The Rayleigh Taylor instability in the two-fluid approach

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Summary

The Rayleigh Taylor instability has been frequently observed at the interface between a prominence and the solar corona. We study the growth rate of the instability in a smoothly non uniform medium in the two fluid approximation, using different configurations for the background magnetic field. We run 2D simulations with the magnetic field perpendicular to the plane defined by the gravity and the 1D perturbation, slightly rotated, and sheared. We also run 3D simulations with a 2D perturbation in the plane perpendicular to the direction of the gravity and using a sheared background magnetic field configuration. In the simulations we include non-linear effects, viscosity, thermal conduction, most of the terms in the Ohm's law and of those related to the collisions between neutrals and charges: ionization/recombination, energy and momentum transfer, and frictional heating. We compare the linear growth rate calculated from the numerical solutions to the semi-analytical solutions.

References

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Hillier, A. 2017, Reviews of Modern Plasma Physics, 2, 1
Khomenko, E., Díaz, A., de Vicente, A., Collados, M., & Luna, M. 2014, A&A 565, A45
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Equations:

We assume hydrogen plasma, ideal gas law for both species :

internal energy: $e_j = \frac{1}{\gamma-1}p_j$ (where j=c for charges and j=n for neutrals) , $p_n = \frac{k_B}{m_n}\rho_n T_n$, $p_c = 2\frac{k_B}{m_n}\rho_c T_c$

Continuity:
$$\frac{\partial \rho_n}{\partial t} + \nabla\cdot(\rho_n\vec{v}_n) = S_n$$
$$\frac{\partial \rho_c}{\partial t} + \nabla\cdot(\rho_c\vec{v}_c) = -S_n$$
$$S_n = \rho_c\Gamma^{\rm rec} - \rho_n\Gamma^{\rm ion}$$

Ohm's law :
$$[\vec{E} + \vec{v}_c\times\vec{B}] = \frac{1}{en_e}[\vec{J}\times\vec{B}] - \frac{1}{en_e}\vec{\nabla}p_e + \frac{\rho_e\nu_{en}}{(en_e)^2}\vec{J} - \frac{\rho_e(\nu_{en}-\nu_{in})}{en_e}(\vec{v}_c-\vec{v}_n)$$

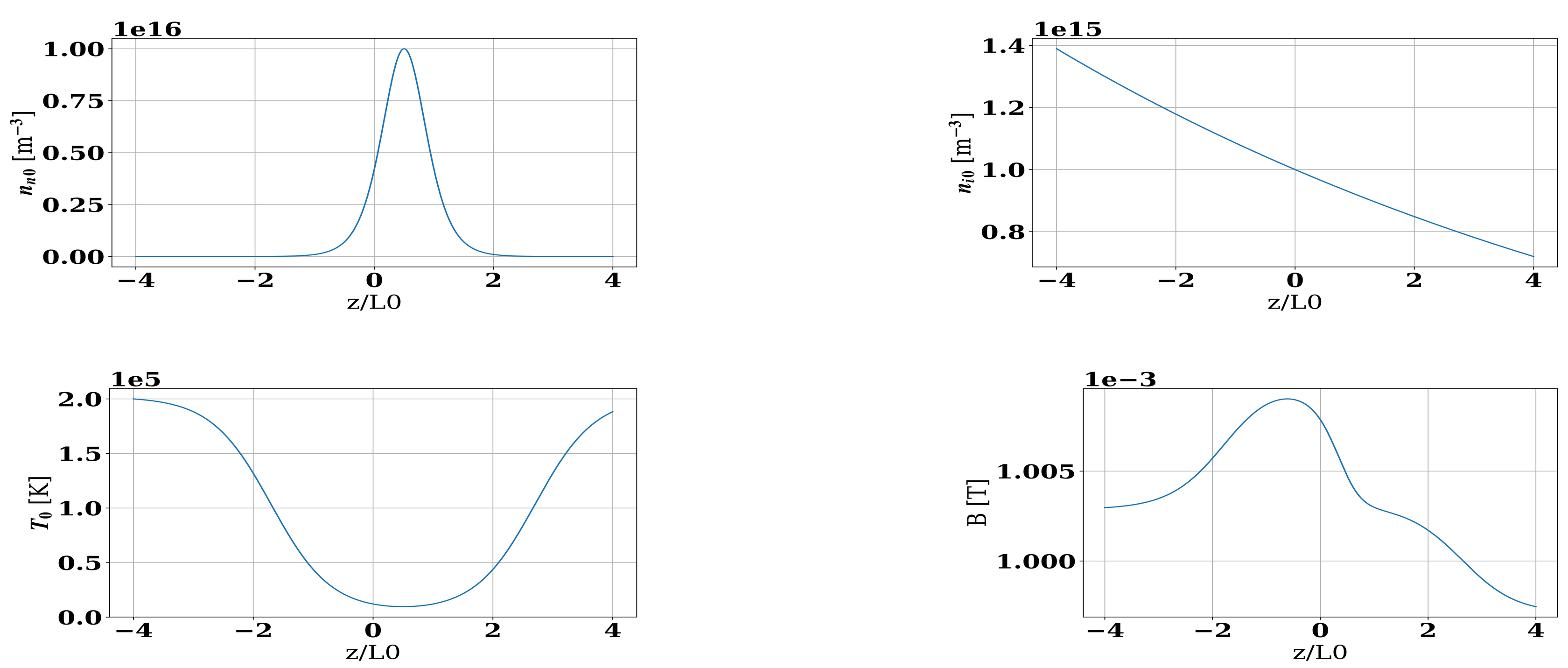
Induction equation : $\frac{\partial\vec{B}}{\partial t} = -\nabla\times\vec{E}$

Momentum:
$$\frac{\partial(\rho_n\vec{v}_n)}{\partial t} + \nabla\cdot(\rho_n\vec{v}_n\otimes\vec{v}_n + \hat{p}_n) = \rho_n\vec{g} + \vec{R}_n$$
$$\frac{\partial(\rho_c\vec{v}_c)}{\partial t} + \nabla\cdot(\rho_c\vec{v}_c\otimes\vec{v}_c + \hat{p}_c) = [\vec{J}\times\vec{B}] + \rho_c\vec{g} - \vec{R}_n$$
$$\vec{R}_n = \rho_c\vec{v}_c\Gamma^{\rm rec} - \rho_n\vec{v}_n\Gamma^{\rm ion} + \vec{R}', \vec{R}' = \alpha\rho_n\rho_c(\vec{v}_c - \vec{v}_n)$$

where α is defined through $\rho_c\rho_n\alpha = \rho_e\nu_{en} + \rho_i\nu_{in}$, and $\vec{J} = \frac{1}{\mu_0}\nabla\times\vec{B}$ and pressure tensors $\hat{p}_{n,c}$ include viscous tensors.

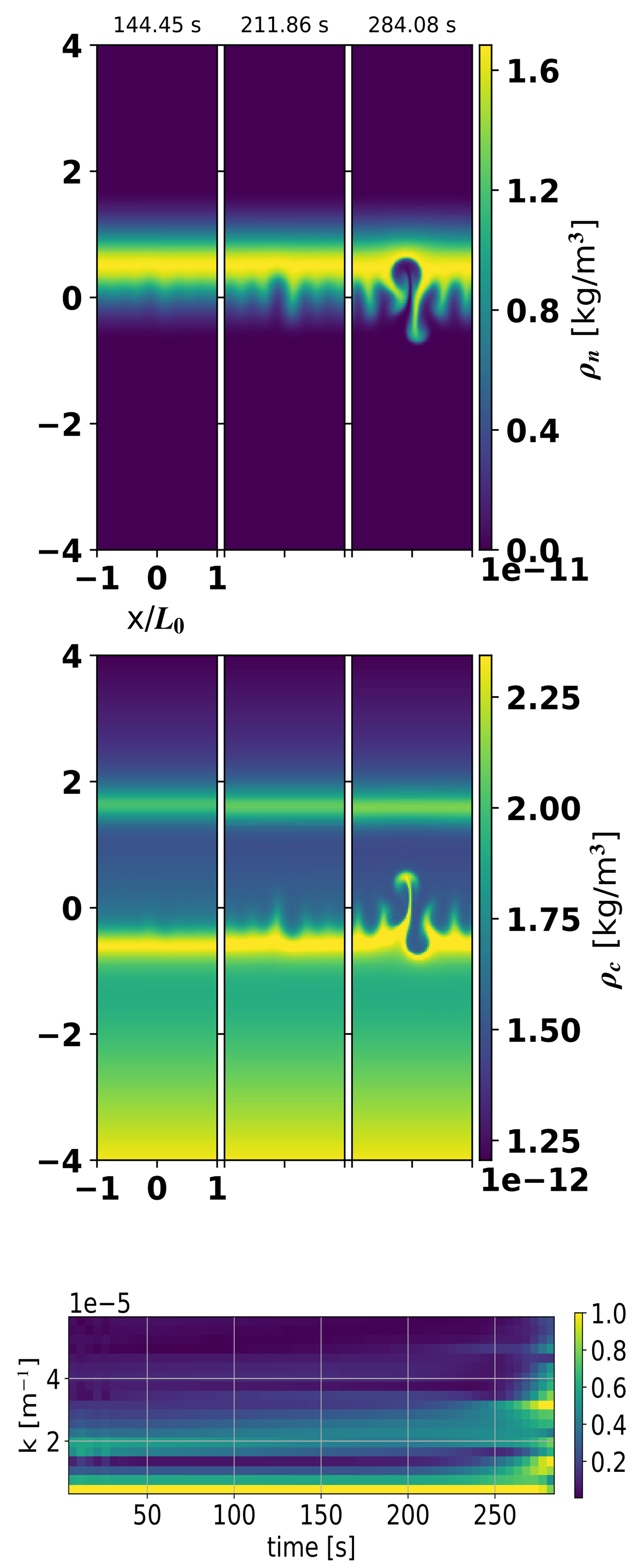
Energy :
$$\frac{\partial}{\partial t}\left(e_n + \frac{1}{2}\rho_n v_n^2\right) + \nabla\cdot\left(\vec{v}_n(e_n + \frac{1}{2}\rho_n v_n^2) + \hat{p}_n\vec{v}_n - K_n\vec{\nabla}T_n\right) = \rho_n\vec{v}_n\vec{g} + M_n$$
$$\frac{\partial}{\partial t}\left(e_c + \frac{1}{2}\rho_c v_c^2\right) + \nabla\cdot\left(\vec{v}_c(e_c + \frac{1}{2}\rho_c v_c^2) + \hat{p}_c\vec{v}_c - K_c\vec{\nabla}T_c\right) = \rho_c\vec{v}_c\vec{g} + \vec{J}\vec{E} + M_c$$
$$M' = \frac{1}{2}\Gamma^{\rm rec}\rho_c v_c^2 - \frac{1}{2}\rho_n v_n^2\Gamma^{\rm ion} + \frac{1}{\gamma-1}\frac{k_B}{m_n}\left(\rho_c T_c\Gamma^{\rm rec} - \rho_n T_n\Gamma^{\rm ion}\right) + \frac{1}{2}(\vec{v}_c-\vec{v}_n)^2\alpha\rho_n\rho_c + \frac{B}{\gamma-1}\frac{k_B}{m_n}(T_c - T_n)\alpha\rho_n\rho_c$$
$$(M_c = -M_n), M_n = M' + \vec{v}_n\vec{R}', M_c = M' - \vec{v}_c\vec{R}'$$

Setup



∢ (magnetic field, the plane): 90°

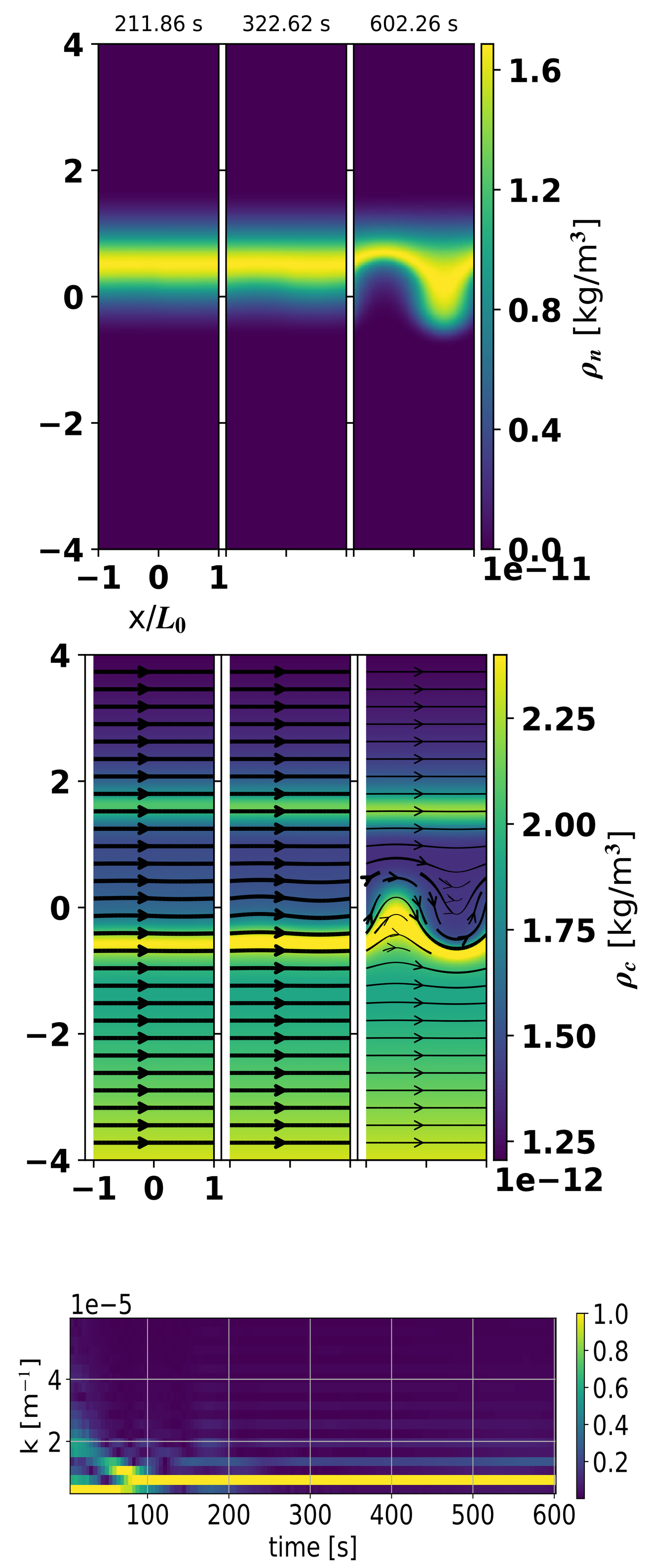
Mean linear growth rate: **2.44** × **10^{-2} s^{-1}**



Normalized Fourier power

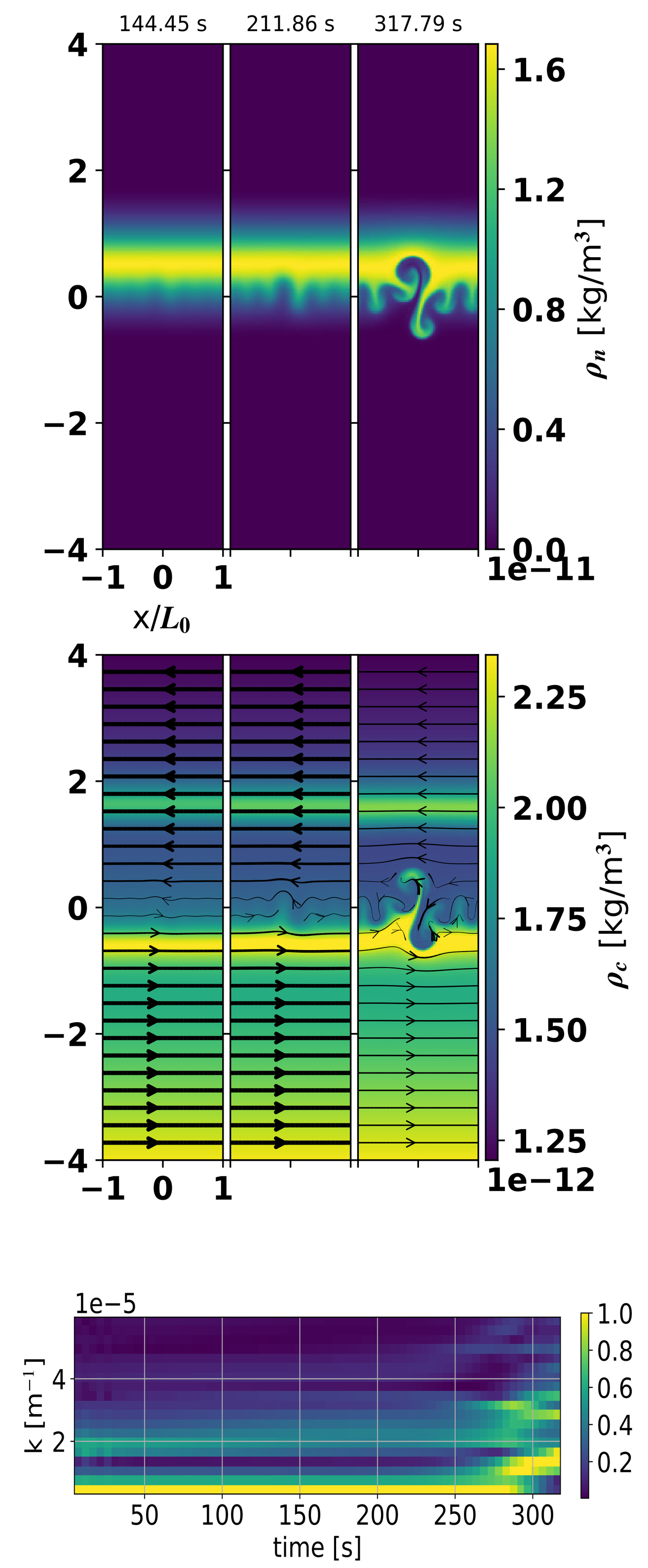
89°

1.17 × 10^{-2} s^{-1}

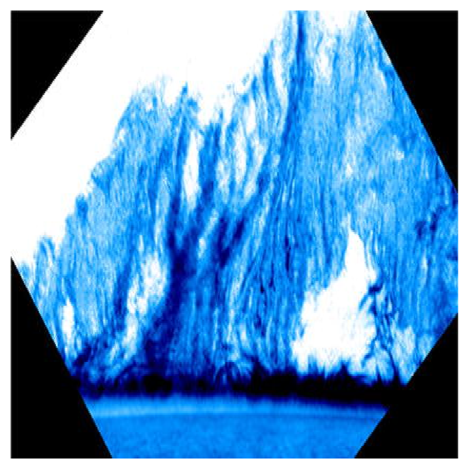


Sheared from 89° to 91°

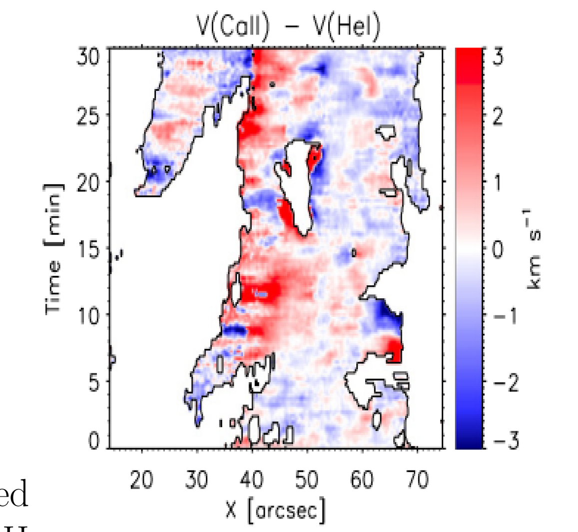
2.29 × 10^{-2} s^{-1}



Observations

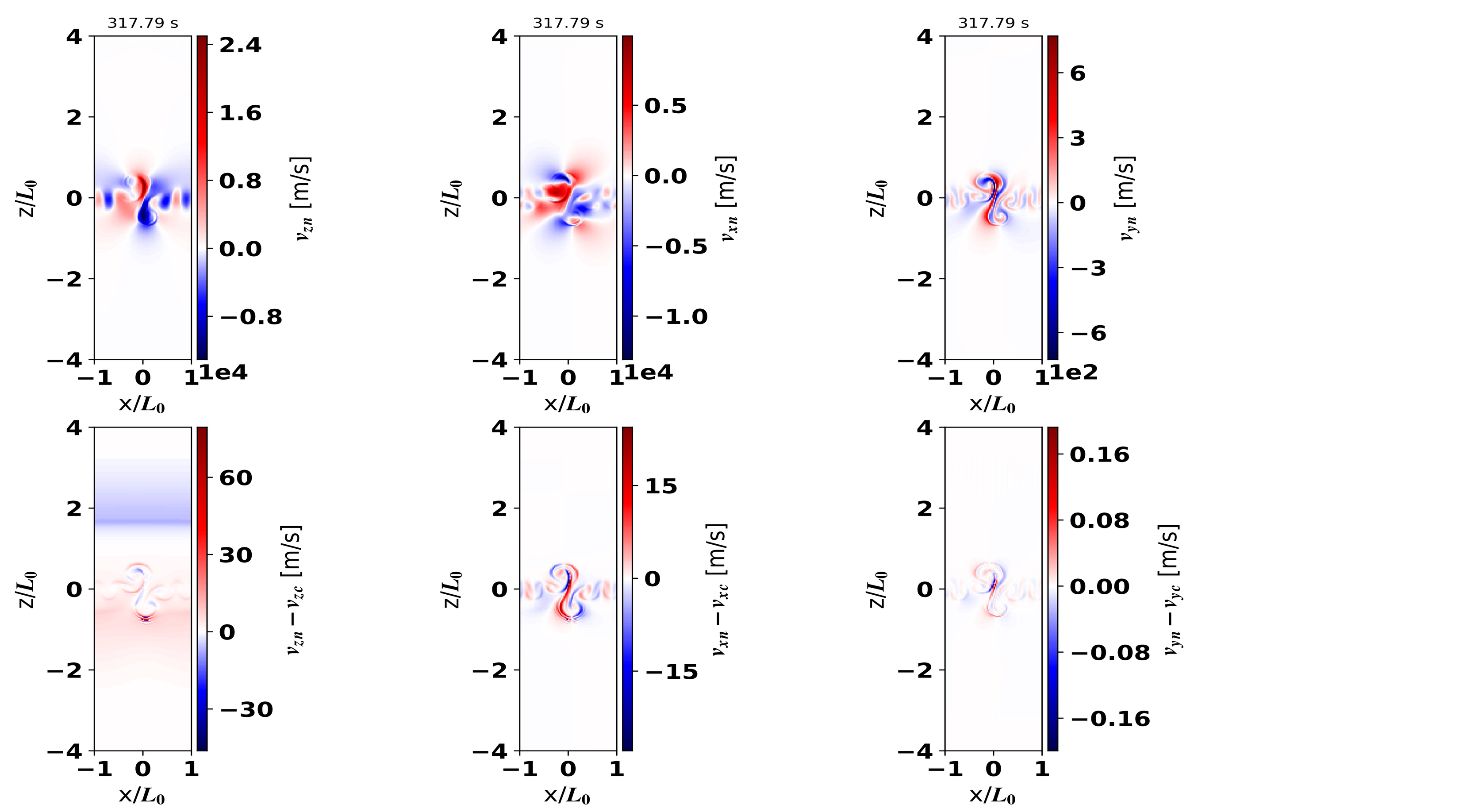


A quiescent prominence observed by Hinode SOT using the Ca II H broadband filter on 29 September 2008. Fig. 2 from Hillier (2017)



Ion-neutral drift velocity measured in a prominence. Fig. 7 from Khomenko et al. (2016)

Decoupling in velocities for the sheared magnetic field configuration



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