Lecture IV — Linear Waves in MHD.

Linear Waves, Instabilities and Energy Principle

→ Contents

- this unit presents the linear structure, response theory and energetics for MHD

- proceed by: a.) linear waves
  b.) Least Action and Energy Principle
  c.) simple linear instabilities

- Later discuss nonlinear evolution, i.e.:
  i.e. a.) MHD shocks
  b.) collisionless shocks
  c.) MHD turbulence (later).

A) Linear Waves in MHD

i.) Simple Cases

- before proceeding with full crank useful to discuss some limiting cases in depth
- always have

$$\boxed{\begin{array}{l} \underline{B_0} = B_0\,\hat{z} \\ \rho = \rho_0,\ P = P_0 \end{array} \Big\rangle \text{ uniform}}$$

- consider

	$\nabla\cdot\underline{V} = 0$	$\nabla\cdot\underline{V} \neq 0$	
$\underline{k} = k\hat{z}$	Shear Alfven	Acoustic	– parallel propagation
$\underline{k} = k\hat{x}$	X	Magnetosonic	– perpendicular propagation

Shear Alfven Wave

$\rightarrow \underline{k} = k\hat{z}, \quad \underline{\nabla}\cdot\underline{V} = 0$

$$\left.\begin{aligned} \rho_0 \frac{\partial \tilde{\underline{V}}}{\partial t} &= -\nabla\left(\tilde{p} + \frac{\tilde{B}^2}{8\pi}\right) + \frac{\underline{B}_0\cdot\underline{\nabla}\,\tilde{\underline{B}}}{4\pi} \\ \frac{\partial \tilde{\underline{B}}}{\partial t} &= \underline{B}_0\cdot\underline{\nabla}\,\tilde{\underline{V}} \end{aligned}\right\} \text{linearized eqns.}$$

Now, $\underline{\nabla}\cdot\tilde{\underline{V}} = 0 \Rightarrow$

$$-\nabla^2\left(\tilde{p} + \frac{\underline{B}_0\cdot\tilde{\underline{B}}}{8\pi}\right) + \underline{B}_0\cdot\nabla\cancel{(\nabla\cdot\tilde{\underline{B}})}^{\,0} = 0$$

ρ_0, B_0 uniform

$$\therefore \quad \boxed{\tilde{p} + \frac{\underline{B}_0\cdot\tilde{\underline{B}}}{8\pi} = 0}$$

→ "perturbed pressure balance"

→ holds for incompressible (and weakly compressible) modes

$$\Rightarrow \quad \rho_0 \frac{\partial \tilde{\underline{V}}}{\partial t} = \frac{B_0}{4\pi}\frac{\partial}{\partial z}\tilde{\underline{B}}$$

$$\frac{\partial \tilde{\underline{B}}}{\partial t} = B_0 \frac{\partial}{\partial z}\tilde{\underline{V}}$$

$$\therefore \quad \boxed{\frac{\partial^2 \tilde{\underline{V}}}{\partial t^2} = \frac{B_0^2}{4\pi\rho_0}\frac{\partial^2}{\partial z^2}\tilde{\underline{V}}}$$

$B_0^2/4\pi\rho_0 = V_A^2$ Alfven velocity

$\Rightarrow \left\{ \begin{array}{l} \omega^2 = k_\parallel^2 V_A^2 \rightarrow \text{dispersion relation for Shear Alfven wave} \\ V_{ph} = V_{gr} = V_A \hat{z} \rightarrow \text{speed} \left\{ \begin{array}{l} \text{phase} \\ \text{group} \end{array} \right. \end{array} \right.$

wave propagates along $\hat{z}$ at Alfven speed

→ wave is consequence of magnetic tension

$\frac{T}{\mu} \rightarrow \frac{B/4\pi}{\rho_0/B}$ ~ tension-in-line $\Rightarrow V_A^2$

↳ mass-per-line

→ tension ⟺ plucking $\Rightarrow \tilde{\underline{V}} \perp B_0$

$\left(\begin{array}{c} \nabla \cdot \underline{V} = 0 \\ \text{parallel variation} \end{array} \right)$

i.e. $\left\{ \begin{array}{l} \tilde{\underline{V}} = \tilde{V}_x \hat{x} \\ \tilde{\underline{B}} = \frac{\partial}{\partial z} (\tilde{V}_x B_0) = \tilde{B}_x \hat{x} \end{array} \right.$

in shear Alfven wave:

$\left\{ \begin{array}{l} \tilde{\underline{V}}, \tilde{\underline{B}} \perp \underline{B_0} \\ \tilde{\underline{V}} \parallel \tilde{\underline{B}}, \text{ but out of phase} \end{array} \right.$

→ energetics → construct "Poynting theorem"

$$\rho_0 \frac{\partial \tilde{\underline{V}}}{\partial t} = \frac{B_0}{4\pi} \frac{\partial}{\partial z} \tilde{\underline{B}} \qquad (1)$$

$$\frac{\partial \tilde{\underline{B}}}{\partial t} = B_0 \frac{\partial}{\partial z} \tilde{\underline{V}} \qquad (2)$$

∴ construct energy evolution

Exercise

$$\underline{\mathcal{E} = \frac{\rho \tilde{V}^2}{2} + \frac{\tilde{B}^2}{8\pi}} \rightarrow \text{energy density}$$

∴ $(1) \cdot \underline{V}$ and $(2) \cdot \underline{B}$ ⇒

$$\frac{\partial}{\partial t}\left(\rho_0 \frac{\tilde{\underline{V}}^2}{2} + \frac{\tilde{\underline{B}}^2}{8\pi}\right) = \frac{B_0}{4\pi}\left(\underline{V} \cdot \frac{\partial \tilde{\underline{B}}}{\partial z} + \tilde{\underline{B}} \cdot \frac{\partial \underline{V}}{\partial z}\right)$$

∴

$$\frac{\partial}{\partial t}\left(\rho_0 \frac{\tilde{V}^2}{2} + \frac{\tilde{B}^2}{8\pi}\right) = \frac{B_0}{4\pi} \frac{\partial}{\partial z} (\tilde{\underline{V}} \cdot \tilde{\underline{B}})$$

and have Poynting form: $\frac{\partial \mathcal{E}}{\partial t} + \underline{\nabla} \cdot \underline{S} = 0$

$$\boxed{\underline{S} = -\frac{B_0}{4\pi} (\underline{V} \cdot \underline{B})} \rightarrow \left[\begin{array}{l}\text{wave energy density flux} \\ \int d^3 \underline{v} \cdot \underline{b} \rightarrow \text{cross helicity}\end{array}\right.$$

N.B. $\underline{S} = \frac{c}{4\pi} \underline{E} \times \underline{B}$, $\underline{P} = \underline{S}/c^2$

wave energy density flux ↳ wave momentum density

$\underline{E} = -\frac{\underline{V} \times \underline{B}_0}{c}$

$$\underline{S} = -\frac{1}{4\pi} (\tilde{\underline{V}} \times \underline{B}_0) \times \tilde{\underline{B}} = \frac{1}{4\pi}\left[(\cancel{\tilde{\underline{B}} \cdot \underline{B}_0}) \tilde{\underline{V}} - (\tilde{\underline{V}} \cdot \tilde{\underline{B}}) \underline{B}_0\right]$$
$$= -\frac{\underline{B}_0}{4\pi} (\tilde{\underline{V}} \cdot \tilde{\underline{B}})$$

$$\underline{S} = -\frac{\underline{B}_0}{4\pi} \underline{V} \cdot \underline{B}$$

i.e. - energy flows along field

$\rightarrow \underline{S} \sim \underline{V} \cdot \underline{B}$

Show

$H_c = \int d^3x \, \tilde{\underline{V}} \cdot \tilde{\underline{B}}$ → cross helicity
→ conserved in ideal MHD

Ex.: Show H_c conserved.

→ another way to formulate shear Alfven wave

velocity, es potential

since $\tilde{\underline{V}} \perp B_0$ write $\tilde{\underline{V}} = \underline{\nabla}\phi \times \vec{z}$
$\tilde{\underline{B}} \perp B_0$ $\underline{B} = \underline{\nabla}A \times \vec{z}$

↳ magnetic potential

i.e. $\underline{E} = \underline{E}_\perp$ so $\tilde{\underline{V}} = \frac{c}{B_0^2} \underline{E} \times \underline{B}_0$ in shear Alfven now, $\quad \frac{\partial \underline{v}}{\partial t} = -\frac{1}{\rho_0} \underline{\nabla} \left(\tilde{p + \frac{B^2}{8\pi}} \right) + \frac{\underline{B_0} \cdot \underline{\nabla}\, \underline{B}}{4\pi\rho_0}$

as $\tilde{\underline{v}}, \tilde{\underline{B}} \perp B_0$, take $\hat{z} \cdot \underline{\nabla} \times \quad \Rightarrow$

$$\hat{z} \cdot \frac{\partial \underline{\omega}}{\partial t} = 0 + \frac{B_0 \partial}{4\pi\rho_0 \partial z} \hat{z} \cdot (\underline{\nabla} \times \tilde{\underline{B}})$$

Now, $\quad \underline{v} = \underline{\nabla}\phi \times \hat{z}$

$\qquad = (\partial_y \phi, -\partial_x \phi, 0)$

$\hat{z} \cdot \underline{\nabla} \times \tilde{\underline{B}} = \frac{4\pi}{c} \tilde{J}_z$

$\cancel{\underline{\nabla}(\underline{\nabla} \cdot \underline{A})} - \nabla^2 A_z = +\frac{4\pi}{c} \tilde{J}_z$

$\underline{\omega}_z = \hat{z} \cdot \underline{\omega} = -\nabla_\perp^2 \phi \rightarrow \hat{z}$ component vorticity

$\rightarrow$ magnetic torque

$\Rightarrow$

$$\underbrace{\frac{\partial}{\partial t} \nabla_\perp^2 \phi}_{\text{vorticity evolution}} = \frac{B_0}{4\pi\rho_0} \frac{\partial}{\partial z} \nabla_\perp^2 A$$

$\underline{\nabla} \times (\underline{\nabla} \times \underline{A})$

and $\quad \frac{\partial \tilde{\underline{B}}}{\partial t} = B_0 \frac{\partial}{\partial z} \underline{v} \qquad$ and $\hat{z} \cdot \underline{\nabla} \times \quad \Rightarrow$

$$\underbrace{\frac{\partial}{\partial t} \nabla_\perp^2 A}_{\text{current evolution}} = B_0 \underbrace{\frac{\partial}{\partial z} \nabla_\perp^2 \phi}_{\parallel \text{ vorticity gradient}}$$

observe if "$\omega n - \nabla_\perp^2$", have:

$$\frac{\partial A}{\partial t} - B_0 \frac{\partial}{\partial z} \phi = 0$$

$\Rightarrow$ basically means $E_\parallel = 0$ for Alfven waves.

$$\underline{E} = -\frac{\underline{v} \times \underline{B}_0}{c} \quad , \therefore \quad \hat{z} \cdot \frac{\tilde{\underline{v}} \times B_0 \hat{z}}{c} = 0 \quad \checkmark$$

$\therefore$ can write shear Alfven wave equations as

$$\left.\begin{aligned} E_\parallel = 0 = \frac{\partial A}{\partial t} - B_0 \frac{\partial \phi}{\partial z} = 0 \\ \frac{\partial}{\partial t} \nabla_\perp^2 \phi = \frac{B_0}{4\pi \rho_0} \frac{\partial}{\partial z} \nabla_\perp^2 A \end{aligned}\right\}$$

$\Rightarrow$ example of 'reduced equations'.

Now, need also consider:

$\Rightarrow \underline{k} = k\hat{z}$, $\quad \nabla \cdot \underline{v} \neq 0$

what happens?

Now, $$\frac{\partial \underline{v}}{\partial t} = -\left(\frac{1}{\rho_0}\right) \underline{\nabla}\left(\tilde{p} + \frac{\underline{B}_0 \cdot \tilde{\underline{B}}}{4\pi}\right) + \frac{\underline{B}_0 \cdot \underline{\nabla}\, \underline{B}}{4\pi \rho_0}$$

$$\frac{\partial \tilde{\underline{B}}}{\partial t} = \underline{B}_0 \cdot \underline{\nabla}\, \underline{v} - B_0\, \underline{\nabla} \cdot \tilde{\underline{v}}$$

$\underline{k} = k\,\hat{z}$ $\qquad \underline{\nabla} \cdot \underline{v} \neq 0$

$$\Rightarrow \frac{\partial \tilde{v}_z}{\partial t} = -\frac{\partial}{\partial z}\left(\frac{\tilde{p}}{\rho_0}\right) - \cancel{\frac{\partial}{\partial z}\left(\frac{B_0 \cdot \tilde{B}}{4\pi \rho_0}\right)} + \cancel{B_0 \frac{\partial}{\partial z}\left(\frac{\tilde{B}_z}{4\pi \rho_0}\right)}$$

$$\& \quad \frac{\partial \tilde{B}_z}{\partial t} = \cancel{B_0\, \partial_z \tilde{v}_z} - \cancel{B_0\, \partial_z \tilde{v}_z}$$

$\therefore$ all that's left is simple acoustic mode

$$\frac{\partial \tilde{v}_z}{\partial t} = -\frac{\partial}{\partial z}\left(\frac{\tilde{p}}{\rho_0}\right)$$

$$\frac{\tilde{p}}{p_0} = \gamma \frac{\tilde{\rho}}{\rho_0} \qquad \text{from } p = p_0 (\rho/\rho_0)^\gamma$$

$$\frac{\partial \tilde{\rho}}{\partial t} = -\rho_0\, \underline{\nabla} \cdot \tilde{\underline{v}} = -\rho_0\, \partial_z \tilde{v}_z$$

$$\Rightarrow \frac{\partial^2 \tilde{\rho}}{\partial t^2} = \gamma \frac{p_0}{\rho_0} \frac{\partial^2}{\partial z^2} \tilde{\rho}$$

$\Rightarrow \quad \omega^2 = c_s^2 k_z^2 \quad , \quad c_s^2 = \gamma \, \underbrace{P}_{\text{"stiffness"}}^{\text{energy density}} / \rho_0$

$\rightarrow \underline{k} = k \, \vec{x}$ — Perpendicular Propagation

Now $\underline{B} = B_0 \hat{z}$, so

$\rightarrow \underline{k} = k \, \hat{x}$ must compress magnetic field

$\therefore$

$\rightarrow$ no incompressible cross-field propagation is possible

Now

$$\frac{\partial \underline{v}}{\partial t} = -\frac{\underline{\nabla}}{\rho_0}\widetilde{\left(P + \frac{B^2}{8\pi}\right)} + \cancel{\frac{B_0 \cdot \underline{\nabla} \, \underline{\tilde{B}}}{4\pi\rho_0}}$$

and

$$\frac{\partial \underline{B}/\rho}{\partial t} = \cancel{\frac{B_0 \cdot \underline{\nabla} \, \underline{\tilde{v}}}{\rho_0}} \quad \text{— freezing in}$$

so can take short-cut via:

$$\boxed{\frac{d}{dt} B/\rho = 0} \quad \Rightarrow \quad \tilde{B} = B_0 \frac{\tilde{\rho}}{\rho_0}$$

$$\therefore \quad \frac{\partial \underline{V}}{\partial t} = -\frac{1}{\rho_0} \nabla \Big(\underbrace{P_T}_{\text{thermal}} + \underbrace{P_B}_{\text{magnetic}} \Big)$$

$$P_T = P_0 (\rho/\rho_0)^\gamma , \qquad \tilde{P}_T = \gamma P_0 (\tilde{\rho}/\rho_0)$$

$$P_B = B^2/8\pi , \qquad \tilde{P}_B = 2 \frac{B_0^2}{8\pi} (\tilde{\rho}/\rho_0)$$

(i.e. "γ_{eff}" $= 2$, for field)

$$\frac{\partial}{\partial t}(\nabla \cdot \tilde{\underline{V}}) = -\nabla^2 \left[\frac{\gamma P_0}{\rho_0} + \frac{2 B_0^2}{8\pi\rho_0} \right] \frac{\tilde{\rho}}{\rho_0}$$

but $\nabla \cdot \underline{V} = -\frac{\partial}{\partial t} \frac{\tilde{\rho}}{\rho_0}$

$$\Rightarrow \quad \frac{\partial^2}{\partial t^2}(\tilde{\rho}/\rho_0) = \nabla^2 \left[\frac{\gamma P_0}{\rho_0} + \frac{2 B_0}{8\pi\rho_0} \right] (\tilde{\rho}/\rho_0)$$

$$\equiv \nabla^2 \left[C_s^2 + V_A^2 \right] (\tilde{\rho}/\rho_0)$$

$$\boxed{\omega^2 = k_\perp^2 (C_s^2 + V_A^2)}$$

$\rightarrow$ "magnetosonic" or "compressional Alfven wave"

N.B.:

$$\boxed{\begin{array}{l}\text{→ magnetosonic wave has } c^2 = C_s^2 + V_A^2 \\ \text{↔ combines acoustic, magnetic speeds} \\ \text{→ always faster (higher phase speed) than} \\ \quad \text{shear Alfven or acoustic mode.}\end{array}}$$

i.e. $\underline{k} = \underline{k}_\perp$ magnetosonic wave is "fastest" MHD wave

→ recalling class discussion ? ⇒ how reconcile ?

- magnetosonic wave carried by field energy density → $B_0^2/8\pi\rho_0$

yet

- $V_{magn}^2 = V_A^2$, as in shear Alfven, which is carried by magnetic tension $B_0^2/4\pi\rho_0$.

Resolution: Freezing-in condition ⇒ B/ρ = const, here

⇒ $\gamma_{eff} = 2$

i.e. freezing-in condition ⇒ field is stiff — indeed stiffer than gas, $\gamma = 5/3$ — acoustic medium i.e. $C_S^2 = c_s^2 + c_B^2$

$$= \frac{dP_{Th}}{d\rho} + \frac{dP_B}{d\rho}$$

$$= \gamma \frac{P_{Th_0}}{\rho_0} + 2\frac{P_B}{\rho_0}$$

i.e. for $\beta = P_{Th}/P_B = 1 \Rightarrow c_B^2 > c_s^2$.

To can summarize simple cases:

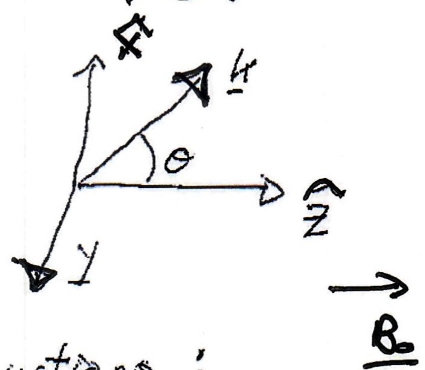
	$\nabla \cdot \underline{V} = 0$	$\nabla \cdot \underline{V} \neq 0$
$\underline{k} = \underline{k}_{\parallel}$	$\omega^2 = k_{\parallel}^2 V_A^2$ shear Alfven	$\omega^2 = k_{\parallel}^2 c_s^2$ acoustic
$\underline{k} = \underline{k}_{\perp}$	X	$\omega^2 = k_{\perp}^2 (c_s^2 + V_A^2)$ magnetosonic wave.

Note that magnetosonic is 'fastest' of waves.

ii.) Full Crank — Read Kulsrud, Chapt. 5

Now, consider full crank, for arbitrary $\underline{k}$.

geometry:



$$\begin{cases} \rho_0 = \rho_0 = \text{const} \\ \underline{B} = B_0 \hat{z} \end{cases}$$

have MHD equations:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \underline{v}) = 0$$

$$\rho \frac{d\underline{v}}{dt} = -\underline{\nabla} p + \frac{\underline{J} \times \underline{B}}{c}$$

$$\frac{\partial \underline{B}}{\partial t} = \underline{\nabla} \times (\underline{v} \times \underline{B})$$

$$\frac{d}{dt}(p/\rho^\gamma) = 0 \quad \Rightarrow \quad \frac{1}{p}\frac{dp}{dt} - \frac{\gamma}{\rho}\frac{d\rho}{dt} = 0$$

and continuity $\Rightarrow$

$$\frac{1}{p}\frac{dp}{dt} = -\gamma \, \underline{\nabla} \cdot \underline{v}$$

Now, convenient to write $\underline{V}(\underline{x}, t) = \frac{\partial \underline{\xi}(\underline{x}, t)}{\partial t}$

$\underline{\xi}(\underline{x}, t) \equiv$ displacement of fluid element, originally at $\underline{x}$ at t

$\Rightarrow$ with linearization! $\tilde{\underline{V}} = \frac{\partial \underline{\xi}}{\partial t}$, $\rho = \rho_0 + \delta\rho$, etc. :

$$\delta\rho = -\rho_0 \underline{\nabla} \cdot \underline{\xi}$$

$$\delta P = -\gamma P_0 \underline{\nabla} \cdot \underline{\xi}$$

$$\delta \underline{B} = \nabla \times (\underline{\xi} \times \underline{B}_0)$$

$$\rho_0 \frac{\partial^2 \underline{\xi}}{\partial t^2} = -\underline{\nabla}\, \delta p + \frac{\delta \underline{J} \times \underline{B}_0}{c}$$

so can assemble the pieces, assuming $\underline{\xi} = \underline{\xi}_k e^{i(k \cdot x - \omega t)}$ and omitting subscript $\Rightarrow$

EOM.

$\delta J = \underline{\nabla} \times \delta \underline{B}$

$$-\rho_0 \omega^2 \underline{\xi} = -\gamma P_0 \underline{k} (\underline{k} \cdot \underline{\xi}) - \frac{1}{4\pi} \left[\underline{k} \times (\underline{k} \times (\underline{\xi} \times \underline{B}_0)) \right] \times \underline{B}_0$$

from induction

- eigenmode equation for arbitrary displacement
- note as $\underline{\xi}$ is a 3 component vector, above is 3 linearly coupled equations, ω^2 is the eigenvalue! So ...

so - solution is $\det|3\times 3| \Rightarrow$ cubic equation for ω^2. $\Rightarrow$ expect $\underline{\underline{3}}$ waves. ω^2 each.

N.B.: Based on simple cases, what might these be?

$$\boxed{-\rho_0\omega^2\underline{\xi} = -\gamma P_0\underline{k}(\underline{k}\cdot\underline{\xi}) - \frac{1}{4\pi}\{\underline{k}\times[\underline{k}\times\underline{\xi}\times\underline{B_0}]\}\times\underline{B_0}}$$

$\rightarrow$ the $\underline{3}$ waves are, for the obvious profound reason, called the "fast", "slow" and "intermediate" waves...

- now, <u>choose</u>:

$$\left\{\begin{array}{l}\underline{k} = k(\sin\theta\,\hat{x} + \cos\theta\,\hat{z}) \\ \underline{\xi} = \xi\,\hat{y}\end{array}\right.$$

[oblique in x, z plane

i.e. $\underline{k}\cdot\underline{\xi} = 0 \Rightarrow \underline{\nabla}\cdot\underline{V} = 0$

$\Rightarrow$ "intermediate wave" $\rightarrow$ clearly shear Alfven

now $\boxed{\underline{k}\cdot\underline{\xi} = 0}$

and crank $\Rightarrow \left[\underline{k}\times[\underline{k}\times(\underline{\xi}\times\underline{B_0})]\right]\times\frac{\underline{B_0}}{4\pi}$

$$= \frac{(\underline{k}\cdot\underline{B_0})}{4\pi}[\underline{k}\times(\underline{\xi}\times\underline{B_0})]$$

$$= \frac{(\underline{k}\cdot\underline{B_0})^2}{4\pi}\underline{\xi}$$

$\circledast$ $$\boxed{-\rho_0 \omega^2 \underline{\xi} = -\frac{(\underline{k}\cdot \underline{B}_0)^2}{4\pi}\, \underline{\xi}}$$

$\underline{\xi} = \xi_y \vec{y}$

$\Rightarrow$ $\omega^2 = k_{\parallel}^2 V_A^2$ with $\underline{\xi} = \xi_y \vec{y}$

shear Alfven $\rightarrow$ physical properties as before

$\therefore$ "intermediate wave" is shear Alfven

$\underline{\underline{\text{so}}}$ "fast wave" must connect to magnetosonic

$\therefore$ "slow wave" must connect to acoustic

$(c_s^2 < V_A^2)$

Let's see ...

— fast and slow waves:

again: $\underline{k} = k(\sin\theta\, \hat{x} + \cos\theta\, \hat{z})$

$\underline{\xi} = \xi_x \hat{x} + \xi_z \hat{z}$

COMP

point here is that $\underline{k}\cdot\underline{\xi} \neq 0$ $\Rightarrow$ unlike intermediate, these are compressional so now, crank ⇒

$$\frac{1}{4\pi}\left\{\underline{k}\times\left[\underline{k}\times(\underline{\xi}\times\underline{B}_0)\right]\right\}\times\underline{B}_0 = -\frac{k^2 B_0^2}{4\pi}\,\xi_x\,\hat{x}$$

and

$$-\nabla p_1 = -\gamma p_0 \underline{k}\,(\underline{k}\cdot\underline{\xi})$$

so
$$-\frac{\partial p_1}{\partial x} = -k^2\gamma p_0\left(\sin^2\theta\,\xi_x + \sin\theta\cos\theta\,\xi_z\right)$$

$$-\frac{\partial p_1}{\partial z} = -k^2\gamma p_0\left(\sin\theta\cos\theta\,\xi_x + \cos^2\theta\,\xi_z\right)$$

now, defining $\left.\begin{array}{l} c_s^2 = \gamma p_0/\rho_0 \\ V_A^2 = B_0^2/4\pi\rho_0 \end{array}\right\}$ as usual ⇒

$$\boxed{\begin{array}{l} -\omega^2\xi_x = -k^2(c_s^2\sin^2\theta + V_A^2)\,\xi_x - k^2 c_s^2\sin\theta\cos\theta\,\xi_z \\ -\omega^2\xi_z = -k^2 c_s^2\sin\theta\cos\theta\,\xi_x - k^2 c_s^2\cos^2\theta\,\xi_z \end{array}}$$

⇒ coupled equations for ξ_x, ξ_z

⇒ standard crank gives:

$$\begin{vmatrix} k^2 V_A^2 + k^2 c_s^2\sin^2\theta - \omega^2, & k^2 c_s^2\sin\theta\cos\theta \\ k^2 c_s^2\sin\theta\cos\theta, & k^2 c_s^2\cos^2\theta - \omega^2 \end{vmatrix} = 0$$

and $$\boxed{\omega^4 - k^2 (C_s^2 + V_A^2)\omega^2 + k^4 C_s^2 V_A^2 \cos\theta = 0}$$,

is "the dispersion relation".

Now can solve to:

$$\boxed{\frac{\omega^2}{k^2} = \frac{V_A^2 + C_s^2}{2} \pm \frac{1}{2}\left[(V_A^2 - C_s^2)^2 + 4 C_s^2 V_A^2 \sin^2\theta\right]^{1/2}}$$

→ upper root → "fast" wave

→ lower root → "slow" wave.

Now, check :

$\sin\theta = 0 \Rightarrow \underline{k} = k\hat{z}$

$$\frac{\omega^2}{k^2} = \frac{V_A^2 + C_s^2}{2} \pm \frac{(V_A^2 - C_s^2)}{2} \longrightarrow \begin{cases} V_A^2 \rightarrow \text{Alfven} \\ C_s^2 \rightarrow \text{acoustic} \end{cases}$$

$\sin\theta = 1 \Rightarrow \underline{k} = k\hat{x}$

$$\frac{\omega^2}{k^2} = \frac{V_A^2 + C_s^2}{2} \pm \frac{1}{2}\left[(V_A^2)^2 + (C_s^2)^2 - 2V_A^2 C_s^2 + 4 C_s^2 V_A^2\right]^{1/2}$$

$$= \frac{V_A^2 + C_s^2}{2} \pm \frac{1}{2}\left[(V_A^2 + C_s^2)^2\right]^{1/2} = \begin{cases} 0 \\ V_A^2 + C_s^2 \end{cases}$$

→ Magnetosonic wave.

Note: can observe:

- for $\perp$ propagation, fast wave $\Leftrightarrow$ magnetosonic wave ✓
[slow = intermediate wave : $\omega^2 = 0$]
- for $\parallel$ propagation, fast $\Leftrightarrow$ Alfven ✓ ($\beta < 1$)
slow $\Leftrightarrow$ acoustic ✓
[fast $\Rightarrow$ intermediate] ($\beta > 1$, vice versa)
- always have $V_{ph_{slow}}^2 \leq V_{ph_{int}}^2 \leq V_{ph_{fast}}^2$

$\Rightarrow$ have general result that polarizations of fast and slow modes are orthogonal

can show via:

$\rightarrow$ matrix from eqns $\Leftrightarrow$ 2x2

$$-\rho \omega_s^2 \underline{\xi_s} = \underline{\underline{M}} \cdot \underline{\xi_s} \qquad (1)$$

$$-\rho \omega_f^2 \underline{\xi_f} = \underline{\underline{M}} \cdot \underline{\xi_f} \qquad (2)$$

$\underline{\xi_f} \cdot (1) - \underline{\xi_s} \cdot (2) \Rightarrow$

$$-\rho (\omega_s^2 - \omega_f^2) \underline{\xi_s} \cdot \underline{\xi_f} = \underline{\xi_f} \cdot \underline{\underline{M}} \cdot \underline{\xi_s} - \underline{\xi_s} \cdot \underline{\underline{M}} \cdot \underline{\xi_f}$$

but: recall from determinant

$$\underline{\underline{M}} = \begin{bmatrix} k^2 V_A^2 + k^2 C_s^2 \sin^2\theta \,, & k^2 C_s^2 \sin\theta \cos\theta \\ k^2 C_s^2 \sin\theta\cos\theta \,, & k^2 C_s^2 \cos^2\theta \end{bmatrix}$$

and $\underline{\underline{M}}^T = \underline{\underline{M}}$ so $\underline{\underline{M}}$ self-adjoint!

$\Rightarrow$ ↳ {important structural property in linear MHD}

$$\underline{\xi}_f \cdot \underline{\underline{M}} \cdot \underline{\xi}_s = \underline{\xi}_s \cdot \underline{\underline{M}} \cdot \underline{\xi}_f$$

so $\underline{\xi}_f \cdot \underline{\xi}_s = 0$.

$\rightarrow$ to yet furthur elucidate the waves, can consider two limits
$\beta \ll 1 \rightarrow C_s^2/V_A^2 \ll 1$
$\beta \gg 1 \rightarrow C_s^2/V_A^2 \gg 1$.

a) for $C_s^2 \gg V_A^2$,

l. order $\omega_f^2 = k^2 c_s^2$, $\omega_s = 0$

1st ord. $\frac{\omega_f}{k} \sim C_s + \frac{V_A^2 \sin^2\theta}{2C_s}$, $\quad \tilde{\xi} \parallel \underline{k}$ (note $\xi_f \cdot \xi_s = 0$)

$\frac{\omega_s^2}{k^2} \approx V_A^2 \cos^2\theta \quad \tilde{\xi} \perp \underline{k}$

(otherwise $\tilde{p} \rightarrow$ higher ω)

b) for $c_s^2 \ll V_A^2$,

$$\frac{\omega_F^2}{k^2} \cong V_A^2 + c_s^2 \sin^2\theta$$

$\underline{\mathcal{E} \perp B_0}$

(or no "springiness" to drive fast motion in parallel dir.)

$$\frac{\omega_s^2}{k^2} \simeq c_s^2 \cos^2\theta$$

$\mathcal{E} \parallel B_0$

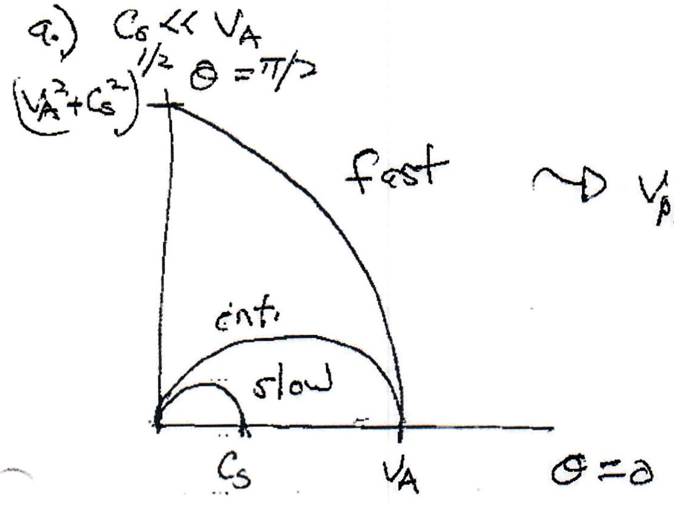
(otherwise, if $\mathcal{E} \perp B \to$ get Alfven)

and again, $\underline{\mathcal{E}_s} \cdot \underline{\mathcal{E}_f} = 0$

→ now, can sum up this slow, intermediate, fast story in the Fredricks Diagram.

consider $c_s \ll V_A$, $c_s \gg V_A$

a.) $c_s \ll V_A$



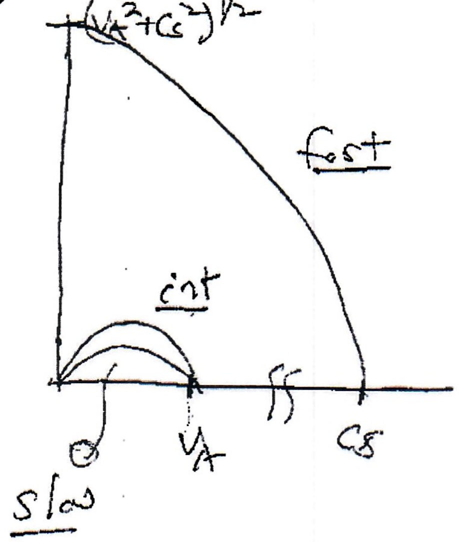
→ V_{phase} vs θ for:

fast → magnetosonic at ⊥
Alfven at ∥

int → Alfven at ∥
nothing at ⊥

slow → acoustic (parallel) at ∥
nothing at ⊥.

b.) $V_A^2 \ll C_S^2$



again:

fast → magnetosonic at ⊥
Alfven at ∥

int. → Alfven at ∥
nothing at perp.

slow → Alfven at ∥
nothing at ⊥

→ now, observe the following:

→ 3 components $\underline{E}$
→ 2 component $\underline{B}$ $(\underline{\nabla}\cdot\underline{B}=0)$
→ P, ρ

⇒

∴ 7 fields

ut 6 waves → 2 each $\left\{\begin{array}{l}\text{fast}\\ \text{intermediate}\\ \text{slow}\end{array}\right.$

$\omega^2 = \_\_$

so, 1 missing mode! → entropy mode!

i.e. $S = T \ln(P/\rho^{\gamma})$

and assumed $P_1/P_0 = \gamma \rho_1/\rho_0$

if relax ⇒ entropy wave $\begin{cases} \delta\rho \neq 0, & \text{all else} = 0 \\ \omega = 0. \end{cases}$

δ relevant in shocks

→ some concluding philosophy ⟺ what is the moral of this story of the trip to the zoo of MHD waves?

- even for a simple dynamical model, like ideal MHD, even minimal anisotropy endroduces great complexity!

- signal propagation $\begin{cases} \text{parameter dependent} \\ \text{anisotropic} \\ \text{has definite polarization} \end{cases}$

- important to understand $\begin{cases} \text{magnetic pressure} \\ \text{magnetic tension} \\ \text{thermal pressure} \end{cases}$

as origins of anisotropic restoring force in waves.