Transverse loop oscillations from 3D MHD simulations

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Observations: standing transverse waves

- Oscillating loops in the solar corona:
  1. Produced by flares
  2. Produced by eruptions
- Fixed footpoints → Transverse standing waves
- Fast attenuation: $\tau_D/P \sim 2-5$

CORONAL SEISMOLOGY

Uchida (1970), Roberts et al. (1984)

Aschwanden et al. (1999), Nakariakov et al. (1999), Nakariakov & Ofman (2001)

Theory: magnetohydrodynamics (MHD)

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0,$$

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot \left(\rho \mathbf{v}\mathbf{v} + p\mathbf{I} - \frac{\mathbf{B}\mathbf{B}}{\mu} + \frac{\mathbf{B}^2}{2\mu} \right) = \rho \mathbf{g},$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B},$$

$$\frac{\partial p}{\partial t} + \nabla \cdot (\gamma p \mathbf{v}) = (\gamma - 1)\left(\mathbf{v} \cdot \nabla p - \mathcal{L}\right).$$

$\mathcal{L} = 0$ (no radiation, conduction or heating)
$\eta = 0$ since $R_m \approx 10^{12}$ (avoid resistive regime)

But still Complex Dynamics!

MHD equations solved numerically in 3D

Theory: basic loop model I

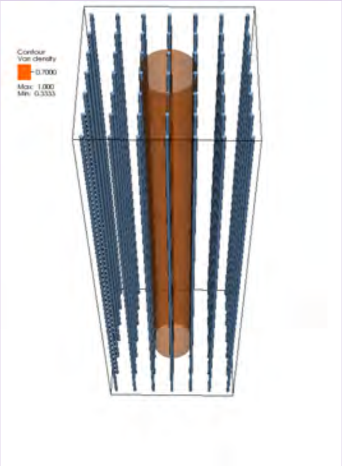
Equilibrium (1D)

- Cylindrically straight magnetic tube with enhanced density

Eigenmodes

- Linearized MHD equations
- Dispersion Relation
  Spruit (1981), Edwin & Roberts (1983), Cally (1986;2003)
- Transverse kink mode, $P = 2L/c_k$,

$$c_k = \frac{\sqrt{2}B_0}{\sqrt{\mu(\rho_i + \rho_e)}}.$$



Theory: basic loop model II

Equilibrium (1D)

- Same as model I but smooth density transition between tube and corona, l/R

Main effect: resonant damping

- Amplitude of the oscillations is damped with time, $\tau_D/P \approx R/l$
- Energy transfer between global motion and azimuthal oscillations

Howlleg & Yang (1988), Goossens et al. (1992), Ruderman & Roberts (2002), Goossens et al. (2002), Terradas et al. (2006)

- Kelvin-Helmholtz instability (KHI) at the boundary
  Terradas et al. (2008), Antolin et al. (2014;2015), Magyar et al. (2015), Magyar & Van Doorsselaere (2016) Terradas et al. (2018)
- Energetically important?
- Heating?

talks of
Antolin, De Moortel,
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3D loop model

Previous works

- Simple curved magnetic field without gravity and gas pressure
  Van Doorsselaere et al. (2004; 2009), Terradas et al. (2006)
  Kink period recovered
- Gas pressure included Pascoe et al. (2009), De Moortel & Pascoe (2009), Pascoe & De Moortel (2014)
  Significant differences in the estimation of B
- Dipolar magnetic field with gravity McLaughlin & Ofman (2008), Selwa et al. (2011)
- Loop produced by emergence of magnetic flux in 3D MHD simulation Chen & Peter (2015)
  Estimation of B from simulations and seismology (diff. of 20%)

Our 3D loop model: relaxation process

- Curved magnetic field
- Change of **B** along and across loop $\rightarrow$ variable loop cross-sec.
- Include gravity force
- MHS solution:

$$
\begin{aligned}
-\frac{\partial p}{\partial s} + \rho g_{\parallel} &= 0, \\
-\nabla_{\perp}\left(p + \frac{B^2}{2\mu}\right) + \frac{B^2}{\mu R}\hat{\mathbf{k}} + \rho \mathbf{g}_{\perp} &= 0.
\end{aligned}
$$

Spruit (1981), Browning & Priest (1986), Ballester & Priest (1989), Hindman & Jain (2013)

Potential magnetic field:

- Based on buried magnetic charges below the photosphere Aschwanden & Sandman (2010)

Stratified density profile:

- Density stratification along and across the loop
- Use overpressure inside the tube

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Examples:

1. Symmetric loop
2. Asymmetric loop
3. Oblique loop
4. Sigmoid type

Results: relaxation

Initial 3D loop model

- Gravity force included
- Loop with enhanced density and pressure
- Symmetric loop
- Potential magnetic field

Loop hotter than environment but initially not in equilibrium

Relaxation process

- Vertical motion (movies 1 and 2)
- Strong changes at the tube boundary related to KHI (movie)
- Relaxation to MHS solution due to generation of scales (phase-mixing) below grid resolution
- B inside loop decreases $\rightarrow$ tension decreases $\rightarrow$ loop rises $\rightarrow$ new equilibrium ($\mathbf{B}$ non potential)

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Results: excitation

Loop Model

- Output from MHD relaxation
- Magnetic field not potential anymore, density and pressure variations along and across the loop

Loop in equilibrium
hotter than environment

Transverse MHD waves

- Vertical excitation (movies 1 and 2)
- Similar to the relaxation process
- Ponderomotive forces specially important for vertical oscillations
- Horizontal excitation (movies 1 and 2)
- Strong dynamics affecting the whole loop, differences with respect to transverse motions in a straight tube

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Results: excitation

Comparison of simulations with theory

$$P_k \approx 2\int_0^L \frac{1}{c_k(s)}\,ds,$$

$$c_k(s) = \frac{\sqrt{2}B(s)}{\sqrt{\mu(\rho_i(s)+\rho_e(s))}}.$$

Loop Model	P_k	P_{Kvert}	P_{Khoriz}
Symmetric	26.5	33.4	33.4
Asymmetric	28.1	31.1	32.2
Oblique	29.8	31.8	32.4

(in units of Alfvén transit times $\approx 20s$)

Maximum percentage difference of 23% in period

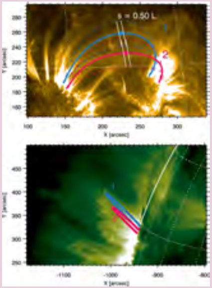
Future work

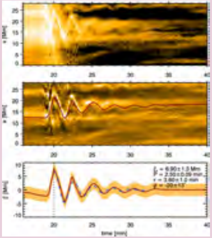
- Perform parametric study of dependence of period:
  1. Dependence with plasma-β
  2. Stronger changes of **B** along loop
- Use non-potential magnetic field, more realistic
- COMPARE MHD SIMULATIONS WITH REAL REPORTED EVENT

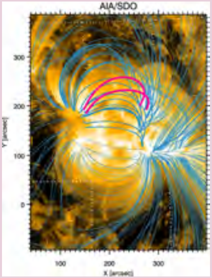
Future work

Study with MHD simulations a real reported event

- Verwichte et al. (2013)







BUILD 3D EQUILIBRIUM OF AR AND SIMULATE TRANSVERSE WAVES