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Evolution of magnetic fields in large scale anisotropic MHD flows

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Outline

- Dilute plasmas;
- Anisotropic MHD description;
  - CGL MHD
  - Braginskii MHD
  - 16 momentum closure MHD
- Linear stability (16-mom. MHD)
- Nonlinear fluctuations in decaying anisotropic MHD;
- Summary

Dilute Plasmas

Magnetized extragalactic plasmas is dilute

collision freq. is much lower then Larmor freq. $\nu/\Omega \ll 1$

(dilute, collisionless, weakly collisional, collision poor)

Exact description: kinetic theory

Particle distribution function; micro physics + fluid effects;

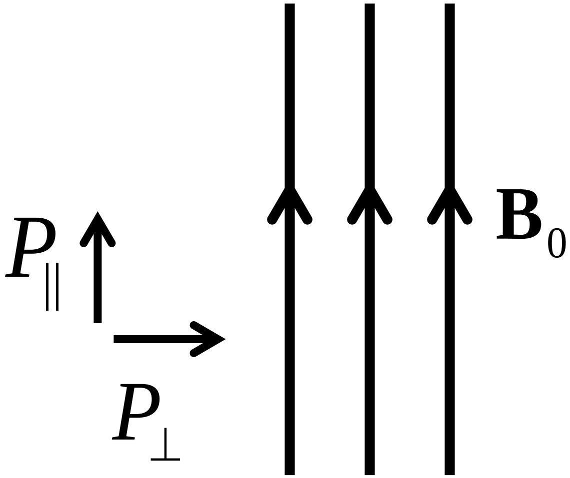
micro instabilities; fluid instabilities; *(highly complex formalism)*

Can the MHD be used to describe such "fluids"?

Collision freq. is much higher then fluid frequencies $\nu/\omega \gg 1$

MHD of Dilute Plasmas

If we insist on fluid description of dilute plasmas, pressure can not be isotropic.



Anisotropic MHD models

(one fluid, one component)

Anisotropic MHD should be able to resolve micro physics (micro instabilities) within simple one fluid (component) formalism. Anisotropic MHD Lab: the solar wind;

Can we be still successful with "naive" MHD at large scales?

Anisotropic MHD models

Isotropic one fluid MHD

Equation of State:

$$\frac{d}{dt}\left(\frac{P}{\rho^{\gamma}}\right)=0$$

CGL (Chew Goldberger Low) MHD

"double adiabatic"

state ($P_{||}$, $P_{\perp}$):

Neglecting heat fluxes

(high freq. processes)

$$\frac{d}{dt}\left(\frac{P_{\parallel}B^{2}}{\rho^{3}}\right)=0$$

$$\frac{d}{dt}\left(\frac{P_{\perp}}{\rho B}\right)=0$$

MHD waves + micro physics (Mirror and Fire-hose instabilities)

Anisotropic MHD models

Anisotropic viscosity MHD (Braginskii MHD)

(Braginskii 1965, Hollweg 1985)

$$\frac{d}{dt}\ln\left(\frac{P_{\parallel}B^2}{\rho^3}\right) = -\frac{2\nu}{3}\frac{P_{\parallel}-P_{\perp}}{P_{\parallel}}$$

$$\frac{d}{dt}\ln\left(\frac{P_{\perp}}{\rho B}\right) = \frac{\nu}{3}\frac{P_{\parallel}-P_{\perp}}{P_{\perp}}$$

ν – viscosity parameter

Local (viscous) properties of anisotropic plasmas

MHD model with heat fluxes: 16 momentum closure model

(Oraevski et al. 1968, Ramos 2003, Dzhalilov et al. 2010)

$$\frac{d}{dt}\left(\frac{P_{\|}B^2}{\rho^3}\right) = -\frac{B^2}{\rho^3}\left[B(\mathbf{h}\cdot\nabla)\frac{S_{\|}}{B} + \frac{2S_{\perp}}{B}(\mathbf{h}\cdot\nabla)B\right],$$

$$\frac{d}{dt}\left(\frac{P_{\perp}}{\rho B}\right) = -\frac{B}{\rho}(\mathbf{h}\cdot\nabla)\frac{S_{\perp}}{B^2},$$

$$\frac{d}{dt}\left(\frac{S_{\|}B^3}{\rho^4}\right) = -\frac{3P_{\|}B^3}{\rho^4}(\mathbf{h}\cdot\nabla)\frac{P_{\|}}{\rho},$$

$$\frac{d}{dt}\left(\frac{S_{\perp}}{\rho^2}\right) = -\frac{P_{\|}}{\rho^2}\left[(\mathbf{h}\cdot\nabla)\frac{P_{\perp}}{\rho} + \frac{P_{\perp}}{\rho}\frac{P_{\perp}-P_{\|}}{P_{\|}B}(\mathbf{h}\cdot\nabla)B\right],$$

16 Momentum MHD

Linear spectrum:

- MHD classical;
- Fire-hose and Mirror instabilities;
- Effects of heat fluxes (entropy modes);

Discrepancies between CGL-MHD and Kinetic theory are removed. (Mirror mode instability crit., Incompressible and compressible fire-hose instabilities, entropy modes);

Dzhalilov, Kuznetsov, Staude 2008, 2010

Somov, Dzhalilov, Staude 2008.

16 Momentum MHD: Linear Analysis

Anisotropic MHD flow in parallel magnetic field

Parameters: $\gamma = {}^{S_{||}}/_{P_{||}C_{||}}$ $\alpha = {}^{P_{\perp}}/_{P_{||}}$

Strong magnetic field:

CGL MHD

$$\omega^2 = 3C_{||}^2 k_x^2$$

"acoustic mode"

16 Momentum MHD

$$\omega_+^2 = C_{||}^2 k_x^2 \eta_+^2,$$

$$\omega_s^2 = C_{||}^2 k_x^2,$$

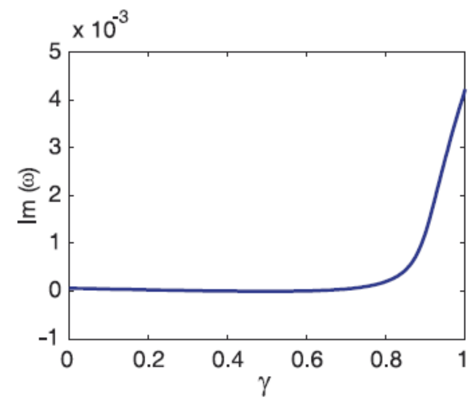
$$\omega_-^2 = C_{||}^2 k_x^2 \eta_-^2, \qquad \eta_-^2 < 1 < \eta_+^2$$

"fast and slow thermo-acoustic modes"

16 Momentum MHD: Linear Analysis

Anisotropic MHD shear flow in uniform magnetic field:

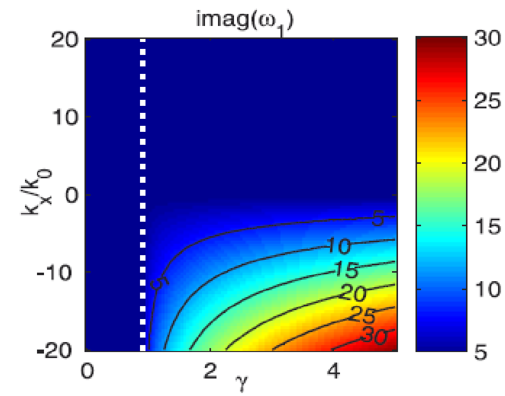
V=(Sy, 0, 0), **B**=(B, 0, 0)



Strong magnetic field

- Heat flux instability ($\gamma_{cr} = 0.85$)
- Shear flow overstability;

(Uchava et al. 2014)



Weak magnetic field

Incompressible linear perturbations;

linear thermo-kinetic invariant;

(Uchava et al. (in prep.))

$$W = \left(\frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}\right) 3C_\perp^2 (C_\perp^2 - C_\parallel^2) S'_\perp + \qquad (22)$$

$$+3j\left(\left(\frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}\right)(C_\parallel^2 V_A^2 + C_\perp^2(C_\parallel^2 - C_\perp^2)) + \frac{\partial^2}{\partial x^2} C_\parallel^2 (V_A^2 + 2(C_\perp^2 - C_\parallel^2))\right) V'_x -$$

$$-\left(\left(\frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}\right)(C_\parallel^2 V_A^2 + C_\perp^2(C_\parallel^2 - C_\perp^2)) + \frac{\partial^2}{\partial x^2} C_\parallel^2 (V_A^2 + C_\perp^2 - C_\parallel^2)\right)(S'_\parallel + 3C_\parallel \gamma_\parallel B'_x + 3ijA\frac{\partial}{\partial x} B'_y).$$

Nonlinear Anisotropic MHD state

Linear theory 16 momentum MHD:

Long way to go … (especially at equipartition);

Development of linear micro instabilities?

- Velocity shear overstability: smoothens velocity field
- Heat flux instability: limits maximal possible γ
- Mirror and Fire-hose family: mimic collision effects?

(Santos-Lima et al. 2014: CGL-MHD)

Anisotropic MHDs saturates to classical MHD?

- At large scales

- Small scales ? MHD dynamo (micro phys. can be important)

Large Scale Magnetic Fluctuations

Large scale magnetic field evolution in decaying anisotropic MHD turbulence;

Stochastic magnetic field with no mean component: $\overline{\mathrm{B}} = 0$

Anisotropy axis is changing stochastically.

(isotropic, turbulence spectrum)

Reformulate 16 momentum MHD EOS:

$$\frac{\mathrm{d}}{\mathrm{d}t} \ln\left(\frac{\alpha\rho^2}{B^3}\right) = \gamma C_{||}\left[\nabla_{||} \ln\left(\frac{B^{2\alpha+1}}{\alpha}\right) - 2\ln(\mathrm{B})\,\nabla_{||}\alpha\right]$$

$$\gamma = {}^{S_{||}}/_{P_{||}C_{||}},\ \alpha = {}^{P_\perp}/_{P_{||}}\ ,\ \nabla_{||} \equiv \frac{\mathbf{B}}{B}\cdot\boldsymbol{\nabla}$$

Large Scale Magnetic Fluctuations

Assumptions:

- ✓ Turbulence fluctuations: incompressible;
- ✓ Constant anisotropy parameters: α, γ .
- ✓ Fluctuation frequency: $\omega_A^2 = V_A^2 k_{\parallel}^2$
- ✓ Fluctuating scale: integral scale of turbulence;
- ✓ Effective magnetic field: $B_{\text{eff}} = \sqrt{4\pi n} V_A$

$$B_{\text{eff}} \propto \gamma(2\alpha + 1)(nT)^{1/2}$$

CGL MHD: $B_{\text{eff}} = 0$

Braginskii MHD: $B_{\text{eff}} \propto const.$

Magnetic Fluctuations in Expanding Universe

Helical MHD turbulence: $B_{\text{eff}} \propto T^{1/3}$

Non-helical MHD turbulence: $B_{\text{eff}} \propto T^{1/2}$

16-m. anisotrop. MHD EOS: $B_{\text{eff}} \propto \gamma(2\alpha + 1)\, T^2$

Kinetic fluctuations: $\delta B \propto n^{3/4}\, T^{1/8} \propto T^{2.375}$

Summary

16 momentum MHD can be used to describe effects of anisotropy in dilute plasmas at large scales;

MHD turbulence decay (helical, or not) predicts higher magnetic field energy then by anisotropic MHD state with constant α and γ.

Possible outcomes

- Anisotropy and/or heat flux effects grow: $\gamma(2\alpha + 1)$
- Anisotropy effects change turbulence spectral shape;