

Lecture -6

磁流体力学

Magnetohydrodynamics

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MHD Instability

Instabilities in a plasma

Because of a multitude of free-energy sources in space plasmas, a very large number of instabilities can develop.

If spatial scale involved is:

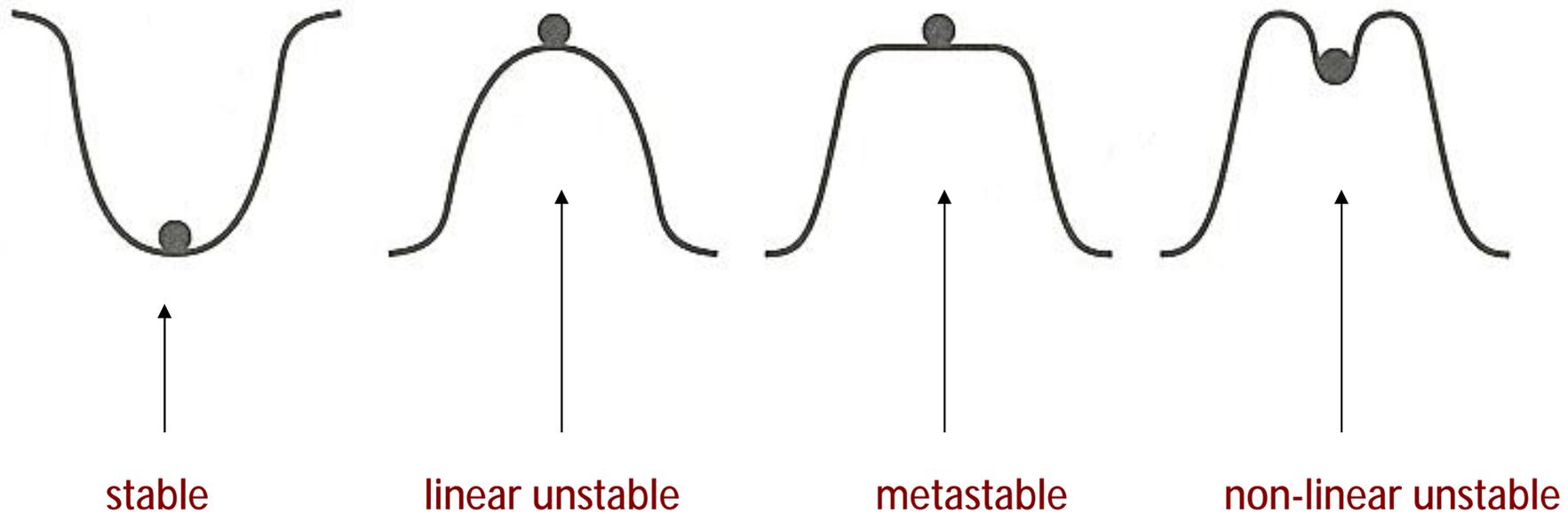
- comparable to macroscopic size (bulk scale of plasma,.....) -> *macroinstability* (affects plasma globally)
- comparable to microscopic scale (gyroradius, inertial length,...) -> *microinstability* (affects plasma locally)

Theoretical treatment:

- *macroinstability*, fluid plasma theory
- *microinstability*, kinetic plasma theory

Concept of instability

Generation of instability is the general way of redistributing energy which was accumulated in a non-equilibrium state.



Methods of Instability Analysis

A method used to study equilibrium problems imagines the system to undergo a small displacement as the result of the application of an arbitrary force. If the force increases the displacement and thereby deforms the system, the system is said to be unstable. If, however, the effects of the force are damped and the system returns to the initial configuration, the system is considered stable.

Normal mode: examine whether the perturbation grows or damps by studying the motion of the particles in the immediate neighborhood.

Energy principle methods: by calculating the energy of the initial and final states.

Methods of Instability Analysis

Consider two point masses in a one-dimensional potential field $V(x)$ as shown. A small perturbation applied to point A will cause the mass to oscillate about the equilibrium point while perturbation applied to at point B will accelerate the mass away from the equilibrium point. System A is stable and system B is unstable.

Let the coordinate of the equilibrium position be given by x_0 and the force $F(x)$. The equation of motion of the mass m at position x , obtained by Taylor expansion about the point x_0 :

$$\begin{aligned} m \frac{d^2 x}{dt^2} = F(x) &= F(x_0) + F'(x_0)(x - x_0) + \dots \\ &= F'(x_0)(x - x_0) + \dots \end{aligned}$$

Where x_0 is the equilibrium position, $F(x_0)=0$

Methods of Instability Analysis

Let $\xi = x - x_0$, and ignored higher-order terms,

$$m \frac{d^2 \xi}{dt^2} = F'(x_0) \xi$$

The solution of this equation:

$$\xi = \xi_0 \exp\left\{ \left[\frac{F'(x_0)}{m} \right]^{1/2} t \right\} = \xi_0 \exp(i\omega t),$$

$$\text{where } \omega^2 = -\frac{F'(x_0)}{m}$$

A: $F'(x_0) < 0$, ω real, the solution is oscillatory

B: $F'(x_0) > 0$, the disturbance grows exponentially.

Interchange Instability

As another example, consider two vessels in which there are two kinds of fluids in a gravitational field. Let the fluid on the top in one case (left) be lighter than one on the bottom, and let the reverse be true in other case (right). Both systems are initially in equilibrium.

Introduce now a small perturbation in the form of waves, to the interface of two fluids.

Left: the waves will oscillate about the equilibrium and will eventually damp out.

Right: the waves will grow, which will lead to the interchange of the positions of the upper and lower fluids.

The lower energy state is reached by lowering the potential energy.

Linear instability

The concept of linear instability arises from consideration of a linear wave function. Assume any field (density, field, etc.) denoted by A , the fluctuation of which is δA , that can be Fourier decomposed as

$$\delta A = \sum_{\mathbf{k}} A_{\mathbf{k}} \exp(i\mathbf{k} \cdot \mathbf{x} - i\omega t)$$

In general the dispersion relation (DR) has complex solutions: $\omega = \omega_r + i\mathbf{g}$. For real frequency the disturbances are oscillating waves.

For complex solutions the sign of \mathbf{g} decides whether the amplitude A growth ($\mathbf{g} > 0$) or decays ($\mathbf{g} < 0$).

Two-stream Instability (Buneman Instability)

As a simple example of a streaming instability, consider a uniform plasma the ions are stationary and the electrons have a velocity v_0 relative to the ions. Let the plasma be cold ($kT_e = kT_i = 0$), and let there be no magnetic field ($B_0 = 0$). We first separate the dependent variables into two parts: an “equilibrium” part indicated by a subscript 0, and a “perturbation” part indicated by a subscript 1.

$$n_e = n_0 + n_1, \mathbf{v}_e = \mathbf{v}_0 + \mathbf{v}_1, \mathbf{E} = \mathbf{E}_0 + \mathbf{E}_1$$

The equations of motion for the ions and the electrons are, to first order:

$$Mn_0 \frac{\partial \mathbf{v}_{i1}}{\partial t} = en_0 \mathbf{E}_1$$

$$mn_0 \left[\frac{\partial \mathbf{v}_{e1}}{\partial t} + (v_0 \cdot \nabla) \mathbf{v}_{e1} \right] = -en_0 \mathbf{E}_1$$

Two-stream Instability (Buneman Instability)

We look for electrostatic waves $\mathbf{E}_1 = E e^{i(kx - \omega t)} \hat{x}$

Where x is the direction of v_0

$$-i\omega M n_0 \mathbf{v}_{i1} = e n_0 \mathbf{E}_1 \Rightarrow \mathbf{v}_{i1} = \frac{ie}{M\omega} E \hat{x}$$

$$m n_0 (-i\omega + ikv_0) \mathbf{v}_{e1} = -e n_0 \mathbf{E}_1 \Rightarrow \mathbf{v}_{e1} = -\frac{ie}{m} \frac{E \hat{x}}{\omega - kv_0}$$

The velocities are in the x direction, and we may omit the subscript x . The ion equation of continuity yields:

$$\frac{\partial n_{i1}}{\partial t} + n_0 \nabla \cdot \mathbf{v}_{i1} = 0 \Rightarrow n_{i1} = \frac{k}{\omega} n_0 v_{i1} = \frac{ien_0 k}{M\omega^2} E$$

Note that the other terms in $\nabla \cdot (n\mathbf{v}_i)$ vanish because $v_{oi} = 0$

Two-stream Instability (Buneman Instability)

The electron equation of continuity is:

$$\frac{\partial n_{e1}}{\partial t} + n_0 \nabla \cdot v_{e1} + (v_0 \cdot \nabla) n_{e1} = 0$$

$$(-i\omega + ikv_0)n_{e1} + ikn_0 v_{e1} = 0$$

$$n_{e1} = \frac{kn_0}{\omega - kv_0} v_{e1} = -\frac{iek n_0}{m(\omega - kv_0)^2} E$$

Since the unstable waves are high-frequency plasma oscillations, we may not use the plasma approximation but use Poisson's equation: :

$$\epsilon_0 \nabla \cdot \mathbf{E}_1 = e(n_{i1} - n_{e1})$$

$$ik\epsilon_0 E = e(ien_0 k E) \left[\frac{1}{M\omega^2} + \frac{1}{(\omega - kv_0)^2} \right]$$

Two-stream Instability (Buneman Instability)

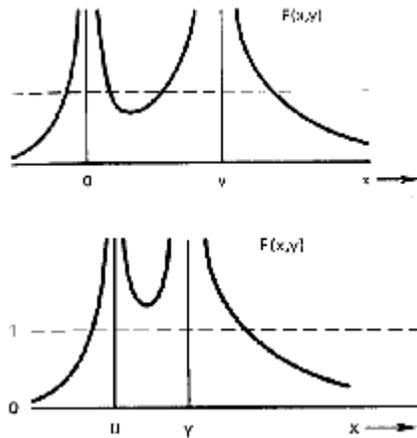
The dispersion relation is found upon dividing by $ik\epsilon_0 E$

$$1 = \omega_p^2 \left[\frac{m/M}{\omega^2} + \frac{1}{(\omega - kv_0)^2} \right]$$

Let us see if oscillations with real k are stable or unstable. If all the roots ω_j are real, each root would indicate a possible oscillation.

If some of the roots are complex, they will occur in complex conjugate pairs. Positive $\text{Im}(\omega)$ indicates an exponentially growing wave; negative $\text{Im}(\omega)$ indicates a damped wave. Since the roots occur in conjugate pairs, one of these will always be unstable unless all the roots are real.

The dispersion relation can be analyzed without actually solving the fourth-order equation. Let us define



$$x \equiv \frac{\omega}{\omega_p} ; y = \frac{kv_0}{\omega_p}$$

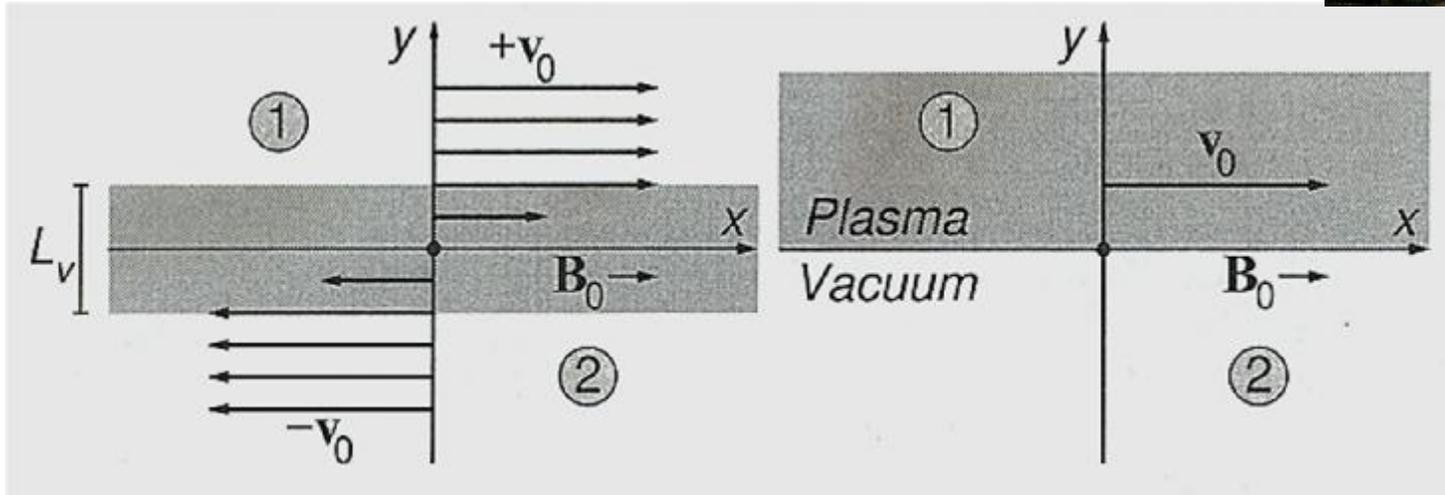
$$1 = \frac{m/M}{x^2} + \frac{1}{(x - y)^2} = F(x, y)$$

For any given value of y , we can plot $F(x,y)$ as a function of x . This function will have singularities at $x = 0$ and $x = y$. In the example of (a), there are four intersection's, so there are four real roots (stable). However if we choose a smaller value of y , there are only two real roots. The other two roots must be complex, and one of them must correspond to an unstable wave.

The growth rate can be predicted is

$$\gamma \approx \frac{\omega_p}{\sqrt{\frac{m\omega_p^2}{M\omega_0^2} - 1}}$$

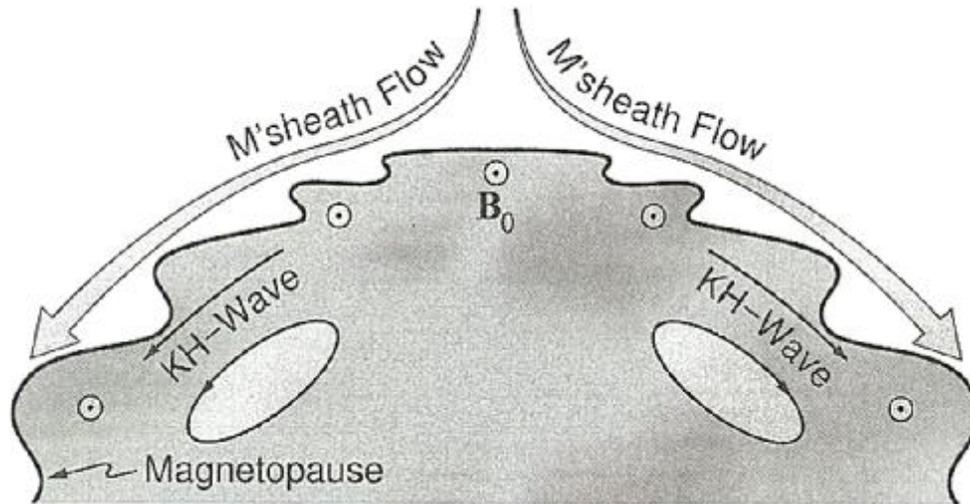
Kelvin-Helmholtz instability



- *Shear flow at magnetised plasma boundary may cause ripples on the surface that can grow.....*
- *The rigidity of the field provides the dominant restoring*

Linear perturbation analysis in both regions shows that *incompressible waves confined to the interface* can be excited

$$\frac{1}{n_{02} [\omega^2 - (\mathbf{k} \cdot \mathbf{v}_{A2})^2]} + \frac{1}{n_{01} [(\omega - \mathbf{k} \cdot \mathbf{v}_0)^2 - (\mathbf{k} \cdot \mathbf{v}_{A1})^2]} = 0$$



Excitation of geomagnetic pulsations!

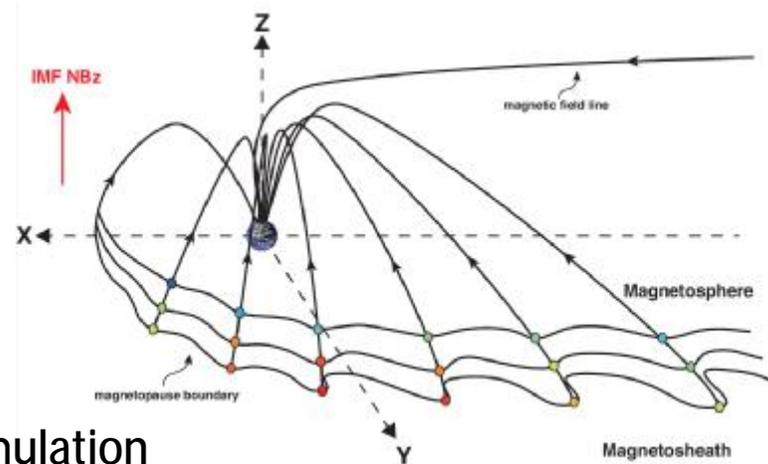
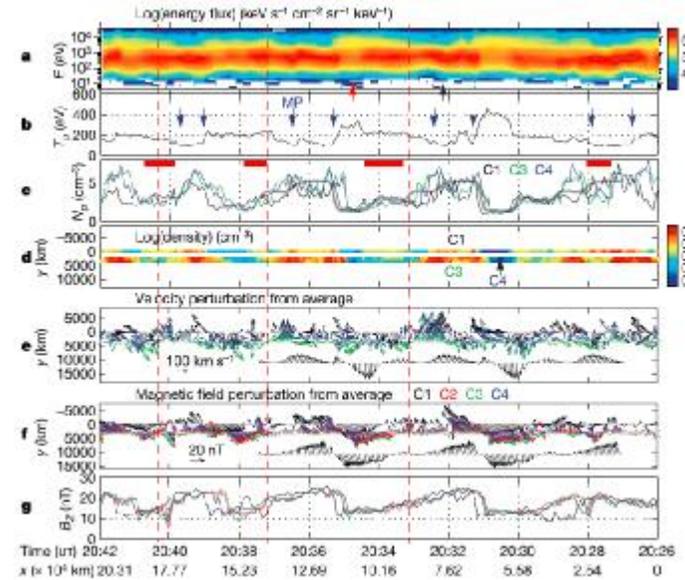
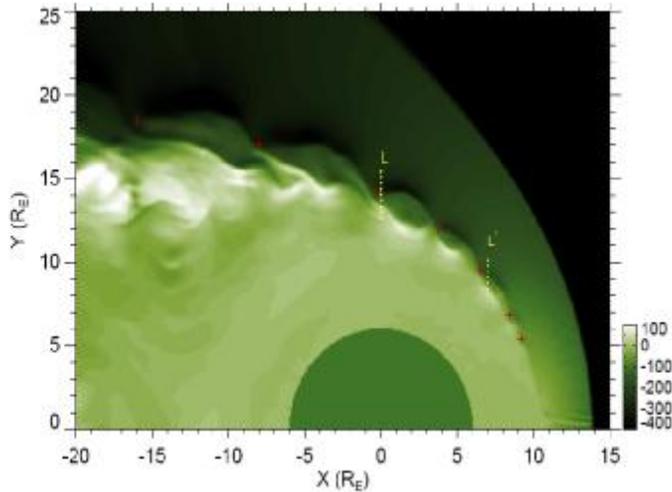
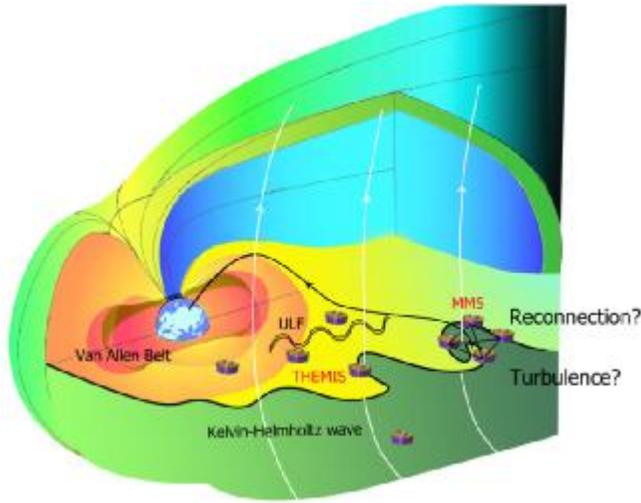
The in w quadratic dispersion relation yields an unstable solution given by:

$$\omega_{kh} = \frac{n_{01} \mathbf{k} \cdot \mathbf{v}_0}{n_{01} + n_{02}}$$

corresponding to the appearance of a complex conjugate root if the streaming is large enough, i.e. if the subsequent inequality is fulfilled:

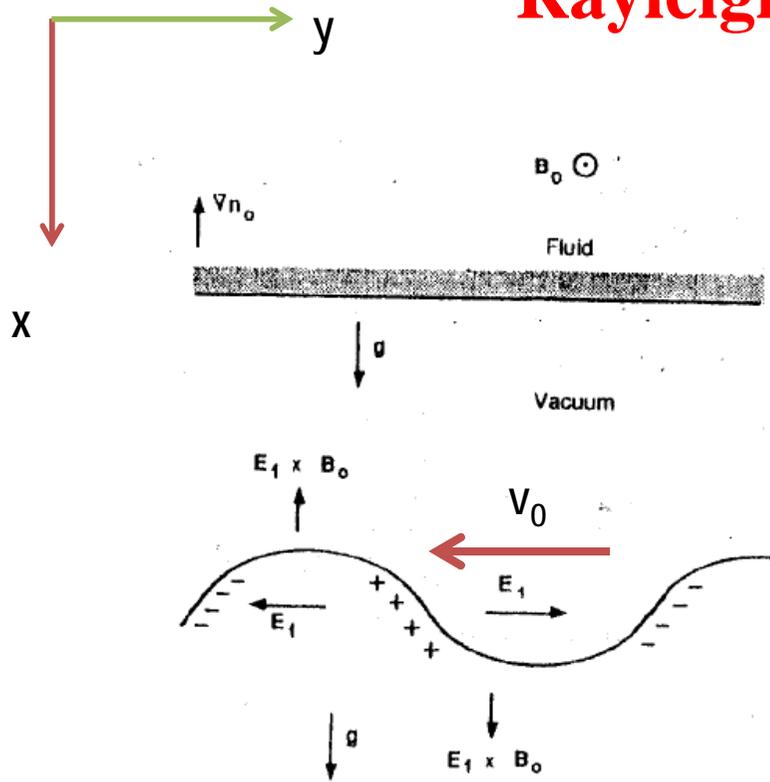
$$(\mathbf{k} \cdot \mathbf{v}_0)^2 > \frac{n_{01} + n_{02}}{n_{01} n_{02}} \left[n_{01} (\mathbf{k} \cdot \mathbf{v}_{A1})^2 + n_{02} (\mathbf{k} \cdot \mathbf{v}_{A2})^2 \right]$$

KH instability at the magnetopause



3D Global MHD Simulation

Rayleigh-Taylor instability



In a plasma, a R-T instability can occur because the magnetic field acts as a light fluid supporting a heavy fluid (the plasma). To treat the simplest case, consider a plasma boundary lying in the y - z plane. Let \mathbf{B}_0 be in the z -direction. We assume the plasma β is low so that we can let $kT_e = kT_i = 0$. This implies that there is no diamagnetic current (due to ∇n)

In the equilibrium state, the ions obey the equation:

$$Mn_0(v_0 \cdot \nabla)v_0 = qm_0 v_0 \times \mathbf{B}_0 + Mn_0 \mathbf{g}$$

If \mathbf{g} is constant, v_0 will be also, and $(v_0 \cdot \nabla)v_0$ vanishes. Taking the cross product of the above equation with \mathbf{B}_0 , we find

$$(\mathbf{v}_0 \times \mathbf{B}_0) \times \mathbf{B}_0 = B_0(\mathbf{v}_0 \cdot \mathbf{B}_0) - \mathbf{v}_0(B_0 \cdot \mathbf{B}_0) = -\mathbf{v}_0 B_0^2$$

$$\mathbf{v}_0 = \frac{M}{q} \frac{\mathbf{g} \times \mathbf{B}_0}{B_0^2} = -\frac{g}{\Omega_c} \hat{y}$$

which is just the guiding center drift of ions acted on by the gravitational force. Here $\Omega_c = qB/M$ is the ion Larmor frequency.

We can obtain a similar equation for the electrons that drift in the opposite direction. However, in the limit $m/M \sim 0$, the electron contribution can be ignored.

Introduce now a small disturbance so that the boundary becomes rippled. Because the $\mathbf{g} \times \mathbf{B}_0$ drift is mass dependent, the ions will drift faster than the electrons, hence it can be easily deduced that the v_0 of the ions over the rippled surface will cause the charges to build up as shown. This charge separation produces an electric field E_1 and the ripples, $\mathbf{E}_1 \times \mathbf{B}_0$ is in the x-direction the minimum and in the $-x$ direction at the peaks. The amplitude of the ripple will thus grow larger and the boundary becomes unstable.

To find the growth rate, we can perform the usual linearized wave analysis for waves propagating in the y direction.

Dispersion relation:

$$\omega = \frac{1}{2} k v_0 \pm \left[\frac{1}{4} k^2 v_0^2 + g \left(\frac{\partial n_0}{\partial x} / n_0 \right) \right]^{1/2}$$

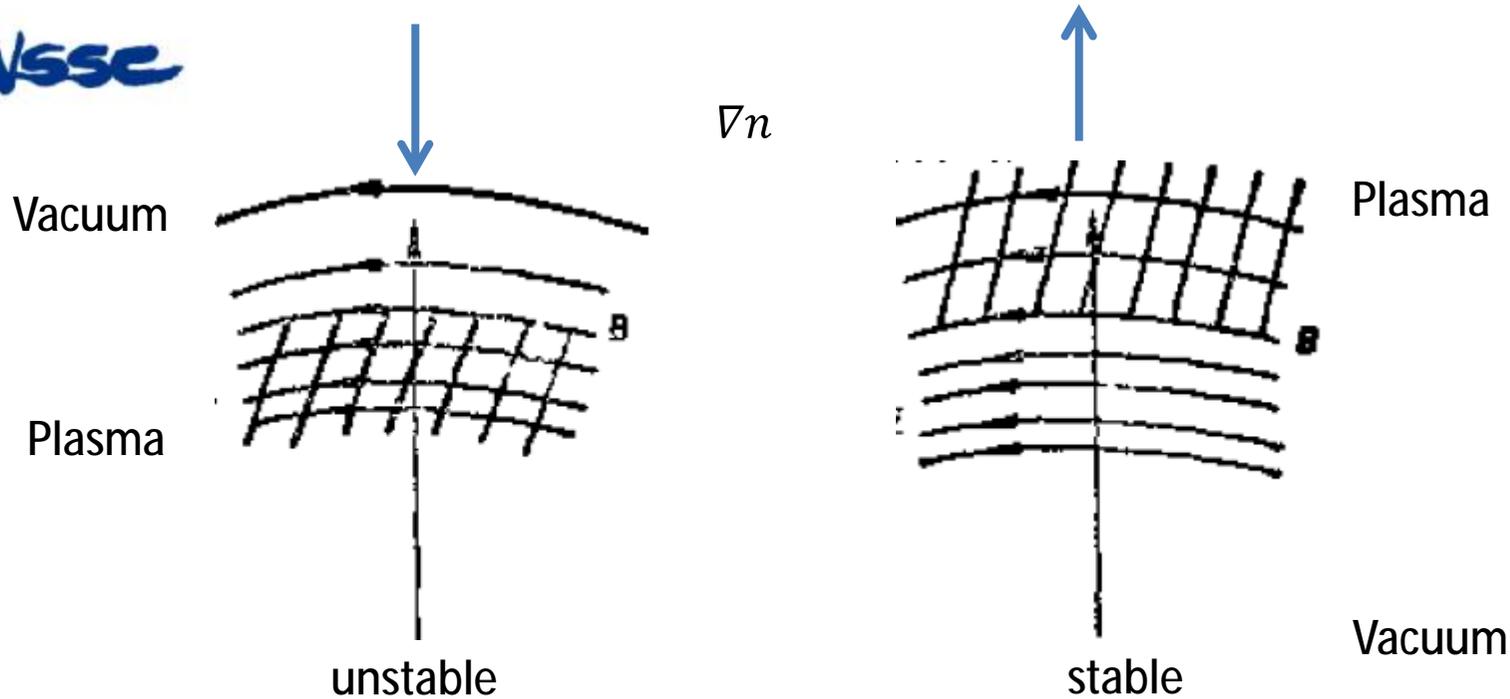
There is instability if ω is complex, that is

$$-g \left(\frac{\partial n_0}{\partial x} / n_0 \right) > \frac{1}{4} k^2 v_0^2$$

Which requires g and $\partial n_0 / \partial x$ to have opposite sign. This is just the statement that the light fluid is supporting the heavy fluid.

RT instability occurs in the Ionosphere

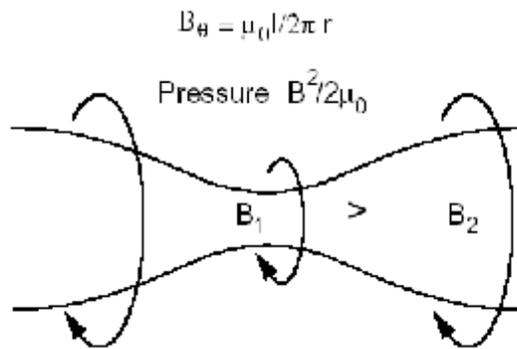
A good example of the RT instability occurs in the ionosphere near the magnetic equator, where the magnetic field is nearly horizontal. Under certain conditions, “bubbles” of low density plasma from near the base of the ionosphere rise upwards into the ionosphere, causing plume-like disturbances, that can be detected by ground-based radars.



$$\mathbf{v}_R + \mathbf{v}_{\nabla B} = \frac{1}{q} (mv_{\parallel}^2 + \frac{1}{2}mv_{\perp}^2) \frac{\mathbf{R}_c \times \mathbf{B}}{R_c^2 B^2}$$

Since g can be used to model the effects of magnetic field curvature, we see from this that stability depends on the sign of the curvature. Configurations with field lines bending in toward the plasma tend to be stabilizing, and vice versa.

Sausage Instability



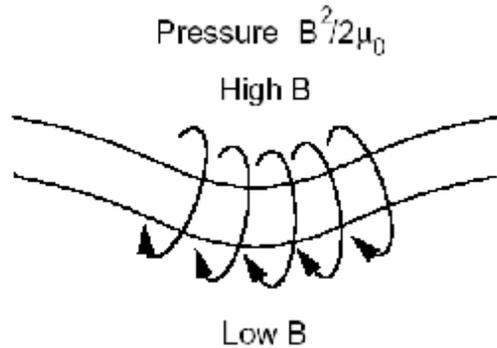
Suppose that the equilibrium state of the pinched plasma column, is disturbed by a wave-like perturbation.

We shall consider that the plasma is constricted in some locations and expanded at others, in such a way that its volume does not change. So, the pressure plasma is left unchanged.

In view of the $1/r$ radial dependence of the azimuthal magnetic field, at the location where the radius has decreased, the magnetic pressure will be larger than the plasma pressure, and will force the surface radially inwards, thus enhancing the constriction. ($m = 0$ sausage instability)

Kick Instability

The kink distortion consists of a perturbation in the form of a bend or kink in the column.

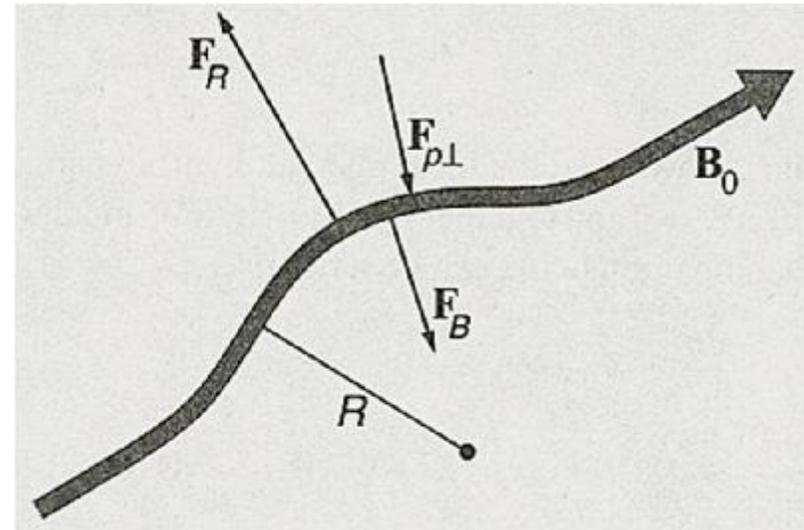


If the column develops a kink, the increased pressure and tension on the high B side increases the bending. This is known as the $m = 1$ kink instability.

Instabilities can be prevented by adding a longitudinal magnetic field B_z to “stiffen” the plasma. The $B_z^2/2\mu_0$ pressure resists the $m = 0$ mode and the tension B_z^2/μ_0 counters the bending.

Firehose instability

Whenever the flux tube is slightly bent, the plasma exerts an outward centrifugal force (curvature radius, R), that tends to enhance the initial bending. The gradient force due to magnetic stresses and thermal pressure resist the centrifugal force. In force equilibrium:



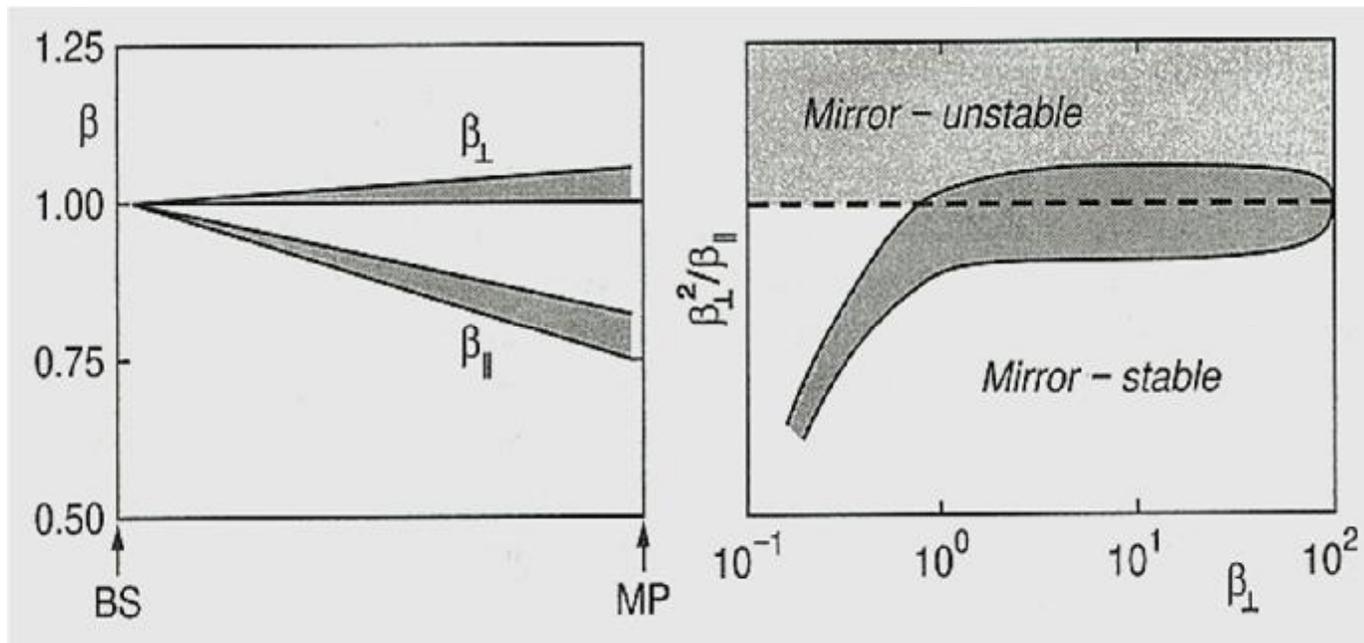
$$\frac{m_i n_0 v_{th\parallel}^2}{R} = \frac{p_{\perp}}{R} + \frac{B_0^2}{\mu_0 R}$$

The resulting instability condition for breaking equilibrium is:

$$p_{\parallel} > p_{\perp} + B_0^2 / \mu_0$$

Mirror instability

This long-wavelength *compressive slow-mode instability* requires consideration of particle motion parallel and perpendicular to the field. Occurs in the Earth's dayside magnetosheet, where the shocked solar wind is heated adiabatically in the perpendicular direction, while the field-aligned outflow cools the plasma in the parallel direction



The particles stream into the mirror during instability, become trapped there and oscillate between mirror points. Density and field out of phase, *slow mode wave!*

