Magnetic whistler wave packets in the front and upstream of quasi-perpendicular shocks

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Summary

Low frequency waves are observed upstream from planetary bow shock. They are either shock precursors related to the shock structure itself or originating from the foreshock region which is produced by backstreaming particles. In the quasi-parallel part of the foreshock, steepened low frequency waves or local nonlinear pulsations are often associated with whistler-mode wave packets. Whistler waves precursors at quasi-perpendicular planetary shock fronts can also be present in supercritical regime while there are often less prominent than for low beta subcritical shocks. They constitute one channel to evacuate incident energy from the shock and balance shock steepening for high Mach number shocks. The properties of such whistler wave packets observed both upstream of the front or in the overshoot of supercritical quasi-perpendicular shocks at Earth have been described in details from a multi-spacecraft analysis. It is crucial to determine their origin either by dispersion from the shock ramp or by local microinstabilities related to the reflected ions. On one hand, theoretical works relate nonlinear whistler dynamics with the shock front nonstationarity. On the other hand, some simulation works have shown that large amplitude coherent whistler waves can be emitted in the foot region and dominate the whole shock front dynamics inhibiting the nonstationarity in certain conditions.

Microturbulence at supercritical Q-perp shocks

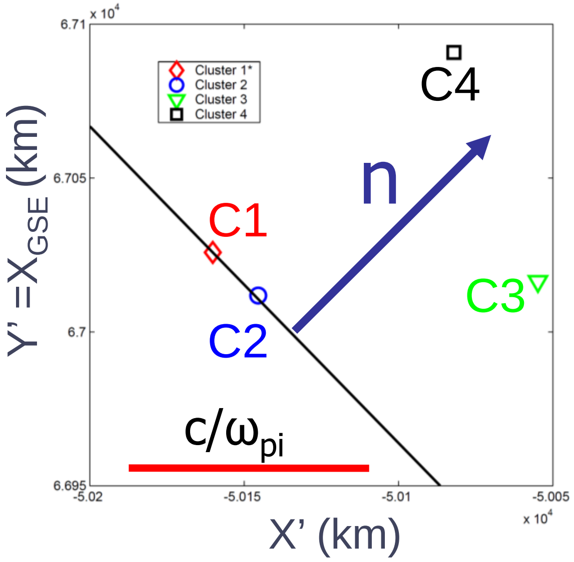
Coherent oblique whistler wave packets observed in the shock foot

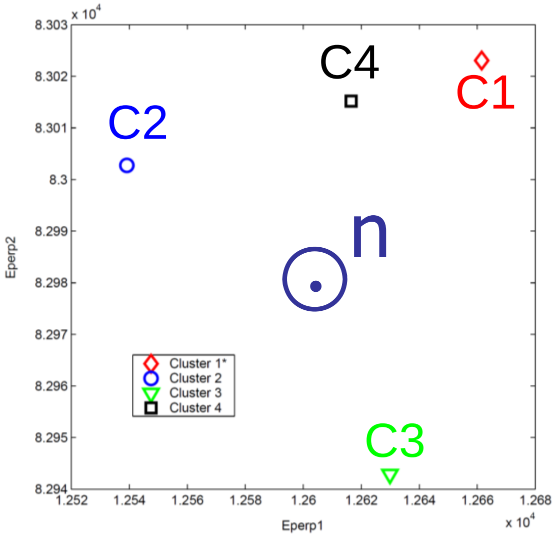
Interest:

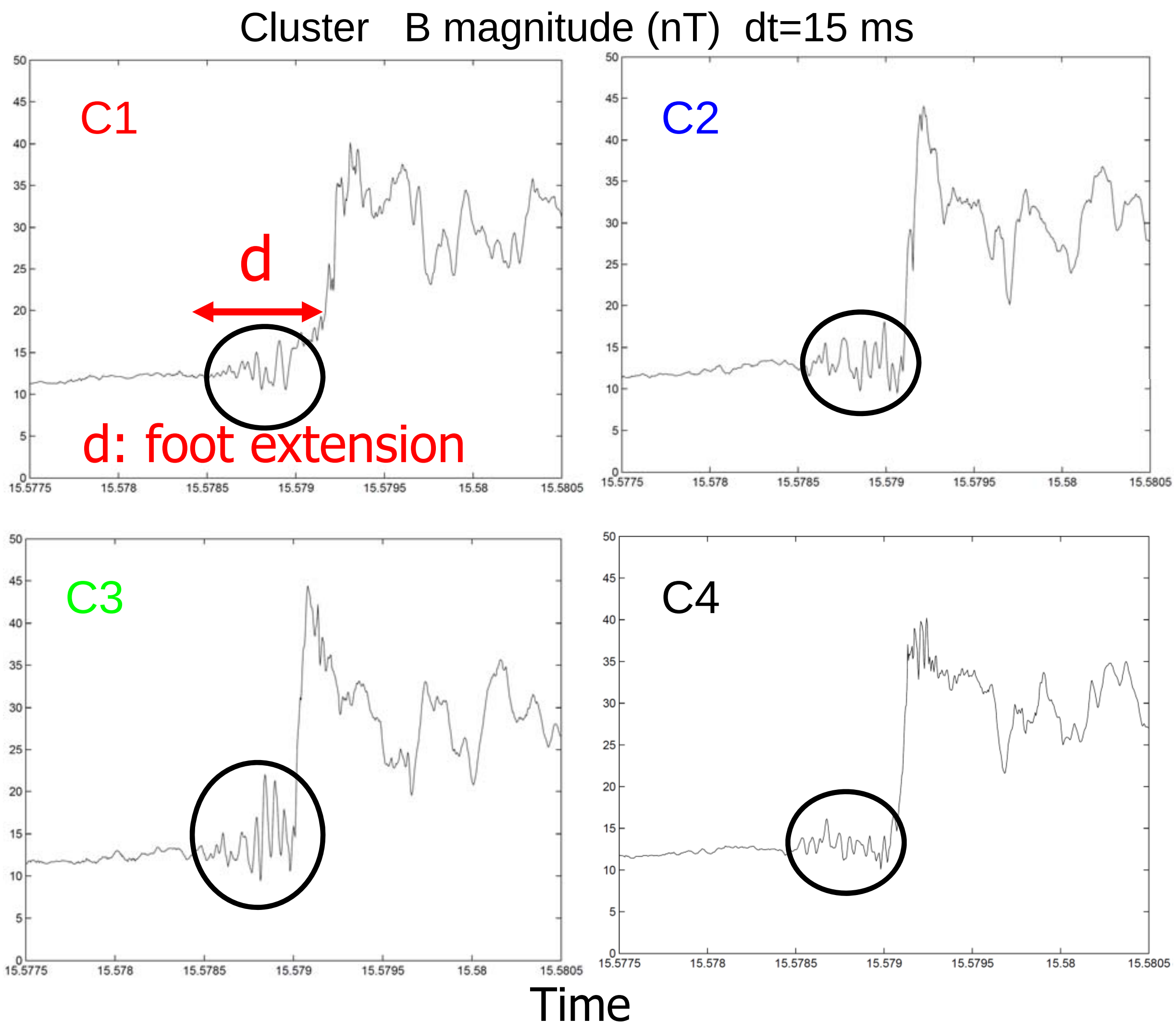
- One channel to evacuate energy from the shock front to balance its steepening.
- Origin: from dispersion at the ramp or from micro-instabilities linked to reflected ions?
- Can play a role in mechanism responsible for shock nonstationarity (*e.g.* Hellinger, 2007).

Wave packets in the magnetic foot

Shock 11 θ_{Bn}= 76° M_A=5.6 β_i=0.3



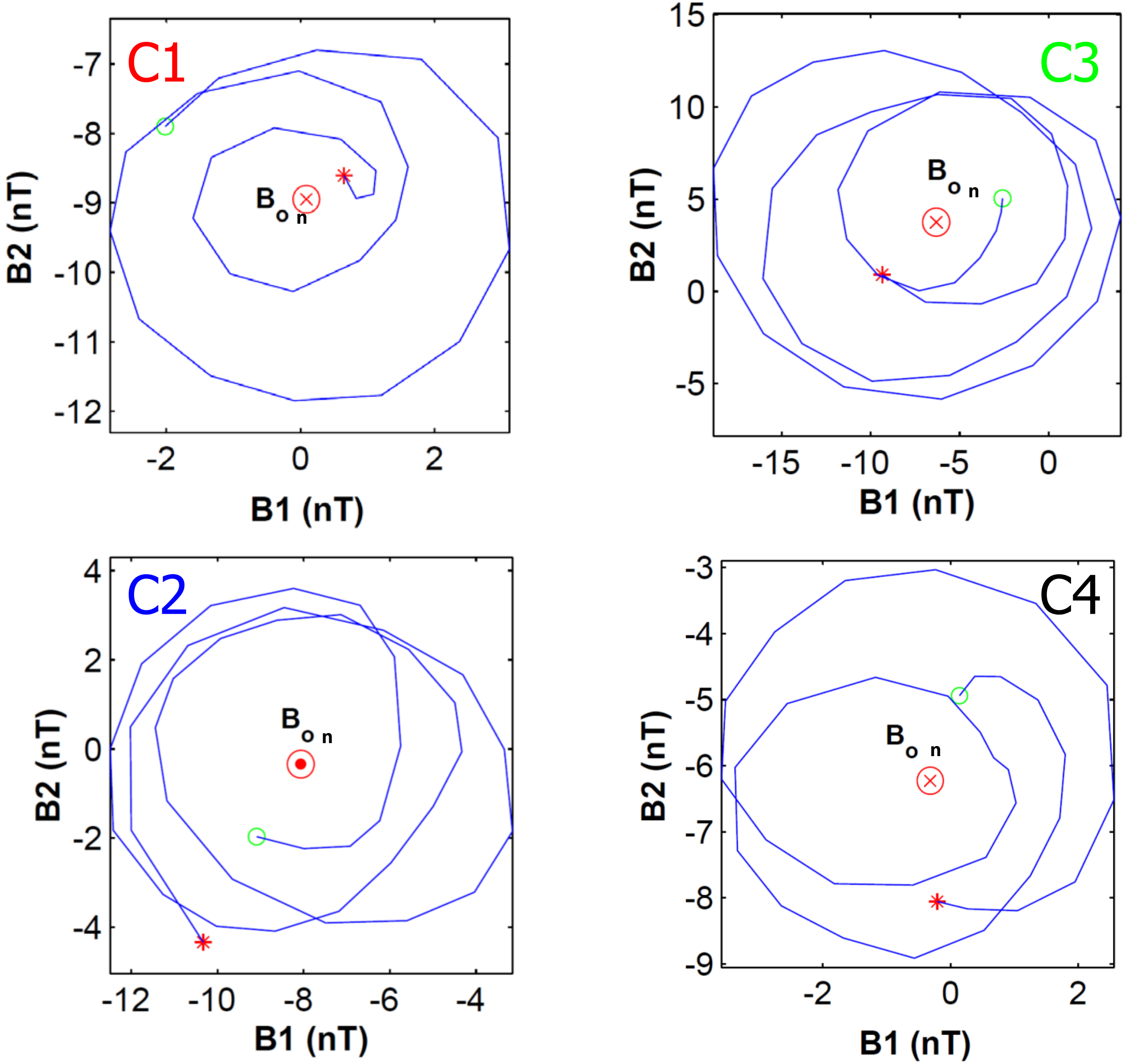




inter-spacecraft separation ~ 100 km ~ c/ω_{pi}

wave packets seen on the 4 s/c
→ multi-spacecraft analysis possible

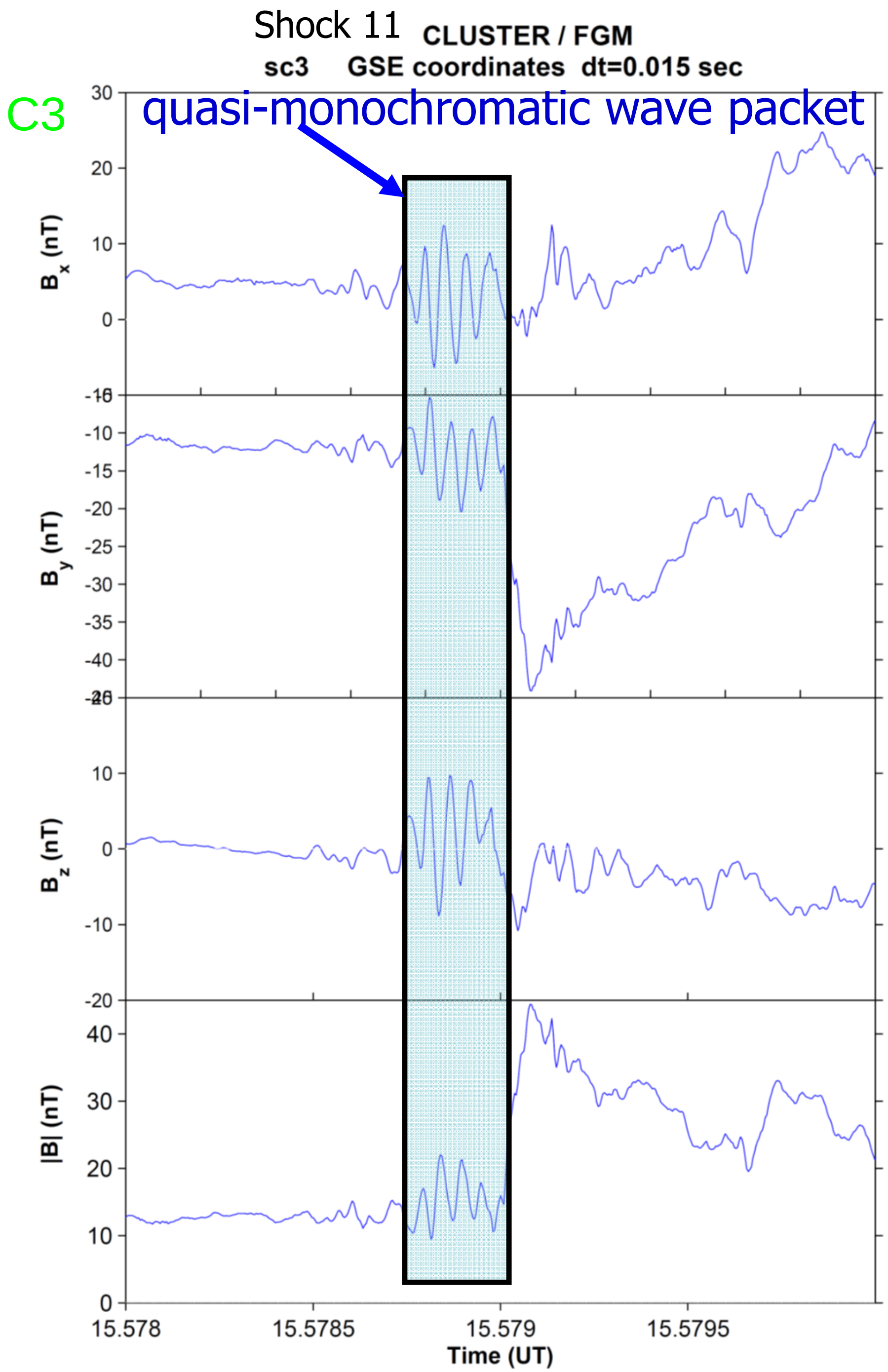
Hodograms: comparison between the 4 s/c



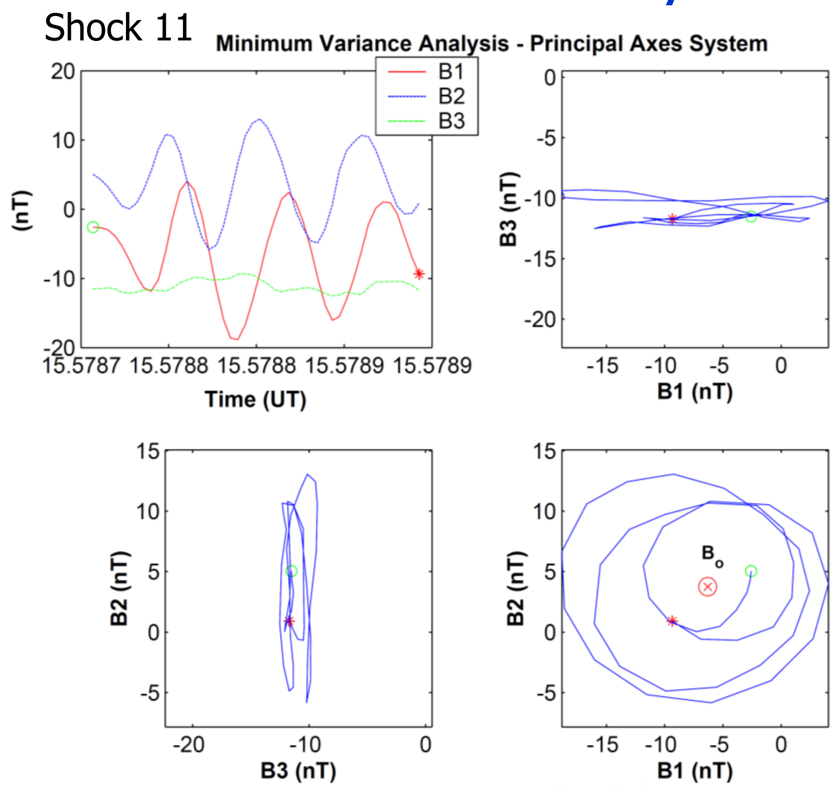
Right-hand Polarization in s/c frame

Oblique foot whistlers

θ_{Bn} = 76° M_A=5.6 β_i=0.3



Polarisation analysis



$\lambda_2/\lambda_3 \sim$ 37 $\lambda_1/\lambda_2 \sim$ 1.4

θ_{kB} = 50° ± 1.5°

θ_{kn} = 55° θ_{kc} = 40°

k oblique w.r.t. $\mathbf{B_o}$, **n** and coplanarity plane

wave vector from 4-spacecraft determination

Magnetic foot oblique whistler mode wave properties

multi-spacecraft analysis results:

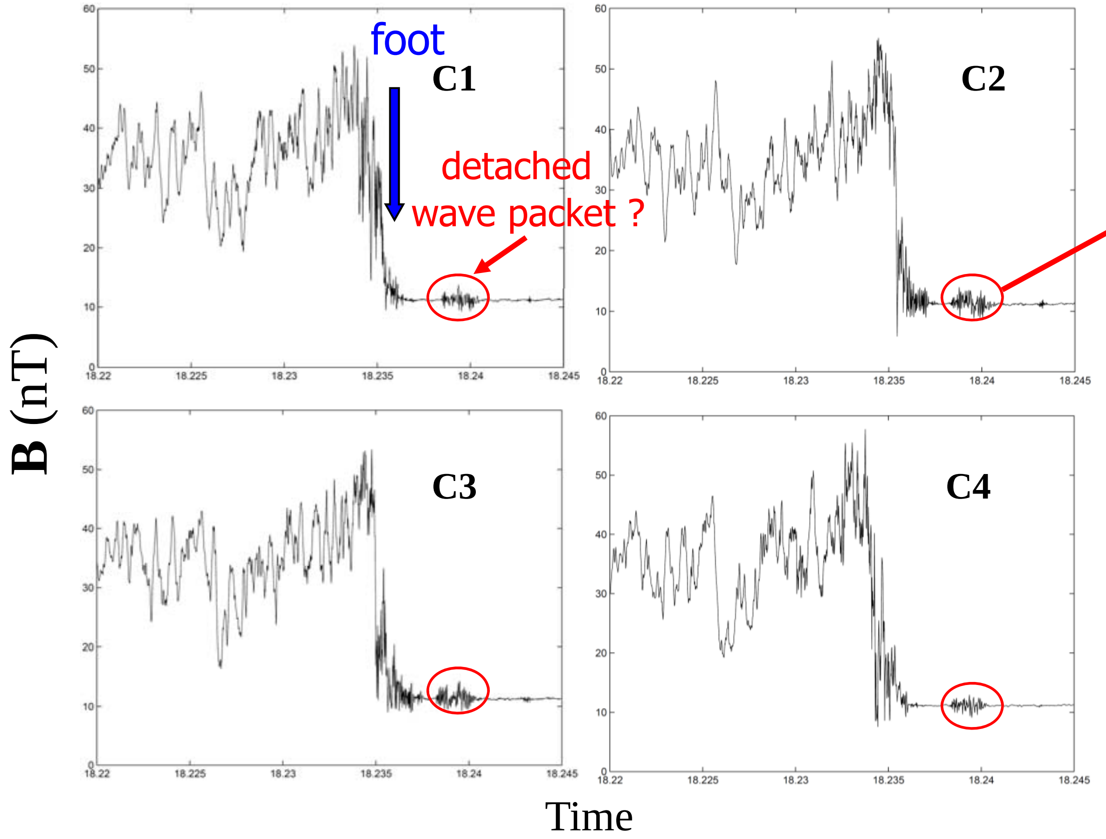
- Frequency in s/c frame: 5 Hz (< 10 Hz: instrumental limit)
- Wavelength = 52 km = 0.7 c/ω_{pi}
- Frequency: 6 Hz in Solar wind frame $\omega \sim 25\ \Omega_p$
- Phase velocity: V_{ph} = 370 km/s = 5 V_A = 10 V_{th_p}
- Group velocity: V_g = 560 km/s = 7.5 V_A = 16 V_{th_p} > Vsw
- Shock moving towards Earth at ~ 170 km/s

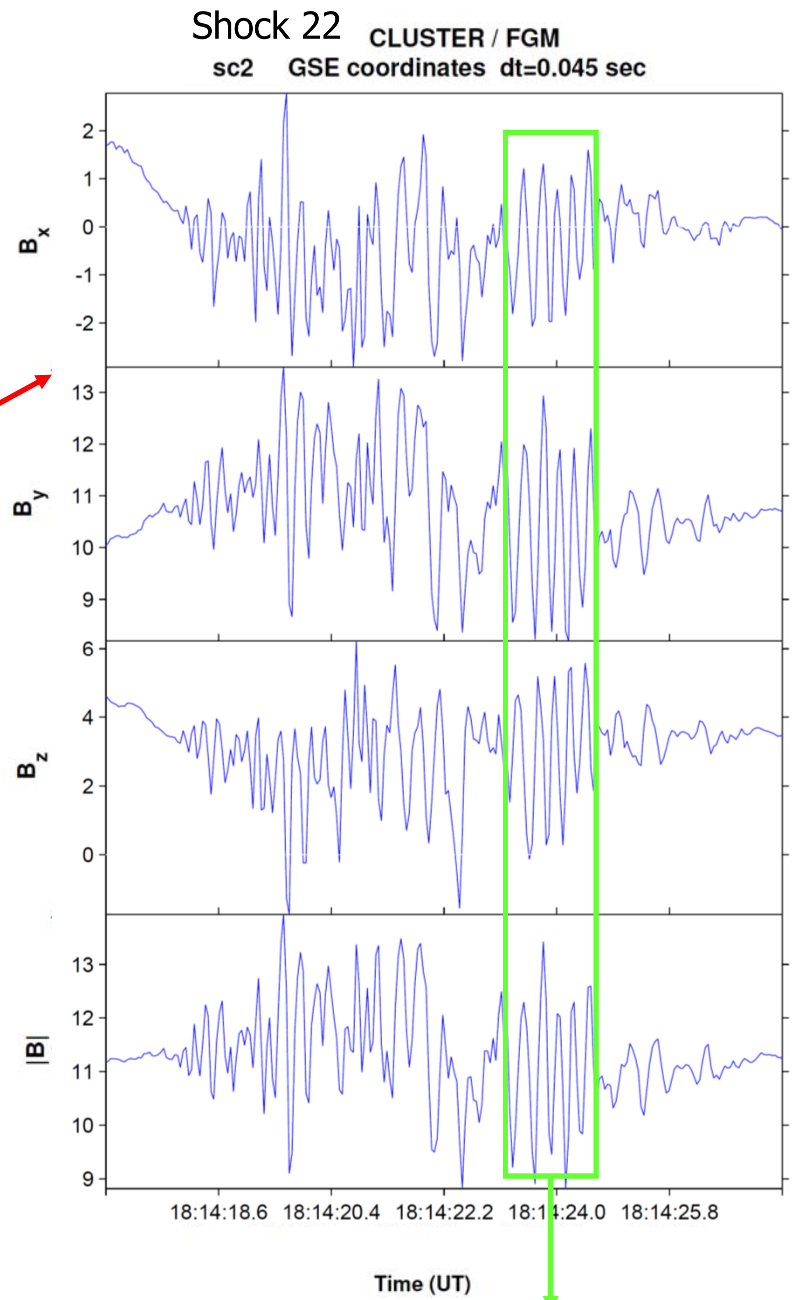
- Waves propagating upstream in the shock frame
  Consistent with emission from the shock front (ramp or foot)

Estimate of a **minor limit** value for coherence length:
~ maximum separation between s/c since observed on the 4 s/c
gives 1.5 c/ω_{pi} (>2 wavelengths)

Detached upstream wave packet

$\theta_{Bn} = 78°$ $M_A = 5.2$ $\beta_i = 0.2$





Polarisation analysis

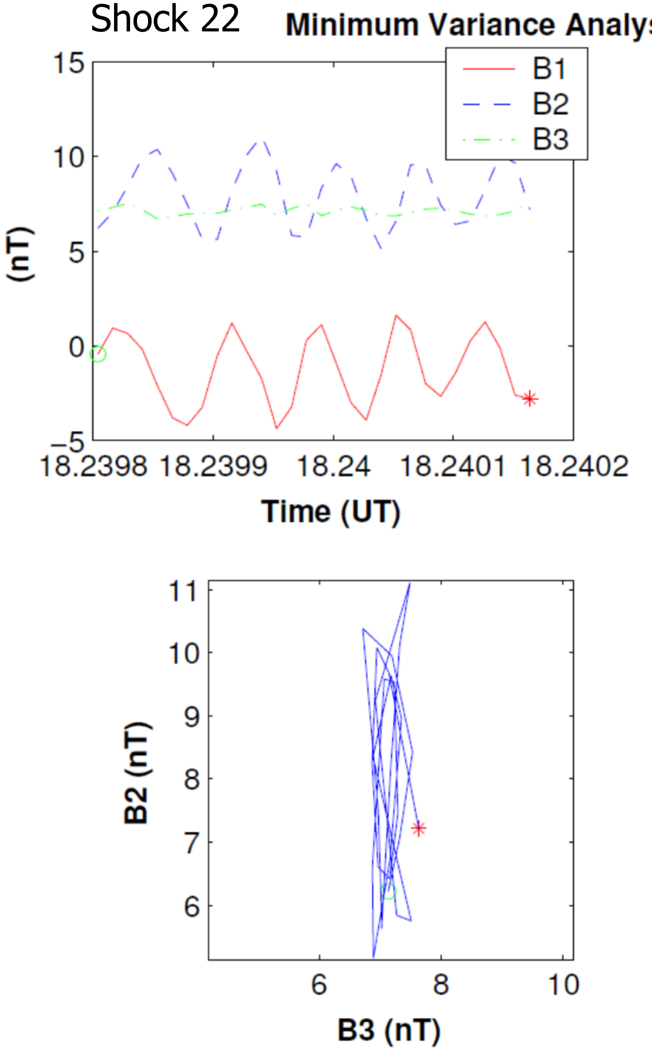
inter-spacecraft separation ~ 100 km ~ c/ω_{pi}

Seen on the 4 s/c

→ multi-spacecraft analysis possible

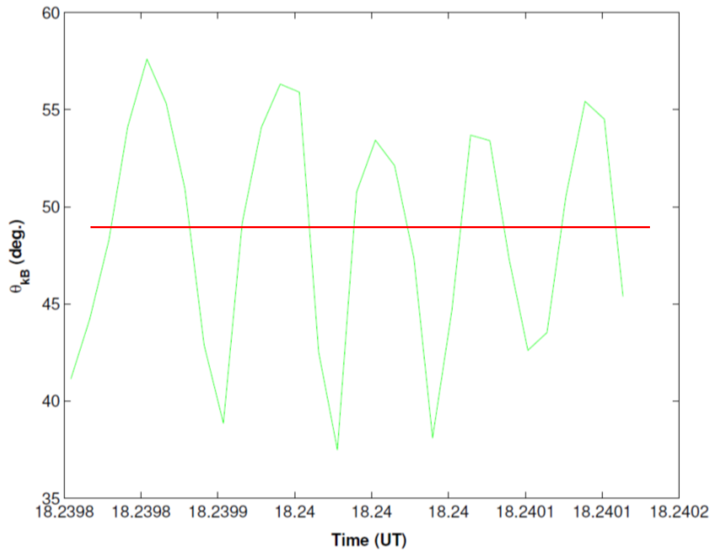
Polarisation analysis s/c 2

Shock 22



$$\lambda_2/\lambda_3 \sim 52$$

$$\lambda_1/\lambda_2 \sim 1.2$$



θ_{kB} = 49 ± 1.5°

θ_{kn} = 40° θ_{kc} = 51°

planarity + circular polarisation

k oblique w.r.t. $\mathbf{B_o}$, **n** and coplanarity plane

wave vector from 4-spacecraft determination

‘Upstream’ whistler mode wave properties

multi-spacecraft analysis results:

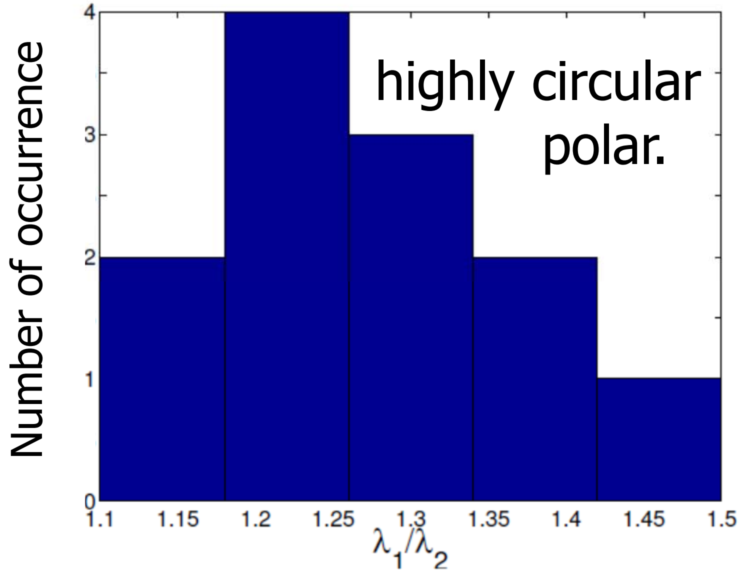
- Frequency in s/c frame: 3.8 Hz (< 10 Hz: instrumental limit)
- Wavelength = 47 km = 0.5 c/ω_{pi}
- Frequency: 5 Hz in Solar wind frame $\omega \sim 26\ \Omega_p$
- Phase velocity: V_{ph} = 240 km/s = 3 V_A = 6 V_{th_p}
- Group velocity: V_g = 560 km/s = 7 V_A = 14 V_{th_p} > Vsw
- Shock moving towards the Earth at ~ 23 km/s

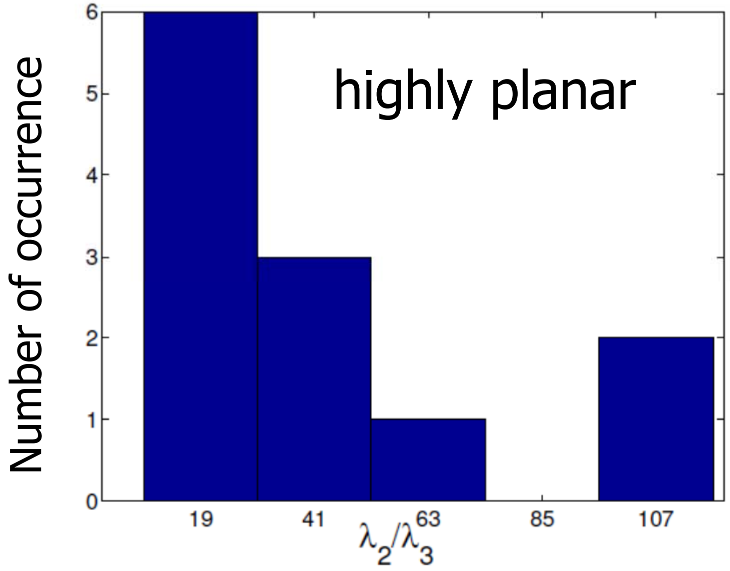
- Upstream waves **propagating upstream in the shock frame**

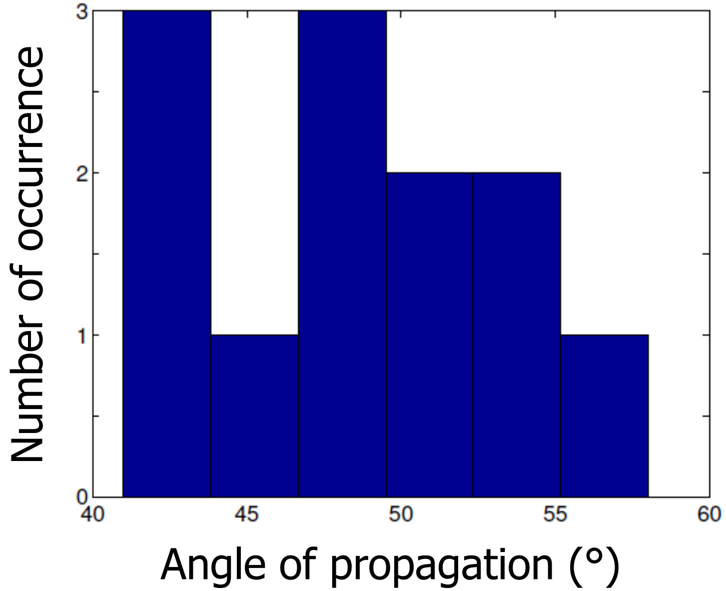
Consistent with emission ‘appearently detached’ from the shock foot
(due to sudden inversion of shock front velocity previous to observation?)

Estimate of a **minor limit** value for coherence length:
~ maximum separation between s/c since observed on the 4 s/c
gives 2 c/ω_{pi} (about 4 wavelengths)

Polarization (MVA) and Propagation Angle
Statistical results: 12 events analyzed







wave vector from 4-spacecraft determination

Source mechanisms for oblique whistlers

Still under strong debate!

I. Dispersive Process?

[*e.g.*, Krasnoselskikh *et al.*, 2002; Sunqvist *et al.*, 2012]

- ❑ Alfven Mach at or above critical limit where reformation expected to occur.

  $M_A \geq |\cos(\theta_{Bn})|(m_i/m_e)^{1/2}/2^{1/2}$.
- ❑ LF whistlers carry Poynting flux upstream.
- ❑ Wave vectors of LF whistlers make transition from oblique to parallel propagation as you go from ramp to upstream.

- ❑ **Limits:** Emphasizes relative balance between nonlinearity and dispersion.
- ❑ Completely ignores dissipation effects associated with reflected ions which may be very important.
- ❑ Currently 1D in nature -> wave vectors predefined to be aligned with the shock normal. At least would require 2D extension for comparison.

II. Microinstabilities

Usually two favored classes of instability mechanisms for waves near lower hybrid frequencies [*e.g.*, Wu *et al*. 1983, Scudder 1986c]:

1. Lower hybrid drift instability (LHDI)
   - Excited by electron-ion (incoming or reflected) drifts $\perp$ $\mathbf{B_0}$ and ∇N.
   - **k** oriented out of coplanarity plane.
   - but **k** mainly close to $\perp$ $\mathbf{B_0}$ and highly elliptical to linear polarization (*e.g.* Wilson *et al*., 2004, 2007).

2. Kinetic cross field streaming instability (KCFSI) also called modified two stream instability (MTSI). Excited by electron-ion (incoming and/or reflected) drift parallel to coplanarity plane.
   - Oblique whistler wave vectors **k** preferentially oriented well outside magnetic coplanarity plane does not favor MTSI.
   - **k** also mainly close to $\perp$ $\mathbf{B_0}$ (*e.g.* Matsukiyo and Schoeler, 2006).

Other possible microinstability:

3. Ion-ion beam (incident-reflected) instability

Source of the whistler wave packets

- Low frequency whistlers ($\omega<\omega_{LH}$).
- **k** highly oblique whith respect to $\mathbf{B_0}$, **n** and the **coplanarity plane**
- Results highly consistent with results from 3D–Hybrid simulations by Hellinger (1997):
  - Parameters: θ_{Bn}= 80° M_A=5 $\beta_i=\beta_e$=0.5 (similar to observ.)
  - Results: $\omega \sim 27\ \Omega_p$ $\lambda\sim c/\omega_{pi}$ $V_{ph} \sim 5.1\ V_A$ directed upstream
    θ_{kB} = 41° θ_{kn} = 51° θ_{kc} = 56° **k** off coplanarity plane

<u>Source of the whistlers</u>:

Near the shock by reflected ions which gyrate back to the shock (ion foot).

Agreement with linear theory by Goldstein and Wong (1988): resonant beam-plasma instability.

<u>Role</u>:

Escape from shock front and then subject to electron Landau damping.

Transfer kinetic energy of reflected ions to electron thermal energy.

Quantitative role in shock energy dissipation still to be evaluated.

Conclusions

micro-turbulence in the foot of supercritical quasi-perpendicular shocks:

whistler wave trains both inside the foot or apparently ‘detached’ upstream

consistent with production in the shock foot by micro-instability due to specularly reflected proton beams