MHD Kelvin-Helmholtz instability in the anisotropic solar wind plasma

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Problem setup

We study wave instabilities in a magnetized, anisotropic, collisionless plasma in the fluid approximation using the 16-momentum MHD formalism. We discuss cases when the interfaces between solar wind components are Kelvin-Helmholtz unstable, including the dimensionless parameter as the ratio of flow speeds ($h = V_{01}/V_{02}$), the values of which provide a enough condition for velocity shear through interfaces.

Obtained equation

After linearization and simplifying equations (1-8), we obtain a second-order differential equation of the form

$$(v^2-\Delta^2)\frac{\partial}{\partial v}\Big[A(v)(v^2-\Delta^2)\frac{\partial}{\partial v}B_x\Big]- -\frac{k^2\,\Delta^2}{\sigma^2}\,\beta_A(v)\,B_x = 0\,, \qquad (9)$$

where $\Delta = (h-1)/(h+1)$ and

$$A(v) = \frac{\beta_A\beta_\star}{(1-\ell)\beta_\star + \ell\beta_A}\,,\; v = \frac{V_0(x)}{\overline{V}_0} - 1\,.$$

β_A and $\beta_\star$ are determined as

$$\beta_A = \beta - \bar{\alpha} - \xi^2\,, \qquad \beta_\star = \beta + 2\,\alpha + +2\,\alpha^2\,\frac{\xi^4+2\,\gamma\,\xi^3+2\,\gamma^2\xi^2-5\,\xi^2-6\,\gamma\,\xi+3}{(\xi^4-6\,\xi^2-4\,\gamma\,\xi+3)\,(\xi^2-1)}\,.$$

where for the basic unperturbed physical parameters (indexes zero are dropped) dimensionless parameters were used

$$\alpha = \frac{p_\perp}{p_\parallel}\,,\; \bar{\alpha} = 1-\alpha\,,\; c^2{}_\parallel = \frac{p_\parallel}{\rho}\,, \eta = \frac{c_\parallel k\sqrt{\ell}}{\omega_z}\,,$$

$$\beta = \frac{B^2}{4\pi p_\parallel} = \frac{\mathrm{v}^2{}_A}{c^2{}_\parallel}\,,\; \gamma_\parallel = \frac{S_\parallel}{p_\parallel c_\parallel}\,,\; \gamma_\perp = \frac{S_\perp}{p_\perp\,c_\parallel}\,.$$

Here $\omega_z = \omega - k\sqrt{\ell}\,V_0(x)$ is the Doppler shifted frequency and $\gamma = \gamma_\parallel = \gamma_\perp$. We also used θ for the wave propagation angle relative to the magnetic field, $\cos^2\theta \equiv \ell$.

Boundary conditions

We eliminate the heat flux, and chose the step discontinuity function for the velocity profile (V_{01}, $x<0$; V_{02}, $x>0$). We also select the same physical parameters in both flows, and solve the dispersion equation. And we should require that the found solution must satisfy the boundary conditions

$$\left\{\frac{\mathrm{v}_x}{\omega_z}\right\}_{x=0} = 0 \quad \text{(displacement)}\,, \qquad (12)$$

$$\left\{p'_\perp + \frac{B_0 B_z}{4\pi}\right\}_{x=0} = 0\,\text{(total pressure)}\,. \qquad (13)$$

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The 16 momentum MHD set of equations

$$\frac{d\rho}{dt} + \rho\,\mathrm{div}\vec{v} = 0\,, \qquad (1)$$

$$\rho\frac{d\vec{v}}{dt} + \nabla(p_\perp + \frac{B^2}{8\pi}) - \frac{1}{4\pi}(\vec{B}\cdot\nabla)\vec{B} = = (p_\perp - p_\parallel)\big[\vec{h}_B\mathrm{div}\vec{h}_B + (\vec{h}_B\cdot\nabla)\vec{h}_B\big] + \vec{h}_B(\vec{h}_B\cdot\nabla)(p_\perp - p_\parallel) + \rho\vec{g} \qquad (2)$$

$$\frac{d}{dt}\frac{p_\parallel B^2}{\rho^3} = -\frac{B^2}{\rho^3}\Big[B(\vec{h}_B\cdot\nabla)\Big(\frac{S_\parallel}{B}\Big) + \frac{2S_\perp}{B}(\vec{h}_B\cdot\nabla)B\Big], \qquad (3)$$

$$\frac{d}{dt}\frac{p_\perp}{\rho B} = -\frac{B}{\rho}(\vec{h}_B\cdot\nabla)\Big(\frac{S_\perp}{B^2}\Big), \qquad (4)$$

$$\frac{d}{dt}\frac{S_\parallel B^3}{\rho^4} = -\frac{3p_\parallel B^3}{\rho^4}(\vec{h}_B\cdot\nabla)\Big(\frac{p_\parallel}{\rho}\Big)\,, \qquad (5)$$

$$\frac{d}{dt}\frac{S_\perp}{\rho^2} = -\frac{p_\parallel}{\rho^2}\Big[(\vec{h}_B\cdot\nabla)\Big(\frac{p_\perp}{\rho}\Big) + \frac{p_\perp}{\rho}\frac{p_\perp - p_\parallel}{p_\parallel B}(\vec{h}_B\cdot\nabla)B\Big]\,, \qquad (6)$$

$$\frac{d\vec{B}}{dt} + \vec{B}\mathrm{div}\vec{v} - (\vec{B}\cdot\nabla)\vec{v} = 0\,, \qquad (7)$$

$$\mathrm{div}\vec{B} = 0\,. \qquad (8)$$

where $\vec{h}_B = \vec{B}/B$ and $d/dt = \partial/\partial t + (\vec{v}\cdot\nabla)$ is the convective derivative. Here $S_\parallel$ and $S_\perp$ are the heat fluxes along the magnetic field due to parallel and perpendicular thermal kinetic motions of ions.

Results

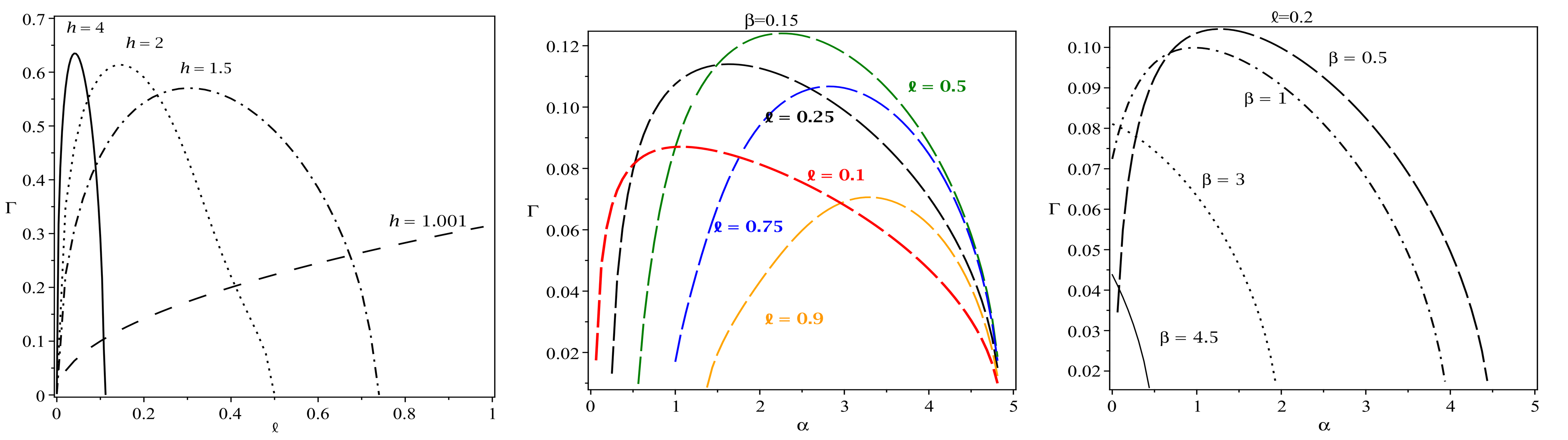
Assuming a step discontinuity function for the velocity profile yields the follow solutions $B_x = C_1\,e^{-\kappa\,x}$, $x>0$; $B_x = C_2\,e^{\kappa\,x}$, $x<0$,. Applying boundary conditions and regarding to B_x component we can write dispersion relation

$$\sum_{i=1}^{2}\frac{\beta_A(\xi_i)\,p_{\parallel 0i}}{\kappa_i\,B_{0i}} = 0, \qquad \kappa = \sqrt{1-\ell+\ell\,\frac{\beta_A(\xi)}{\beta_\star(\xi)}} \qquad (10)$$

where $\xi_1 = \Omega - \Delta$, $\xi_2 = \Omega + \Delta$, $i = 1,2$ indicates two different flows. Hereafter we choose all the flow plasma parameters the same except for the velocities, $V_{01} \neq V_{02}$ and $\gamma = 0$. We then get a polynomial equation of the 16th order, which contains only even powers of Ω:

$$\sum_{n=1}^{8}(a_{2n} - \ell\,b_{2n})\Omega^{2n} + (M^2\,\Delta^2 - \alpha - \beta + 1)(a_0 - \ell\,b_0) = 0\,. \qquad (11)$$

Growth rates (Γ) of wave modes depending on the wave propagation angle parameter (ℓ) for various velocity ratios h (left) and on the anisotropy parameter α for varius ℓ (central) and β (rigth).



A future direction

In the future, we will investigate the properties of KHI depending on the parameters of anisotropy and heat fluxes. The results can be used to explain the observed wave turbulence in the solar wind, the stellar wind, and in the magnetosphere of the planet. In CIR, lateral contact discontinuities occur in the interaction of fast and slow solar wind components. The solar wind is always a turbulence of any size, both in time and in space.

References

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