Three-dimensional structuring and shock formation in the coronal streamer belt: a numerical study

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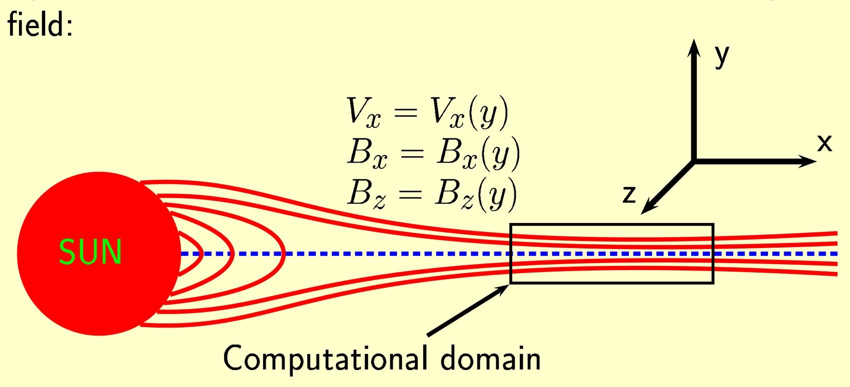
Model

CORONAL STREAMER BELT: magnetohydrodynamic configurations which have shear both in velocity and magnetic field:

$$V_x = V_x(y)$$
$$B_x = B_x(y)$$
$$B_z = B_z(y)$$



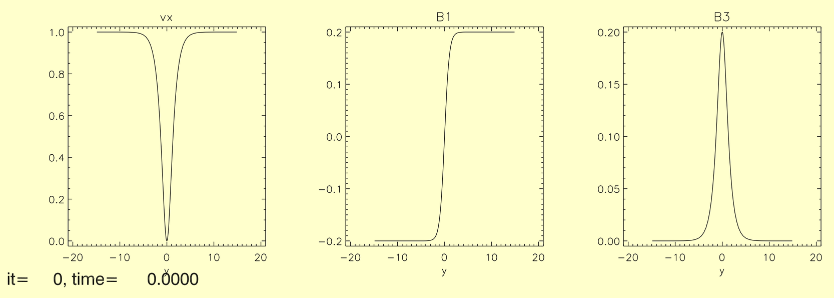
MODEL: 1D Magnetized wake co-spatial with a current sheet:
force–free equilibrium configuration[1]:

$$V_x = 1 - \frac{1}{\mathrm{Cosh}\, y},\ V_y = 0,\ V_z = 0.$$

$$B_x = \frac{1}{M_a}\mathrm{Tanh}\frac{y}{W},\ B_y = 0,\ B_z = \frac{1}{M_a}\mathrm{Cosh}^{-1}\frac{y}{W},$$

$$\rho = 1.0,\quad P_{thermal} = (\gamma M_s^2)^{-1}.$$

M_s – sonic Mach number, M_a – Alfvén Mach number, $\gamma = 5/3$ – adiabatic index, W – width of the current sheet.

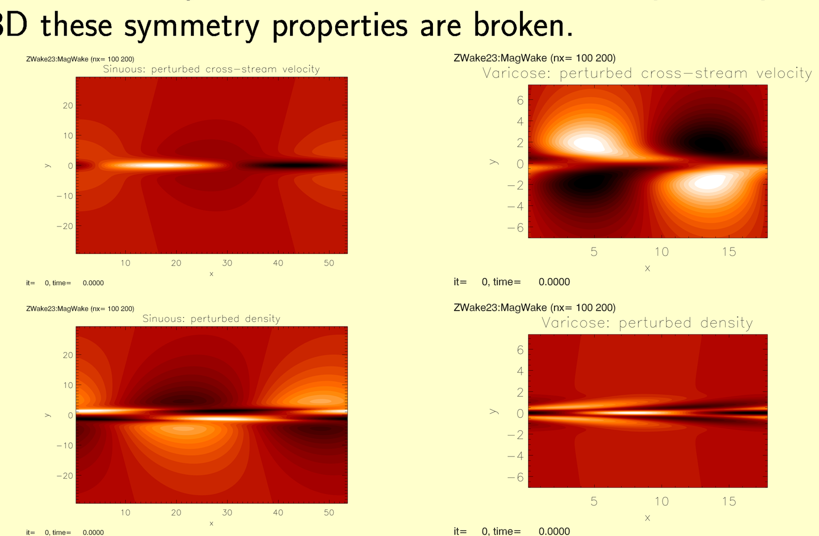


Questions under consideration:

- Types of MHD instabilities in sheared configurations
- Ideal sinuous instability: parameter ranges of stable/unstable behavior
- 3D versus 2D instability, interaction and interplay between 2D and 3D unstable modes
- Saturation and nonlinear evolution: structure and shock formation

MHD instabilities in wake configuration

THREE unstable modes: ideal *sinuous* mode, ideal *varicose* mode and resistive *varicose* (tearing-type) mode. In two-dimensional case unstable modes have symmetries. Sinuous: EVEN cross-stream perturbed velocity, ODD cross-stream perturbed magnetic field. Varicose: opposite symmetry. In 3D these symmetry properties are broken.



Summary

- Wake-current sheet configuration can be unstable with respect to ideal sinuous and varicose instabilities and tearing-type (resistive varicose) instability.
- In contrast to the incompressible case, there exist some ranges of Mach number M_s and Alfvén Mach number M_a, where the most unstable sinuous mode is oblique to the shear layer, and pure three-dimensional instability develops faster than 2D does.
- For the dominant 3D instability, the Mach number should exceed some threshold value ($M_s > 2.6$). With increase of M_s, the range of M_a corresponding to 3D instability decreases, however even for sufficiently high M_s dominant 3D instability still exists in some range of M_a.
- At the nonlinear stage of sinuous instability in supersonic regime, self-consistent formation of fast magnetosonic shocks carrying the density perturbations far away from the wake's center is observed. Depending on the wake velocity contrast and magnetic field magnitude, as well as on the streamwise and spanwise scale of initial perturbation, these shocks may have two-dimensional as well as three-dimensional structure.
- Fast magnetosonic shocks develop only when Mach number is larger than some critical value M_s^{cr}, which depends on M_a.

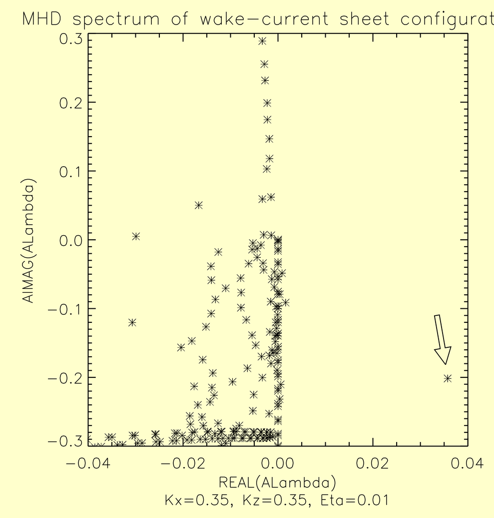
References

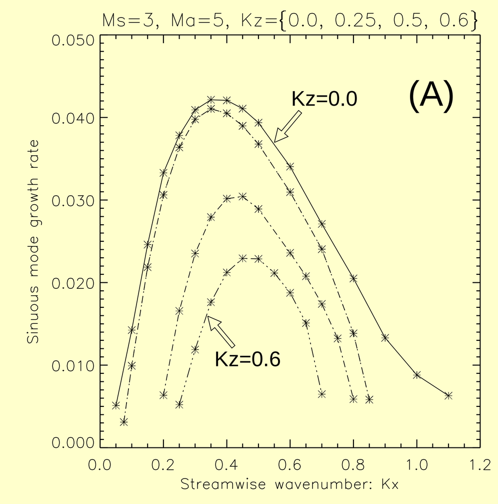
1. G. Einaudi, P. Boncinelli, R. Dahlburg, J. Karpen. JGR, 104, A1, 1999.
2. R. Nijboer, B. van der Holst, S. Poedts, J.P. Goedbloed. Comput. Phys. Commun., 101, 39, 1999.
3. G. Tóth. Astrophys. Lett. Commun., 34, 245, 1996.

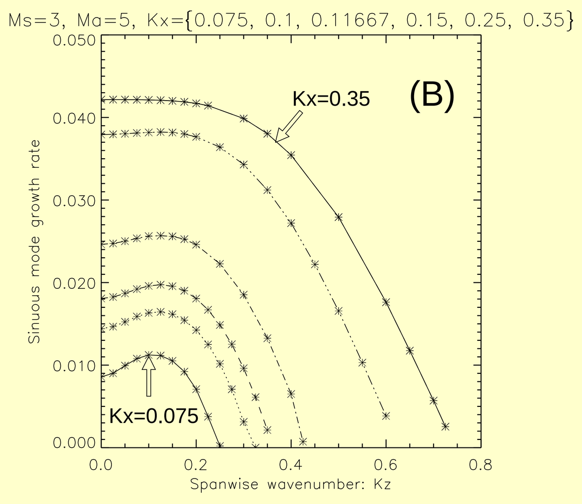
Linear stability analysis: LEDAFLOW[2]

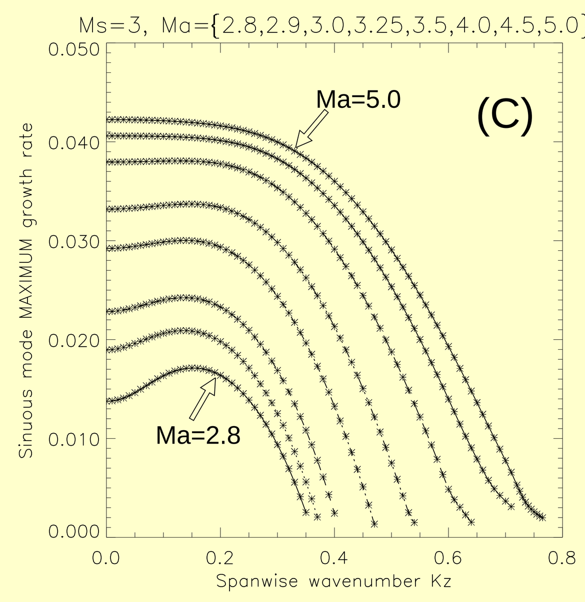
MODE 1: finds the complete HD or MHD spectrum.
MODE 2: iterates to one particular eigenvalue.

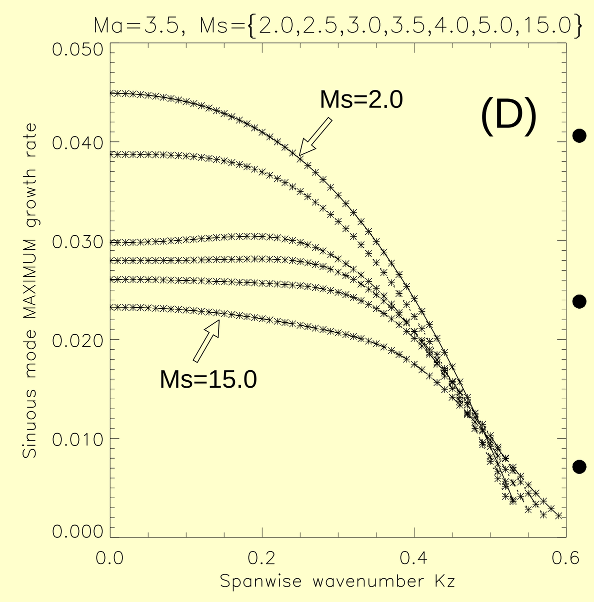
Entire MHD spectrum: $M_s = 3$, $M_a = 5$, $\eta = 0.01$. $Re\,\lambda > 0$, $\rightarrow$ instability. Sinuous mode is marked by arrow.







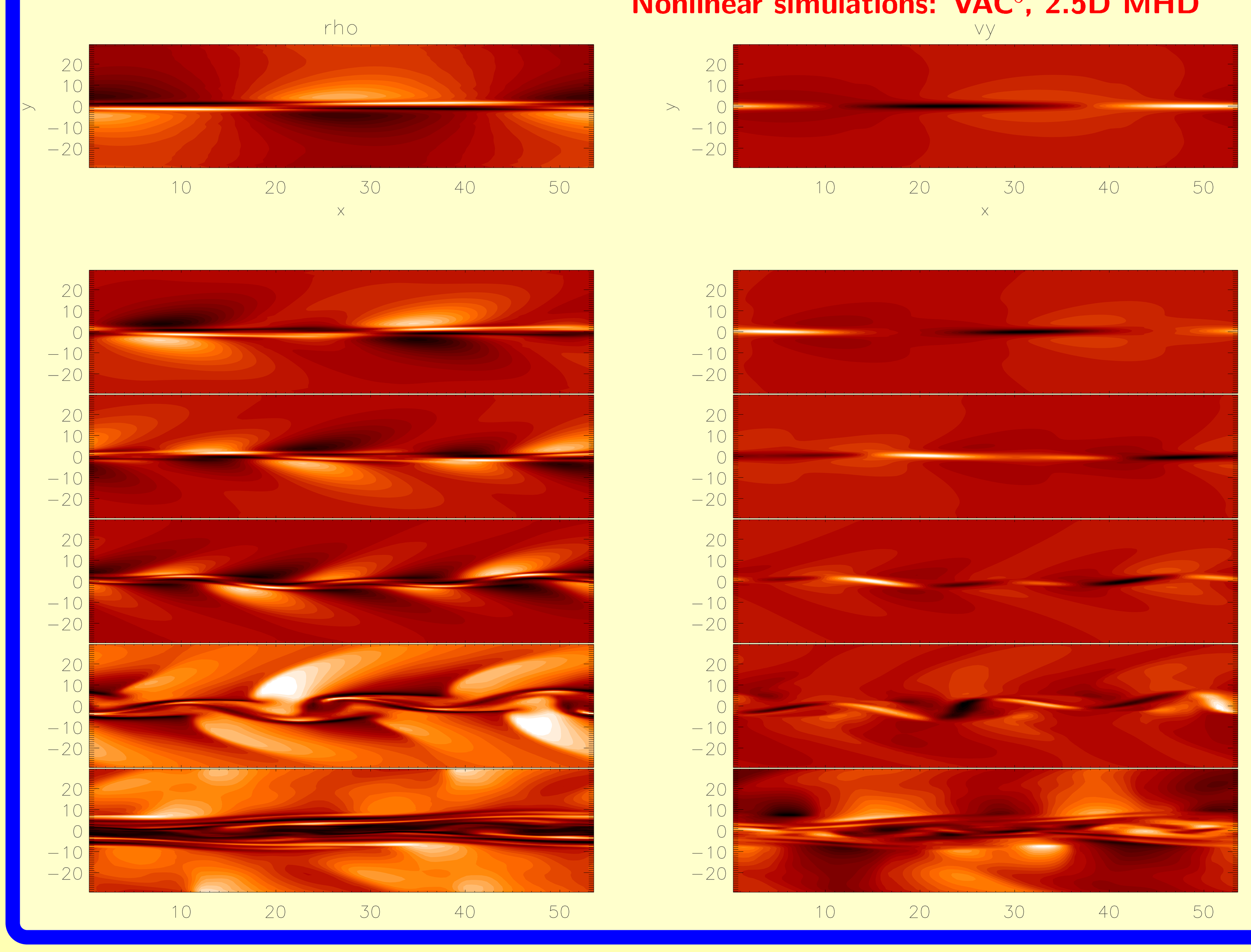


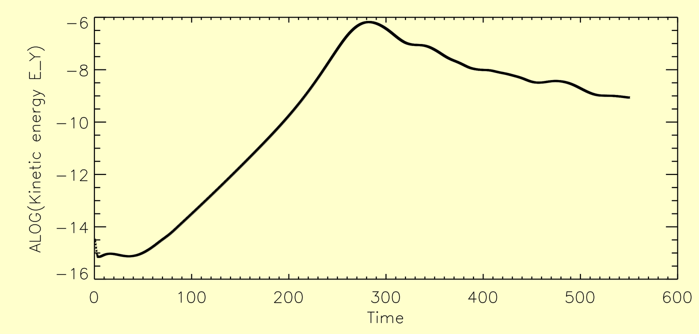


Sinuous instability in wake – current sheet configuration:

- The range of destabilized streamwise wavenumbers K_x is most wide in 2D (A), and it decreases with increase of K_z. The range of destabilized spanwise wavenumbers K_z increases monotonically with increase of K_x (B).
- Maximum growth rate occurs for nonmagnetized case, pure 2D perturbations. Magnetic field decrease both maximum growth rate and destabilized wavenumber diapason of sinuous instability (C), and stabilizes it for $M_a < 2.45$.
- For a given Mach number $M_s > 2.5$ there exist a range of Alfvén Mach numbers M_a, where the most unstable sinuous mode is oblique to the shear layer (has nonzero spanwise wavenumber K_z) (D). With increase of M_s, the size of such M_a range corresponding to 3D dominant instability decreases.

Nonlinear simulations: VAC[3], 2.5D MHD





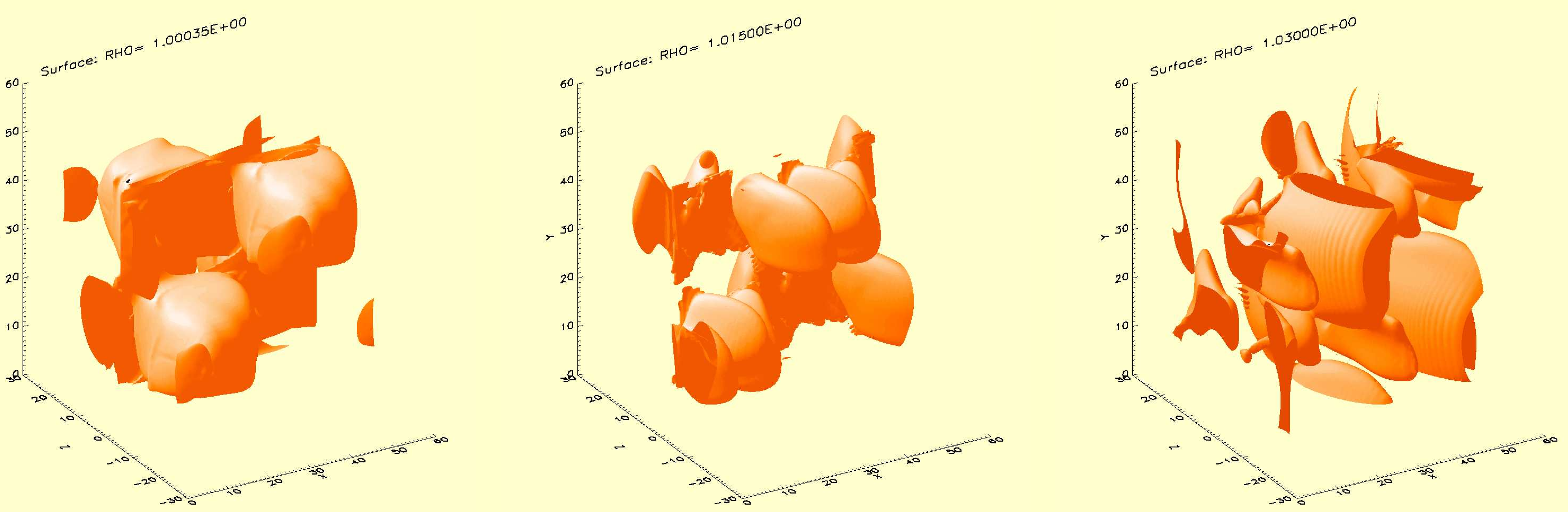
Initial perturbation: two sinuous modes, $K_{x1} = 0.35$, $Amp = 2.5 \cdot 10^{-5}$ and $K_{x2} = 0.35/3 = 0.11667$, $Amp = 10^{-2}$. Grid resolution: 200x400.

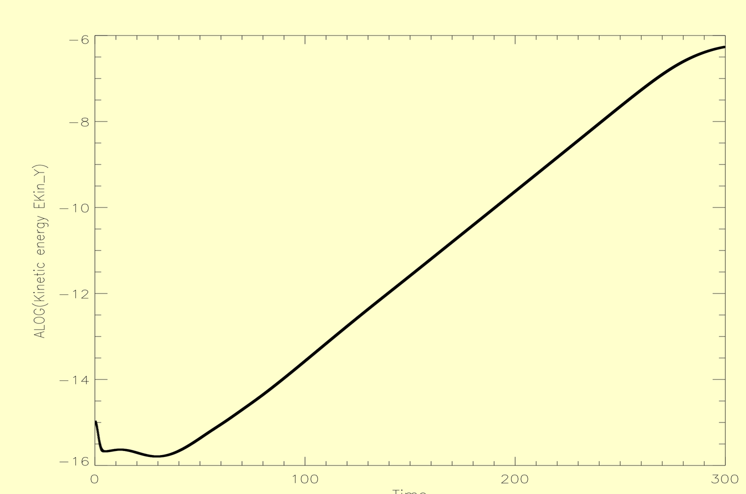
On the top: vertical kinetic energy $E_y^{Kin} = \frac{1}{L_x L_y}\int \frac{\rho V_y^2}{2} dx dy$ versus time.

On the left: plasma density ρ and cross-stream velocity V_y at times t = 100, 175, 200, 250, 300, 500 (up to down).

At early times, the mode $K_x = 0.11667$ is seen to grow with the growth rate $\gamma \sim 0.018$. However, at time around 200, the second mode $K_x = 0.35$ clearly appears with comparable amplitude. Further nonlinear evolution leads to formation of fast magnetosonic shocks; number of shocks correspond to mode $K_x = 0.35$, but they have unequal amplitudes indicating that initial evolution was influenced by the longer-wavelength $K_x = 0.11667$ mode.

Nonlinear simulations: VAC[3], 3D MHD





Initial perturbation: 3D sinuous mode ($K_x = 0.11667$, $K_z = 0.25$) having amplitude $Amp = 10^{-2}$. Maximum growth rate in the considered case ($M_s = 3$, $M_a = 5$) has a pure 2D sinuous mode ($K_x = 0.35$, $K_z = 0$). Grid resolution: 150x150x100.

On the top: surfaces of constant plasma density at times $T = 125, 250, 300$.
On the left: log of vertical kinetic energy versus time.

First, the three-dimensional sinuous instability ($\gamma \sim 0.02$) clearly develops ($T = 125$). However, since the dominant instability in this parameter range is 2D with two times smaller length scale in X-direction, each density structure tends to split into two parts ($T = 250$). After the saturation, a set of nearly two-dimensional (as is seen from the density structure at times around $T = 300$) fast magnetosonic shocks is formed. The X-scale of developed structure corresponds to initially excited 3D instability, but these shocks are elongated in Z direction, reflecting the 2D nature of dominant instability.

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