Alfven wave turbulence and magnetic reconnection

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The presence of alfvenic turbulence is well documented in astrophysical plasmas, the solar wind. AW spectrum believed to power the "turbulent Alfvenic aurora". AW spectrum is claimed to exist inside current sheets (Earth's neutral sheet).

Alfven waves possess a parallel electric field, they are energetic. Good candidates to explain electron acceleration or re-acceleration (e.g. during flares).

Alfven waves can be produced by a current driven instability. Such current driven instability is central to the notion of "anomalous resistivity " in magnetic reconnection.

The kinetic and inertial regimes of the Alfven wave

Alfven wave : kinetic or inertial depending if the parallel electric field is balanced by field-aligned electron pressure gradient or electron inertia.

Kinetic Alfven wave : plasma beta larger than m_e/m_i

$$\omega = k_{\|} v_A \sqrt{1 + \rho_s^2 k_\perp^2}$$

Inertial Alfven waves: plasma beta smaller than m_e/m_i

$$\omega = \frac{k_{\|} v_A}{\sqrt{1+k_\perp^2 d_e^2}}$$

Current driven Alfven instability

Equilibrium drifting Maxwellian for electrons : field aligned current

Unstable to the emission of Alfven Waves when $v_{\|} > \dot{v}_A$
(inverse Landau damping)

AW instability occurs before Ion Acoustic instability (despite $C_S < V_A$)
Rate of ion Landau damping smaller for AW than acoustic waves

A) Emitted wave momentum absorbed by an ion : anomalous resistivity
B) Wave momentum absorbed by an electron: anomalous viscosity

Both resistivity and electron viscosity break the frozen-in conditions

Current sheets can become unstable to current driven AW instability and this can drive alfven turbulence.

Forced Magnetic reconnection

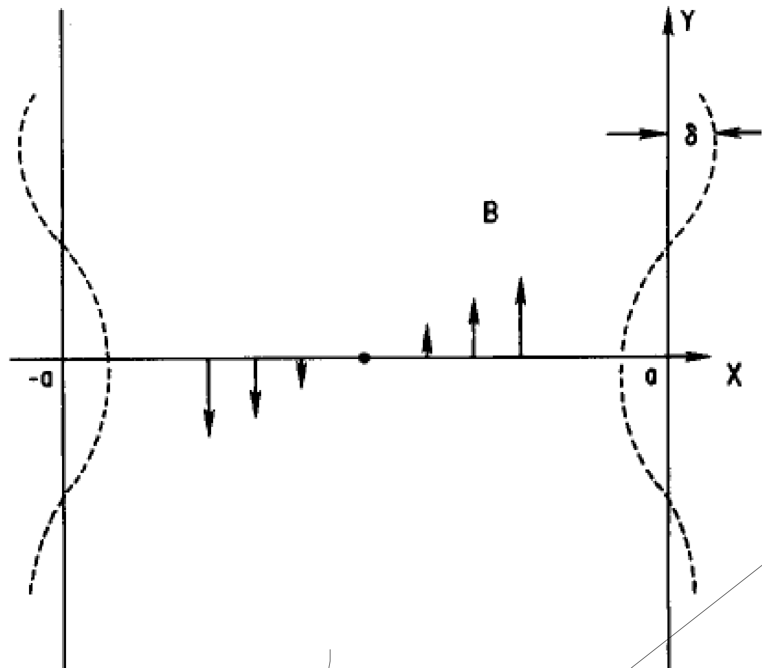
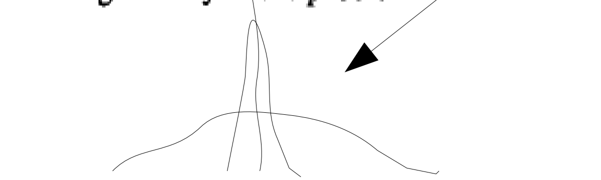


FIG. 1. The geometry of the problem.



Slow boundary perturbations

Phase A) : current build-up at the resonant surface.

Phase B) : magnetic reconnection

Does the current driven AW instability occurs before or after reconnection is triggered by the current build-up?

The current sheet becomes unstable to the emission of Alfven waves prior to reconnection.

Occurs when $v_{\parallel} \sim \dot{v}_A$

when $\delta \sim d_i$

AW instability triggered when the current sheet width is the ion skin depth
Magnetic field remains frozen-in the electron fluid.

Remarks :

In standard MHD : consequence of the kinetic instability is modeled by increasing the resistivity once current larger than the critical value.

But increase in hyper-resistivity (electron viscosity) is expected as well.

For forced reconnection : triggering anomalous magnetic diffusion would also trigger reconnection at scale di if the anomalous diffusion region larger than di.

Anisotropic Alfven turbulence

Goldreich-Sidrar theory: A) AW turbulence is 3D anisotropic (Kolmogorov type in the perpendicular plane)

B) anisotropy of AW turbulence is fixed by the ordering

$$k_{\|} / k_{\perp} \sim \delta B / B_0 \ll 1,$$

They call it critical balance condition and it is equivalent to reduced-MHD ordering.

Gyrofluid model

$\partial_t n_e + [\phi, n_e] - \nabla_\parallel J = 0,$ Electron density equation

$\partial_t \psi + \nabla_\parallel (\rho_s^2 n_e - \phi) = 0.$ $E_\parallel = -\rho_s^2 \nabla_\parallel n_e$ Electron momentum equation

$(1 - \rho_i^2 \nabla_\perp^2) n_e = \nabla_\perp^2 \phi.$ Gyro-Poisson equation

$k_\perp \rho_i \ll 1$ $n_e = \nabla_\perp^2 \phi.$ Reduced MHD

$k_\perp \rho_i \gg 1$ $n_e = -\phi / \rho_i^2,$ Reduced Electron MHD

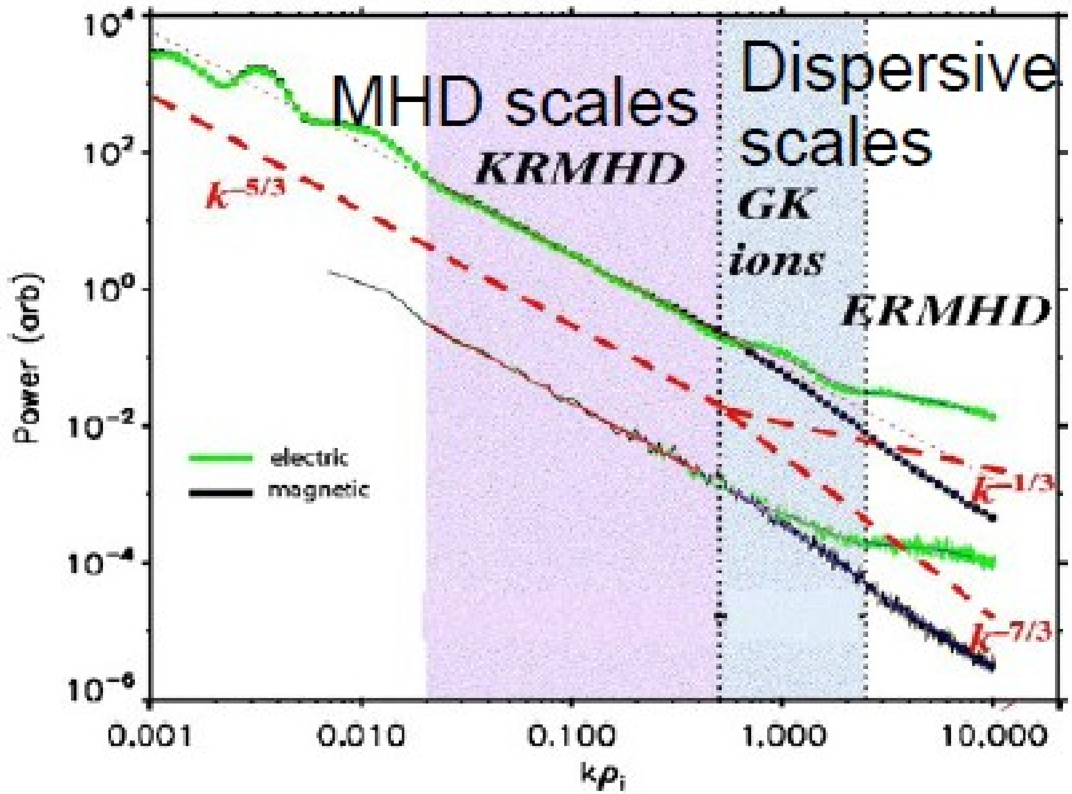
$$\omega^2 = k_\parallel^2 [1 + k_\perp^2 (\rho_s^2 + \rho_i^2)],$$

Weakness of Hall-MHD

Hall MHD is a cold ion model (T_i=0) : not suitable for many astrophysical situations
Where the electron and ion temperature are of same order. Bad when Ti larger than Te

Gyrofluid : arbitrary electron/ion temperature ratio
Two scales : ion Larmor radius, ion sound Larmor radius (equal when T_i=T_e)

The turbulent Alfvenic solar wind



Measurements by Bale et al.

$$E_{k_\perp} = C\epsilon^{2/3}k_\perp^{-5/3}(1+\rho_s^2k_\perp^2)^{-1/3}$$

$$\left(\quad \delta B_\perp = C^{1/2}\epsilon^{1/3}k_\perp^{-1/3}(1+\rho_s^2k_\perp^2)^{-1/6} \quad \right)$$

$$k_{||}(k_\perp) \sim \epsilon^{1/3}k_\perp^{2/3}(1+\rho_s^2k_\perp^2)^{-1/6}$$

Parallel electric field spectrum of Alfvenic turbulence

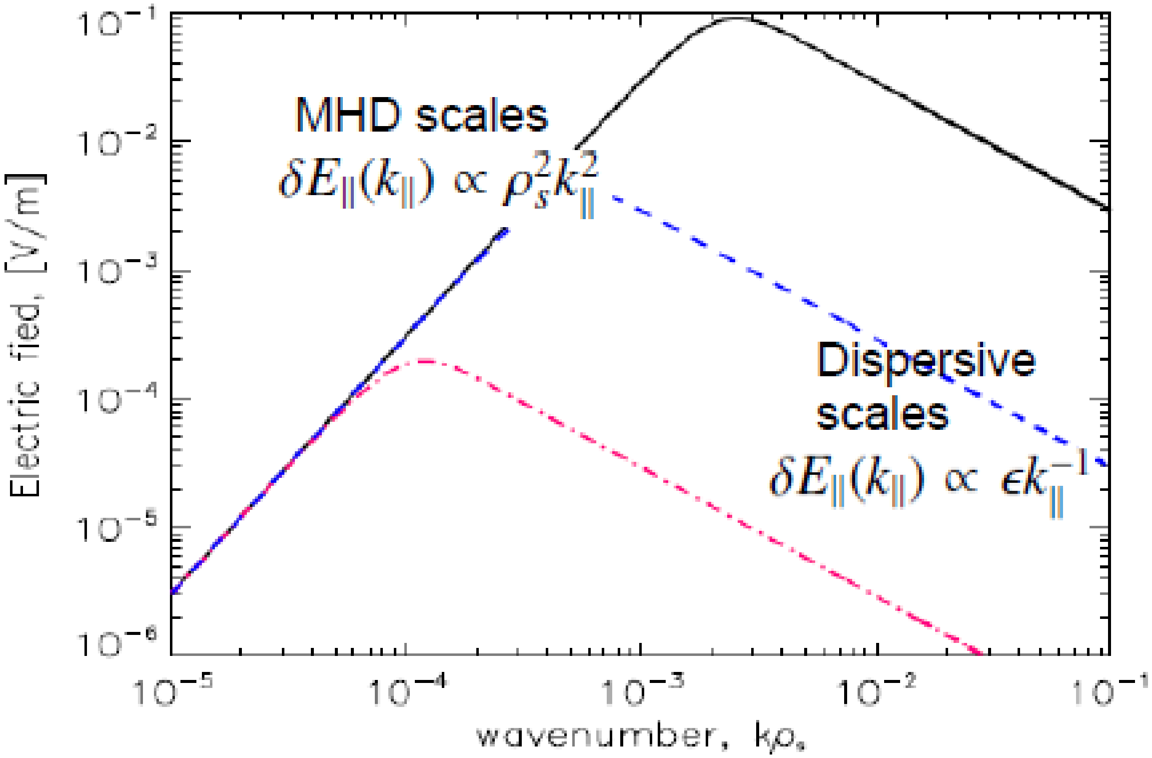


Fig. 1. Parallel electric field, $\delta E_{\|}$, as a function of $k_{\|}\rho_s$ for different values of the large scale magnetic field perturbation $\epsilon = (\delta B_{\perp}/B_0)^2$, 1- solid black line, 10^{-2}- dash blue line, 10^{-4} - dash-dot red line.

$$\delta E_{\|}^{max} \sim \epsilon^{2/3}\rho^{2/3} \quad (\ 2 \times 10^{-4} - 10^{-1}\ \mathrm{V}m^{-1}\ )$$

$$k_{\|}^{max} \sim \epsilon^{1/3}\rho_s^{-2/3}$$

Maximum of the parallel electric field at the boundary between the MHD and dispersive regime. $k_{\perp}\rho_s \sim 1$

If such spectrum is present, the electron field-aligned acceleration and cross field transport model via quasilinear theory

$$\frac{\partial f}{\partial t} = \sum_k \nabla[(\frac{e}{m_e})^2 \frac{\pi}{2} \delta(\omega - k_{\|} v_{\|}) E_{\|}^2 \nabla f]$$

$$\nabla = \nabla_{v_{\|}} + \frac{k_{\perp} v_{\|}}{\omega \omega_{ce}} \nabla_x$$

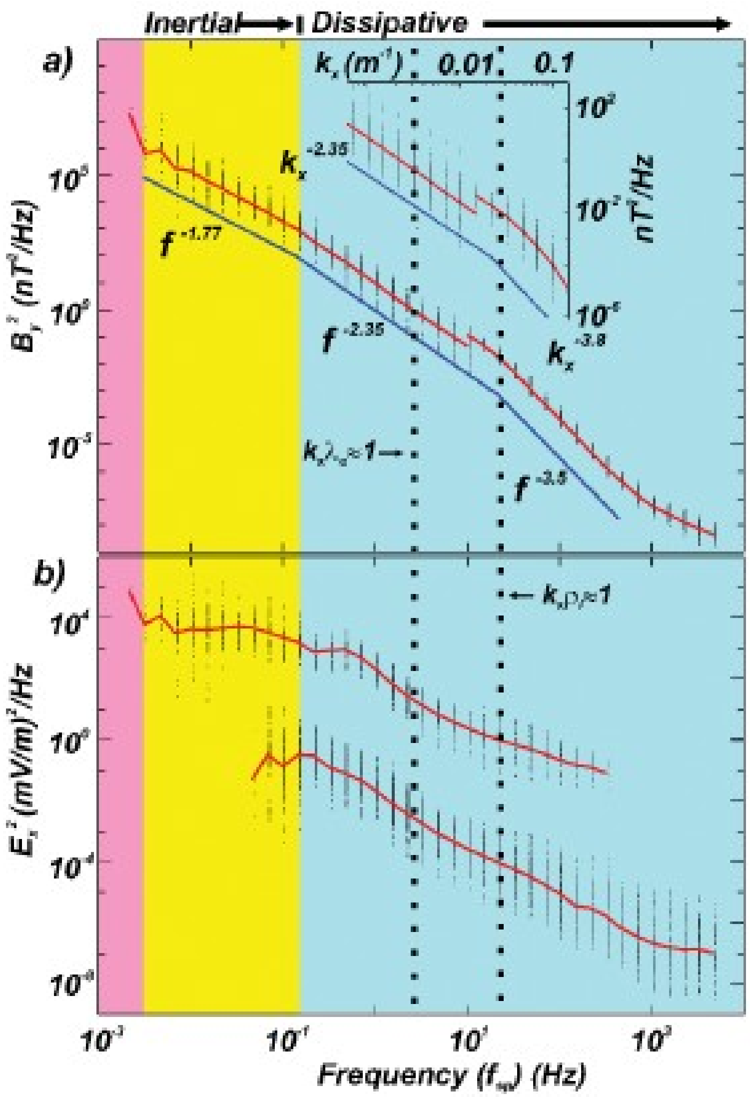


FIG. 2 (color). (a) Average $B_y^2(f_{sp}, k_x)$ spectra. (b) Average $E_x^2(f_{sp})$ spectra for survey and burst data collection modes. The latter is down-shifted by 4 orders of magnitude. The black bars are composed of points representing individual measurements in each f_{sp} or k_x bin.

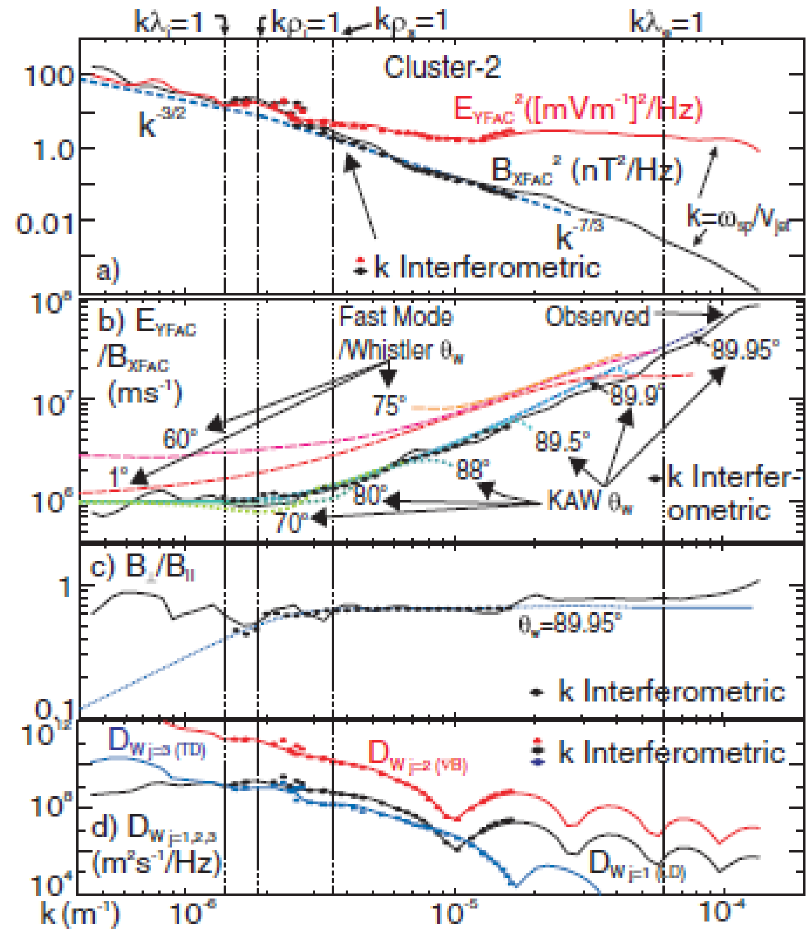


FIG. 4 (color). (a) $B_{YFAC}{}^2$ and $E_{YFAC}{}^2$ spectrograms from interferometry (symbols) and Doppler shift. (b) E_{YFAC}/B_{YFAC} observed and predicted results for KAWs and whistlers. (c) $B_\perp/B_\parallel$ observed and predicted result for KAWs at $\theta_W = 89.95°$. (d) D_W spectrogram as described in text. λ_i and λ_e denote the ion and electron inertial lengths, respectively. ρ_i and ρ_s denote the ion and ion acoustic gyroradii.