Small-Scale Electromagnetic Fluctuations in the Solar Wind: Nature and Properties

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Introduction

- Electromagnetic fluctuations in the inertial range of solar wind MHD turbulence and beyond (up to frequencies of 10Hz) have recently been studied for the first time using both magnetic field and electric field measurements on Cluster [*Bale et al.*, PRL, 2005].

- It has been shown that at frequencies above the spectral breakpoint at ~0.4Hz, in the so-called dissipation range, the wave modes become dispersive and are consistent with ***Kinetic Alfven Waves*** (**KAW**).

- This interpretation is based on the simple assumption that the *measured frequency spectrum is actually a Doppler shifted wave number spectrum* ($\omega \approx k.V_{SW}$), commonly used in the solar wind and known as *Taylor's hypothesis*. While Taylor's hypothesis is valid in the inertial range of solar wind turbulence, it may break down in the dissipation range where temporal fluctuations can become important.

- The (proton) *whistler is another possible wave mode* in the solar wind in this frequency regime. The temporal fluctuations of the whistler mode combined with a slight Doppler shift can lead to the same apparent properties in the spacecraft (s/c) frame as strongly Doppler-shifted KAW. ***Can we rule out the whistler wave interpretation?***

In this work

- We analyze the effect of Doppler shift on KAW as well as compressional proton whistler waves, at kinetic scales into the transition to the dissipation range of solar wind turbulence ($0.1 < f/f_{ci} < 10$).
- We revisit Cluster electric and magnetic field data using this approach, focusing on a typical, low β (< 1), solar wind interval, where the plasma is sufficiently distant from instability thresholds (in this case, $T_{p\perp}/T_{p\parallel} \lesssim 1$) for such mechanisms to be likely to contribute to the turbulent dynamics.
- The electric and magnetic field properties of the KAW and the whistler wave modes from linear theory are used to construct (both analytically and numerically) spacecraft-frame frequency spectra of the electric to magnetic field ratio $(|\delta\mathbf{E}|/|\delta\mathbf{B}|)_{s/c}$ and compressibility $(|\delta B_{||}|/|\delta\mathbf{B}|)_{s/c}$, allowing for a direct comparison to spacecraft data, without the use of Taylor's hypothesis.
- We show that these two tests, together, provide an efficient diagnostics into the nature of the small-scale turbulent fluctuations in the solar wind.

The Use of Linear Wave Theory

- The fluctuations must satisfy $\delta B/B_0 \leq 0.2$. This does not mean that the turbulence is weak!!
- Three aspects derived from linear theory remain valid:

  - Eigenfunction relationships (polarizations, correlations between B, E, V, and N).

  - In a weakly collisional plasma, damping is attributable to kinetic damping (Landau, cyclotron, …)

  - Nonlinear energy transfer described phenomenologically by anisotropic turbulence theories

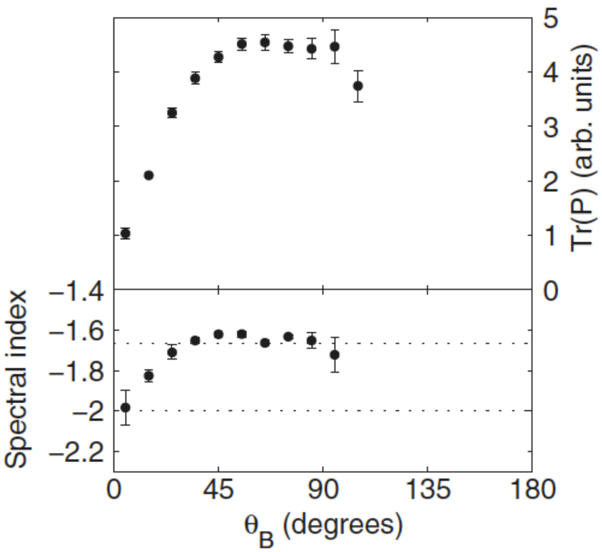
$\Rightarrow$ No one says the solar wind fluctuations are made of monochromatic waves!

$\Rightarrow$ We say that the fluctuations (at kinetic scales) seem to follow roughly some of the characteristics of the linear eigenmodes (especially if critical balance holds). The are wave-like fluctuations, and the idea is to try to determine which mode(s) are dominant, among others.

Evidence for Critical Balance in the Solar Wind

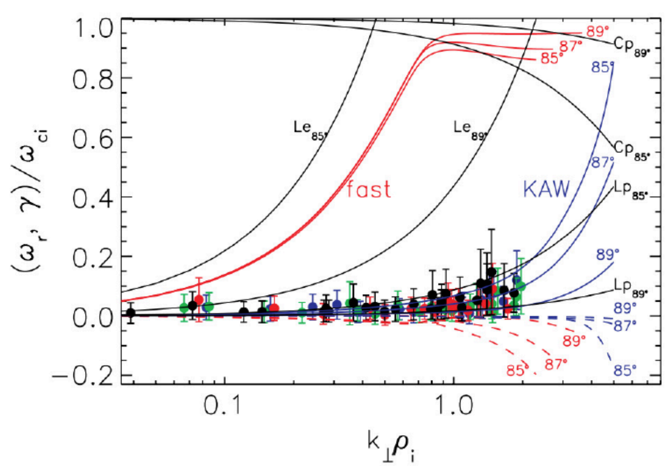
- Weak turbulence: $\omega_{nl} = k_\perp v_\perp \ll \omega_l = v_A k_\parallel$
- Critical Balance implies that $\omega_{nl} \simeq \omega_l$ --> $k_\perp \gg k_\parallel$ at kinetic scales.

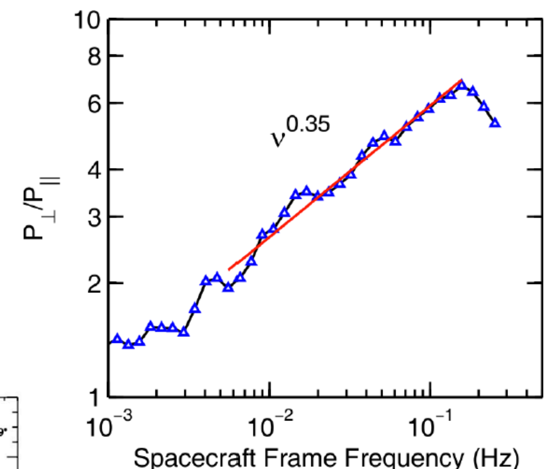
- **Observational evidence of Critical Balance**:



Horbury et al. 2008

Sahraoui et al. 2010





Podesta et al. 2009

Example of Cluster data interval in the solar wind

Time interval:

2003-01-30/03:00:00 - 05:00:00

Plasma Parameters:

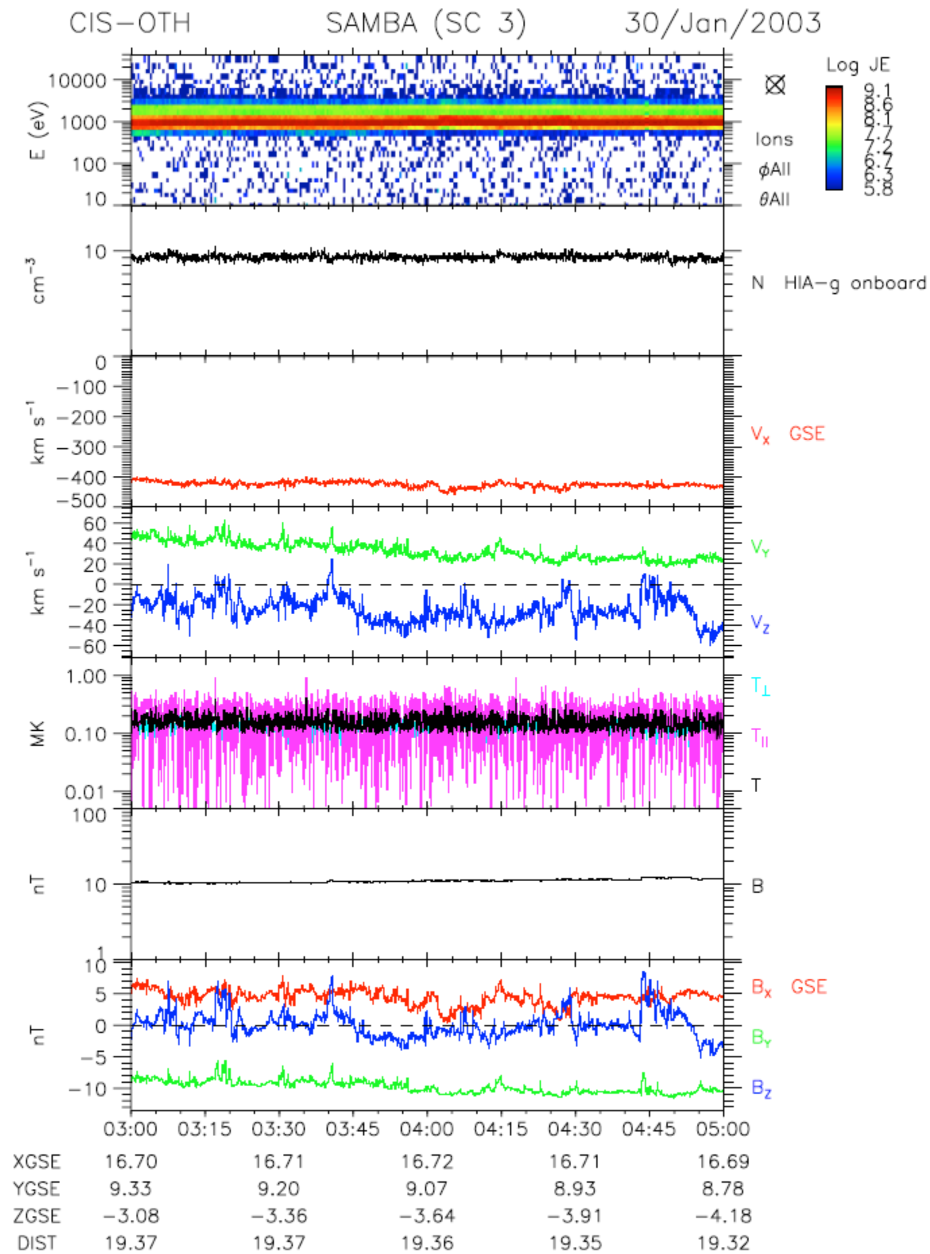
C4 at ~ 19 R_E

N = 9 cm-3 $\quad$ T_e = 13 eV
T_p = 13.6 eV $\quad$ V_{thi} = 36.1 km/s
B = 11 nT $\quad$ V_A = 78.1 km/s
β_i = 0.4 $\quad$ T_e/T_p = 0.96

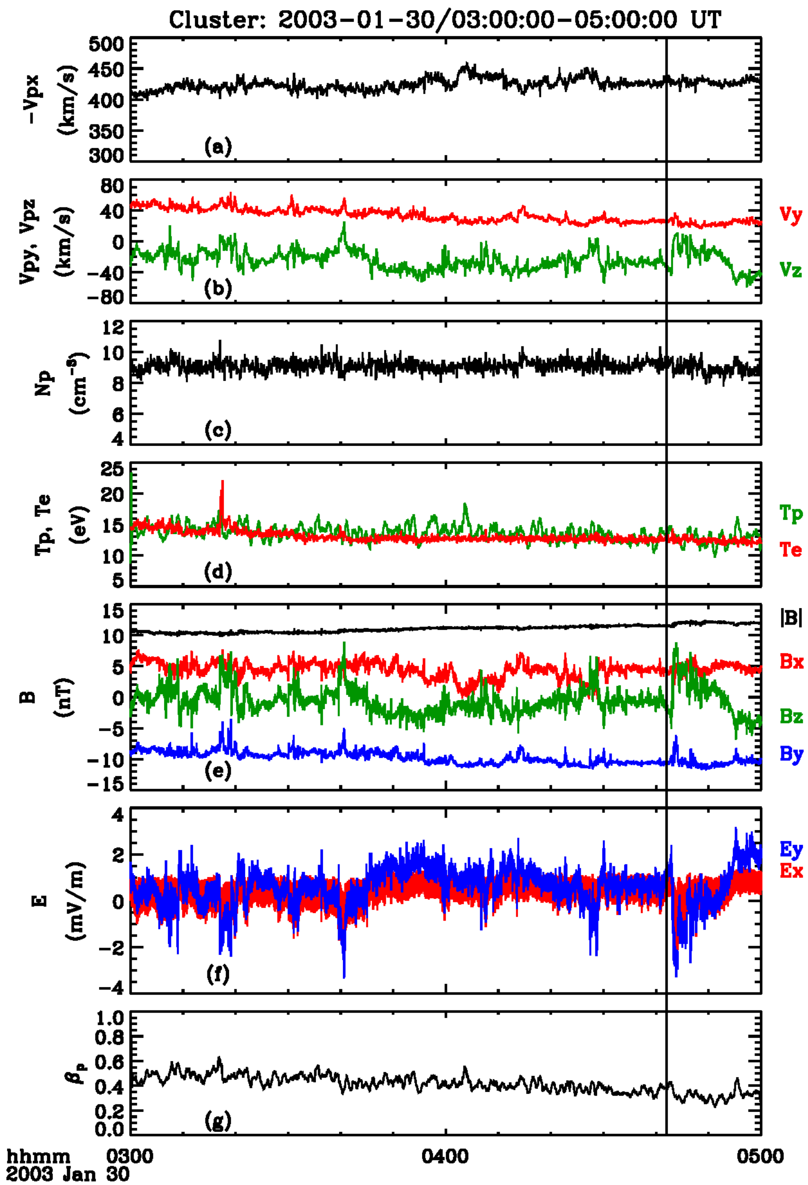
V_{sw} = 427 km/s
V_{par} = -200 km/s $\quad$ cos θ_{VB} = -0.47
V_{per} = 377 km/s $\quad$ sin θ_{VB} = 0.88

f_{ci} = 0.16 Hz $\quad$ f_{pi} = 631.5 Hz
f_{ce} = 302.5 Hz $\quad$ f_{pe} = 27061 Hz

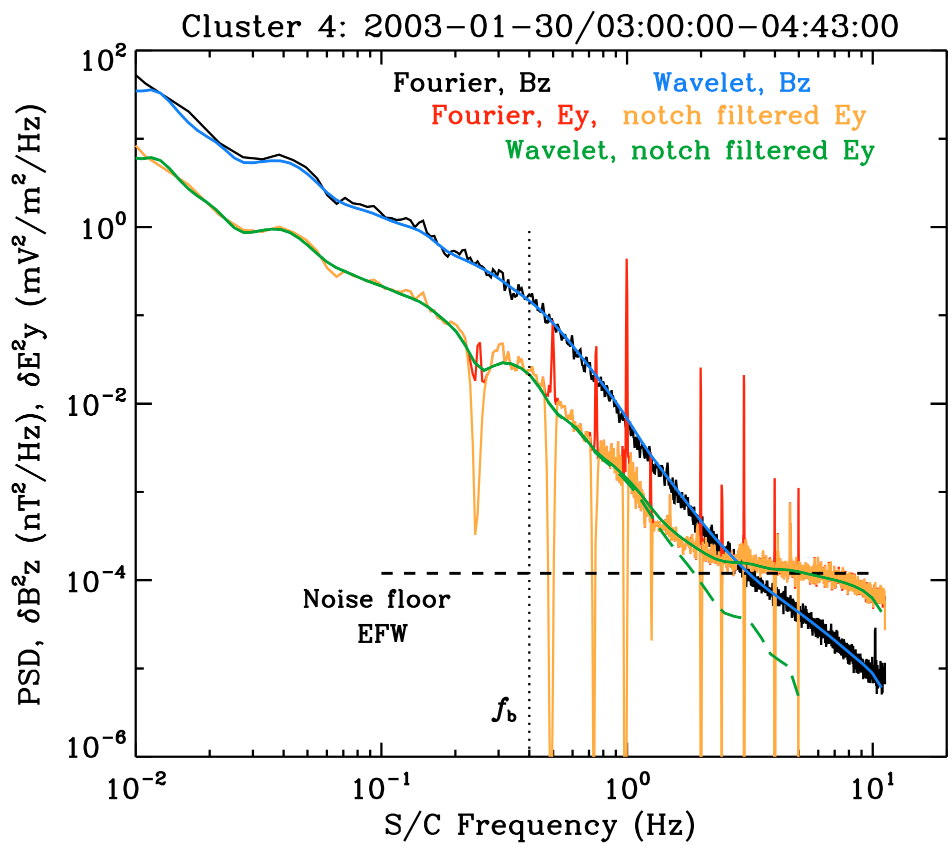
$$\mathbf{T_{p,\perp}/T_{p,\parallel} \sim 0.9 - 1.0}$$



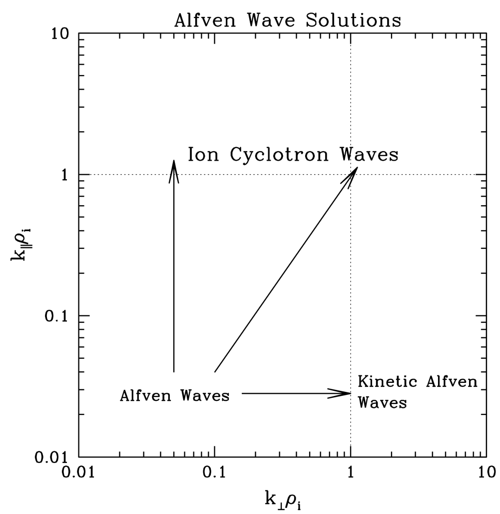
Spectral analysis of Cluster E and B field data

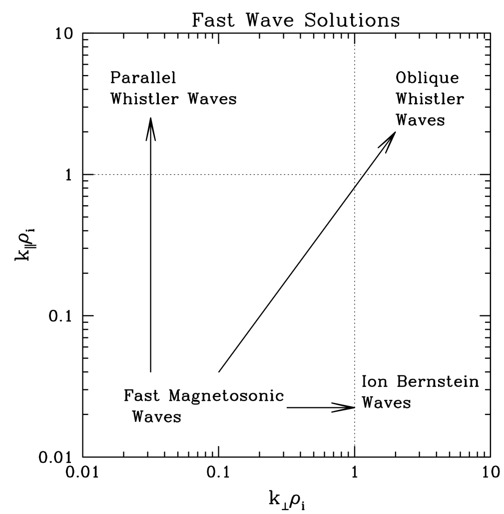


Use of Windowed Fourier Transform and Morlet Wavelet transform of δB_z and δE_y



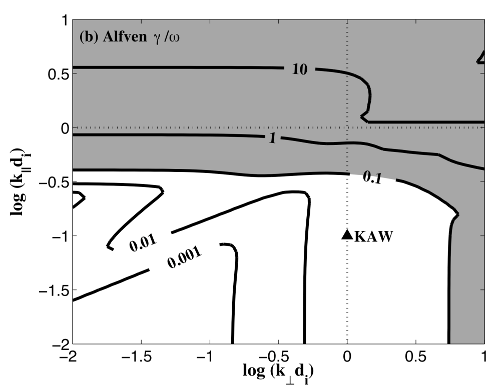
Possible wave modes in the solar wind with $f_{ci} < f < f_{ce}$

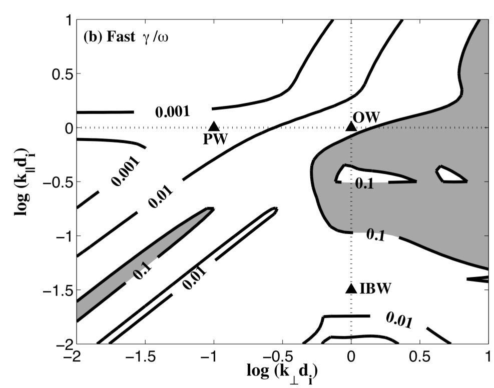




Vlasov-Maxwell plasma:

- Region of (k,k) inhabited by the linear wave mode of the Alfven wave branch (left)
- same for the Fast wave branch (right).





- Normalized linear damping rate for the Alfven wave branch (left)
- Same for the Fast wave branch (right)

Linear Wave Theory

(s/c frame) frequency range considered: 0.1 < f/f_{ci} < 10

$\vec{k}$ in x – z plane $(k_y = 0)$

B_0 along ***z***

Angle of propagation: $\theta = (\vec{k}, \vec{B_0})$

$k_{||} = k \cos\theta \qquad k_\perp = k \sin\theta$

- **The Kinetic Alfven Wave (KAW) mode**:

  Dispersion relation with finite Larmor radius and finite frequency effects
  [*Lysak & Lotko*, 1996; *Stasiewicz et al.*, 2000]

$$\Omega^2 = \frac{K^2\, cos^2\theta\, V_A^2\ \left[1 + K^2\ \sin^2\theta\,(1+\alpha)\right]}{v_{thi}^2 + K^2\, cos^2\theta\, V_A^2\,(1 + K^2\ \sin^2\theta)}$$

$(1+\alpha)$

$$\Omega = \omega/\omega_{ci}$$
$$K = k\,\rho_i$$
$$\rho_i = v_{thi}/\omega_{ci}$$
$$v_{thi} = \sqrt{T_p/m_p}$$
$$\alpha = T_e/T_p$$

- **The Whistler wave mode**:

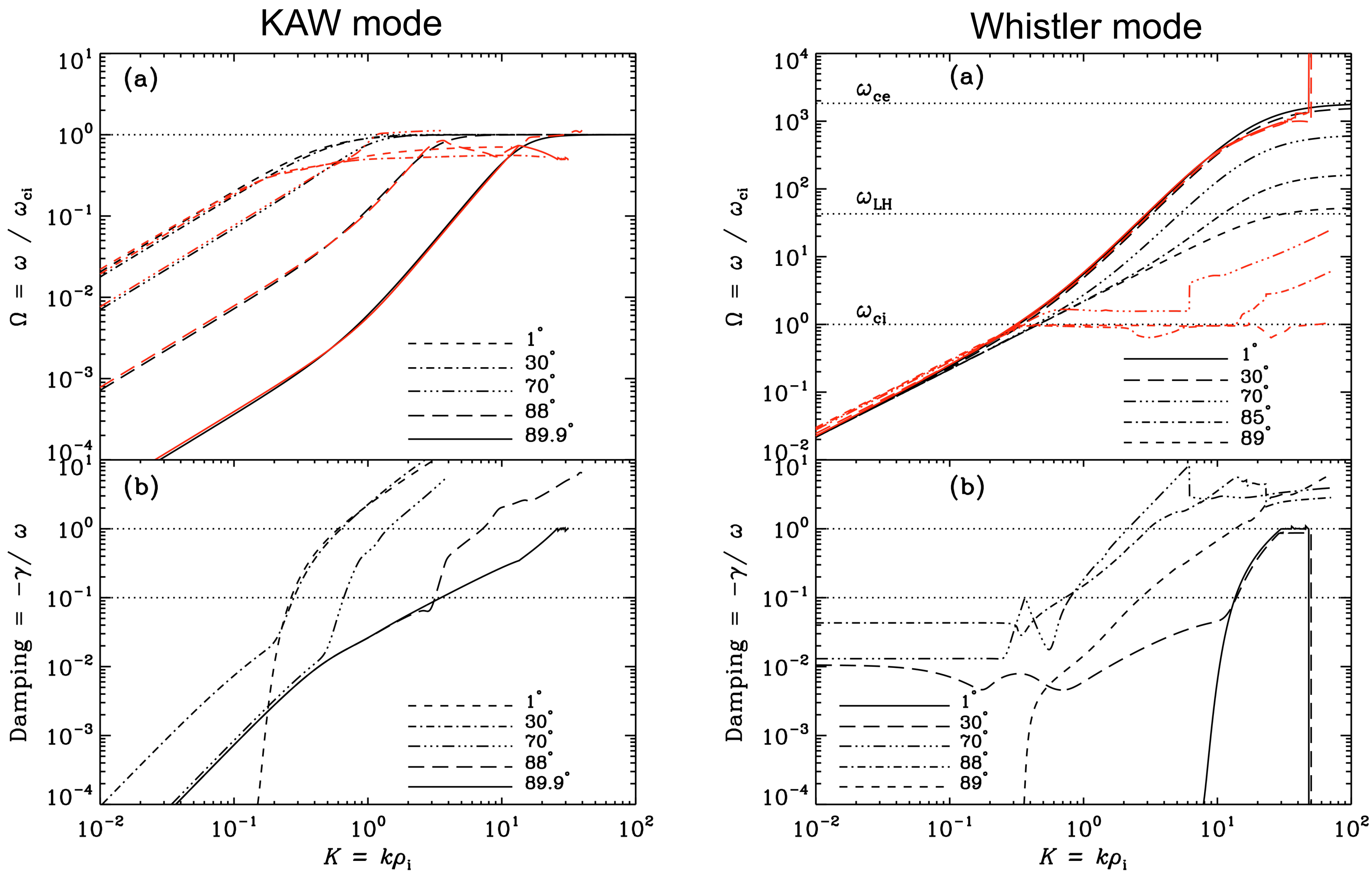
  Use of *Cold Plasma Approximation* ($\omega << \omega_{ce}$)
  [*Sazhin*, 1993; *Swanson*, 2003]

=> Analytical determination of Ω and |δ***E***|/|δ***B***| as functions of *K* and θ.

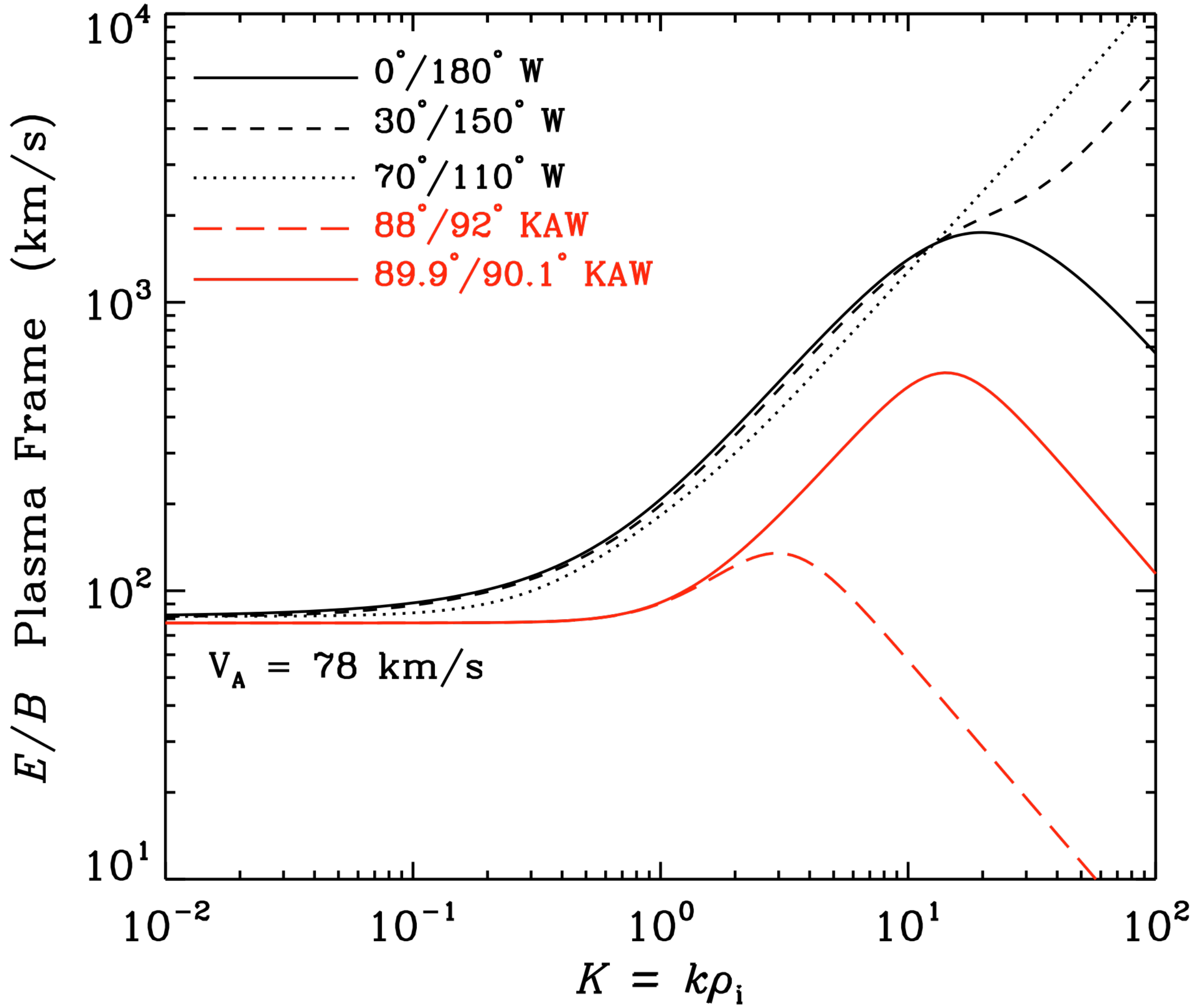
- **Vlasov-Maxwell Theory**:

  Comparison to a numerical solution of the Vlasov-Maxwell hot plasma dispersion relation. And derivation of the compressibility |$\delta B_{||}$|/|δ***B***|.

KAW/Whistler: dispersion curves



KAW/Whistler: |δE|/|δB| ratio

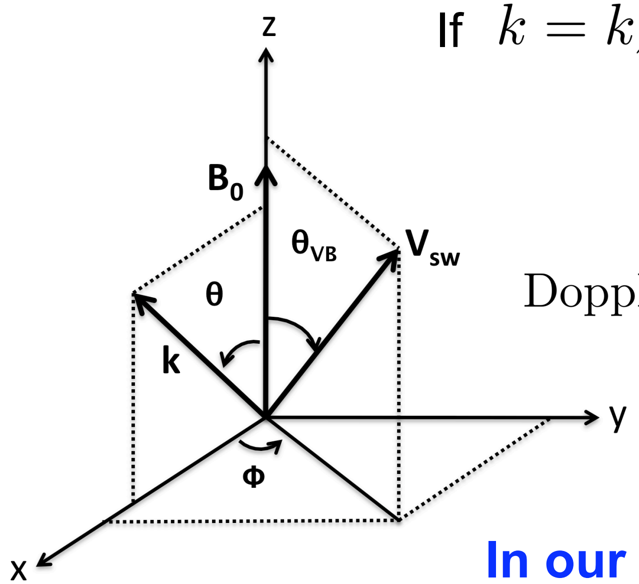


Doppler Shift: Frequency in the s/c frame

Frequency in the s/c frame given by: $$\omega_{s/c} = \left| \omega + \vec{k} \cdot \vec{V}_{sw} \right|$$

If $\vec{k} = k_z \, \vec{\mathrm{z}} + k_x \, \vec{\mathrm{x}}$

$$\begin{aligned} k_z &= k_\parallel = k \, \cos\theta \\ k_x &= k_\perp = k \, \sin\theta \\ k_y &= 0 \end{aligned} \qquad \begin{aligned} V_z &= V_{sw} \, \cos\theta_{VB} \\ V_x &= V_{sw} \, \sin\theta_{VB} \, \cos\phi \\ V_y &= V_{sw} \, \sin\theta_{VB} \, \sin\phi \end{aligned}$$



One can express the Doppler-shift term as

$$\mathrm{Doppler} = \vec{k} \cdot \vec{V}_{sw} = k_\parallel \, \mathrm{V}_{sw} \, \cos\theta_{VB} + k_\perp \, \mathrm{V}_{sw} \, \sin\theta_{VB} \, \cos\phi$$

In our dimensionless parameters (Ω, K, and θ), the frequency in the s/c frame becomes:

$$\Omega_{s/c} = \left| \Omega + K \, \cos\theta \, \frac{V_{sw}}{v_{thi}} \, \cos\theta_{VB} + K \, \sin\theta \, \frac{V_{sw}}{v_{thi}} \, \sin\theta_{VB} \, \cos\phi \right|$$

Lorentz Transformation: the Electric Field in the s/c frame

Since the electric field measurements are made in the s/c frame, we need to express the Electric field in the s/c frame (***E_{sc}***) as a function of ***E*** in the plasma frame using the ***Lorentz transformation***:

$$\vec{E_{sc}} = \vec{E} + \vec{v} \times \vec{B}$$

If we assume the following decomposition:

$$\vec{B} = \vec{B}_0 + \delta\vec{B} \qquad \vec{E} = \vec{E}_0 + \delta\vec{E} \qquad \vec{E}_{sc} = \vec{E}_{0,sc} + \delta\vec{E}_{sc} \qquad \vec{v} = \vec{V}_{sw}$$

and $\vec{E_{0,sc}} = \vec{E}_0 + \vec{V}_{sw} \times \vec{B}_0$

then $\delta\vec{E}_{sc} = \delta\vec{E} + \vec{V}_{sw} \times \delta\vec{B}$

We get (omitting the "δ"): $\vec{E}_{sc} = \vec{E} + \vec{V}_{sw} \times \vec{B}$

$$E_{x,sc} = E_x + V_y\,B_z - V_z\,B_y$$
$$E_{y,sc} = E_y + V_z\,B_x - V_x\,B_z$$
$$E_{z,sc} = E_z + V_x\,B_y - V_y\,B_x$$

z-direction along B_0, x and y perpendicular to B_0:

$$\Rightarrow \left|\frac{E}{B}\right|_{sc} = \left|\frac{E_y}{B_x}\right|_{sc} \sqrt{\frac{1 + \left|\frac{E_x}{E_y}\right|_{sc}^2 + \left|\frac{E_z}{E_y}\right|_{sc}^2}{1 + \left|\frac{B_y}{B_x}\right|^2 + \left|\frac{B_z}{B_x}\right|^2}}$$

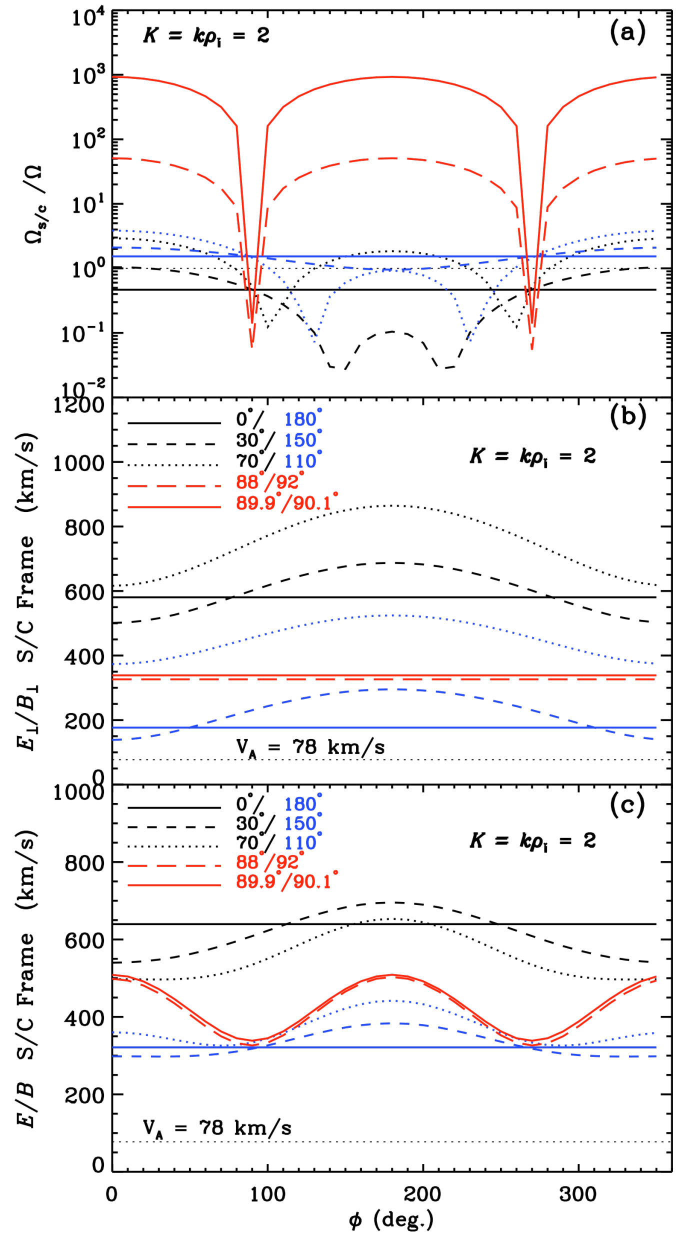
Determination of |E/B|$_{s/c}$ for both KAWs and Whistlers as a function of (K, θ, φ, θ$_{VB}$)

Wave properties in the s/c frame

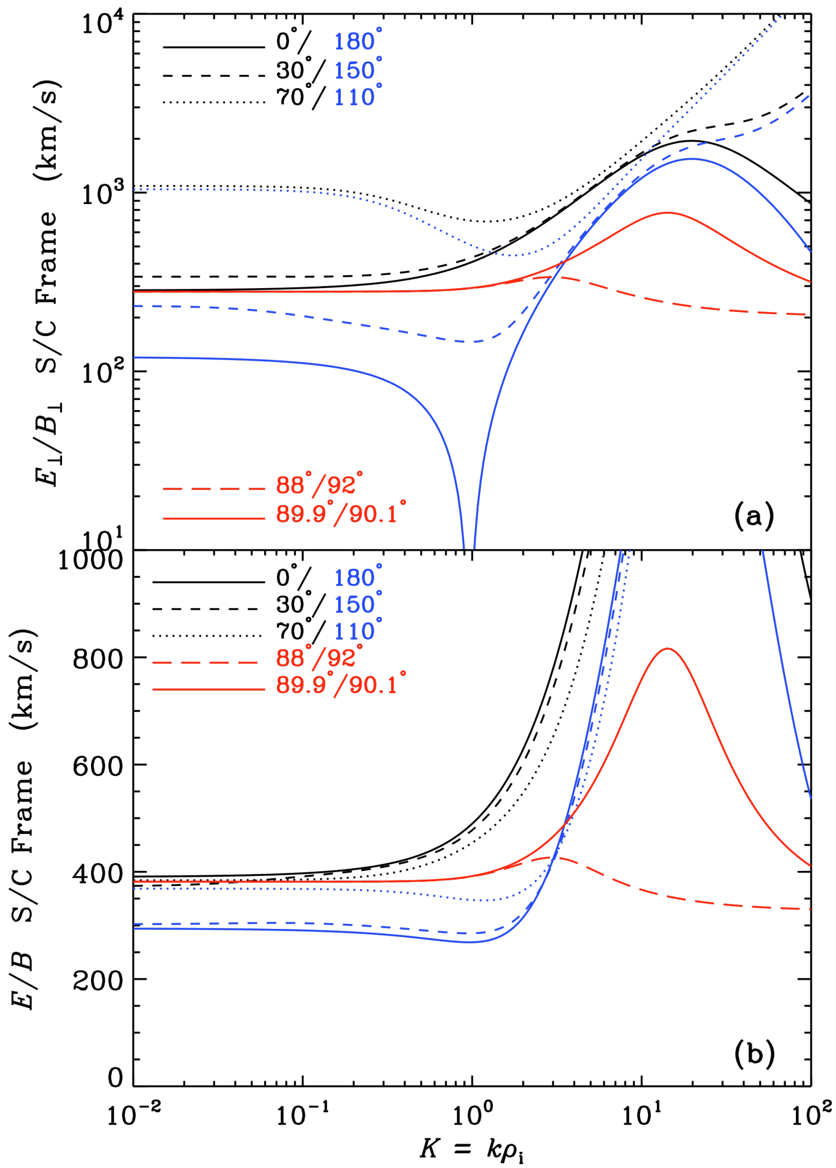
Dependence in ϕ

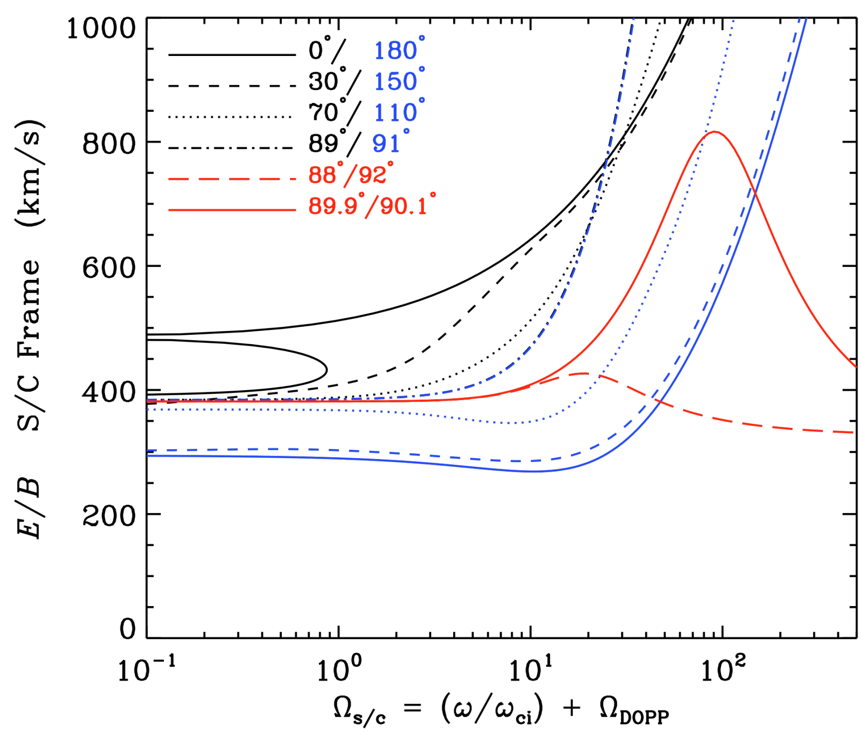
We assume uniform azimuthal distribution of wave power about the magnetic field, we average over the full 2π distribution in ϕ, leaving θ as a parameter that characterizes the model of the turbulent fluctuations.

=> The averaged parameters yield a prediction for the observed electromagnetic fields.



|δE|/|δB| ratio in the spacecraft frame

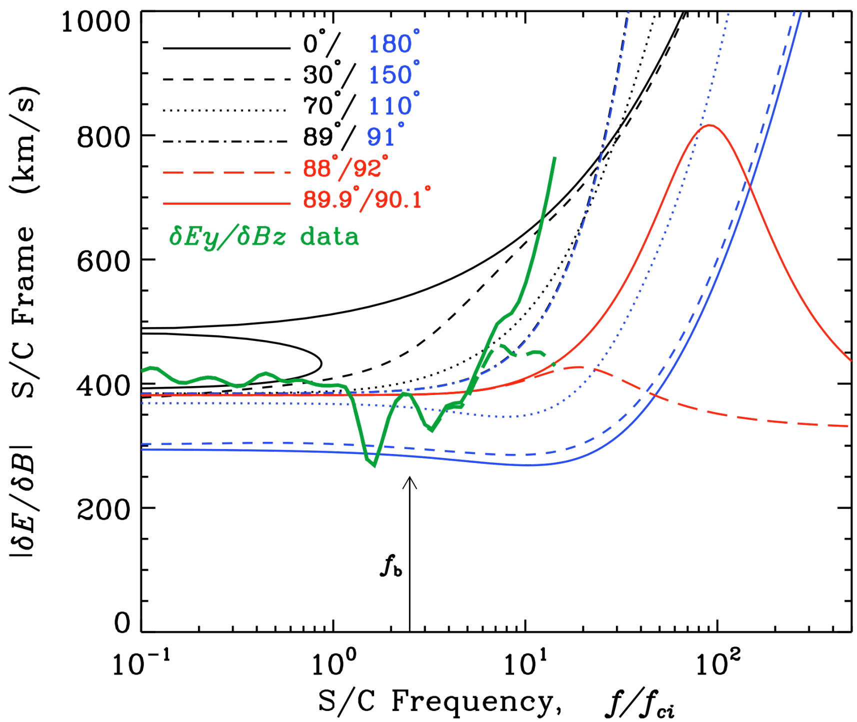


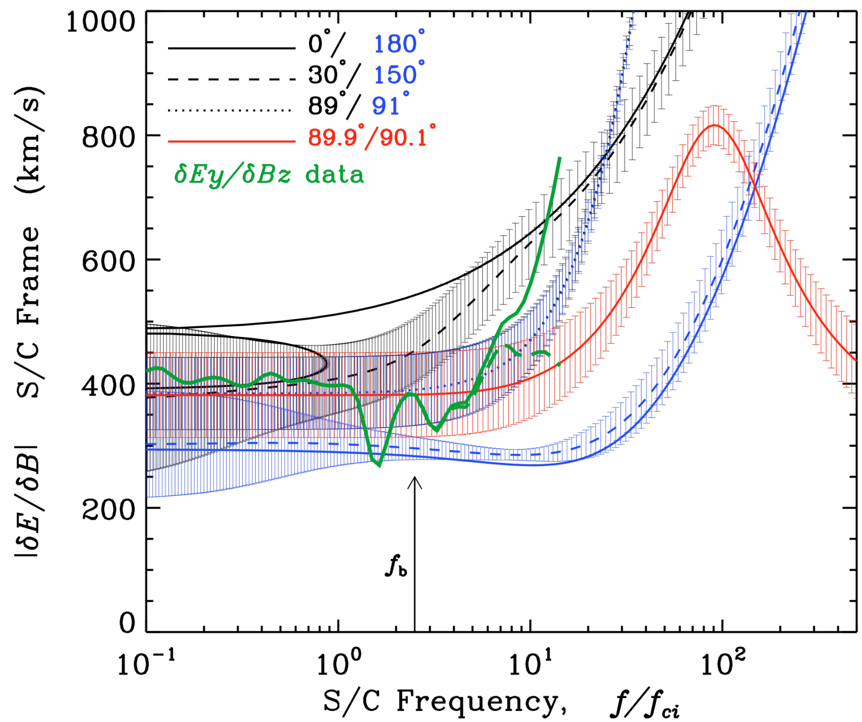


Theoretical predictions versus s/c data (1): Identification of the nature of the fluctuations

|δE|/|δB| ratio

KAWs in red for θ = 88/92° and 89.9/90.1°
Whistlers in black (θ = 0, 30, 70, 89°)
Whistlers in blue (θ = 180, 150, 110, 91°)





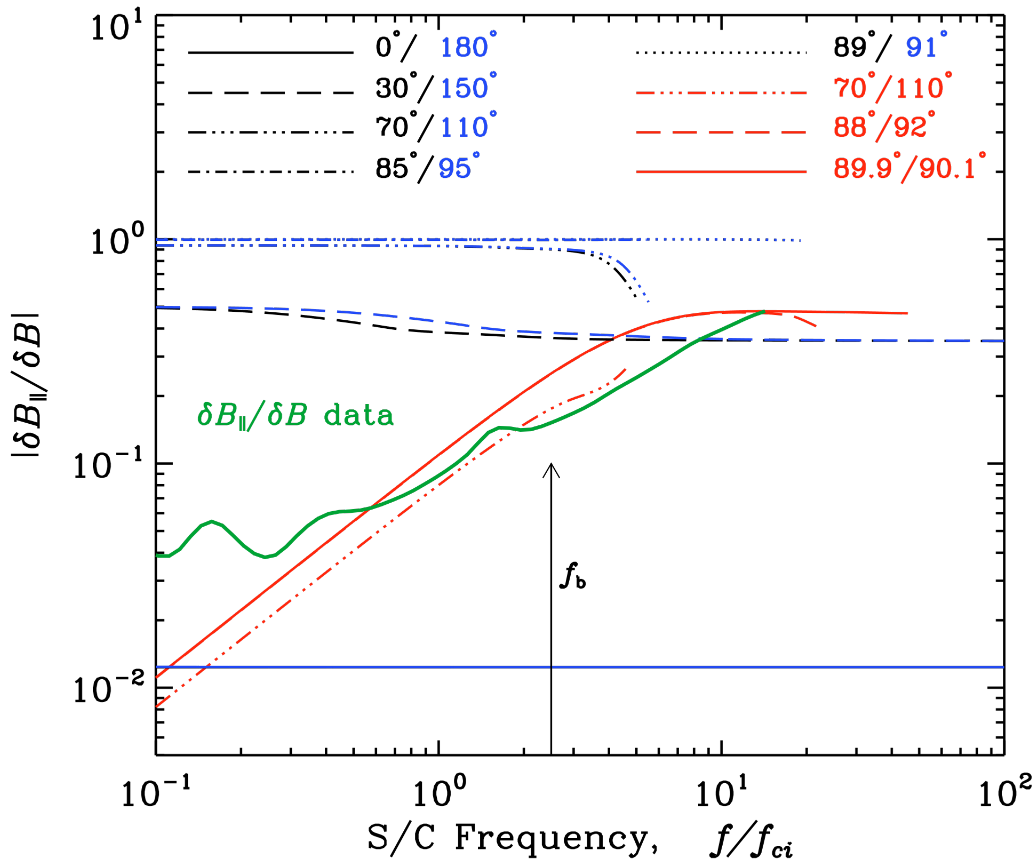
=> KAWs with nearly perpendicular angles or highly oblique whistlers appear to be consistent with the observations

Theoretical predictions versus s/c data (2): Identification of the nature of the fluctuations

Compressibility: $|\delta B_{||}|/|\delta \mathrm{B}|$ ratio to break the degeneracy

- ***The measured parallel magnetic field fluctuations are inconsistent with the whistler wave for any angle of the wavevector.***

- ***There is remarkably good agreement with the prediction for the KAW with a nearly perpendicular angle.***



Conclusions

- KAW and whistler wave properties (dispersion, $|\delta\mathbf{E}|/|\delta\mathbf{B}|$, $|\delta B_{||}|/|\delta\mathbf{B}|$ ratios) in the s/c frame, taking properly into account the effect of Doppler Shift have been determined analytically and numerically at kinetic scales into the transition to the dissipation range of solar wind turbulence ($0.1 < f/f_{ci} < 10$).

- We show that this *technique provides an efficient diagnostics for wave-mode identification in the dissipation range of solar wind turbulence*, as this it allows for a direct comparison with (single s/c) measurements in the solar wind.

- This technique was applied to a typical, low beta, unconnected solar wind interval from Cluster at 19.5 R_E. The **two new tests** we developed, together, show that the ***measured properties of the small-scale turbulent fluctuations*** are found to ***be inconsistent with the whistler wave model*** but ***agree well with the prediction of a spectrum of kinetic Alfvén waves with nearly perpendicular wavevectors***.