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MHD INSTABILITIES IN SHEAR FLOWS OF ANISOTROPIC COSMIC PLASMAS. I. FIRE HOSE MODES

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The stability of the anisotropic collisionless plasma layer to small disturbances in the MHD description is studied based on moment equations obtained from the Vlasov kinetic equation taking into account the heat flow along the spatially shearing flow. To find the complex spectral parameter that determines the growth rate of instability, on the base of the obtained wave equation, the boundary value problem is solved using WKB approximation for the case of a smooth hyperbolic velocity profile. A general integral dispersion equation, based on these solutions is obtained. This equation describes all types of body and interface instabilities in the presence of heat flow along the magnetic field, well studied for infinite stationary and homogeneous anisotropic plasma. It is shown that reducing the layer width greatly enhances the mirror instability, and strongly suppresses the oblique fire-hose instability. We limited ourselves here to study how the spatial gradient of the plasma flow affects the properties of an aperiodical oblique fire-hose instability in a limited layer. It was found that the spatial gradient in flow velocity greatly enhances this instability. With a narrowing of the shearing layer width and an increasing of the velocity gradient, the body hose modes transform into surface Kelvin-Helmholtz modes existing on the interface between the two parts of the flow with the different velocities.

Keywords: Solar wind – anisotropic plasma instability – MHD shearing flows – WKB approximation – Growth rate of instability

APPLICATION AND ACTUALITY

Space Weather and Its Impacts

- Satellite Operations
- Power Grid Stability
- Communications Systems
- GPS Accuracy

Fusion Energy Research

- Tokamak Design Improvements
- Plasma Instability Control

Astrophysical Phenomena

- Stellar Evolution
- Interstellar Medium Dynamics
- Cosmic Ray Propagation

What is MHD?

- **Magnetohydrodynamics (MHD)** is a theoretical framework that combines fluid dynamics with electromagnetism to describe the behavior of electrically conducting fluids. It merges Maxwell's equations of electromagnetism with the Navier-Stokes equations of fluid dynamics, incorporating the effects of magnetic fields on fluid motion and vice versa. MHD equations account for phenomena such as magnetic pressure and tension, frozen-in flux, and the generation of Alfvén waves. This theory is crucial for understanding various natural and laboratory plasma systems, including the solar wind, fusion reactors, and astrophysical objects like stars and galaxies.

WHAT IS SOLAR WIND?

Solar wind is a continuous stream of charged particles, primarily electrons and protons, flowing outward from the Sun's corona into interplanetary space. It plays a crucial role in shaping the heliosphere and influencing space weather. Solar wind varies in density, temperature, and speed, affecting how it interacts with planetary environments.

Causes:

- Driven by the Sun's high-temperature corona and magnetic field dynamics.
- Coronal holes and solar flares contribute to variations in solar wind intensity.

Types (by Velocity):

- **Fast Solar Wind:** Originates from coronal holes and moves at speeds of 500–800 km/s.
- **Slow Solar Wind:** Emanates from the Sun's equatorial regions and moves at speeds of 300–500 km/s.

Particle Composition and Sizes:

- Composed mostly of electrons and protons, with traces of heavier ions such as helium.
- Particle sizes range from individual protons and electrons to larger ion clusters.

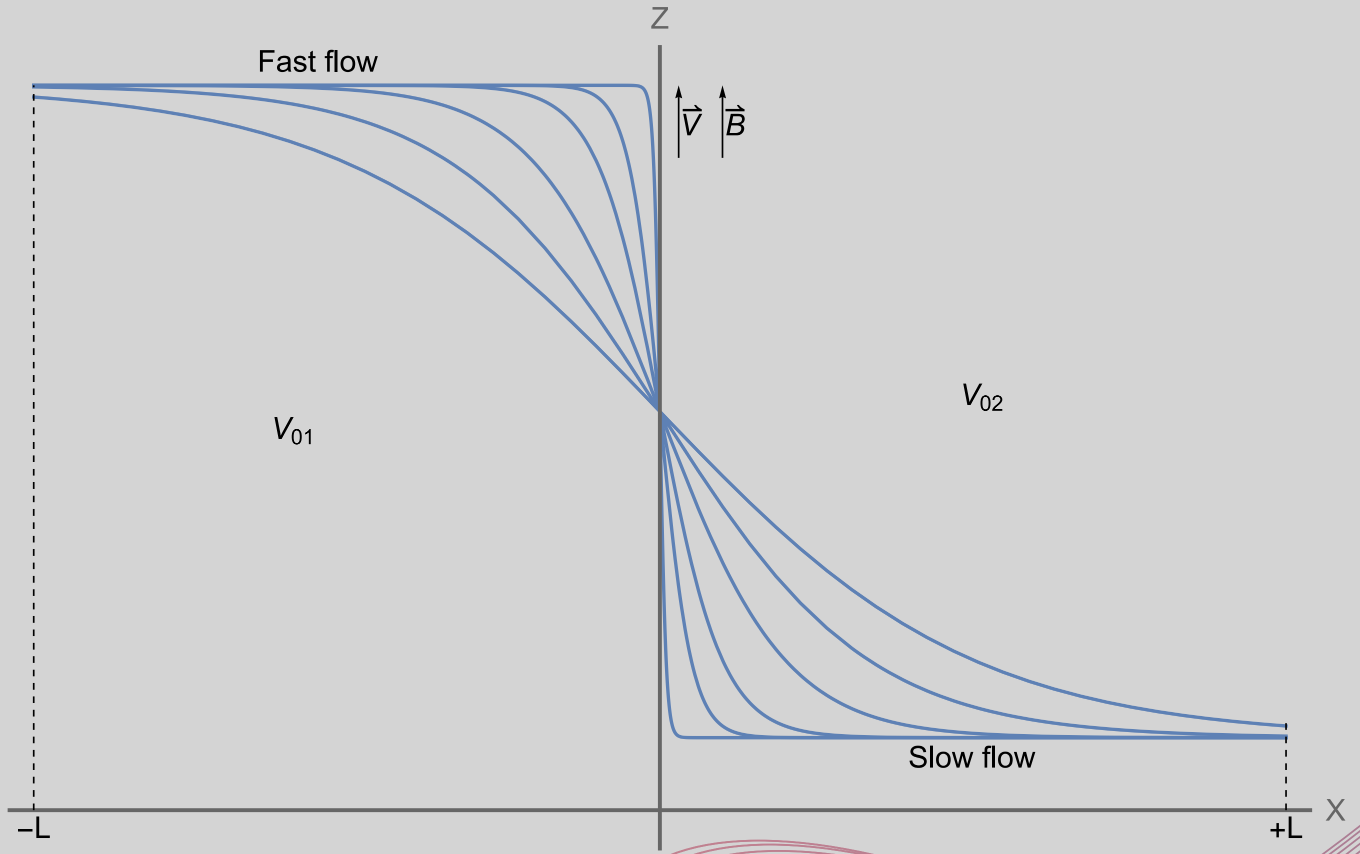
Effects on the Solar System:

- Influences Earth's magnetosphere, causing phenomena like auroras.
- Affects satellite operations and communication systems.
- Plays a role in shaping planetary atmospheres and tails of comets.

SCHEMATIC REPRESENTATION OF MHD PLASMA SHEARING FLOW.

$$V_0(x) = \frac{V_{02}e^{\sigma x} + V_{01}e^{-\sigma x}}{e^{\sigma x} + e^{-\sigma x}}, \quad \sigma \geqslant 0. \quad (1)$$

Here V(−∞) = V01 and V0(+∞) = V02 are the limit velocities and let h = V01/V02 ⩾ 1, V0(0) = (V01 + V02)/2 = ¯V0 is the average of the two velocities. In the ((35)) the σ parameter characterizes the thicknesses of the transition layer L. Figure shows schematically the various profiles of V0(x) for different values of σ. As the parameter σL > 0 increases, the width of the transition layer between the two flows sharply decreases and becomes a discontinuity (σL ≫ 1) between the velocities V01 and V02 (indicated by the solid line in Fig. 1). For the small σL ≪ 1 the width of the transition layer becomes very large.



In the right figure Schematic representation of MHD plasma shearing flow. Different line profiles correspond to different values of σL = σL in Eq.1

METHOD

$$\frac{\partial}{\partial x}\left(A(x)\frac{\partial B_x}{\partial x}\right) - \beta_A(x)B_x = 0 \quad (2) \qquad \frac{d}{dx}\left(\frac{\beta_A\beta_*}{k_y^2\beta_* + k_z^2\beta_A}\frac{dy(x)}{dx}\right) - \beta_A y(x) = 0. \quad (3)$$

This equation represents the fundamental wave equation for the perturbed magnetic field component Bx in a sheared anisotropic plasma flow. It is derived from the linearized 16-moment fluid equations, incorporating effects of pressure anisotropy and heat flows. The coefficients A(x) and β_A(x) encapsulate the complex interplay between various plasma parameters, including the flow velocity profile, pressure anisotropy, heat fluxes, and wave propagation angle. This equation forms the basis for studying stability properties of the plasma, particularly for analyzing various types of instabilities such as firehose and mirror instabilities in the presence of velocity shear.

WKB SOLUTION

So, for the complex P(τ), Q(τ) ⇒ C2(I) functions assuming Re(QP) ≥ 0 we can write the leading expansion term of WKB solutions,

$$\tilde{y}_{1,2} = \frac{e^{\pm iS(\tau)}}{\sqrt{w}}, \quad w = \sqrt{\mathcal{P}Q}, \quad S = \int_{\tau_0}^{\tau}\sqrt{-\frac{Q}{\mathcal{P}}}d\tau. \quad (6)$$

$$\int_0^1\left(\sqrt{f(\xi_+)} + \sqrt{f(\xi_-)}\right)d\tau = \lambda_n, \quad (4) \text{ where,}$$

$$f(\xi) = -\frac{(1-l)\beta_*(\xi) + l\beta_A(\xi)}{\beta_*(\xi)}, \quad \lambda_n = \frac{n\pi}{kL}, = \frac{\lambda_\perp n}{2L}. \quad (5)$$

NUMERIC RESULTS

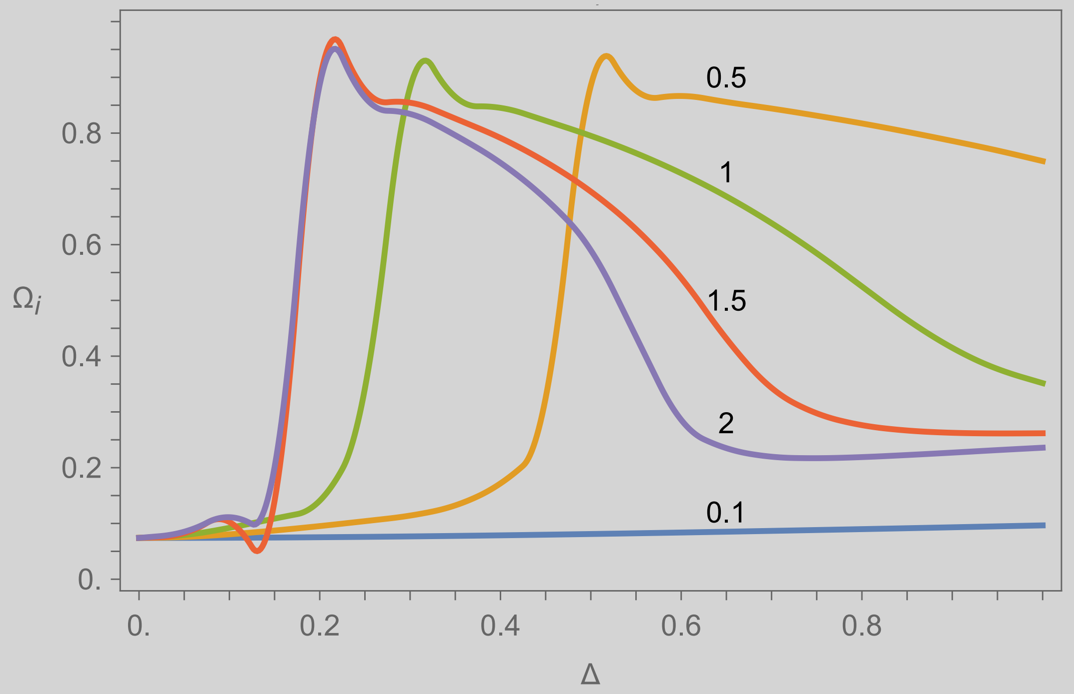
In this study, we examine how instabilities change when the flow is sheared, specifically focusing on oblique fire-hose modes. The key parameters considered are the anisotropy parameter \(\alpha = 0.5\), the magnetic parameter β = 0.1, the propagation angle parameter l = 0.9, the heat flux parameter γ = 0, and the Mach number M = 5 (supersonic flow). Two additional parameters, Δ and σL, are introduced to the problem, requiring the solution of a complex integral dispersion equation. We analyze the dependence of the fire-hose instability growth rate on Δ\ for various values of λn and σL.

λn is The ratio of the wavelength λ in the (y-z) plane to the geometric width (2L) of the plasma layer with a flow. This parameter is influenced by the number of unevenly located nodes n of the eigenfunctions along the x-axis. If (λx = 2L/n) represents the scale of fluctuation structures caused by shear flow along the x-axis and σL is the Characterizes the thickness of the transition layer L.

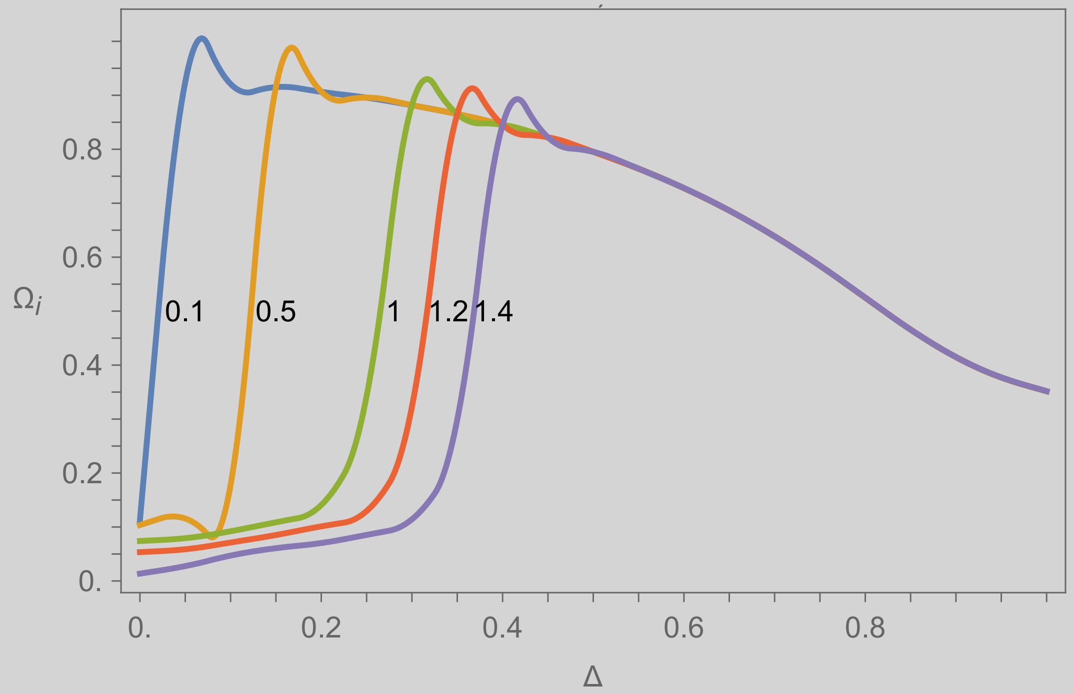
Dependence on Δ for Various λn and σL:

Figures illustrate that even a slight shift in velocity (Δ) significantly intensifies the instability, reaching a maximum quickly. For small λn, even a minor shift enhances the instability sharply. A similar trend is observed with the σL parameter. At small scales of the velocity gradient (σL->0), the flow remains almost uniform, and the instability is weak. As the gradient increases, the instability rises sharply and also we are show from figures the dependence of the fire-hose instability growth rate (Ωi) on the parameter λn for different values of Δ and σL. The analysis covers both wide plasma layers (kL ≫ 1) and narrow layers (kL ≪ 1). Hose modes that arise in a wide layer as body waves disappear as the layer width decreases and approaches zero. The discontinuous case corresponds to L-> 0 and σL ≫ 1.

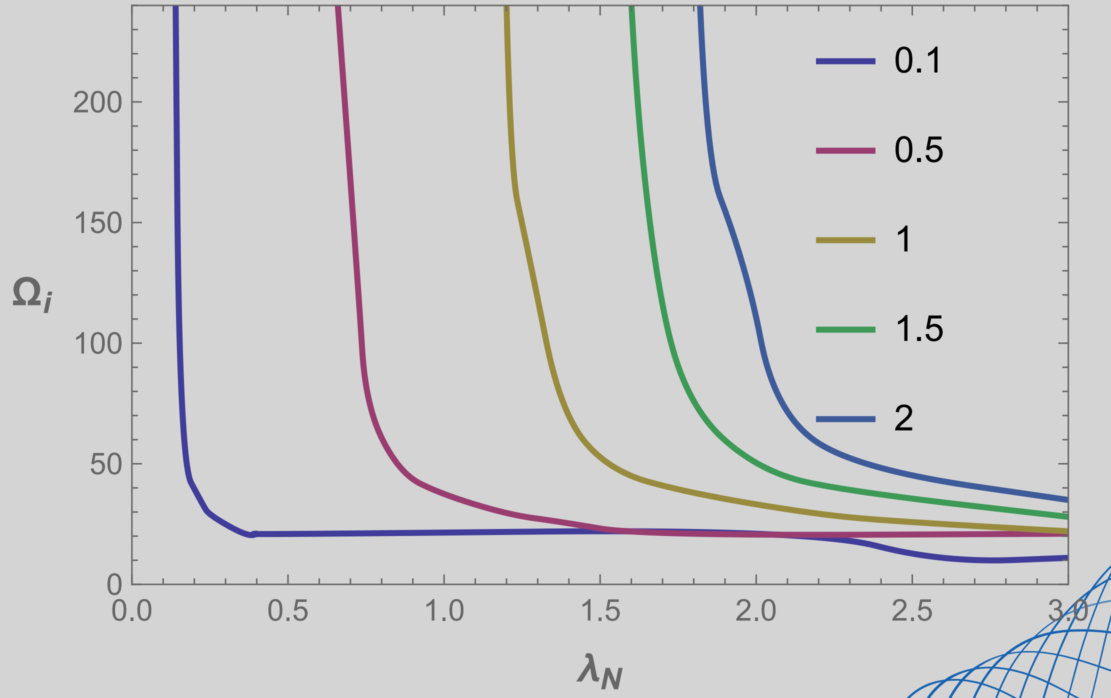
In conclusion, our results highlight the significant impact of velocity shifts and transition layer gradients on the fire-hose instability in plasma shearing flows, providing valuable insights for understanding and controlling these instabilities in practical applications.



The dependence of instability growing rate Ωi of fire-hose modes on the shearing rate of plasma super- sonic flows Δ at different values of σL (numbers at curves) when λn = 1



The dependence of instability growing rate Ωi of fire-hose modes on the shearing rate of plasma super- sonic flows Δ at different values of λn (numbers at curves) when σL = 1.



The dependence of instability growing rate Ωi of fire hose modes on the λn at different values of σL (numbers at the curves) when Δ = 1.5

Thank you for your attention!