Two-fluid simulations of Rayleigh-Taylor instability in a magnetized solar prominence thread

Beatrice Popescu Braileanu[1,2,*], Slava Lukin[3], Elena Khomenko[1,2], and Ángel de Vicente[1,2]

[1]Instituto de Astrofísica de Canarias, Spain
[2]Departamento de Astrofísica, Universidad de La Laguna, Spain
[*]KU Leuven, Belgium
[3]National Science Foundation, USA

Description of the problem

B. Popescu Braileanu, V. Lukin, E. Khomenko, A. de Vicente

- “Two-fluid simulations of waves in the solar chromosphere. I. Numerical code verification” 2019,A&A, V. 627, id. A25, 10.1051/0004-6361/201834154
- “Two-fluid simulations of waves in the solar chromosphere. II. Propagation and damping of fast magneto-acoustic waves and shocks” 2019,A&A, V. 630, id. A79, 10.1051/0004-6361/201935844
- “Two-fluid simulations of Rayleigh-Taylor instability in a magnetized solar prominence thread. I. Effects of prominence magnetization and mass loading” 2021,A&A, V. 646, id. A93 10.1051/0004-6361/202039053
- “Two-fluid simulations of Rayleigh-Taylor instability in a magnetized solar prominence thread. II. Effects of collisionality” 2021,A&A, V. 650, id. A181, 10.1051/0004-6361/202140425

$\textsc{Mancha3D}$ 2F code. Two-fluid equations

$$\textbf{Continuity:}\begin{cases} \frac{\partial \rho_{\rm n}}{\partial t} + \nabla \cdot (\rho_{\rm n} \mathbf{u}_{\rm n}) &= \boxed{S_{\rm n}} \\ \frac{\partial \rho_{\rm c}}{\partial t} + \nabla \cdot (\rho_{\rm c} \mathbf{u}_{\rm c}) &= \boxed{-S_{\rm n}} \end{cases}$$

$$\textbf{Momentum:}\begin{cases} \frac{\partial (\rho_{\rm n} \mathbf{u}_{\rm n})}{\partial t} + \nabla \cdot (\rho_{\rm n} \mathbf{u}_{\rm n} \mathbf{u}_{\rm n} + p_{\rm n} \mathbb{I} - \hat{\tau}_{\rm n}) &= \rho_{\rm n} \mathbf{g} + \boxed{\mathbf{R}_{\rm n}} \\ \frac{\partial (\rho_{\rm c} \mathbf{u}_{\rm c})}{\partial t} + \nabla \cdot (\rho_{\rm c} \mathbf{u}_{\rm c} \mathbf{u}_{\rm c} + p_{\rm c} \mathbb{I} - \hat{\tau}_{\rm c}) &= \mathbf{J} \times \mathbf{B} + \rho_{\rm c} \mathbf{g} \boxed{-\mathbf{R}_{\rm n}} \end{cases}$$

$$\textbf{Energy:}\begin{cases} \frac{\partial}{\partial t}\left(e_{\rm n} + \frac{1}{2}\rho_{\rm n} u_{\rm n}^2\right) + \nabla \cdot \left[\mathbf{u}_{\rm n}(e_{\rm n} + \frac{1}{2}\rho_{\rm n} u_{\rm n}^2) + (p_{\rm n}\mathbb{I} - \hat{\tau}_{\rm n}) \cdot \mathbf{u}_{\rm n} + \mathbf{q}_{\rm n}\right] \\ \qquad = \rho_{\rm n} \mathbf{u}_{\rm n} \cdot \mathbf{g} + \boxed{M_{\rm n}} \\ \frac{\partial}{\partial t}\left(e_{\rm c} + \frac{1}{2}\rho_{\rm c} u_{\rm c}^2\right) + \nabla \cdot \left[\mathbf{u}_{\rm c}(e_{\rm c} + \frac{1}{2}\rho_{\rm c} u_{\rm c}^2) + (p_{\rm c}\mathbb{I} - \hat{\tau}_{\rm c}) \cdot \mathbf{u}_{\rm c} + \mathbf{q}_{\rm c}\right] \\ \qquad = \rho_{\rm c} \mathbf{u}_{\rm c} \cdot \mathbf{g} + \mathbf{J} \cdot \mathbf{E} \boxed{-M_{\rm n}} \end{cases}$$

Ideal induction equation:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \mathbf{u}_{\rm c} \times \mathbf{B}.$$

Collisional terms

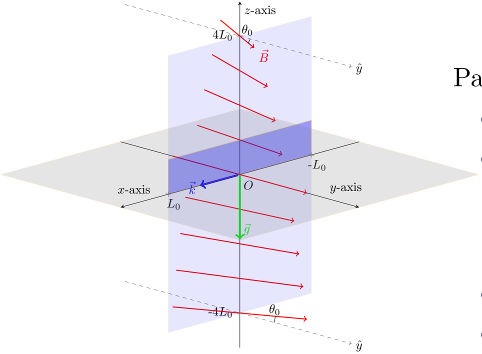
We define α so that : $\rho_e \nu_{en} + \rho_i \nu_{in} = \rho_\mathrm{n} \rho_\mathrm{c} \alpha^\mathrm{el}$; $\alpha = \alpha^\mathrm{el} + \alpha^\mathrm{cx}$

$$\boxed{S_\mathrm{n} = \rho_\mathrm{c} \Gamma^\mathrm{rec} - \rho_\mathrm{n} \Gamma^\mathrm{ion}}$$

$$\boxed{\mathbf{R}_\mathrm{n} = \rho_\mathrm{c} \mathbf{u}_\mathrm{c} \Gamma^\mathrm{rec} - \rho_\mathrm{n} \mathbf{u}_\mathrm{n} \Gamma^\mathrm{ion} + \rho_\mathrm{n} \rho_\mathrm{c} \alpha (\mathbf{u}_\mathrm{c} - \mathbf{u}_\mathrm{n})}$$

$$\boxed{\begin{aligned} M_\mathrm{n} = \frac{1}{2} \Gamma^\mathrm{rec} \rho_\mathrm{c} u_\mathrm{c}^2 - \frac{1}{2} \rho_\mathrm{n} u_\mathrm{n}^2 \Gamma^\mathrm{ion} + \frac{1}{\gamma - 1} \frac{k_\mathrm{B}}{m_\mathrm{n}} \left(\rho_\mathrm{c} T_\mathrm{c} \Gamma^\mathrm{rec} - \rho_\mathrm{n} T_\mathrm{n} \Gamma^\mathrm{ion} \right) \\ + \frac{1}{2} ({u_\mathrm{c}}^2 - {u_\mathrm{n}}^2) \rho_\mathrm{n} \rho_\mathrm{c} \alpha + \frac{1}{\gamma - 1} \frac{k_\mathrm{B}}{m_\mathrm{n}} (T_\mathrm{c} - T_\mathrm{n}) \rho_\mathrm{n} \rho_\mathrm{c} \alpha \end{aligned}}$$

Rayleigh-Taylor instability 2D configuration



Parameters of the simulations:

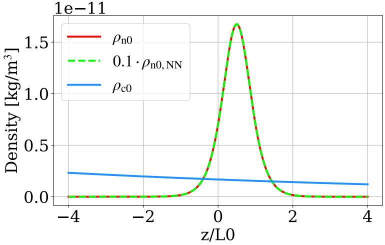
- Density contrast ("NN")
- Configuration of the background magnetic field: perpendicular to the perturbation plane ("P") or sheared ("L1")
- Magnetic field strength ("B")
- Elastic and inelastic collisions

$L_0 = 1$ Mm

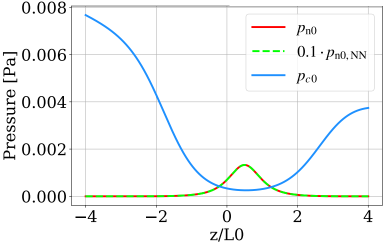
Thu 9 Sep 11:39, sid 10.3, aid 453, Elena Khomenko
Thu 9 Sep 11:26, sid 10.5, aid 444, Slava Lukin

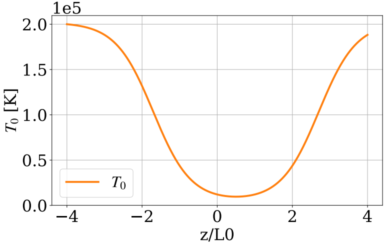
Background atmosphere

Densities

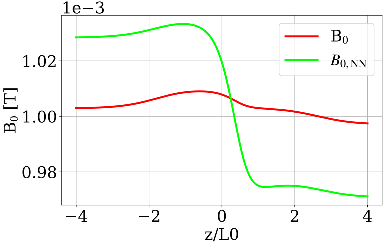


Pressures





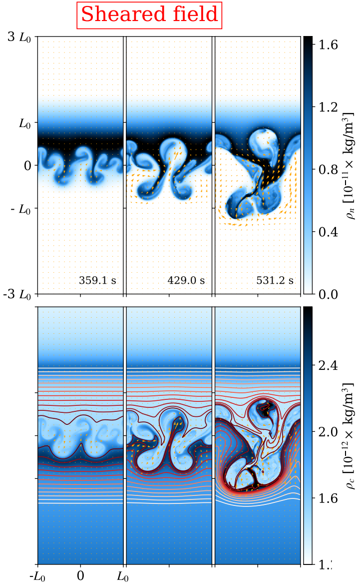
Temperature



Magnetic field

Overview of the simulations

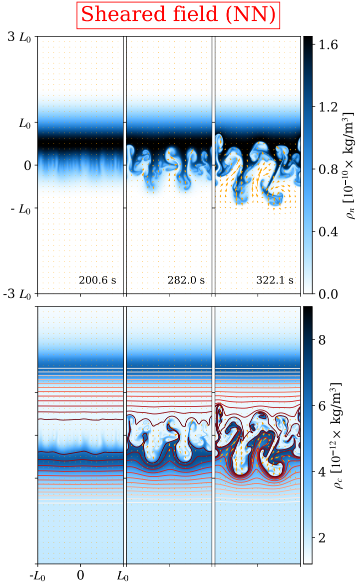
Sheared field



movie

- Bubbles and spikes form in the nonlinear phase of the instability.
- Similar magnetic structures form in the simulations with sheared magnetic field.

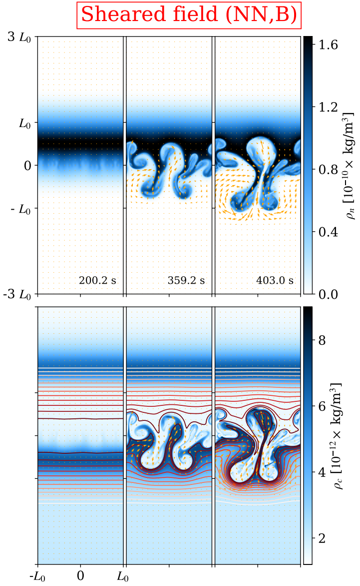
Density contrast



movie

- More smaller scales and larger growth rate when the density contrast is increased

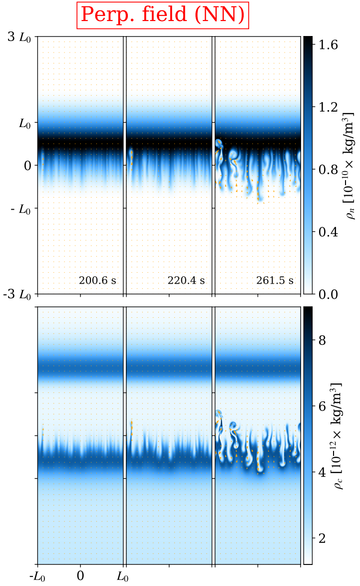
Magnetic field strength



movie

- Fewer smaller scales and smaller growth rate when the magnetic field strength is increased

Perpendicular magnetic field configuration

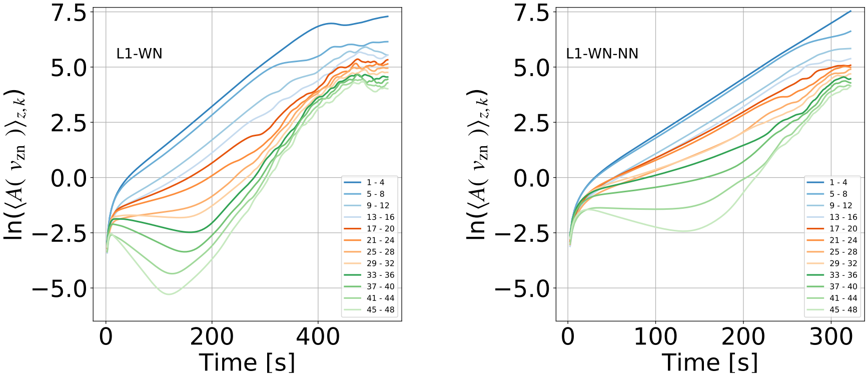


movie

- More smaller scales and larger growth rate when the magnetic field is perpendicular to the plane of the perturbation

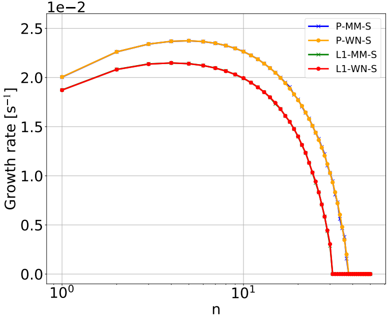
Analysis of the results

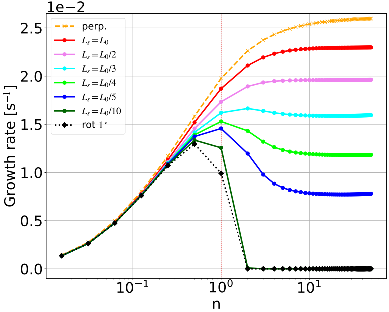
Growth of the modes



The small scales which do not have an initial linear phase are suppressed by the viscosity and ion-neutral collisions.

Linear growth rate

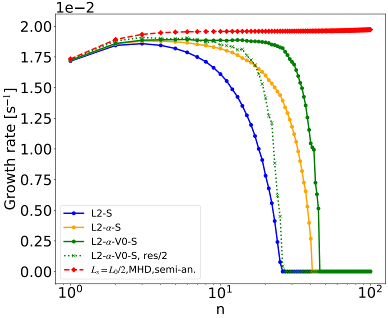


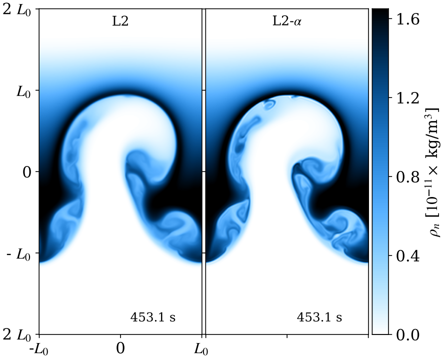


- The linear growth rate is smaller when the field is sheared.
- The linear growth rate decreases when the shear length decreases, going to zero for sufficiently small shear length.
- The small scales cutoff that appears in the simulations is due to the viscosity and ion-neutral collisions.

Elastic collisions

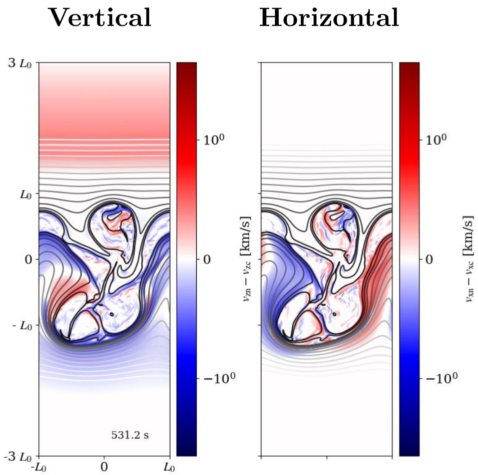
- Comparison of simulated growth rates with/without elastic collisions at different resolutions





- The elastic collisions also suppress the nonlinear development of small scales, which can be viewed as a loss of contrast in the density snapshots.

Decoupling

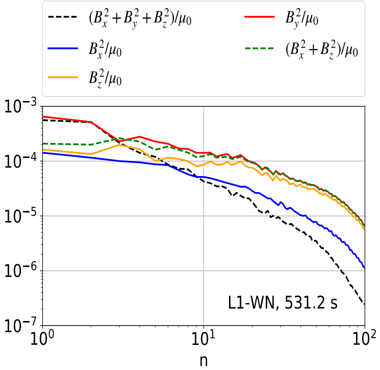


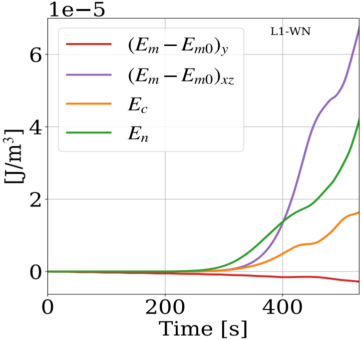
movie

- The largest decoupling is localized where the magnetic field lines are most compressed and bent.
- The decoupling can be as much as 5% of the velocity.

Magnetic structures

E_m=magnetic energy, E_c=charges kinetic energy, E_n=neutrals kinetic energy





- The in-plane and the out of plane components of the magnetic energy become correlated at intermediate and small scales.
- Depending on initial equilibrium, a large fraction of free energy of the prominence may be deposited into the magnetic energy.

Conclusions

- The component of the magnetic field parallel to the direction of the perturbation suppresses the growth of the small scales. The growth rate decreases with the decrease of the shear length of the magnetic field.
- Increased density contrast leads to earlier development of smaller scales.
- The suppression of the growth rate of the small scales is due to the effect of elastic collisions.
- Ion-neutral collisions qualitatively modify the structure of RTI modes for high mode numbers; the effect of viscosity appears at yet smaller scales.
- Nonlinear evolution of RTI shows correlation between the level of magnetic activity, magnetic structure formation, and the degree of the charge-neutral decoupling. On intermediate and small scales, spectral structure of in-plane and perpendicular components of the magnetic field become correlated.