On the role of resonance absorption in flows receptive to the magnetorotational instability

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Engineering and Physical Sciences Research Council

Sustenance of turbulence/dynamo action in protoplanetary discs

- Presence of a linear instability mechanism?
  - Degree of ionization.
  - Different non-ideal MHD terms.
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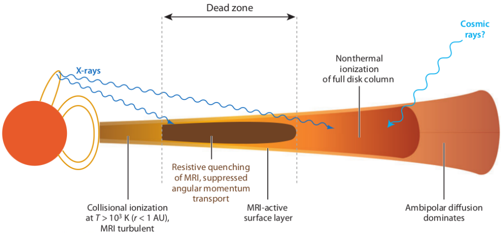

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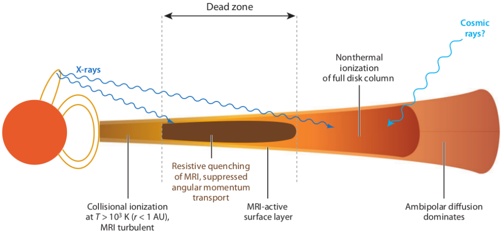

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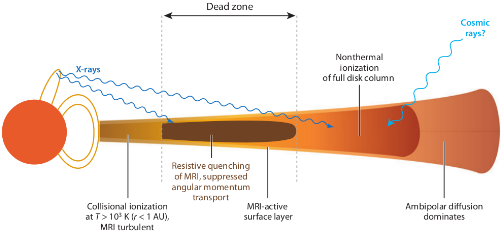

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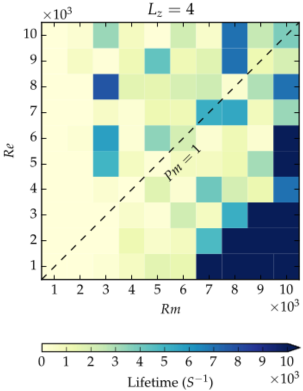
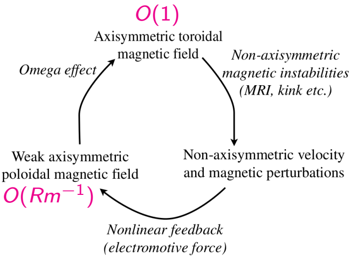


Nauman & Pessah (2018).

Self-sustaining processes in magnetohydrodynamics (MHD)



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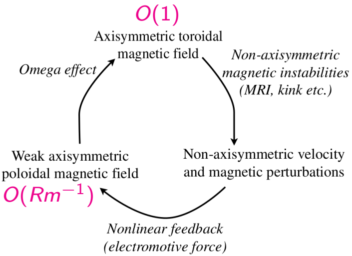

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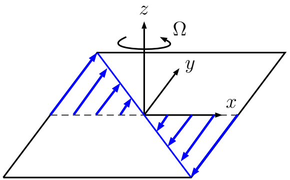

Field decomposition:

$$\boldsymbol{v} = \underbrace{\overline{v}_y \boldsymbol{e}_y + \overline{\boldsymbol{v}}_p}_{y\text{-averaged part}} + \underbrace{\boldsymbol{v}_{3D}}_{\text{Wave}}, \quad \boldsymbol{b} = \underbrace{\overline{b}_y \boldsymbol{e}_y + \overline{\boldsymbol{b}}_p}_{y\text{-averaged part}} + \underbrace{\boldsymbol{b}_{3D}}_{\text{Wave}}$$

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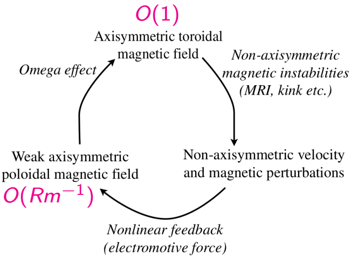

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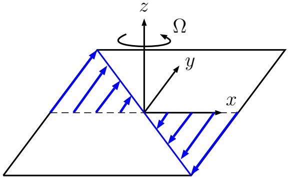

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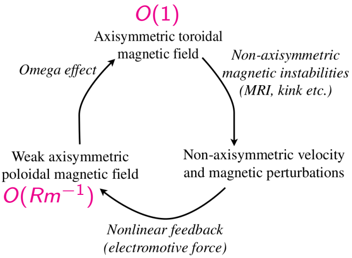

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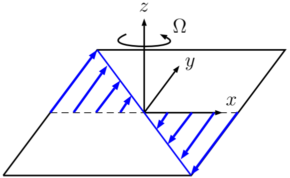

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2. Feedback electromotive force (EMF)

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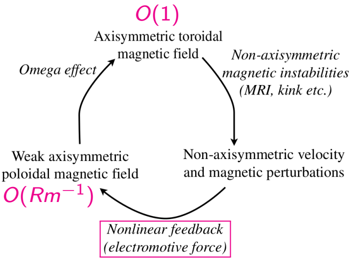

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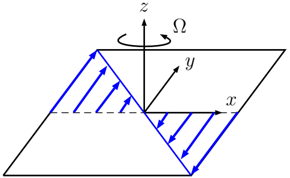

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Research question:

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Consider a system with a continuous background flow $\boldsymbol{V}(\boldsymbol{x})$, a magnetic field $\boldsymbol{B}(\boldsymbol{x})$, and a wave with wavenumber vector $\boldsymbol{k}$ giving the flow frequency $\omega_f = \boldsymbol{V} \cdot \boldsymbol{k}$ and Alfvén frequency $\omega_A = \boldsymbol{B} \cdot \boldsymbol{k}$:

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- As a consequence of the absorption, resonance layers may act as barriers that delimit fluid/plasma motion.

(Barston, 1964; Booker & Bretherton, 1967; Grad, 1969; Uberoi, 1972)

Analytical solution near resonance

- Consider the linearized incompressible ideal Euler and induction equation in cylindrical coordinates

$$\partial_t \boldsymbol{v} + (\boldsymbol{V}\cdot\nabla)\boldsymbol{v} + (\boldsymbol{v}\cdot\nabla)\boldsymbol{V} - (\boldsymbol{B}\cdot\nabla)\boldsymbol{b} - (\boldsymbol{b}\cdot\nabla)\boldsymbol{B} = -\nabla\pi$$
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$$\nabla\cdot\boldsymbol{v} = 0, \quad \nabla\cdot\boldsymbol{b} = 0,$$

with a basic state:

$$\boldsymbol{V}(r) = [0, V_\theta(r), V_z(r)], \quad \boldsymbol{B}(r) = [0, B_\theta(r), B_z(r)],$$

and a perturbation $[\boldsymbol{v}, \boldsymbol{b}, \pi](r,\theta,z,t) = [\hat{\boldsymbol{v}}, \hat{\boldsymbol{b}}, \hat{\pi}](r)e^{i(m\theta+kz-\omega t)}$.

(Goossens *et al.* 1992)

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- By solving the induction equation for $\hat{\boldsymbol{b}}$ and expressing $\hat{\boldsymbol{v}}$ in terms of a Lagrangian displacement $\boldsymbol{\xi}$, one obtains the equation system
$$\begin{bmatrix} \left(C_1 - \frac{D}{r}\right) & -C_2 \\ C_3 & -C_1 \end{bmatrix} \begin{pmatrix} \xi_r \\ \pi \end{pmatrix} = D \begin{pmatrix} \xi_r' \\ \pi' \end{pmatrix},$$
where C_1, C_2 and C_3 are coefficients that depend on m, k, r, $\boldsymbol{B}$, $\boldsymbol{V}$ and
$$\omega_f = \frac{V_\theta}{r}m + V_z k, \quad \Omega = \omega - \omega_f, \quad \omega_A = \frac{B_\theta}{r}m + B_z k, \quad D = \Omega^2 - \omega_A^2.$$

(Goossens *et al.* 1992)

Analytical solution near resonance cont.

- The system has a singularity at $r = r_A$ where $D = 0$. Let $s = r - r_A \ll 1$ and assume that ξ_r and π may be described by modified power series solutions in s:

$$\xi_r(s) = \sum_{n=0}^{\infty} X_n s^{\sigma+n}, \qquad \pi(s) = \sum_{n=0}^{\infty} Y_n s^{\sigma+n}$$

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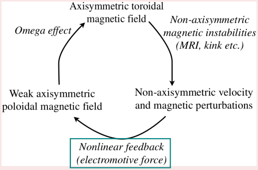
- Taylor expand all functions of ω in $\alpha \ll 1$.

Electromotive force (EMF)

Recall: $\partial_t \chi = \overline{(\boldsymbol{v}_{3D} \times \boldsymbol{b}_{3D})} \cdot \boldsymbol{e}_y + \ldots$



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- Describes the induction of the magnetic field.
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$$\mathcal{E} = \left(\hat{\boldsymbol{v}} e^{i(m\theta+kz-[\omega+i\alpha]t)} + \hat{\boldsymbol{v}}^* e^{-i(m\theta+kz-[\omega+i\alpha]t)}\right) \times \left(\hat{\boldsymbol{b}} e^{i(m\theta+kz-[\omega+i\alpha]t)} + \hat{\boldsymbol{b}}^* e^{-i(m\theta+kz-[\omega+i\alpha]t)}\right).$$

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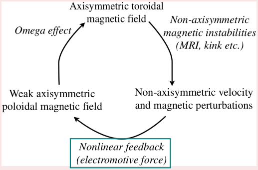

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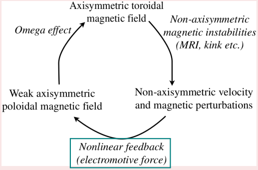

Substitution of the analytical solution:

$$r: \quad Ae^{\pm\phi\sigma_i}\left\{\frac{2kT}{D^{(1)}(m^2+k^2r_A^2)}\frac{1}{s^2+\chi^2}\times \left[sr_A\left(\Omega\omega_A' - \Omega'\omega_A\right) \mp \chi\left(kr_A^2\left(\omega_f\left(\frac{V_\theta}{r}\right)' + \Omega\left(\frac{B_\theta}{r}\right)'\right) - m\left(\omega_f V_z' + \Omega B_z'\right)\right) \pm \alpha\omega_f\frac{4kT}{D^{(1)}} - \alpha\chi r_A\omega_f' \mp \alpha s\left(\left(\frac{B_\theta}{r}\right)' kr_A^2 - B_z' m\right)\right] + r_A\left(B_z'\left(\frac{V_\theta}{r}\right)' - V_z'\left(\frac{B_\theta}{r}\right)'\right)\right\},$$

$$\theta: \quad 4A\alpha\frac{kT\omega_f}{D^{(1)}(m^2+k^2r_A^2)}e^{\pm\phi\sigma_i}\frac{kr_As \mp m\chi}{s^2+\chi^2}, \qquad z: \quad 4A\alpha\frac{kT\omega_f}{D^{(1)}(m^2+k^2r_A^2)}e^{\pm\phi\sigma_i}\frac{ms \pm kr_A\chi}{s^2+\chi^2},$$

Validation of the EMF expression

Numerical ideal MHD calculations (Ogilvie & Pringle, 1996):

Background state: $\boldsymbol{V}(r) = [0, r\Omega_K(r), 0]$, $\boldsymbol{B}(r) = [0, B_0 r^{-1}, 0]$, with $B_0 = 0.2$ and $\Omega_K(r) = r^{-3/2}$ is the Keplerian profile.

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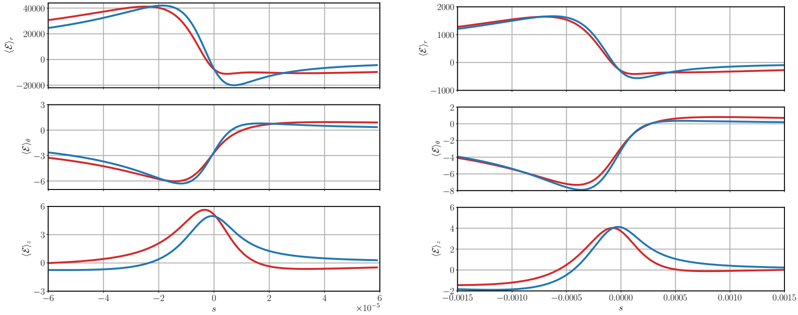

$k = 2,\ m = 5,\ \omega = 4.00 + i5.94 \times 10^{-5}$.

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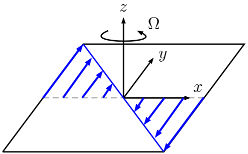
Numerical, Analytical

Cartesian model: stability diagram

No-slip, electr. conducting walls; $Re = 10^3$, $Pm = 1$, $R = -4/3$; $\boldsymbol{B} = (0, B_0, 0)$



Rotating plane Couette flow

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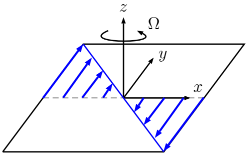

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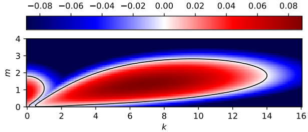
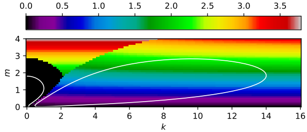


Growth rates



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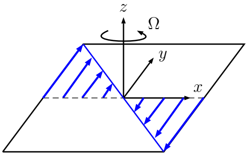

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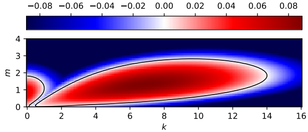

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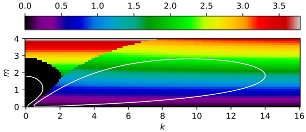
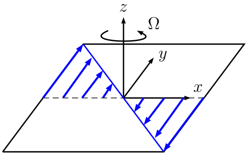


Frequencies

$k = 4$, $m = 2$,
$\omega = 1.49 - i0.00$

Cartesian model: stability diagram

No-slip, electr. conducting walls; $Re = 10^3$, $Pm = 1$, $R = -4/3$; $\boldsymbol{B} = (0, B_0, 0)$



Rotating plane Couette flow

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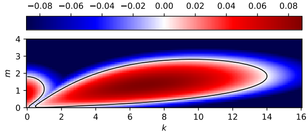
$\omega = 1.49 - i0.00$



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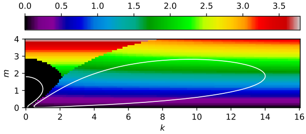

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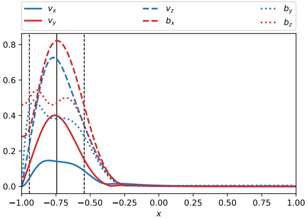
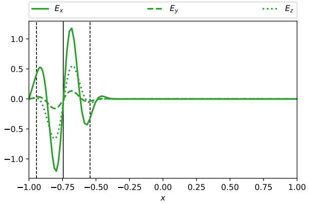


Eigenfunction



EMF

Conclusions and summary

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Thank you for your attention!