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Phase-standing whistler fluctuations detected by SELENE and ARTEMIS around the Moon

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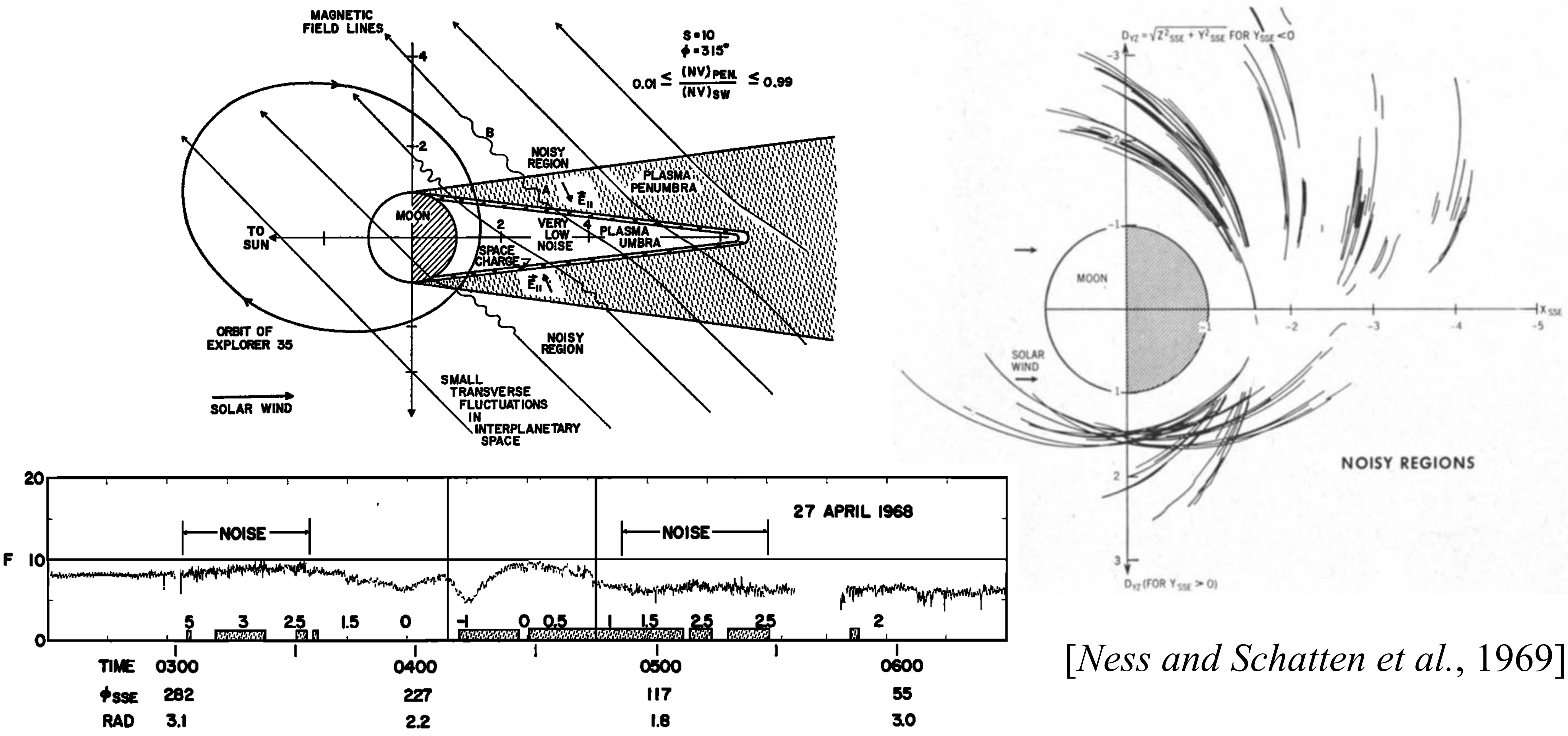
Abstract

Low frequency (<~0.01 Hz) magnetic fluctuations around the Moon in the solar wind have been reported since 1960s. They are extended upstream of the lunar wake edge along the interplanetary magnetic field lines. We analyze magnetic field data detected by SELENE and ARTEMIS to reveal generation processes of the fluctuations.

Our analyses indicate that observed polarizations of the magnetic fluctuations are determined by the spacecraft velocity: right-hand polarization when S/C moves downstream, left-hand polarization when S/C moves upstream. This fact suggests that their phase velocity in the Moon frame is smaller than the spacecraft velocity and they are R-mode in plasma frame, i.e., they are phase-standing whistlers. They are possibly generated as bow waves around the lunar crustal magnetic anomalies and/or ballistic fluctuations carried by electrons modified through the wake.

Low freq. fluctuation around wake edge



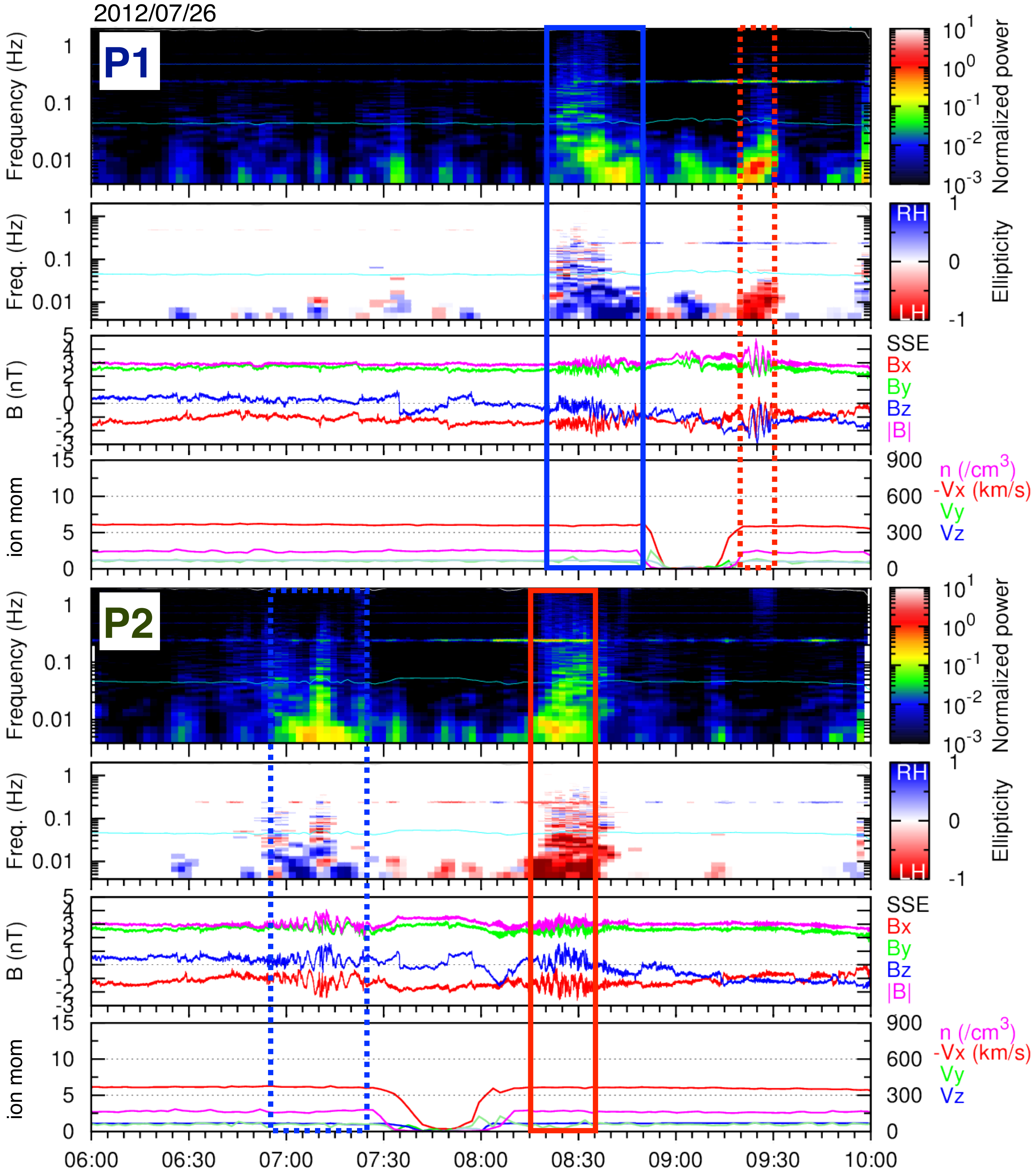
[*Ness and Schatten et al.*, 1969]

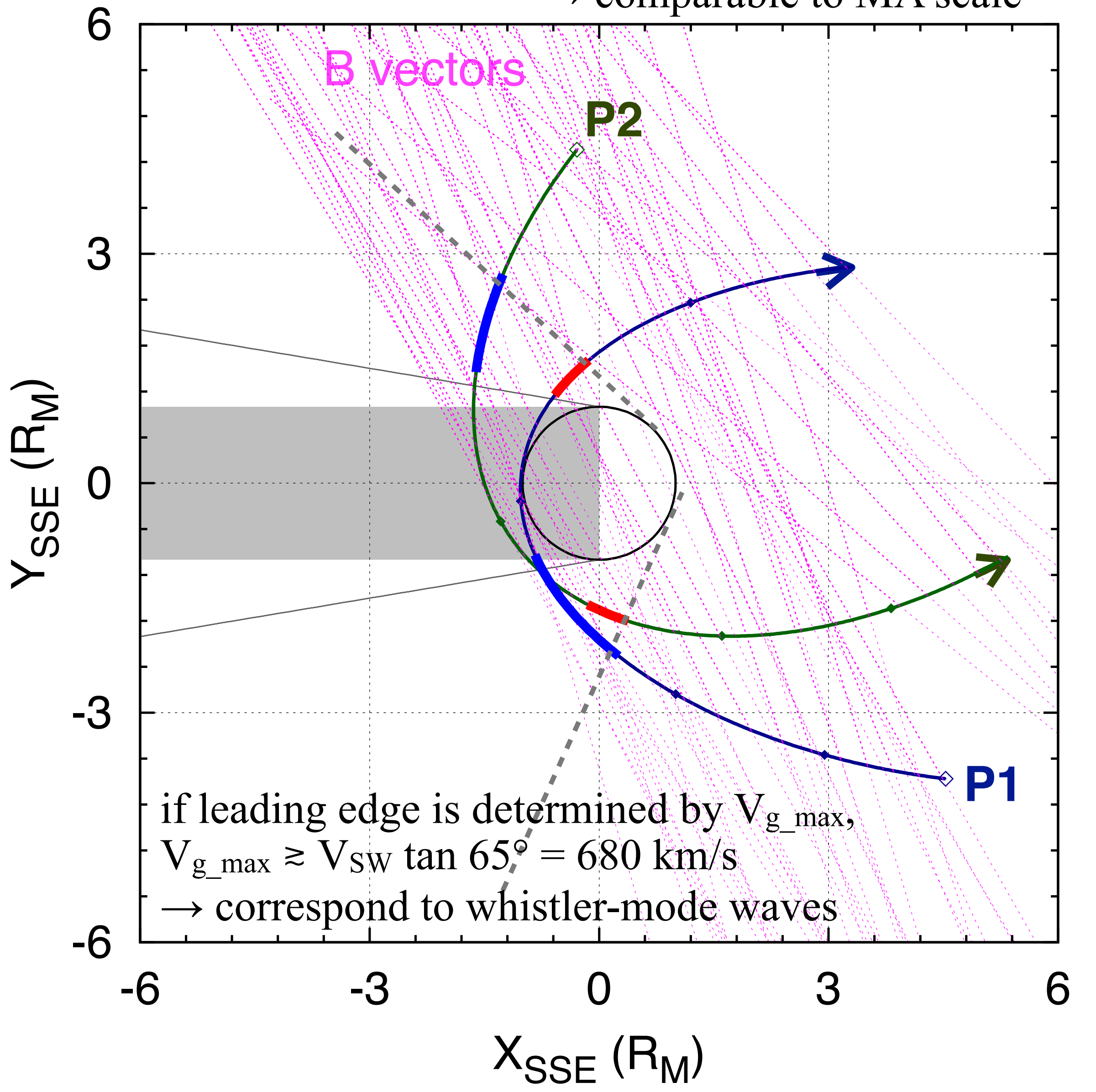
magnetic fluctuations < 5 Hz detected by Explorer 35 [*Ness et al.*, 1967, 1968; *Taylor et al.*, 1968]

- on magnetic field lines which cross the lunar wake
- slightly more transverse than longitudinal
- extend up/downstream for >1000 km from the wake → travelling speed ≧ solar wind speed

ARTEMIS event

if $\omega_{obs} \sim -\mathbf{k} \bullet \mathbf{V}_{sc}$,
$\lambda \sim 1.5$ km/s / 0.01 Hz = 150 km
→ comparable to MA scale

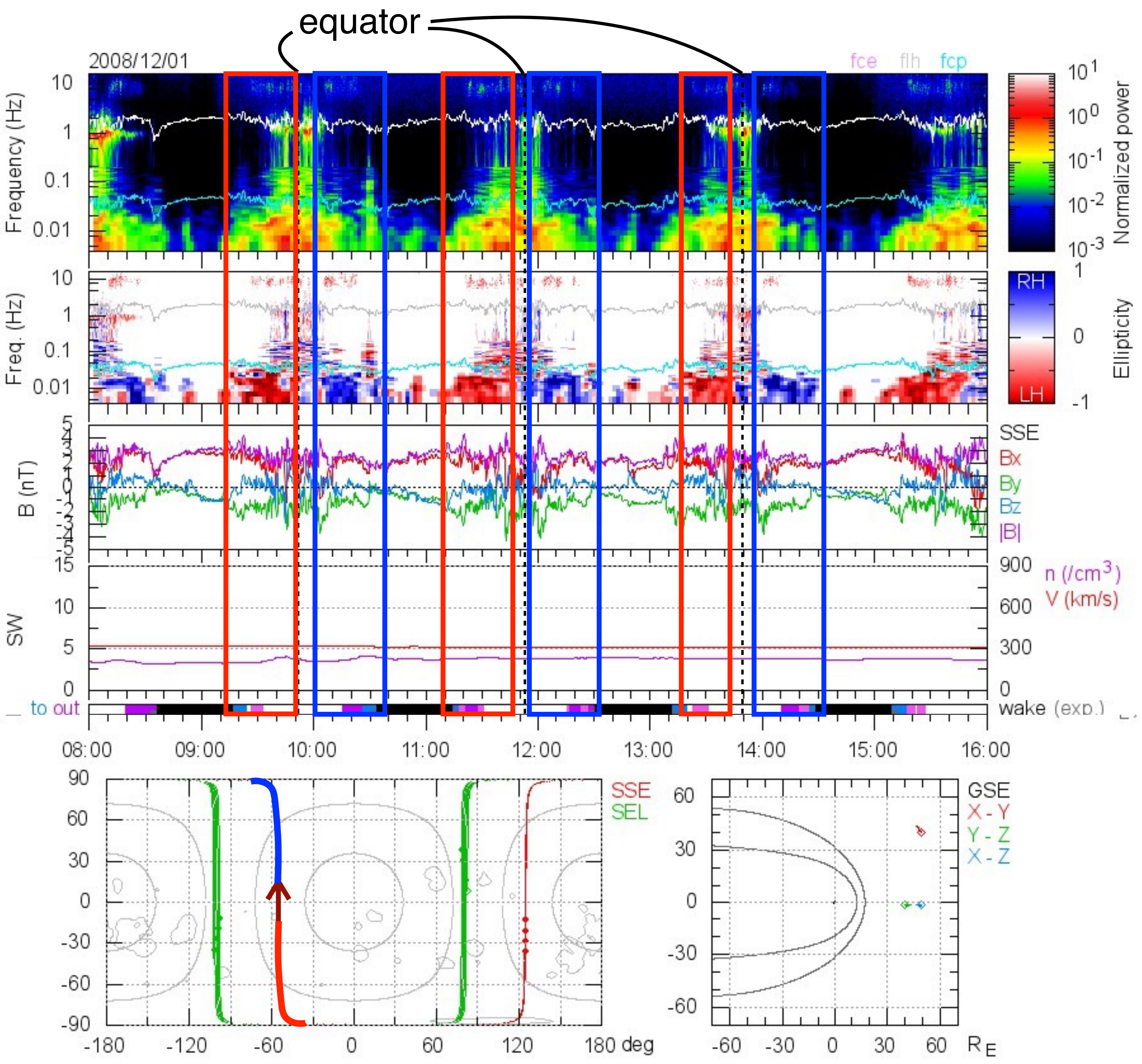




if leading edge is determined by V_{g_max},
$V_{g\_max} \gtrsim V_{SW} \tan 65° = 680$ km/s
→ correspond to whistler-mode waves

- inbound: RH, outbound: LH
  opposite even at the same time & space
  → Doppler-shift by s/c velocity
- from terminator to upstream of expansion region
  → larger Vg than fast MS velocity

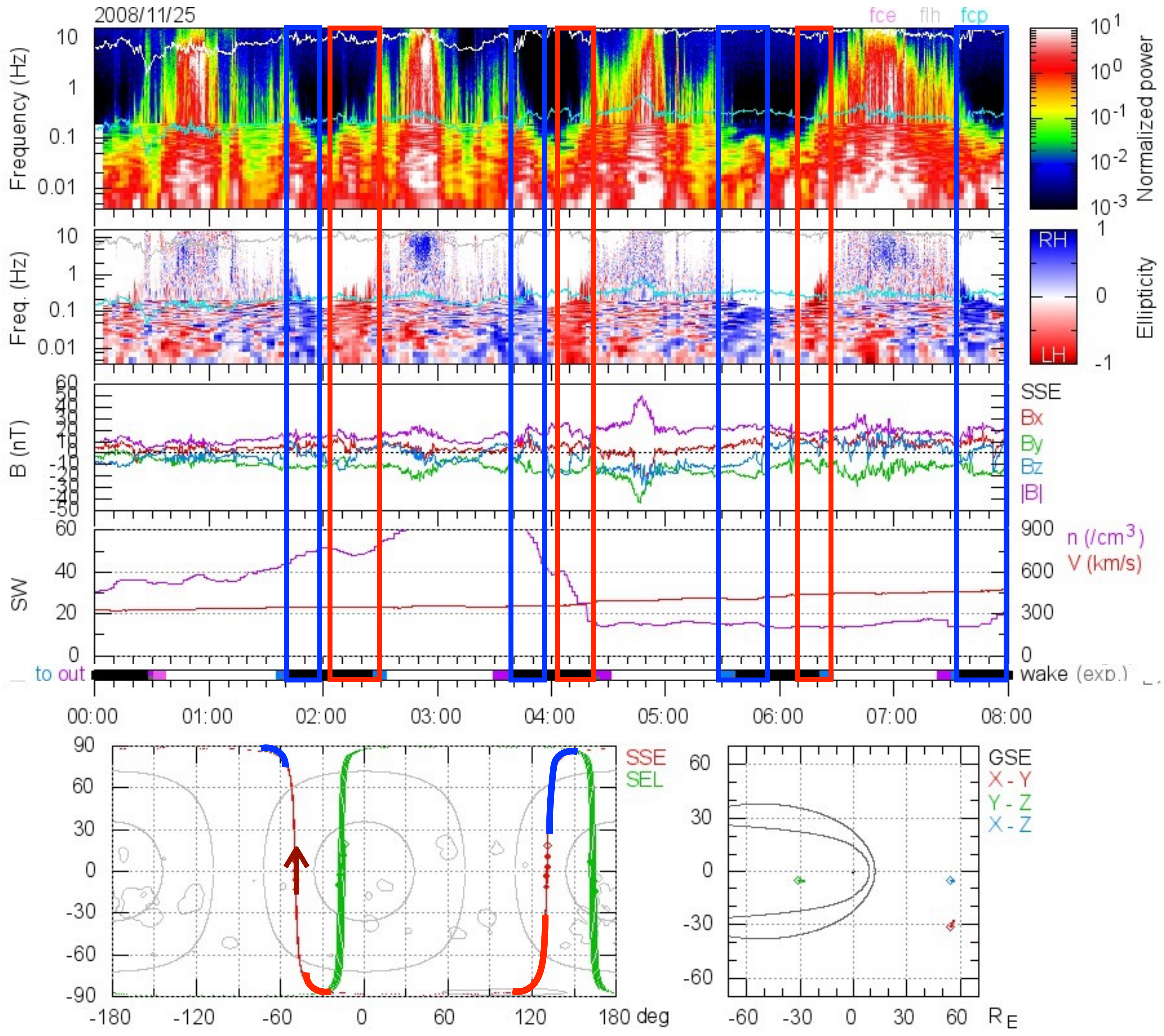
SELENE event 1



- ~100 km altitudes
- in the solar wind (SW)
- Alfven Mach number, $M_A \sim 8$

- polarized fluctuations <~0.01 Hz
- from dayside ~SZA60° to outer wake
- LH inbound to wake
- RH outbound from wake

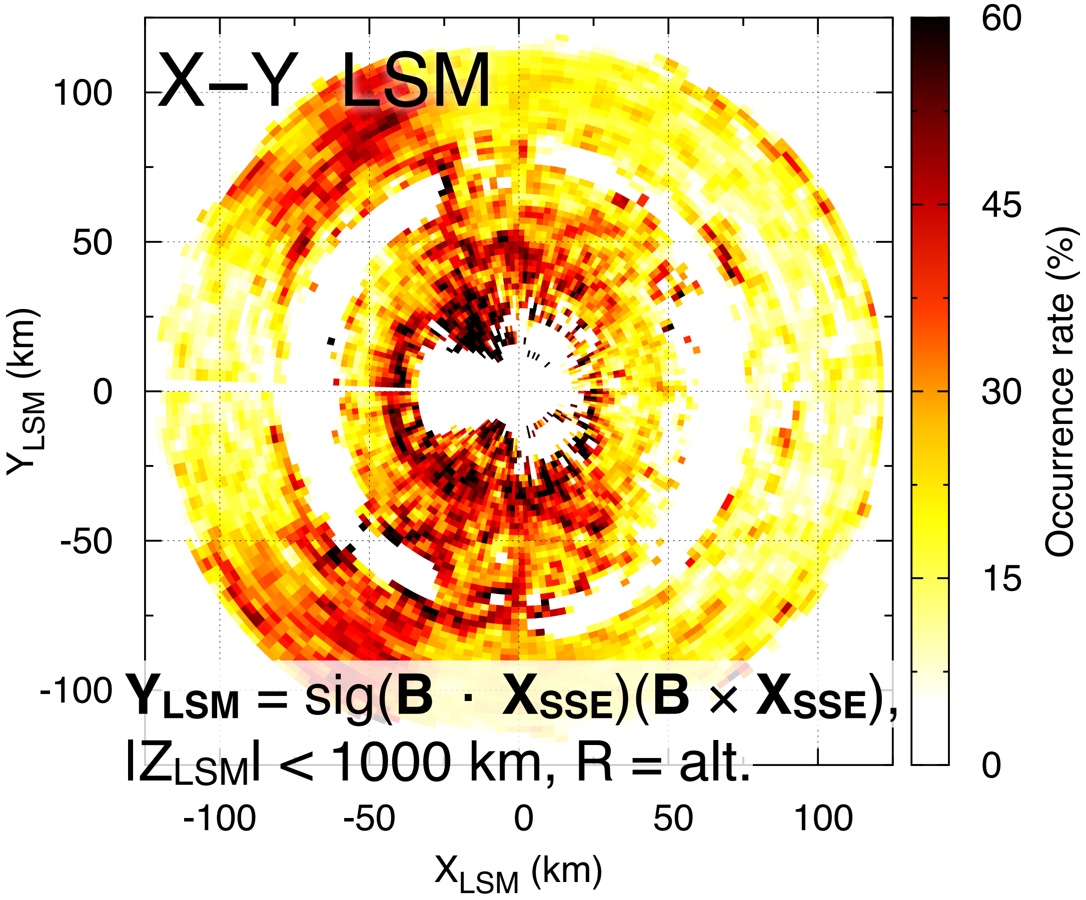
SELENE event 2



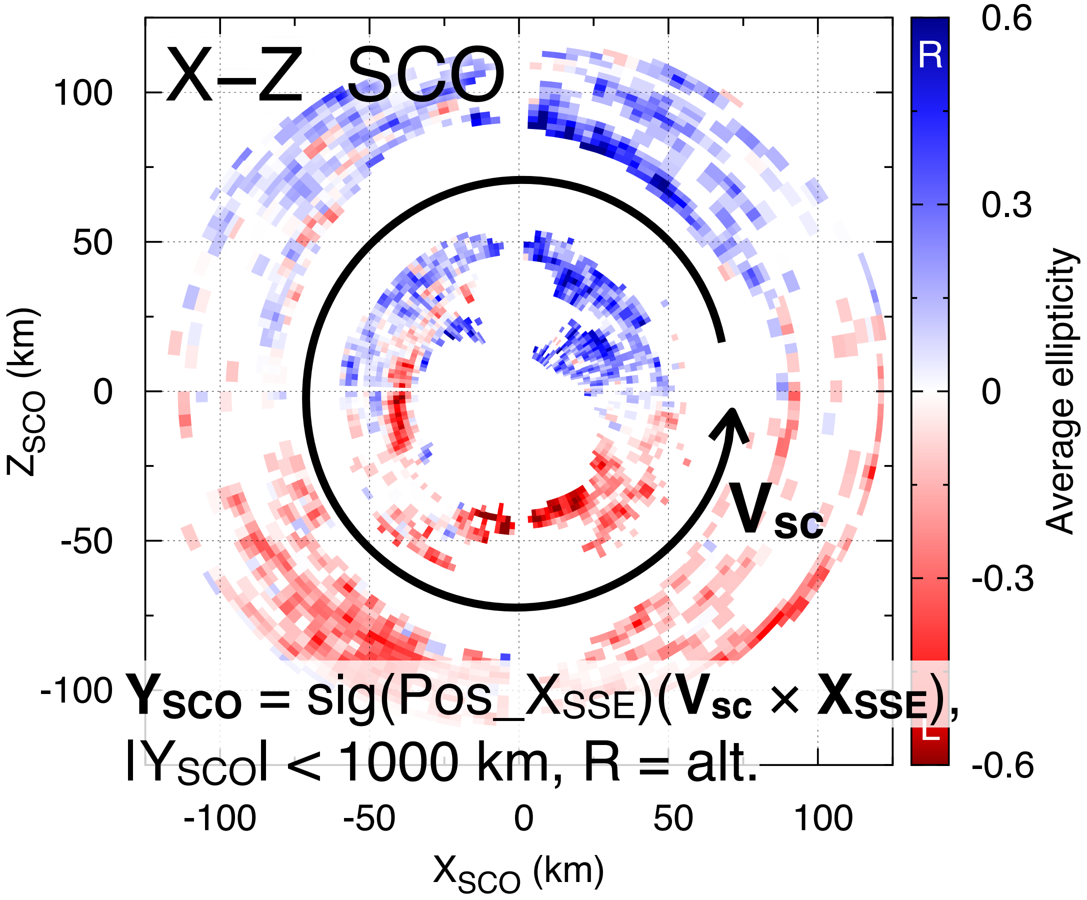
- ~100 km altitudes
- in SW
- higher Mach number, $M_A \sim 16$

- polarized components <~0.1 Hz in disturbed field
- from terminator to inner wake
- LH inbound to wake
- RH outbound from wake

Statistical properties, SELENE

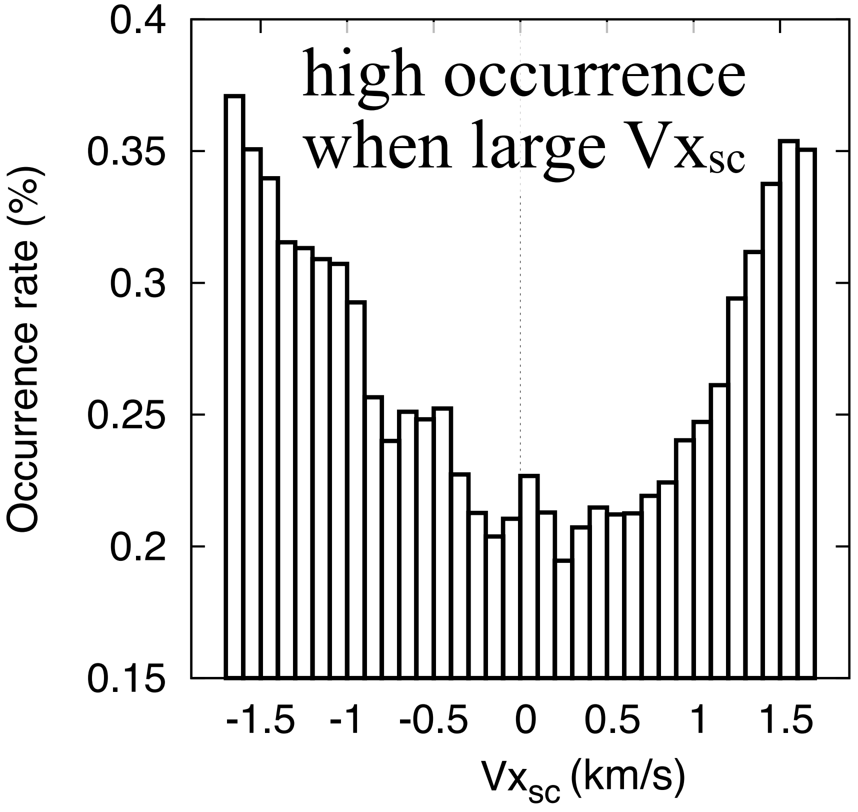


$\mathbf{Y_{LSM}} = \mathrm{sig}(\mathbf{B} \cdot \mathbf{X_{SSE}})(\mathbf{B} \times \mathbf{X_{SSE}})$, $|Z_{LSM}| < 1000$ km, R = alt.

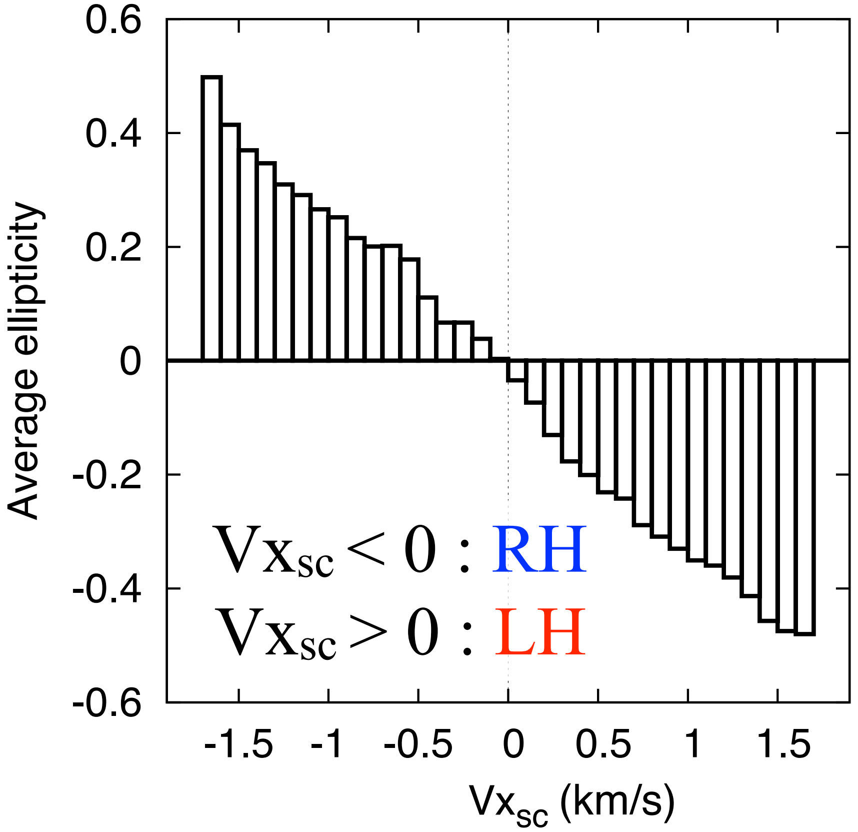


$\mathbf{Y_{SCO}} = \mathrm{sig}(\mathrm{Pos\_X_{SSE}})(\mathbf{V_{sc}} \times \mathbf{X_{SSE}})$, $|Y_{SCO}| < 1000$ km, R = alt.

- RH when s/c goes downstream
- LH when s/c goes upstream



high occurrence when large Vx_{sc}



$Vx_{sc} < 0$: RH

$Vx_{sc} > 0$: LH

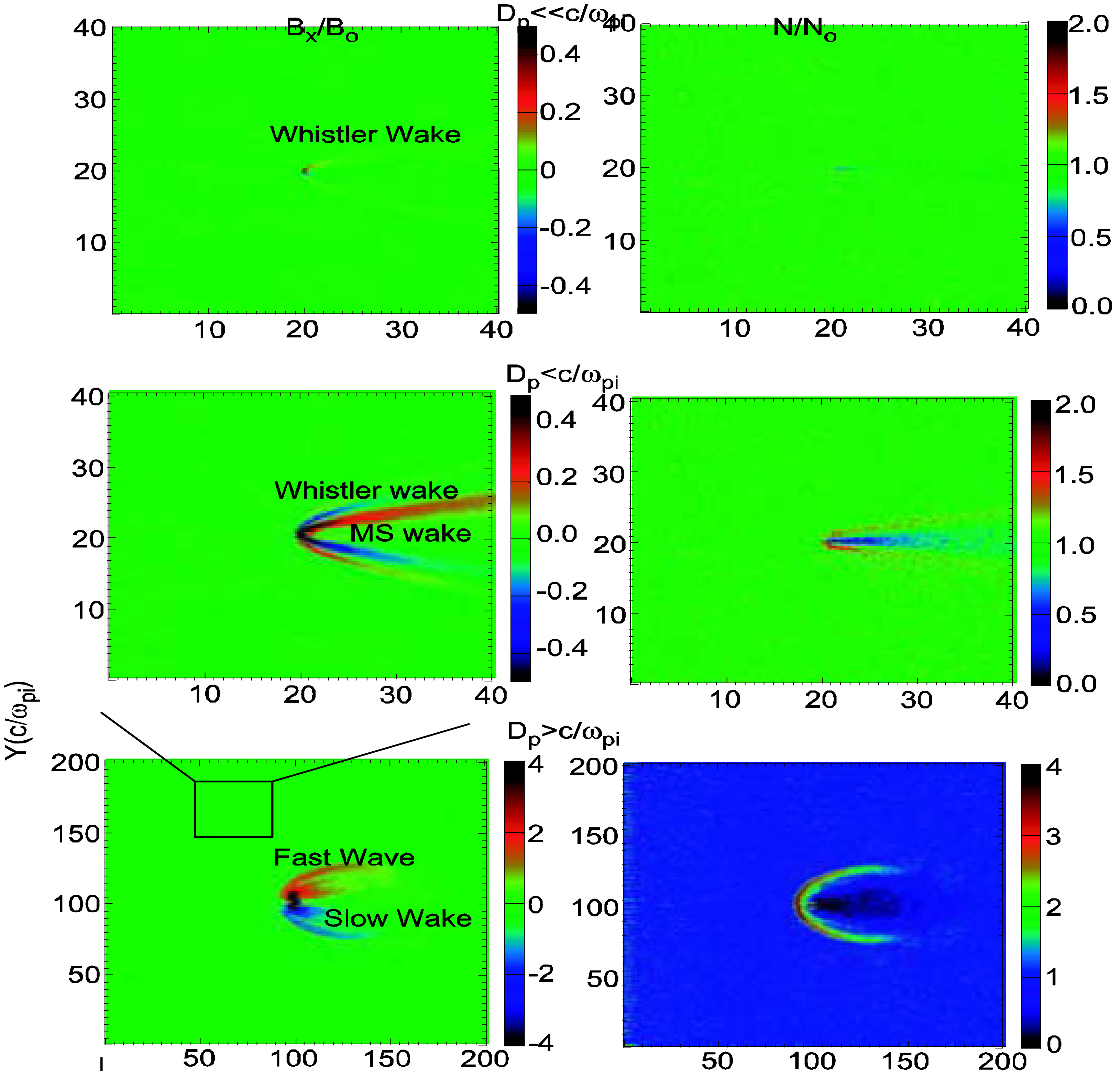
upward k vector & intrinsically RH in plasma rest frame,

Doppler-shifted by s/c velocity

⇓

phase-standing whistlers

Shock/wake waves around obstacles



2-D grobal hybrid simulation [*Russell et al.*, 2005]

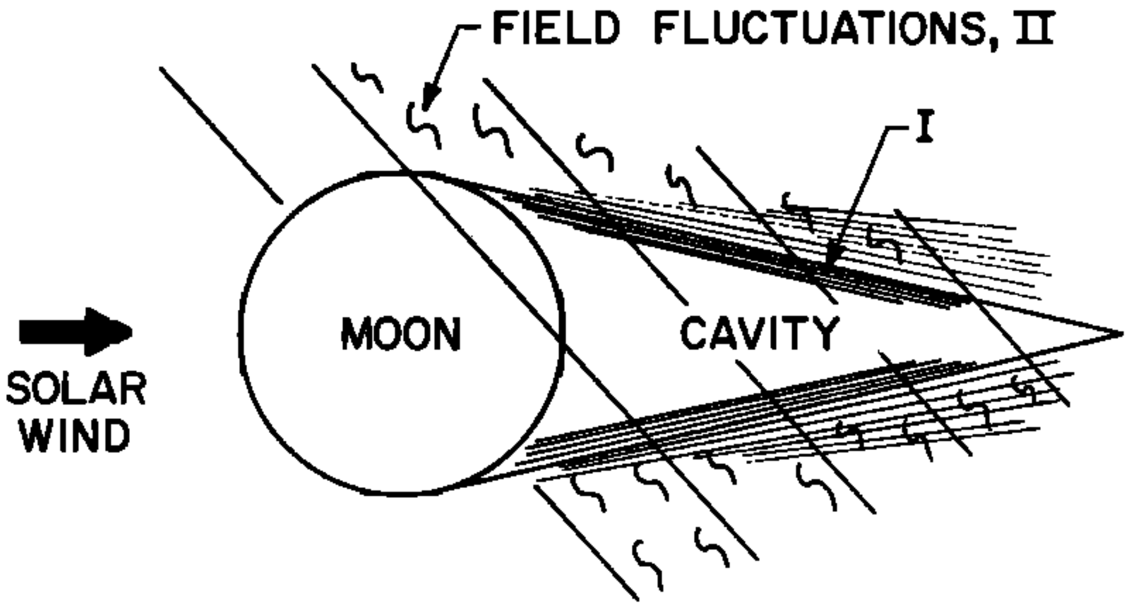
Table 1. Summary of features seen in hybrid simulations as a function of scale size of the obstacle.

D_p	Upstream Plasma Changes	Waves	Magnetospheric features
$<<c/\omega_{pi}$	None	Whistler	None
$<c/\omega_{pi}$	Some flow deflection, n increases, and v decreases at $r>D_p$	Whistler wake, fast and slow magnetosonic waves at wake edges	Precursor of a plasma tail
$>c/\omega_{pi}$	Pileup at $r\sim D_p$ Flow deflection, n, T, B increase, v decreases Reflected ions	Fast mode bow wave upstream Slow mode wake	Particle acceleration at dipole (Particle trapping at belts) Tail with hot plasma Reconnection precursor

c/ω_{pi} in SW ~ 100 km
D_p at lunar magnetic anomalies ~ 10 km

phase-standing whistler wake perturbation around the Moon has been also suggested [e.g., *Halekas et al.*, 2006]

Ballistic effect



- field fluctuations can be carried upstream from the wake edge by reflected thermal electrons along B_0
- no relevance to wave propagation & local instabilities
- $\omega/k \sim V_{\mathrm{drift}} \ll V_e \rightarrow \delta B_\perp > \delta B_\parallel$

$$\bar{\mathbf{E}}_1(k,\omega,z) = \underbrace{\left(\frac{dD}{dK_0}\right)^{-1} e^{iK_0 z} \int d\mathbf{v}\, \frac{\mathbf{G}(v) f_1(0)}{\omega - K_0 v_z}}_{\text{plasma waves}} + \underbrace{\int d\mathbf{v}\, \frac{\mathbf{G}(v) f_1(v, z = 0, k, \omega)}{D\left(k, \frac{\omega}{v_z}, \omega\right)} e^{i\omega z/v_z}}_{\text{ballistic effects}}$$

$$\frac{\delta B_\perp}{\delta B_\parallel} \cong \frac{k V_e}{\omega} \left(\frac{j_{1y}}{j_{1z}}\right)_{z=0}$$

[*Krall and Tidman*, 1969]

Summary

1. We revealed that **polarizations** of low freq (<~0.01 Hz) magnetic fluctuations observed around the Moon and upstream of the lunar wake are determined by the spacecraft velocity: $V_{sc,x}<0$ → RH, $V_{sc,x}>0$ → LH.

2. This fact indicates that their phase velocity in the Moon frame is smaller than the spacecraft velocity and they are R-mode in plasma frame, i.e., they are **phase-standing whistlers**.

3. They are possibly **whistler wake** perturbations generated around the magnetic anomalies and/or **ballistic fluctuations** carried by electrons.