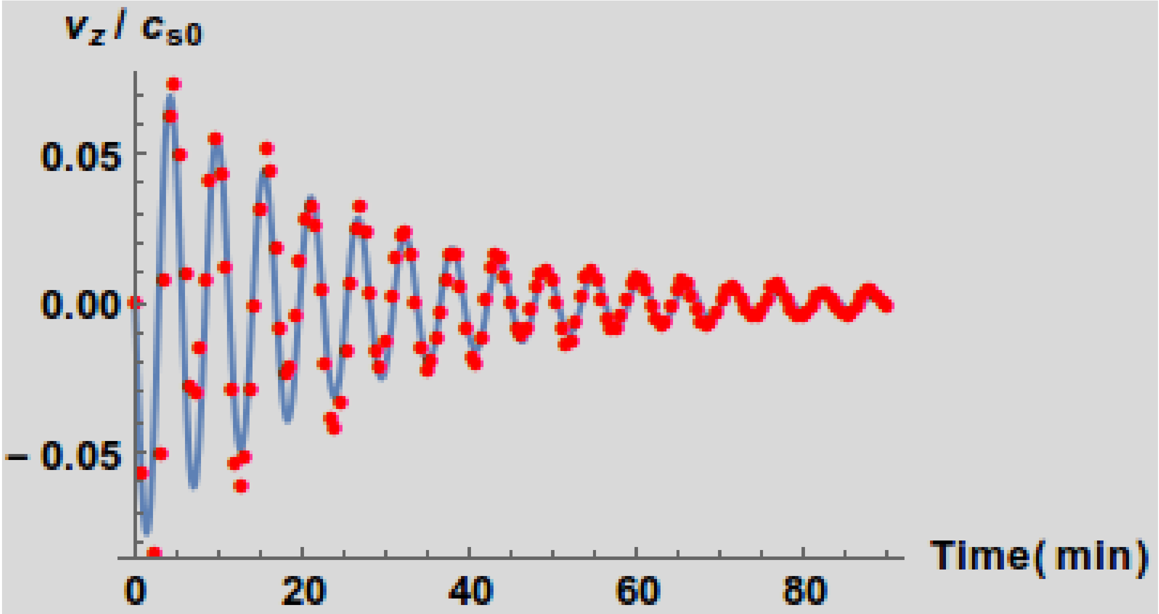
$\mathbf{B}_{\perp} = constant$

$\vec{\mathbf{v}} = \mathbf{0}$

$\rho, \mathbf{s} \rightarrow symmetric$

Relaxation process





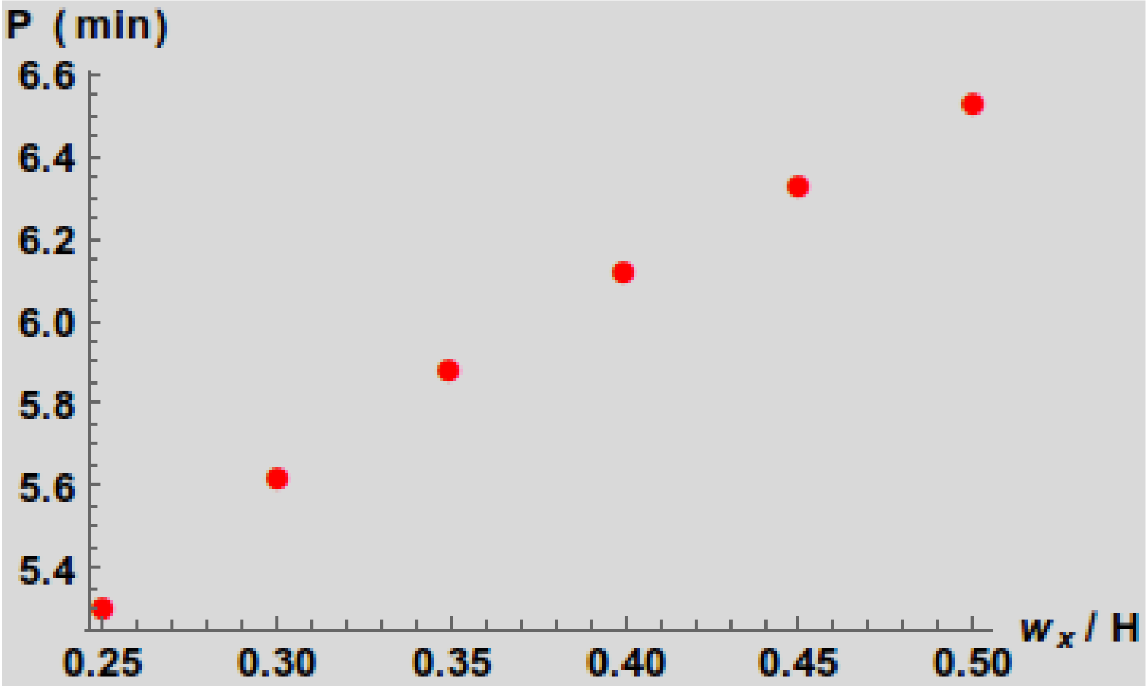
$$P = 5.63 \pm 0.01 min$$

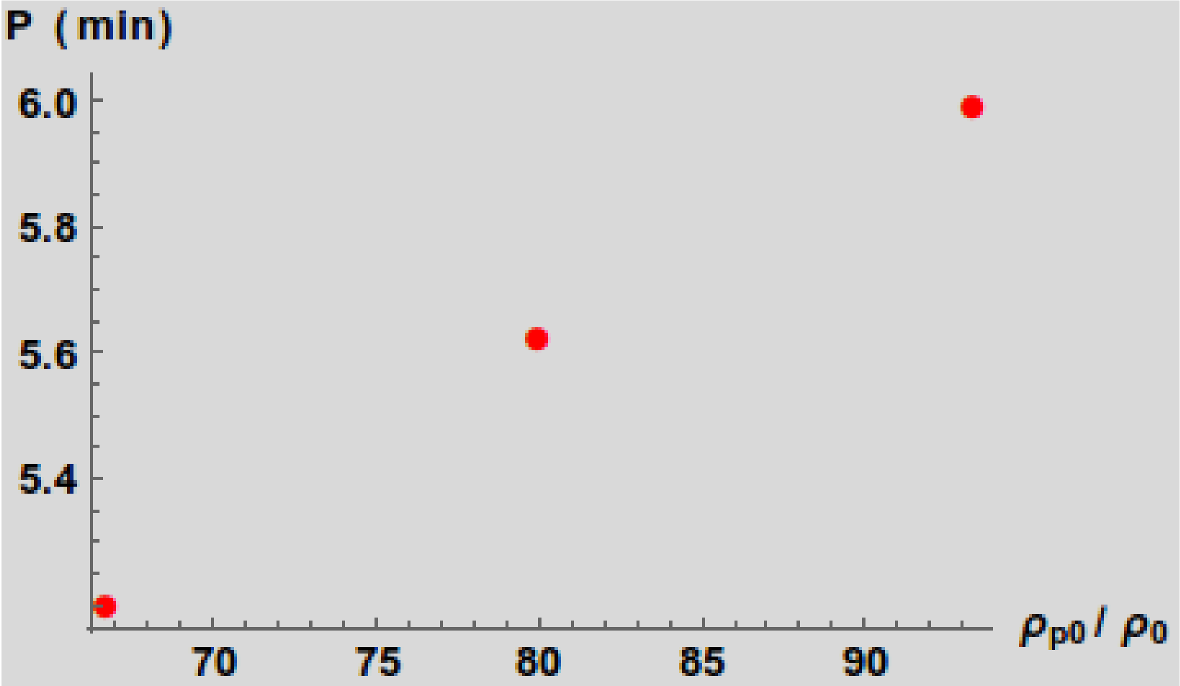
$$\frac{v_z}{c_{s0}} = 0.082 \pm 0.005 \ \ (13.6\ km\ s^{-1})$$

$$t_d = 25 \pm 2 min$$

$$\frac{t_d}{P} = 4.5$$

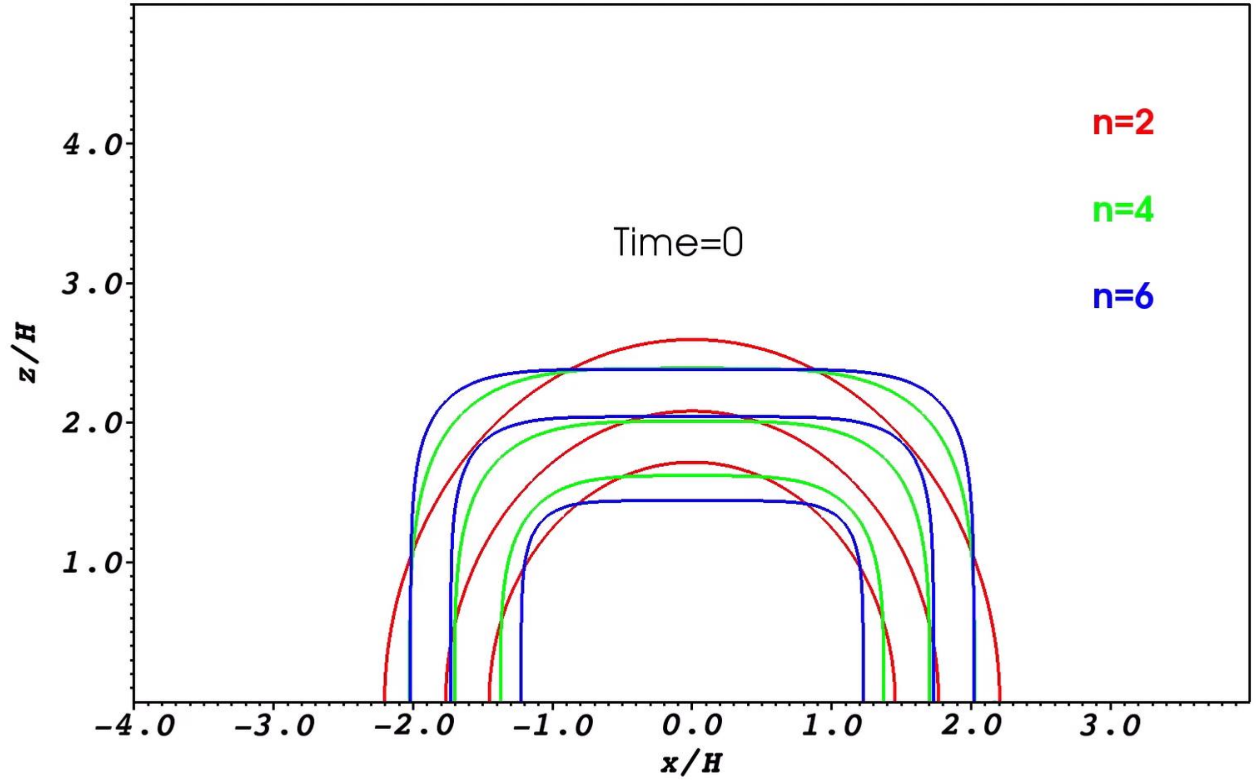
Relaxation process: dependence of period on w_x and ρ_{p0}/ρ_0

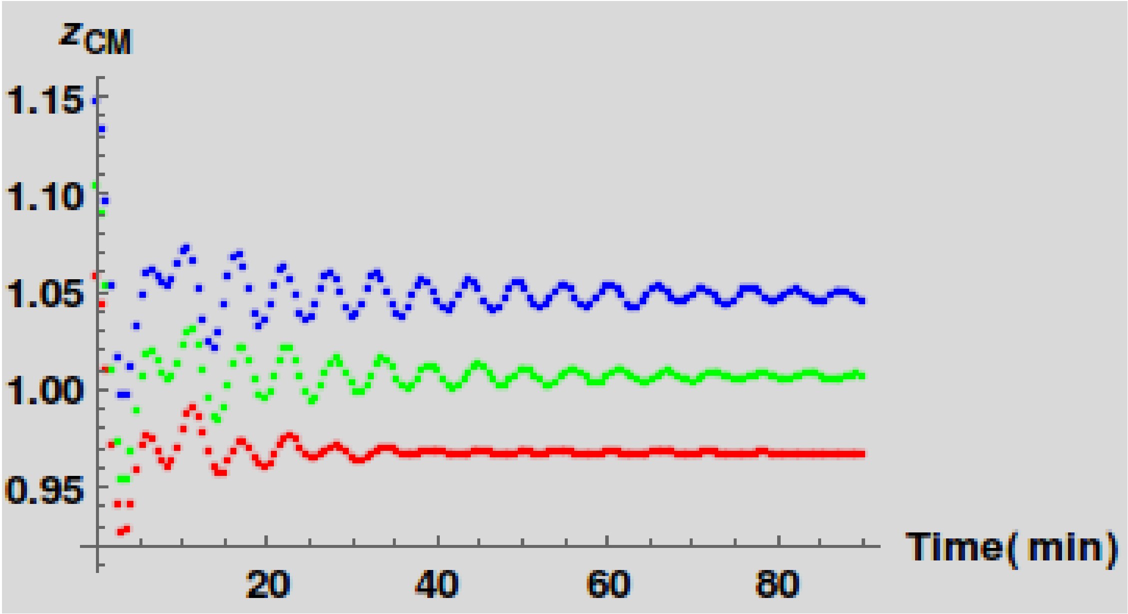




P increases with w_x and ρ_{p0}/ρ_0

Relaxation process: resonant absorption





The smoother the PCTR, the stronger the attenuation.

Longitudinal oscillations

$$\vec{v} = v_p exp\left(-2\left((x/w_{vx})^4 + \left(y/w_{vy}\right)^4 + ((z - z_i)/w_{vz})^4\right)\right)\widehat{e_x}$$

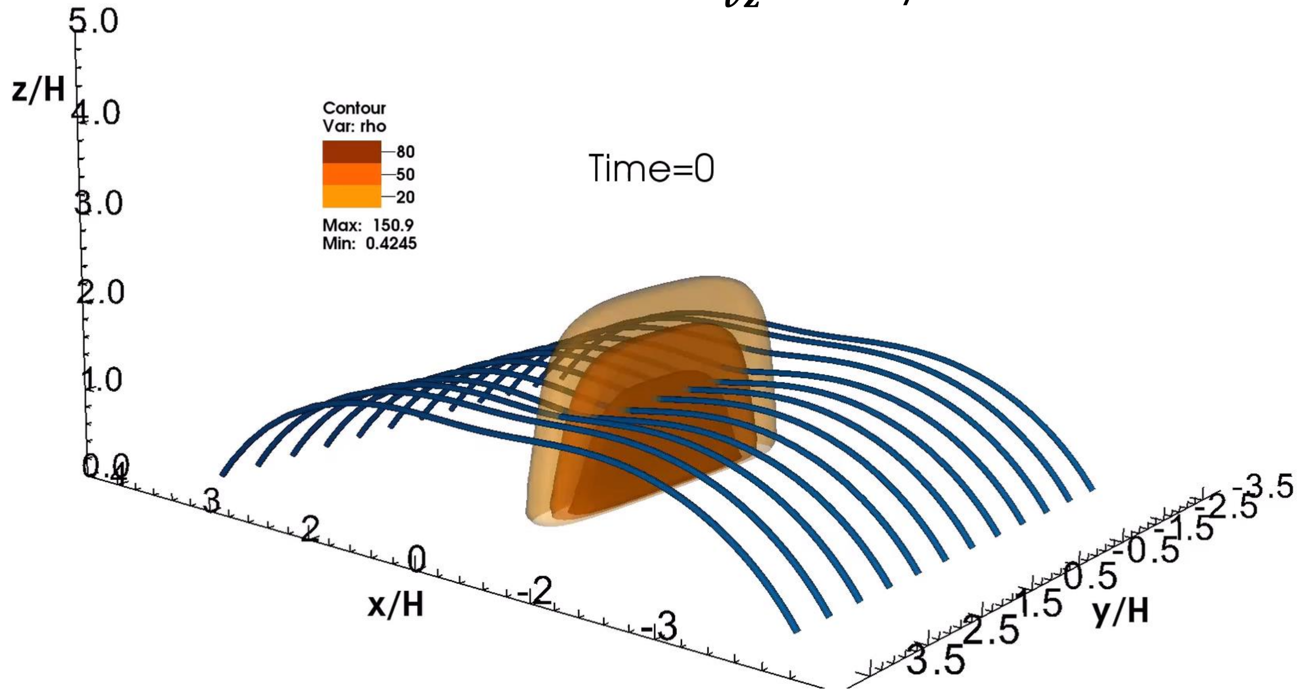
$$v_p = 0.05c_{s0}$$

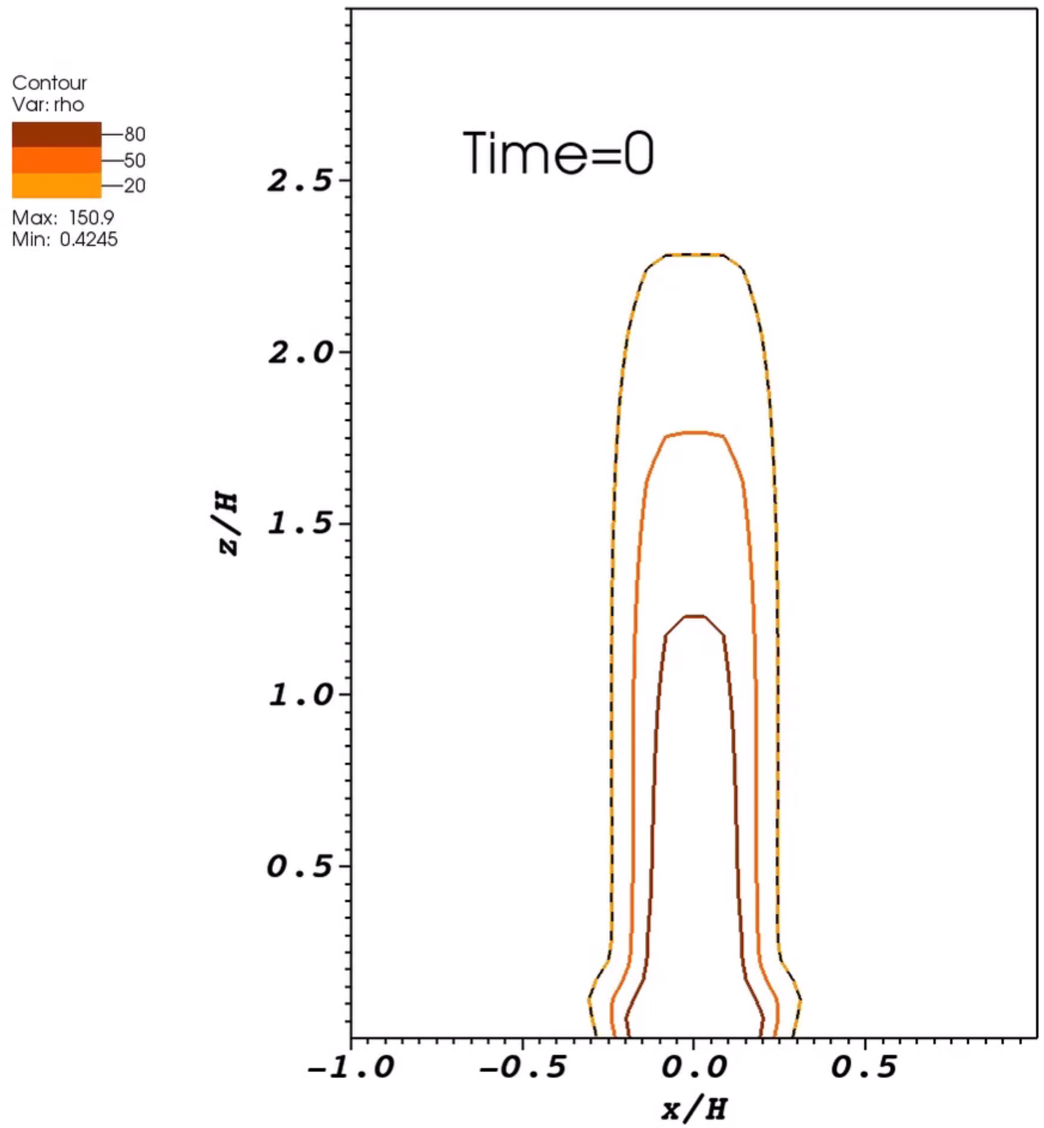
$$z_i = 1.3/H$$

$$w_{vx} = 0.3/H$$

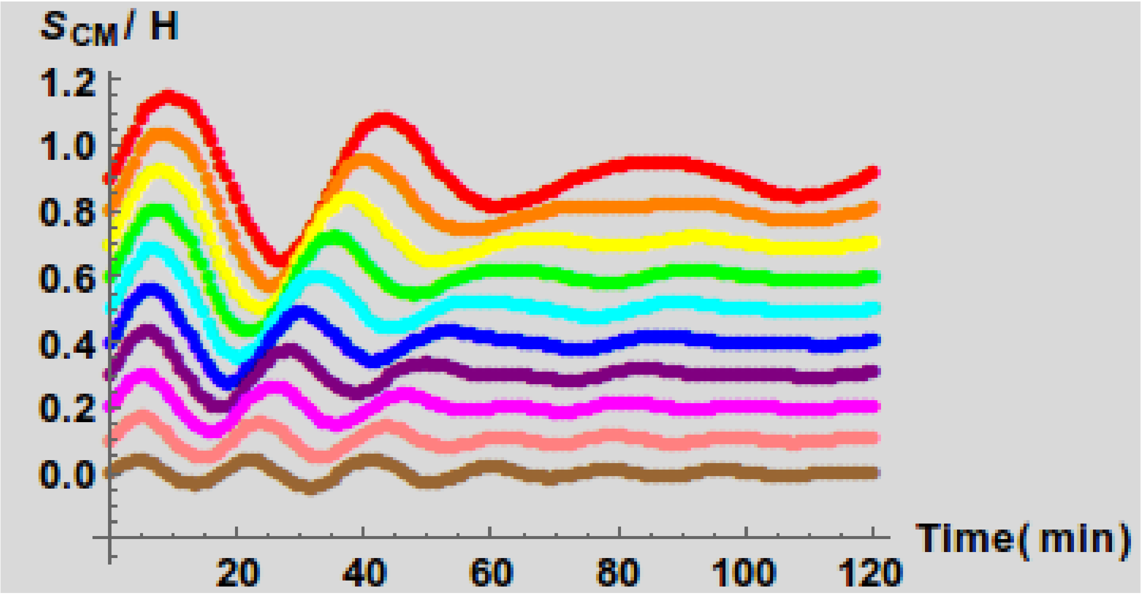
$$w_{vy} = 2.2/H$$

$$w_{vz} = 1.1/H$$



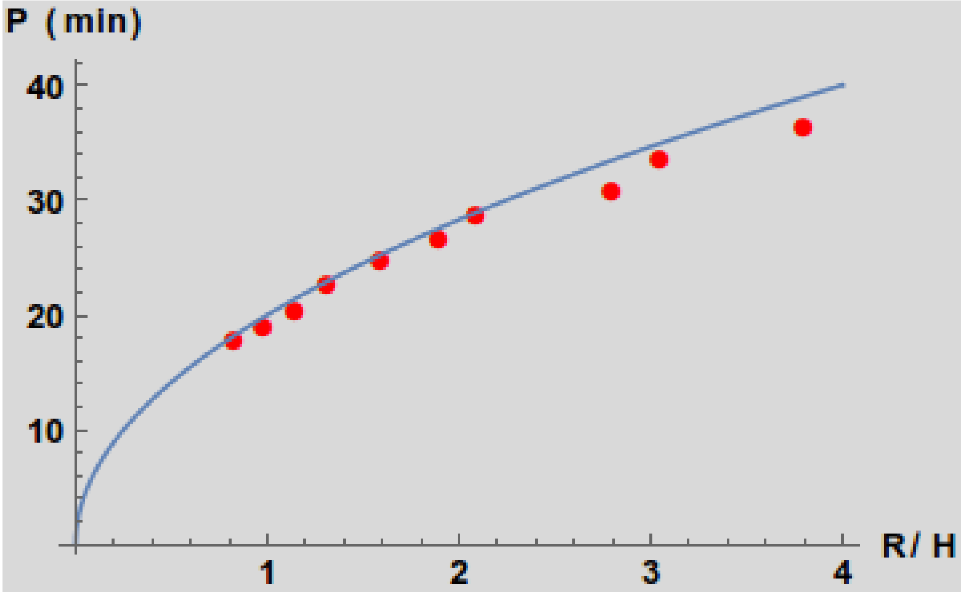


Longitudinal oscillations

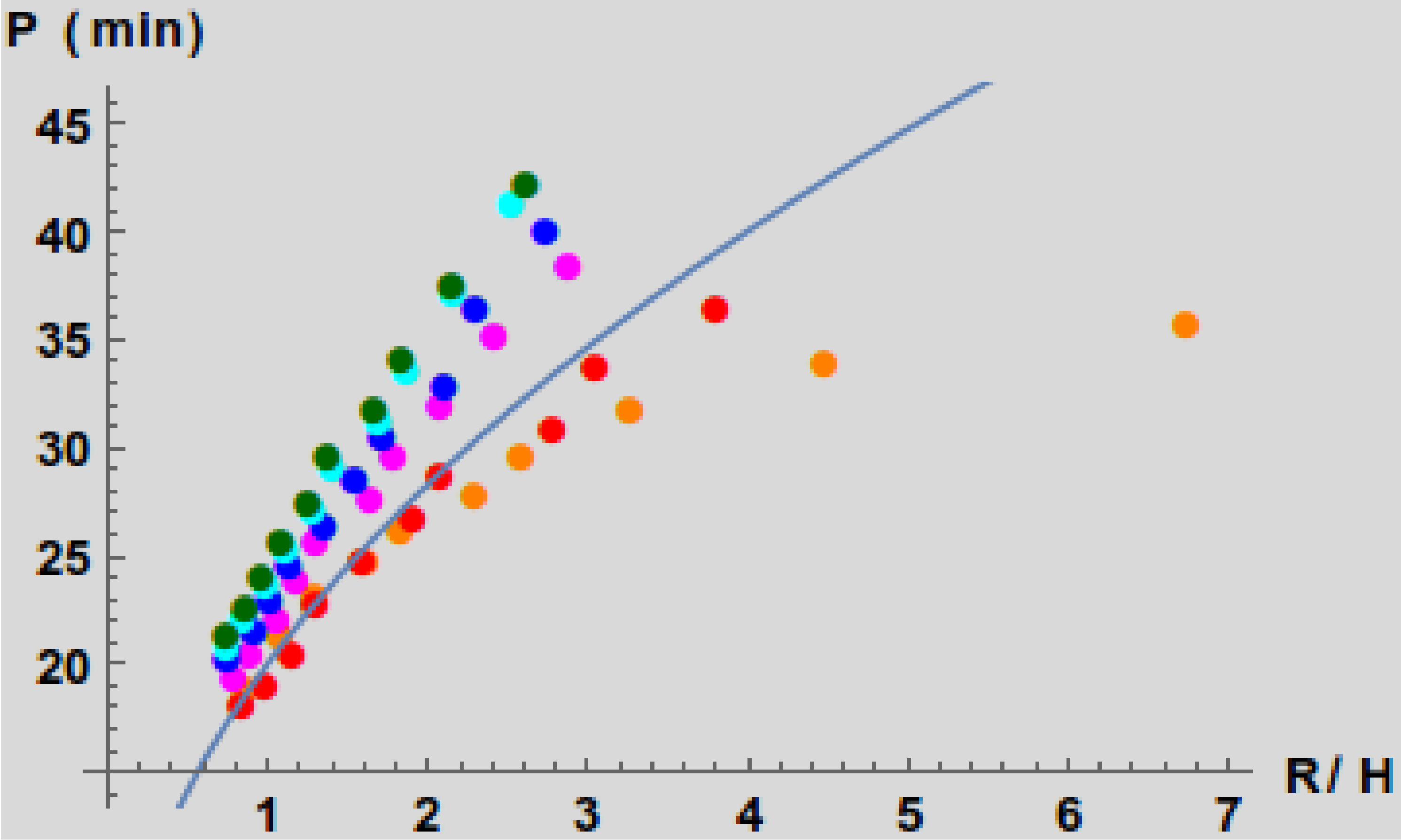


$$P = 2\pi\sqrt{\frac{R}{g}}$$

The period of oscillation varies with the radius



Longitudinal oscillations: dependence on w_x



$w_x/H = 0.25$

$w_x/H = 0.3$

$w_x/H = 0.35$

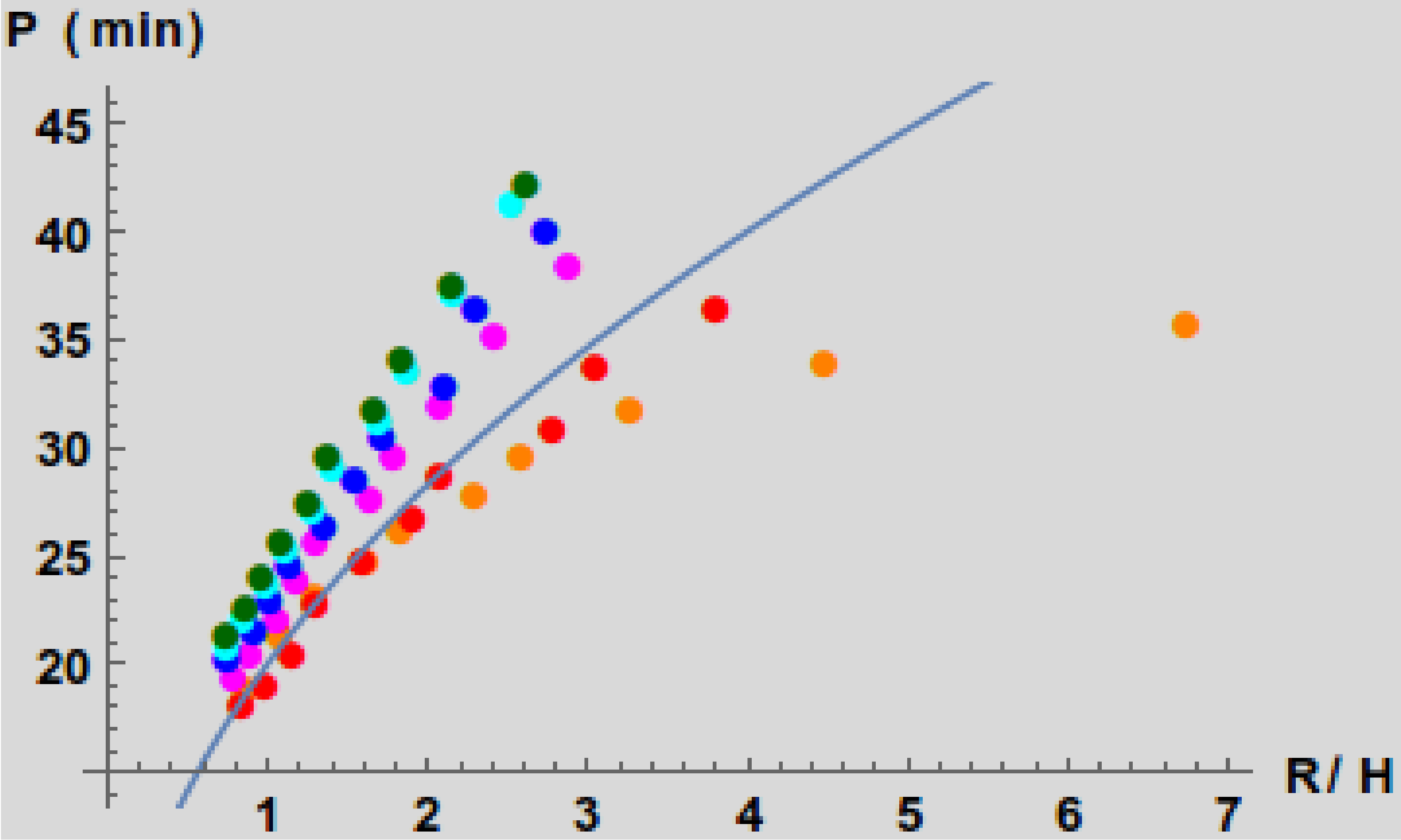
$w_x/H = 0.4$

$w_x/H = 0.45$

$w_x/H = 0.5$

The period of oscillation increases with the width of the structure

Longitudinal oscillations: dependence on w_x



$w_x/H = 0.25$

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$w_x/H = 0.35$

$w_x/H = 0.4$

$w_x/H = 0.45$

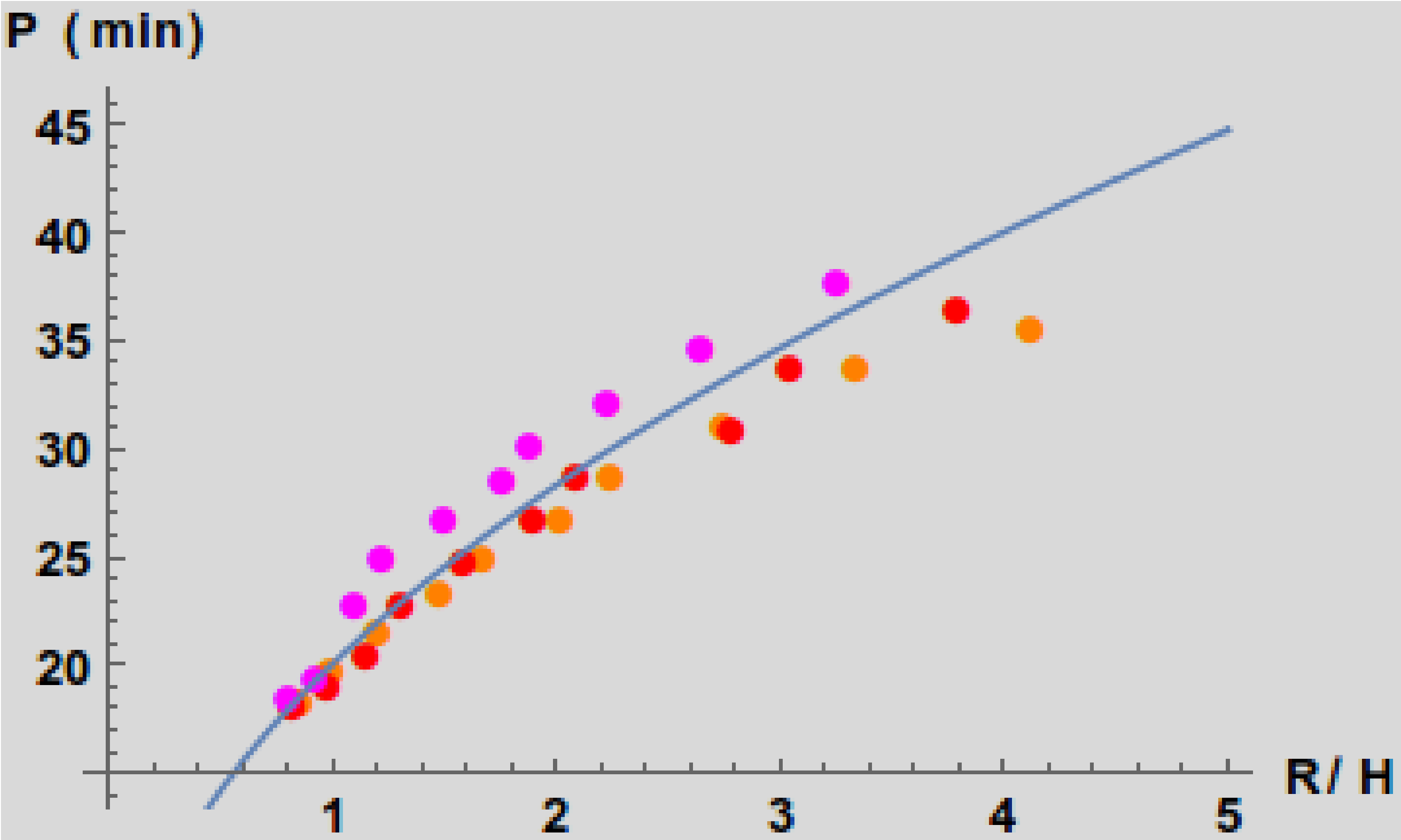
$w_x/H = 0.5$

The period of oscillation increases with the width of the structure

$$P = \frac{2\pi}{\sqrt{\frac{g}{R} + \frac{c_{sc}{}^2}{l(L-l)\chi}}}$$

(Luna et al. 2012)

Longitudinal oscillations: dependence on ρ_{p0}/ρ_0



$\rho_{p0}/\rho_0 = 67$

$\rho_{p0}/\rho_0 = 80$

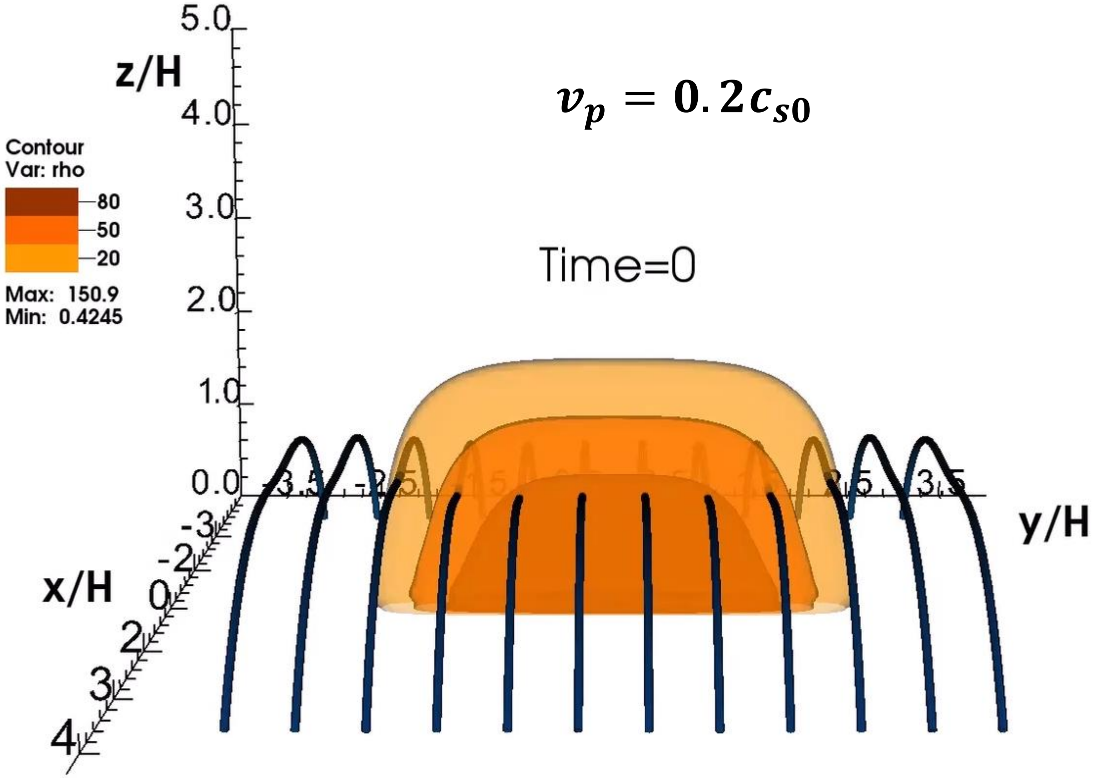
$\rho_{p0}/\rho_0 = 93$

$$\mathbf{P} = \frac{2\pi}{\sqrt{\frac{g}{R} + \frac{c_{sc}{}^2}{l(L-l)\chi}}}$$

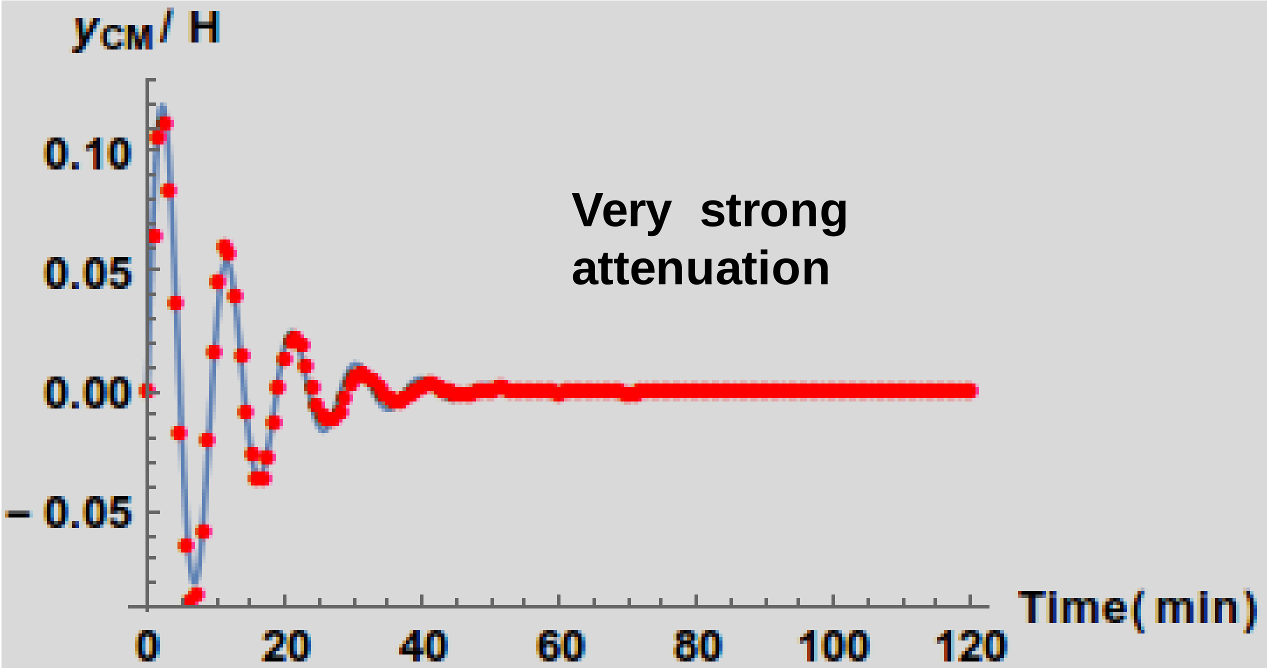
Luna et al. 2012

The period of oscillation increases with the density contrast of the structure

Transverse oscillations



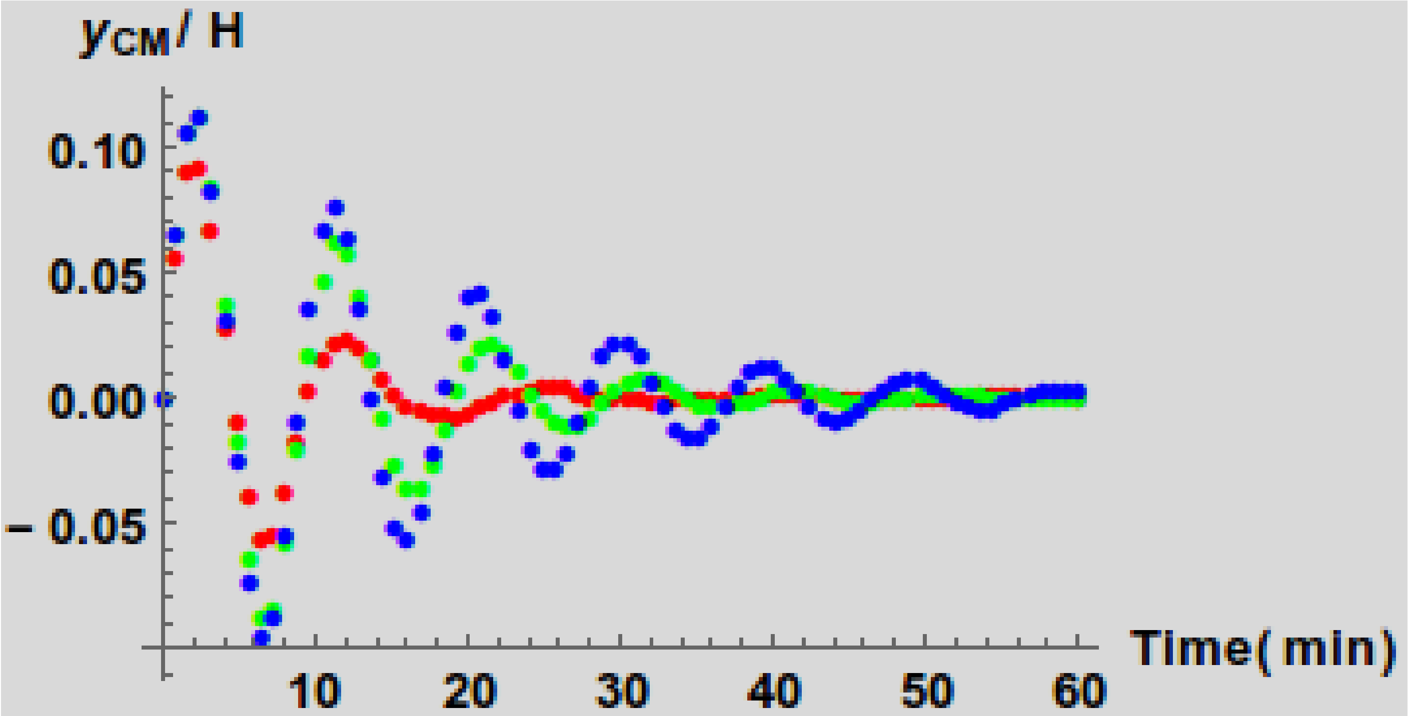
$v_p = 0.2 c_{s0}$



$P = 9.41 \pm 0.02$ $\quad A = 1.14 \pm 0.03\ Mm$

$t_d = 11.9 \pm 0.3$ $\quad \frac{t_d}{P} = 1.3$

Transverse oscillations: resonant absorption



$$n = 2 \rightarrow \frac{t_d}{P} = 0.7$$

$$n = 4 \rightarrow \frac{t_d}{P} = 1.3$$

$$n = 6 \rightarrow \frac{t_d}{P} = 1.9$$

The smoother the PCTR, the stronger the attenuation.

Conclusions

- Part of the attenuation of the vertical oscillations is due to the conversion of energy of the transverse motions into localized motions at the lateral edges of the prominence. This is the resonant absorption process. We have verified that the wider the transition region, the stronger the damping.

- For longitudinal oscillations we have that the pendulum model is a first approximation of the motion. The gas pressure gradient contributes to the restoring force, specially for flat magnetic field lines.

- The attenuation of longitudinal motions for our simulations is most probably due to artificial viscosity.

- A deeper study on the attenuation of transverse oscillations will be necessary. A more detailed parametric study will also be necessary in order to understand the restoring forces and the damping mechanism.