3D numerical simulations of torsional Alfvén waves in solar flux tubes

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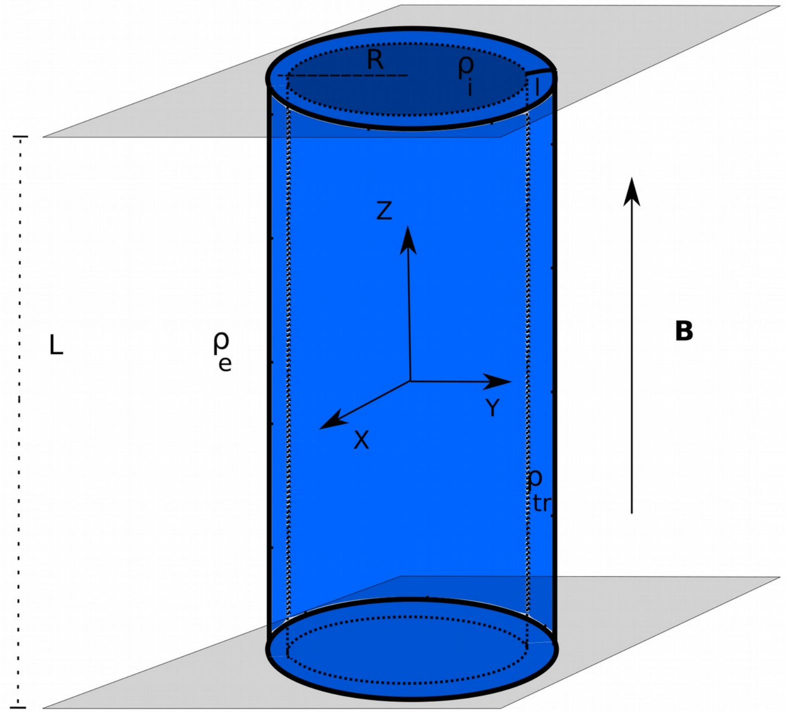
Observations have shown that Alfvén waves are ubiquitous in the solar atmosphere. Recently, torsional Alfvén waves in flux tubes have been first detected. Here, we perform numerical simulations of torsional Alfvén waves and study their nonlinear evolution. We consider a cylindrical, radially inhomogeneous, and straight magnetic flux tube that is line-tied at two rigid walls representing the solar photosphere. Standing torsional Alfvén waves are excited by perturbing the azimuthal component of the velocity. The nonlinear evolution of these waves is obtained with the PLUTO code, which solves the ideal MHD equations using a finite-volume formulation with adaptive mesh refinement. We find that the evolution of the waves is heavily affected by the phase mixing process, which generates small scales across the magnetic field direction. In the case of low amplitudes, the simulations are compared with the results predicted by linear theory. In the fully nonlinear case, we study how the later evolution of phase mixing triggers Kelvin-Helmholtz instabilities.

Context of research

- High-resolution observations have shown the ubiquity of Alfvén waves through the solar atmosphere (e.g., De Pontieu et al. 2007; Jess et al. 2009; McIntosh et al. 2011; De Pontieu et al 2014; Morton et al. 2015; Jafarzadeh et al. 2017; Srivastava et al. 2017).
- They may play a fundamental role in the transport and dissipation of energy and may contribute to the heating of the solar corona (e.g., Hollweg 1978; Cranmer & van Ballegooijen 2005; Cargill & de Moortel 2011; Mathioudakis et al. 2013; Jess et al. 2015; Soler et al. 2019).
- Due to plasma inhomogeneity across the magnetic field, Alfvén waves undergo the process of phase mixing, which cascades energy from large scales to the dissipative scales (e.g., Heyvaerts & Priest 1983; Nocera et al. 1984; De Moortel et al. 2000; Smith et al. 2007).
- In the nonlinear evolution of phase mixing, Kelvin-Helmholtz instabilities are triggered, which can speed up the cascading of energy (e.g., Browning & Priest 1984; Pagano et al. 2018; Van Damme et al. 2020; Howson et al. 2020).

We aim to investigate nonlinear phase mixing of torsional Alfvén waves in a simple configuration representing a coronal loop.

Methodology



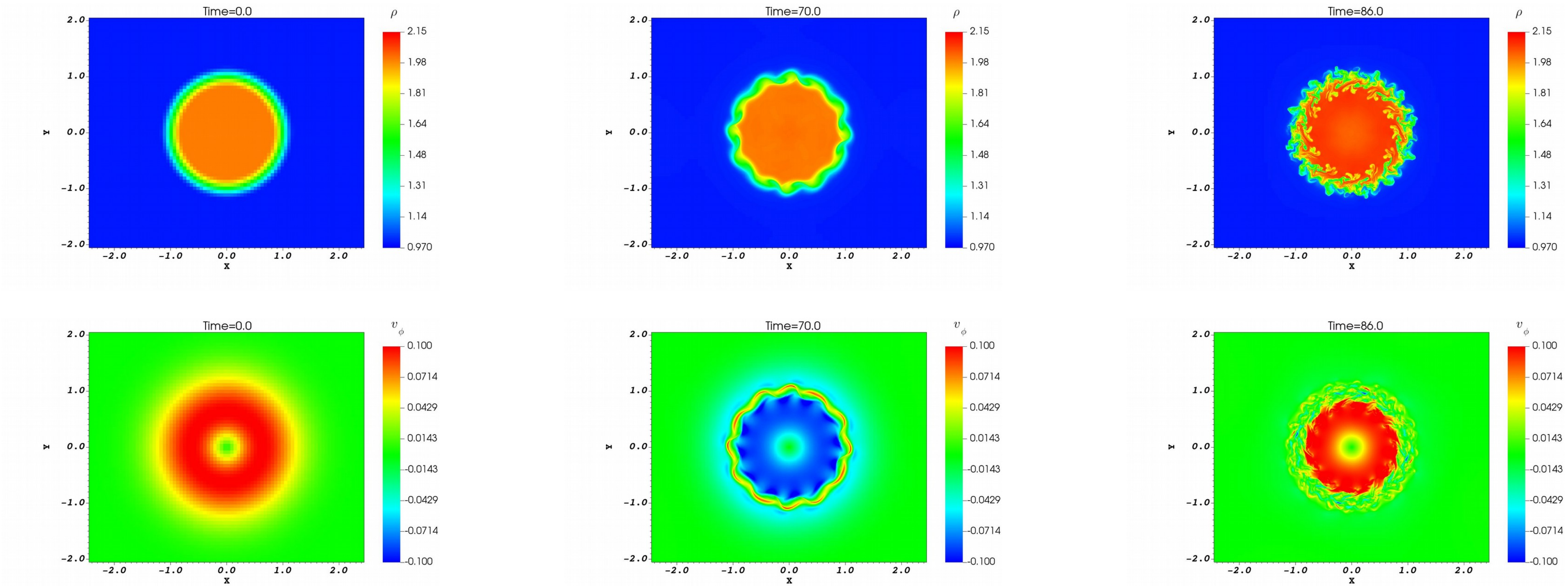
- We consider a cylindrical, radially inhomogeneous, and straight magnetic flux tube that represents a coronal loop. The tube ends are line-tied at two rigid walls representing the solar photosphere.

- The 3D ideal MHD equations are numerically solved with the PLUTO code (Mignone et al. 2007) that uses finite volumes with adaptive mesh refinement (Mignone et al 2012). The largest effective resolution is 1600x1600x1600.

- A standing torsional wave is excited with a prescribed amplitude. The numerical results are compared with those from analytic linear theory.

Results for a particular set-up

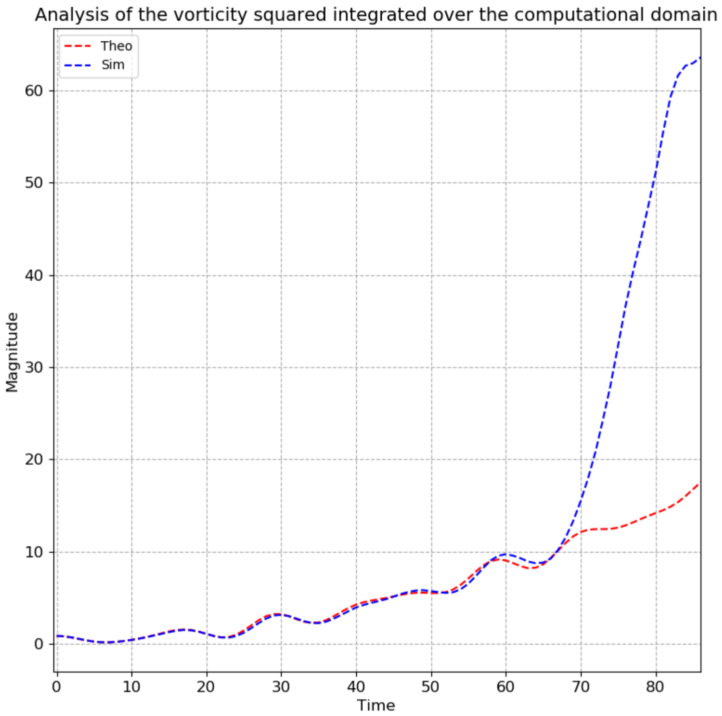
- The top panels display a cross-sectional cut of density at the tube center at three different simulation times. The triggering of Kelvin-Helmholtz instabilities is clear in the later evolution.

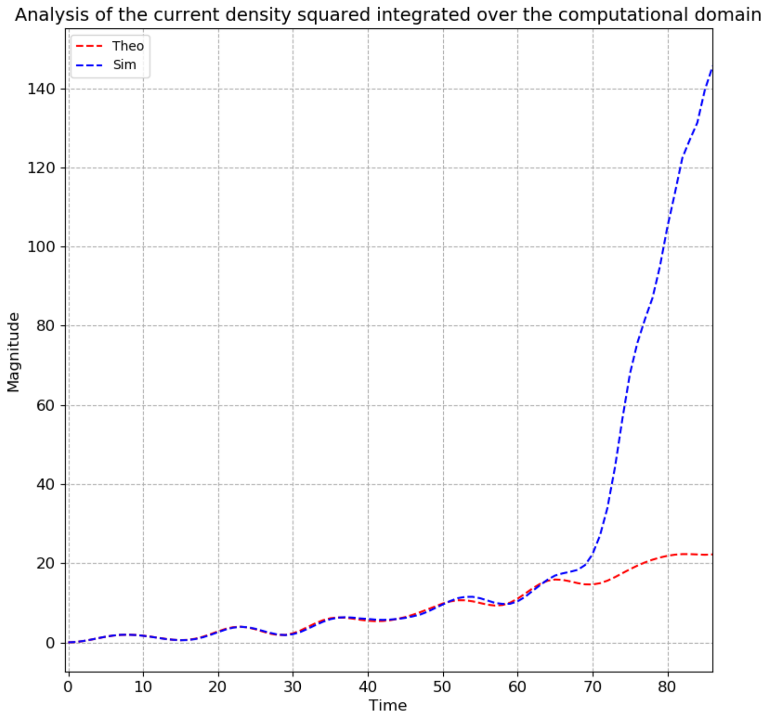


- The bottom panels display the same cut but for the azimuthal component of velocity at the same times as the top panels. Here, the development of phase-mixing (i.e., alternating positive and negative values) can be seen at the tube boundary prior to the development of the instability. An animation of both panels is available.

Comparison of linear theory with full nonlinear simulations

- Vorticity squared (left panel) and current density squared (right panel) integrated over the whole box as a function of the computational time.





- Red dashed lines denote the linear analytic results whereas blue dashed lines denote the numerical results. The increase of both physical quantities with time, predicted by linear theory, is owing to phase-mixing alone. The dramatic increase towards the end of the full nonlinear simulation is due to the triggering of the Kelvin-Helmholtz instability.

Impact and prospects for the future

- Torsional Alfvén waves undergo nonlinear phase-mixing in the inhomogeneous layer. The Kelvin-Helmholtz instability is subsequently triggered in the later evolution.

- The instability significantly increases the total values of current density and vorticity, and takes energy down to smaller scales where it can be efficiently dissipated.

- We expect to shed light on the role of torsional Alfvén waves in the heating of the solar corona.

- A publication based on these results is currently in preparation and will be submitted in Astronomy & Astrophysics.