DYNAMICS OF ION-SCALE COHERENT MAGNETIC STRUCTURES AND COUPLING WITH WHISTLER WAVES DURING SUBSTORMS

Anna Tenerani

University of Pierre et Marie Curie/LPP-Paris

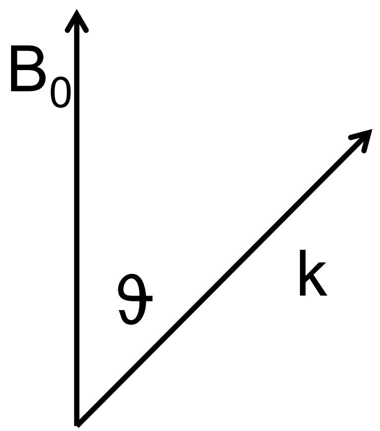
University of Pisa

Outline

- Introduction
- Cluster Data
  - the substorm event of 17th August 2003
    - whistler wave detection inside nonlinear magnetic structures
- Theoretical/numerical analysis of whistler trapping by slow solitons
  - Theoretical background
  - Simulations
  - conclusions

Introduction

- Detection by Cluster spacecraft of large amplitude (0.5-1 nT) whistler wave packets in the Earth's magnetotail correlated to coherent ion-scale magnetic structures, during a substorm event

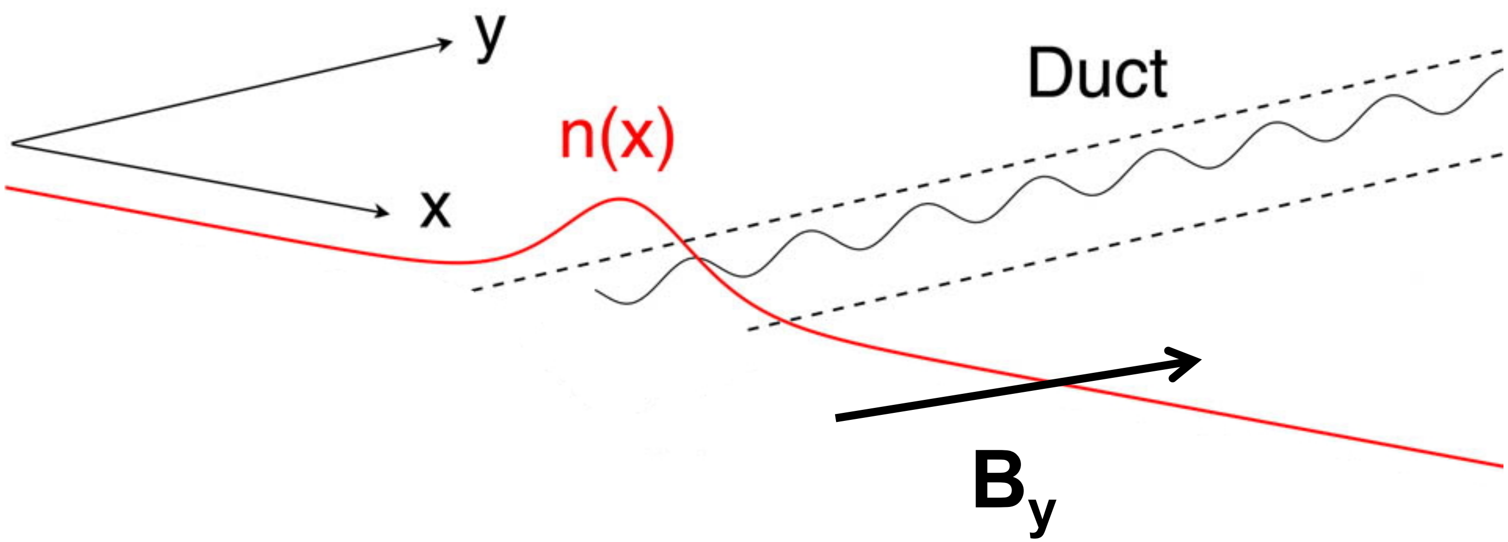


$$\boxed{\frac{\omega}{\omega_{ce}} = \frac{k^2 d_e^2 \cos\vartheta}{1 + k^2 d_e^2}}$$

Whistlers are electromagnetic waves propagating in a magnetized plasma guided along B_0 (background magnetic field). Right handed circular polarization and frequencies $\omega_{ci}<\omega<\omega_{ce}$.

Introduction

whistler trapping



Whistlers propagating in an inhomogeneous plasma can be **trapped by density inhomogeneities perpendicular to the magnetic field.** Frequencies $\omega<1/2\omega_{ce}$ can be trapped in density humps. [Helliwell,1960; Karpman, 1981a-b]. Such a ducted propagation has been confirmed by space measurements and laboratory experiments.

Introduction

aim

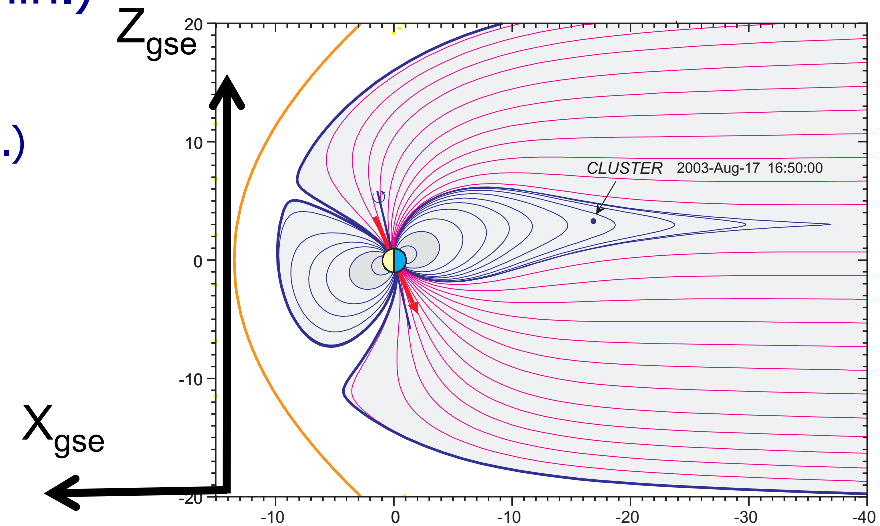
- In space plasmas whistlers are often correlated to ion-scale magnetic depression associated to density humps->pressure balanced structures, mirror modes
- On the other hand a variety of non-linear magnetic waves can naturally arise in warm, magnetized plasmas involving both magnetic field and density modulations on the ion-scales, such as oblique Alfvén or Slow Magnetosonic solitons
- **a new model of self-consistent coupling between low frequency, ion-scale coherent structures with high frequency whistler waves is presented , to interpret satellite datas. The ion-scale inhomogeneity is schematized with a slow type solitary wave**

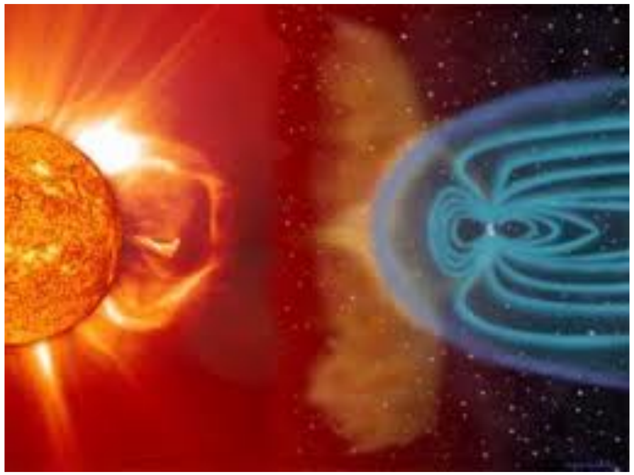
Introduction

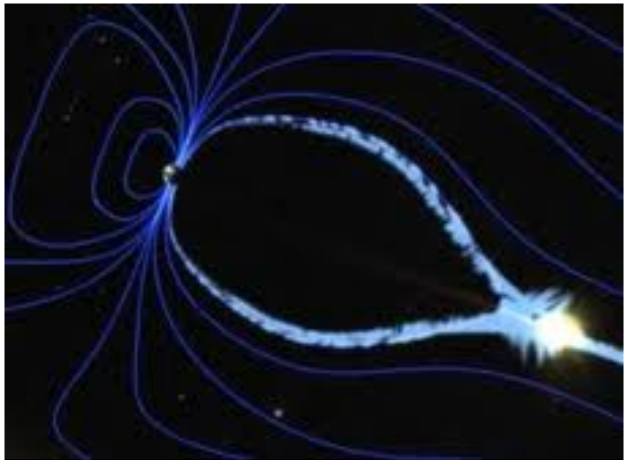
Magnetic substorms (context)

- Process of energy transport from solar wind to Earth
  - Growing phase (30 min. - 60 min.)
  - Onset (<1 min.)
  - Expansion phase (30 min. - 60 min.)
  - Recovering phase
  - the process of energy release

  occurs on different scales



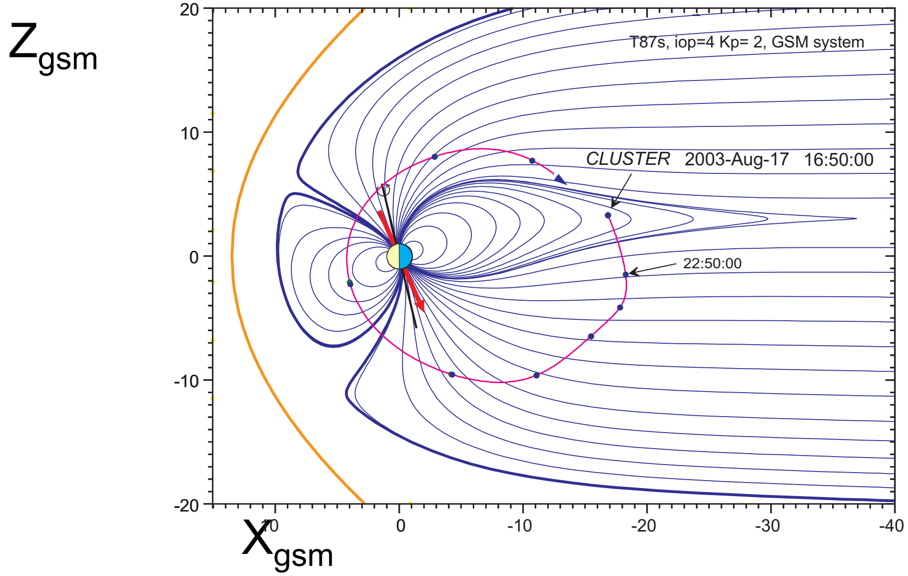




In situ measurements of whistlers correlated to ion-scale magnetic holes

Cluster spacecraft-substorm 17/08/2003
multiscale dynamics inspection

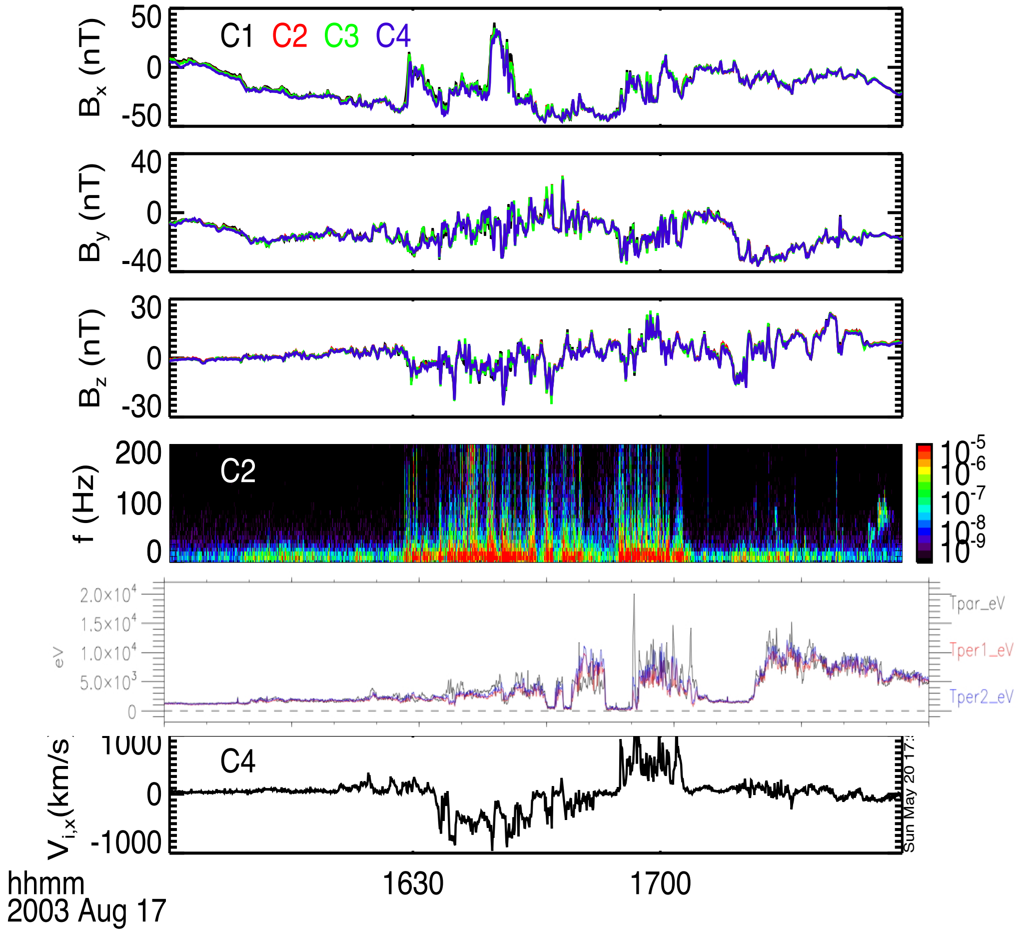
- 4 spacecraft in tetrahedron configuration
- S/C position: X_{GSM}~-17R_E , Y_{GSM}~5.5R_E , Z_{GSM}~4R_E → near the magnetic equator in the tail
- S/C separation: d~200 km → $d \leq d_i$, ρ_i , high frequency sampling rate, i.e. $0.5s^{-1} \sim f_{ci} << f < f_{ce} \sim 1000s^{-1}$
- FGM (0.014 sec → B) , STAFF-SC (0.002 sec → waves b)

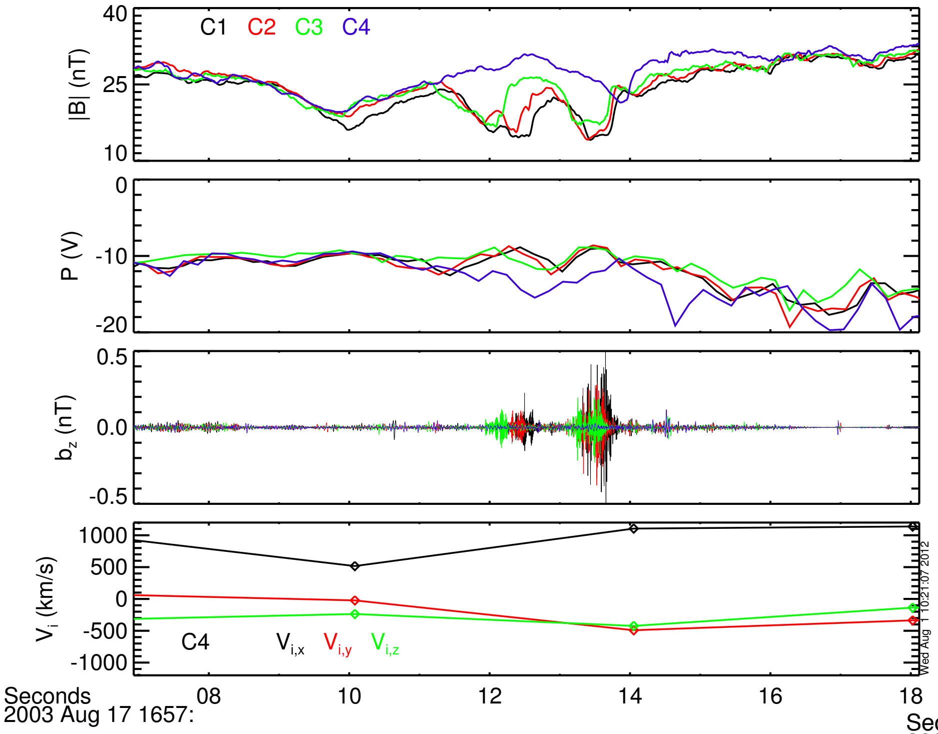


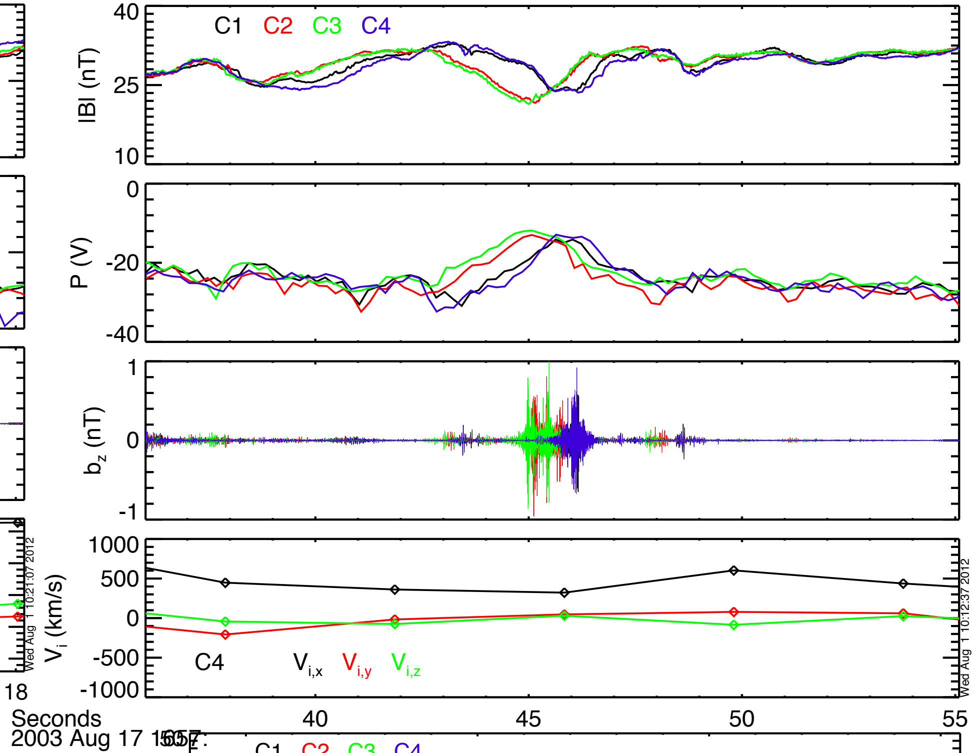
Global overview of the substorm

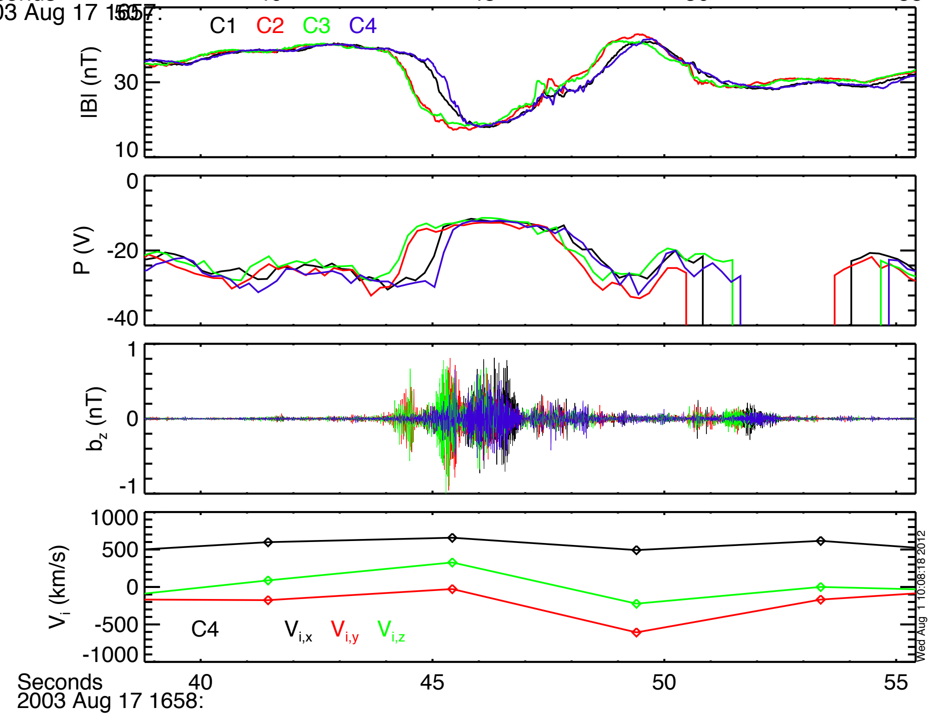
- Typical example of in-situ space measurement during a substorm (my case study)

  - Perturbations from $\omega \sim \omega_{ci}$ to $\omega >> \omega_{ci}$
  - if and how dynamics occurring on different scales are correlated has not yet been investigated in detail





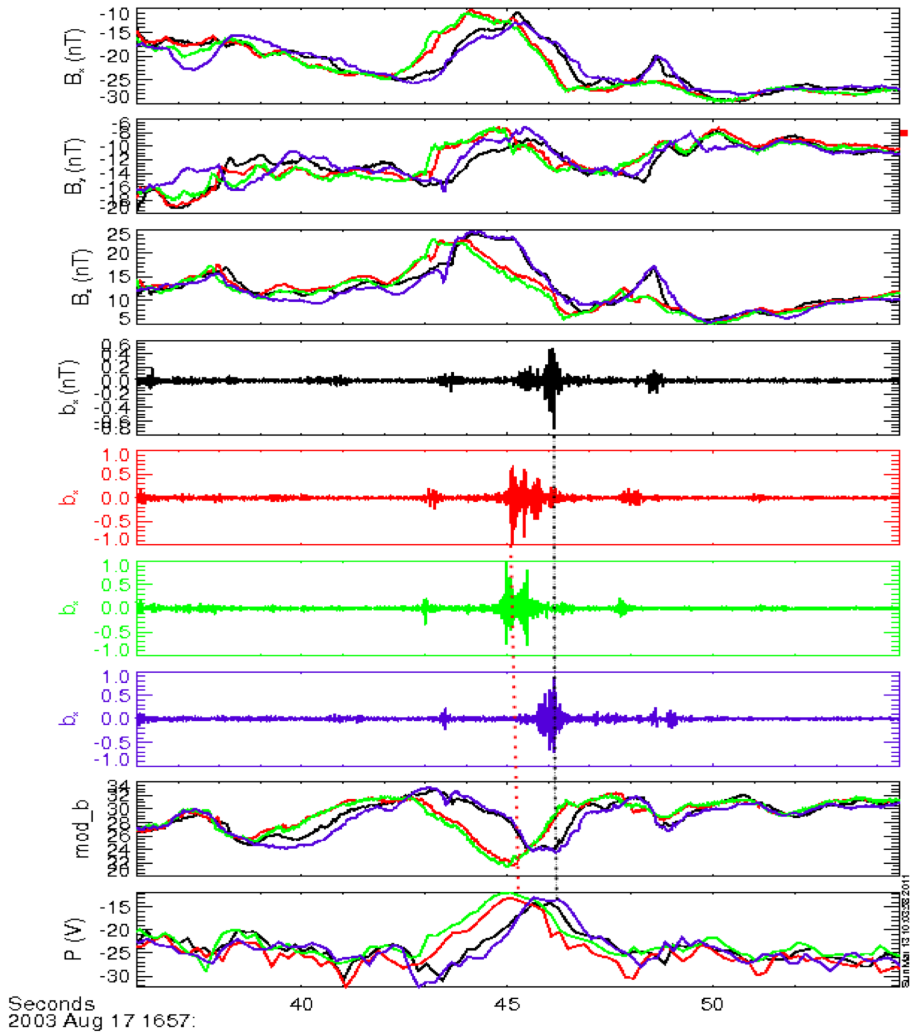




Magnetic structures embedded in ion fast flows (Vi>300 km/s)

Detection of MS correlated to whistlers

- Dynamics on smaller scales (L~900 km) and on short time scales (5 sec)
- Low frequency perturbation in B_0: magnetic depression of ~30% and ~50% density hump
- High frequency waves associated to the low frequency perturbation



Data analysis

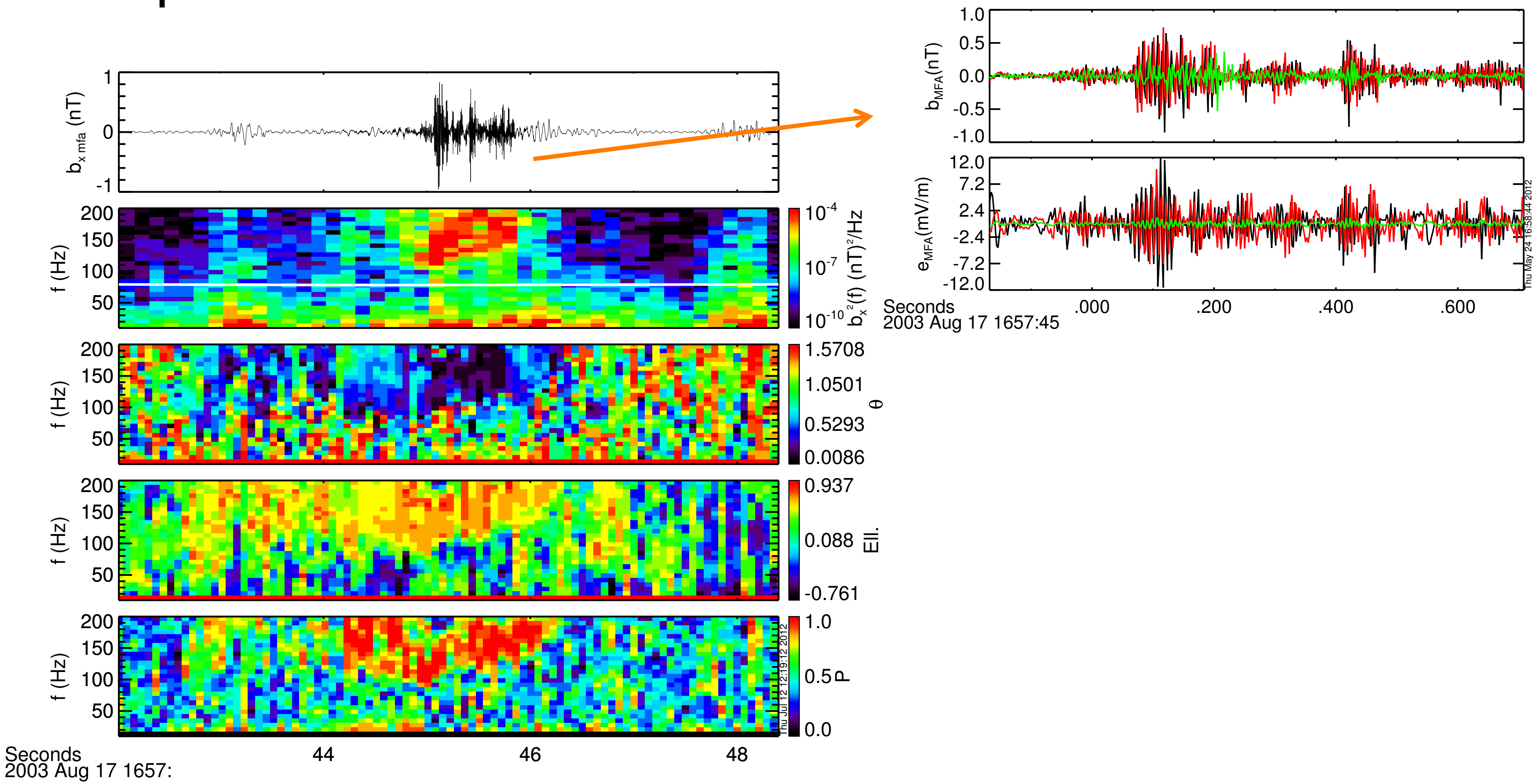
- High frequency wave analysis (whistlers)
  - polarization analysis and particle distribution function

- Low frequency wave analysis (magnetic hole)
  - minimum variance analysis

- Electron pitch angle distributions

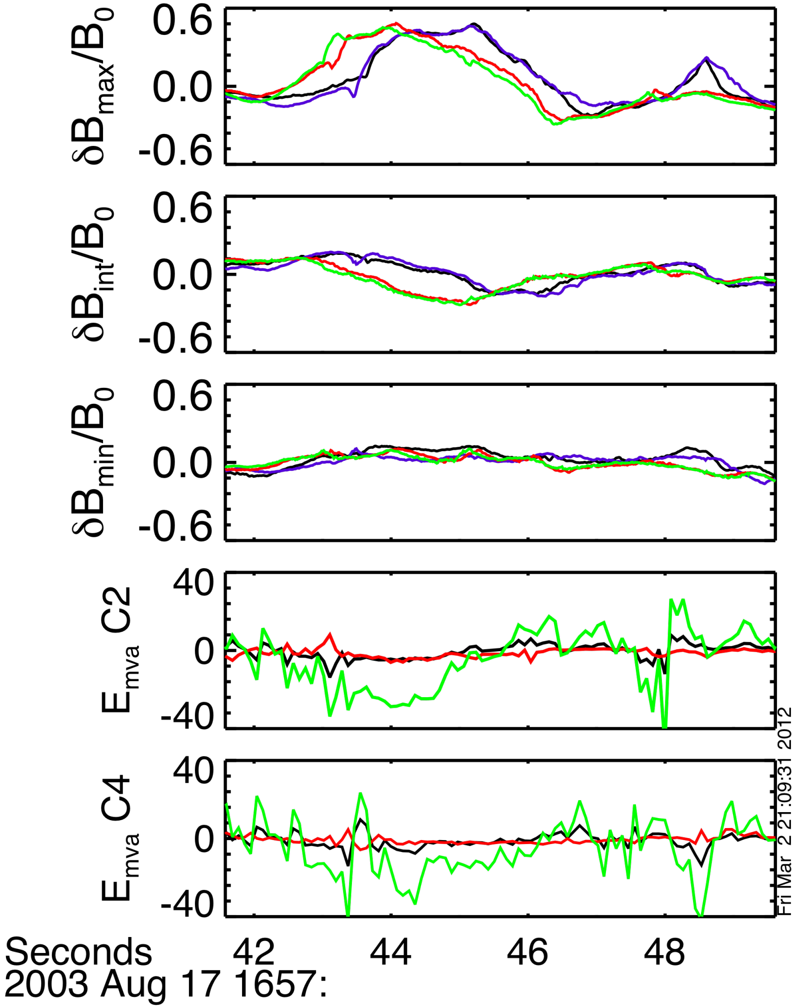
Analysis of whistler wave emissions

- Polarization analysis by Mean's method: **f~100-300 Hz or (0.1-0.4)f_{ce} , ϑ~0°-30°**, right handed polarized

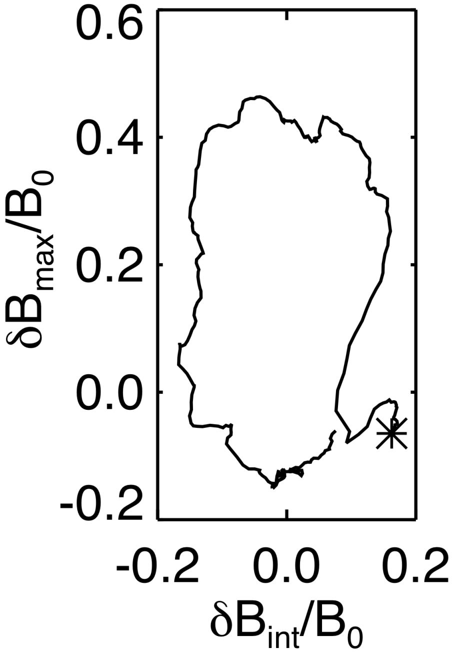


Low frequency structure analysis

$\delta B/B_0$ and E (ISR2)
in the MVA reference of C4



magnetic
hodograph C4



k=(0.5, -0.9, -0.2)
(quasi perp)

λ_{min}=0.0004
λ_{int}=0.01
λ_{max}=0.05.

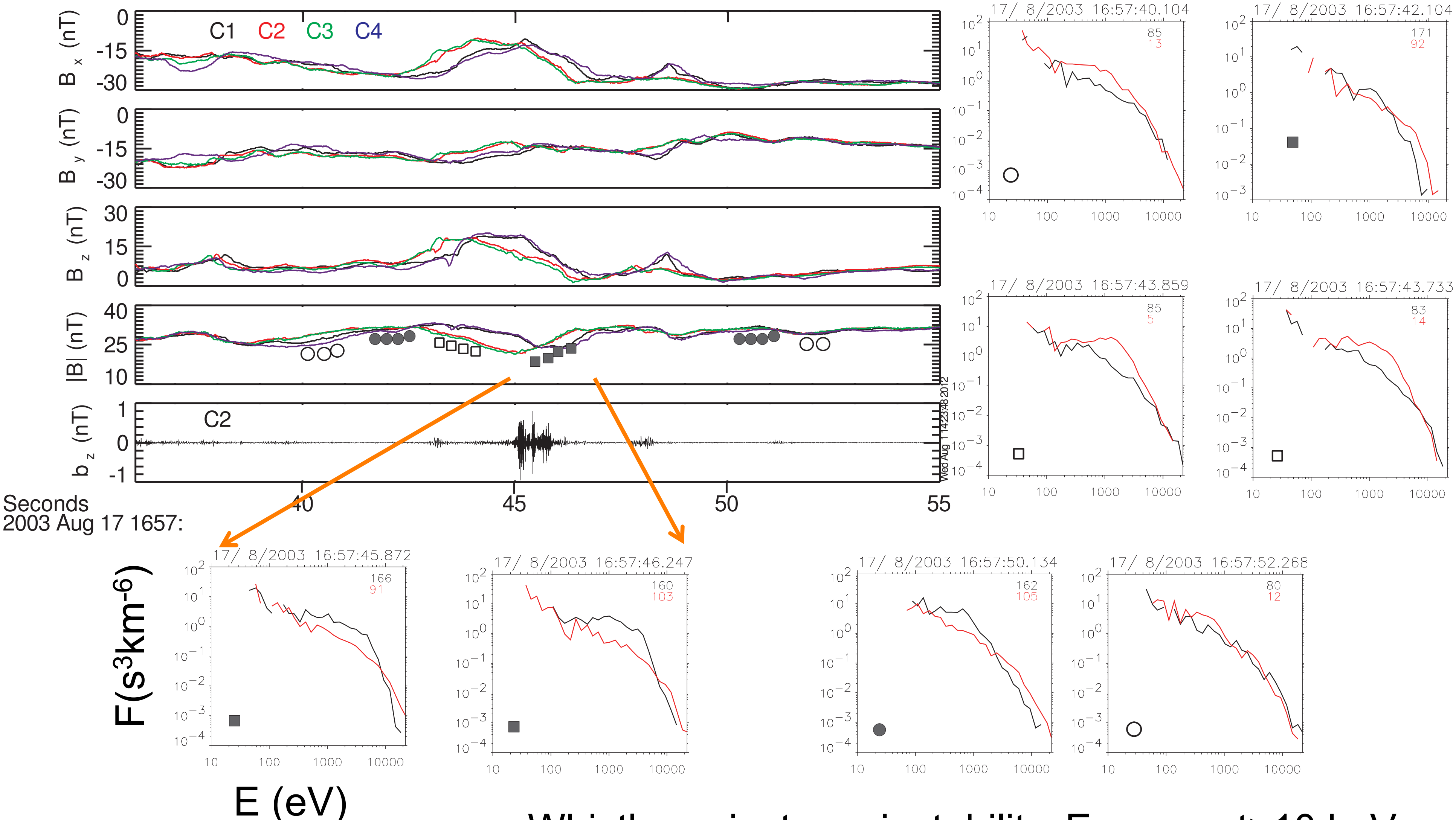
v_k= 174+/- 16 km/s

v_prop~225+/-116km/s

Elliptically (left handed,
in the plasma
rest frame) polarized

[A. Tenerani et al. PRL 2012 (in press)]

Partial electron pitch angle distribution functions in para/perp and antipara/perp directions "mapped" inside the structure.



Whistler anisotropy instability. Eresonant>10 keV

Local plasma parameters

- $n \sim 0.15\ cm^{-3}$
- $T_e \sim 2$ keV, $T_i \sim 7$ keV
- $\beta_i \sim 0.67$, $\beta_e \sim 0.067$
- $d_i \sim \rho_i \sim 600$ km
- B typical width length scale: $L \sim 900$ km
- $V \sim 175$ km/s, quasi perp to the magnetic field
- $V_a \sim 1500$ km/s, $c_s \sim 1000$ km/s
- $E_r \sim 17\text{-}4$ keV$\rightarrow$consistent with electron temperature anisotropy

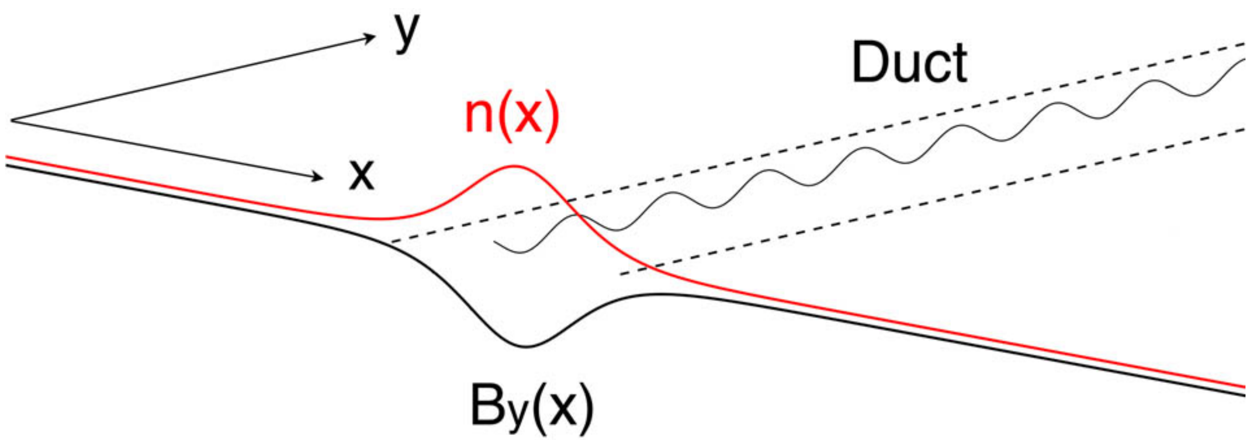
Conclusions from observations

- Data show non linear coherent magnetic structures of the slow type, on the ion scales, correlated with whistlers and propagating quasi perpendicularly

- The magnetic structures are modeled as one dimensional, non linear solitary ion-scale waves, propagating at subsonic speeds and quasi perpendicularly to the mean magnetic field which traps whistlers.

Theoretical/numerical study of whistler trapping by slow magnetosonic solitons

Whistler trapping by “magnetic holes”



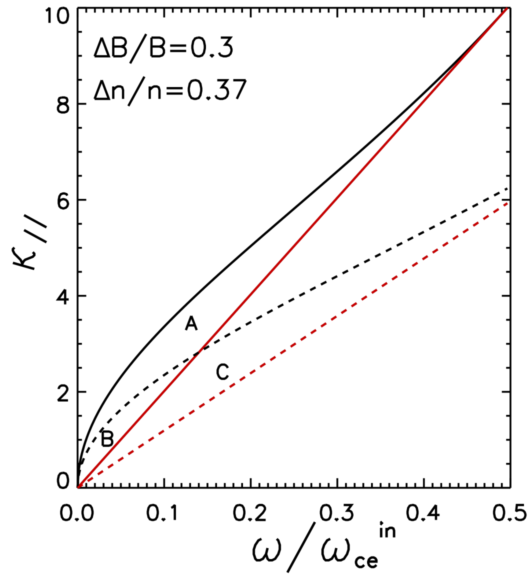
Simpler model to obtain physical insight of whistler trapping.
Extension of whistler trapping to inhomogeneous magnetic field and plasma density with the WKB method [Karpman, 1981b- only for density ducts]

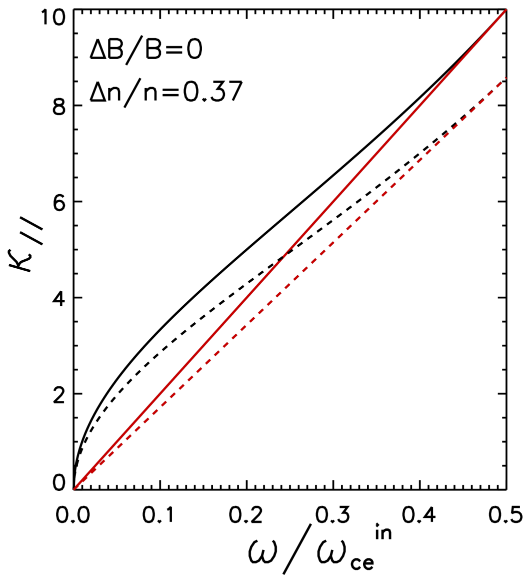
$$B_{x,y,z} \sim \exp\left(ik_{\|}y - i\omega t + i\int^{x} k_{\perp}(x)dx \right)$$

$$k_{\perp,\pm}^2(x) = \frac{1}{2d_e^2\left(\omega/\omega_{ce}(x)\right)^2}\left[k_{\|}^2 d_e^2\left(1-2\left(\frac{\omega}{\omega_{ce}(x)}\right)^2\right) - 2n(x)\left(\frac{\omega}{\omega_{ce}(x)}\right)^2 \pm d_e k_{\|}\sqrt{d_e^2 k_{\|}^2 - 4n(x)\left(\frac{\omega}{\omega_{ce}(x)}\right)^2}\right]$$

Trapping if: $k_{\perp}$ ***real inside*** **the duct and** ***imaginary outside*** **the duct**

Whistler trapping by “magnetic holes”





In a density hump+magnetic field minimum the “lower branch” can be trapped for $\omega<1/2\omega_{ce}$. [A. Tenerani et al. PoP 2012]

$k_{\perp,-}$ **is real if:**

$$k_{\|}^2 > \frac{4n(x)}{d_e^2}\left(\frac{\omega}{\omega_{ce}(x)}\right)^2$$

(Red lines. Solid line: center of the duct; dotted line: outside the duct)

$$k_{\|}^2 < \frac{n/d_e^2}{\omega_{ce}/\omega - 1}$$

(Black lines. Solid line: center of the duct; dotted line: outside the duct)

Region A: trapped modes;
Region B: untrapped modes
Region C: of no interest (damped inside magnetic hole)

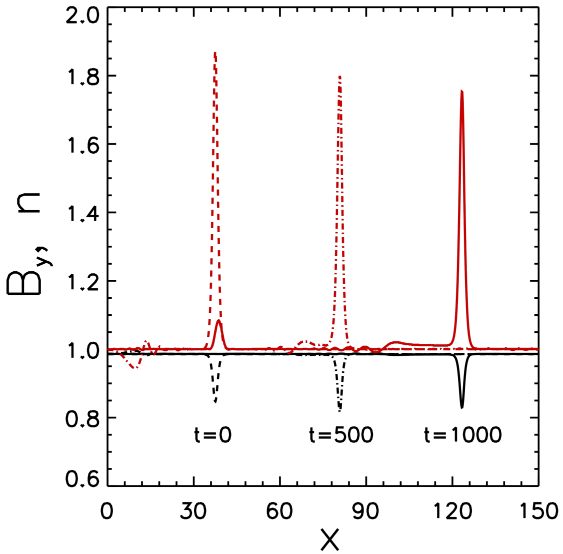
The basic idea

- The whistler trapping mechanism relies on
  - the slow nature of the inhomogeneity which implies magnetic field strength in opposition of phase with the density modulation
  - slow velocity of propagation with respect to the whistler phase velocity
  - quasi perpendicular inhomogeneity

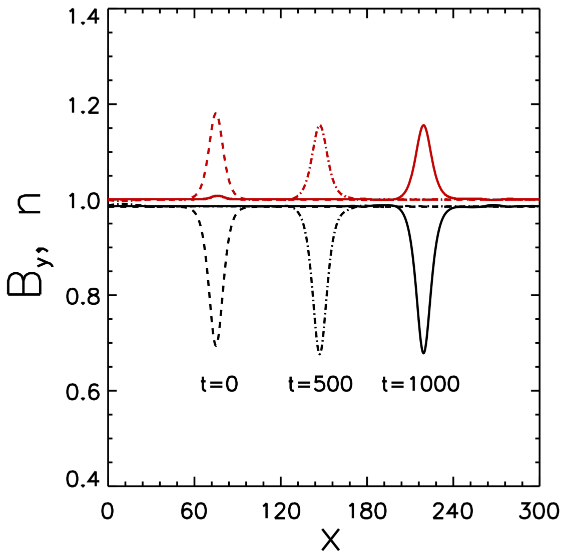
- Slow type non linear waves provide such a theoretical model to act as whistler carriers (*in principle other nonlinear structures with similar features can provide a channel*)

Simulations set up

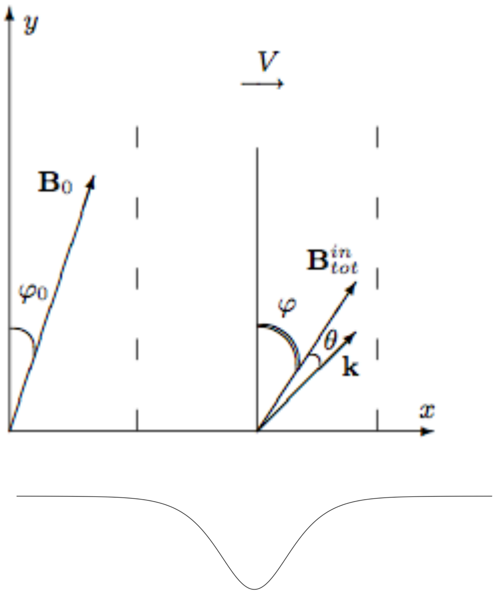
By(x), n(x)



L~4d_i ≤ k^{-1}
V~0.09v_a
c_s~0.4v_a
β=0.2
δB/B_0=0.14
δn/n_0=0.87

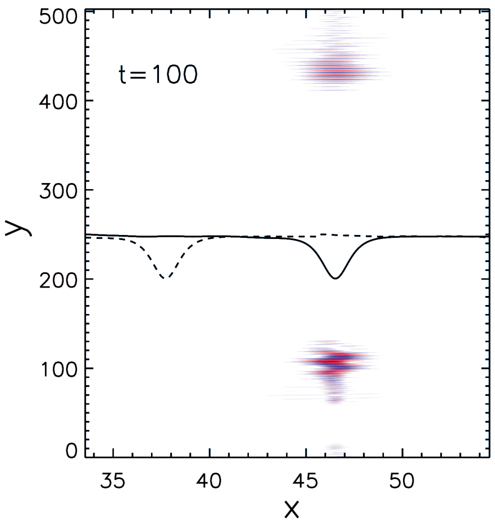


L~12d_i > k^{-1}
V~0.12v_a
c_s~1.26v_a
β=2
δB/B_0=0.28
δn/n_0=0.18

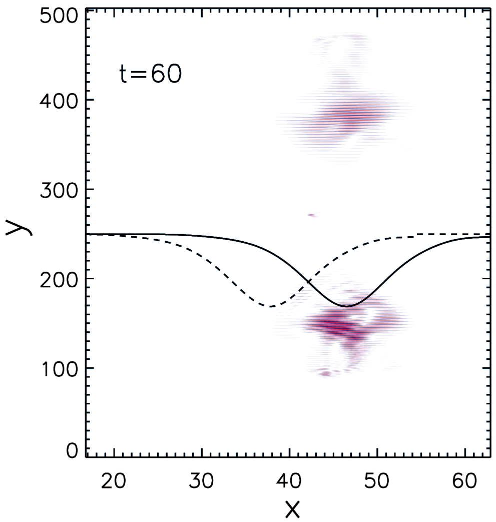


Injection of whistler wave packets with frequency ω and wave vector k making use of a forcing current which switches off after few whistler periods.

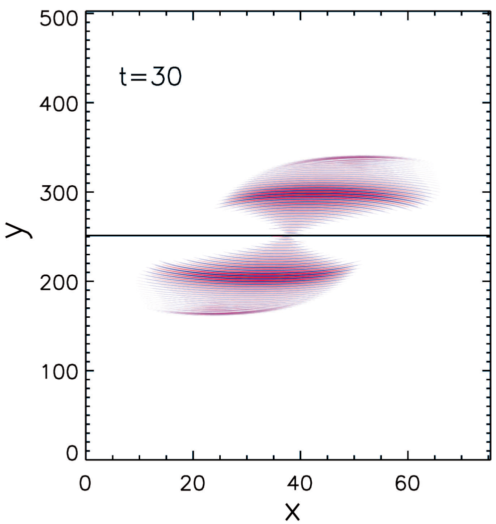
Trapping of whistlers by slow solitary waves



Narrow soliton:
ω/ω_{ce}^{in}~0.02, ϑ=11°



Wide soliton:
ω/ω_{ce}^{in}~0.04, ϑ=13°



Homogeneous plasma:
ω/ω_{ce}^{in}~0.02, ϑ=11°

[A. Tenerani et al. PoP 2012]

Conclusions

- mechanism of whistler energy transport and confinement by slow magnetosonic solitons
- The model suites quite well in the interpretation of satellite data
- Alternative explication to recurrent observation of whistlers correlated to magnetic field minima
- Possible role in energy balance and transport during substorms, e.g., electron scattering into the loss cone. The ion scale wave can extract energy from earthward ion flow
- in progress: investigation about kinetic effetcs on slow and alfvénic mode structures (e.g. LandauFLR).