Multiband chorus in the Earth's magnetosphere

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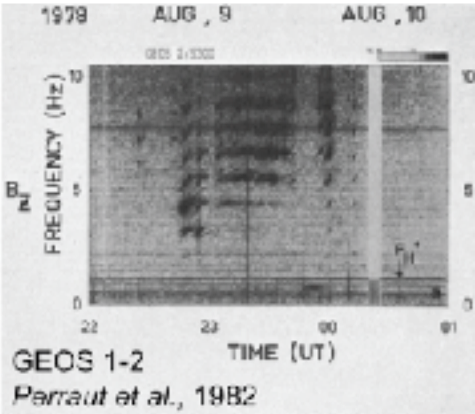
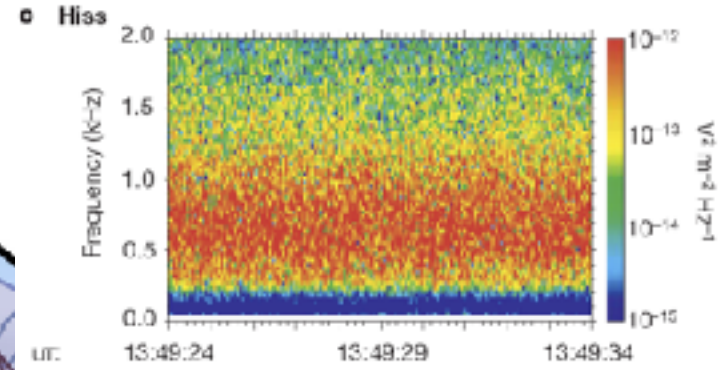
Outline

- Plasma waves in magnetosphere
- Chorus waves
- Multiband chorus:
  Case study, Simulations, and Statistical analysis
- Summary

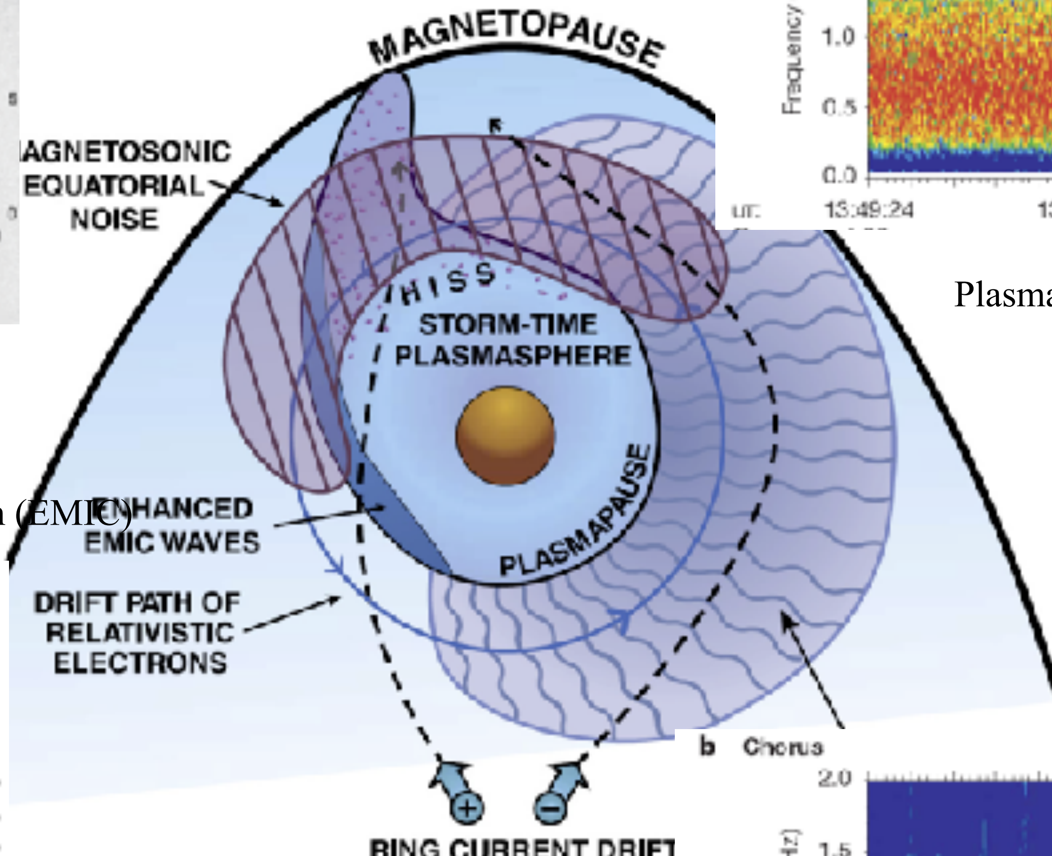
Plasma waves in magnetosphere

Magnetosonic waves

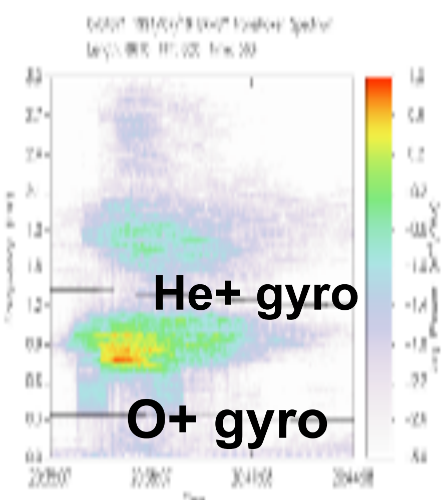




Plasmaspheric Hiss

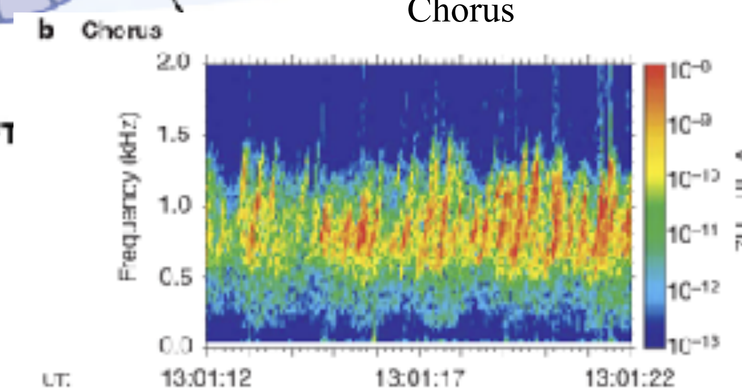


Electromagnetic Ion Cyclotron (EMIC) waves



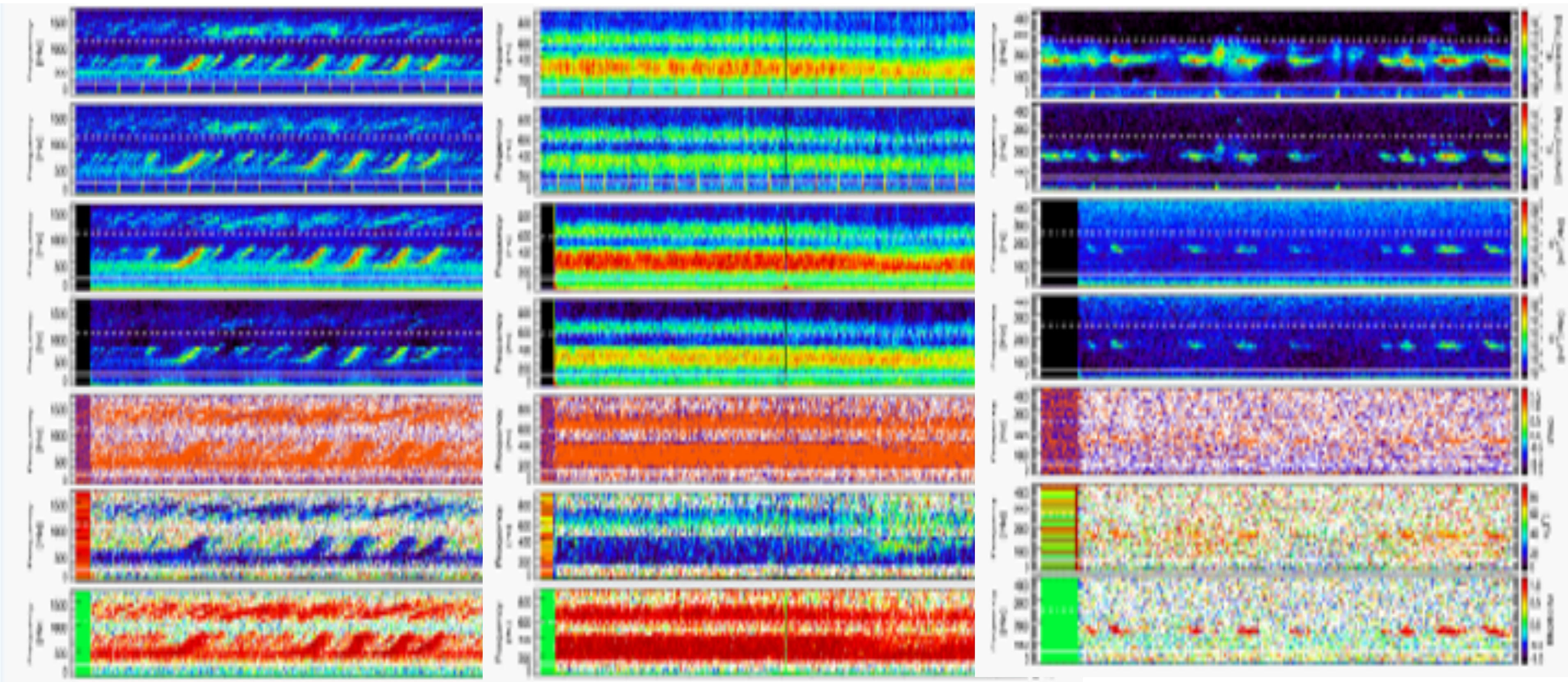
Thorne, GRL, 2010

Chorus



Two remarkable properties

Rising tone | Hiss-like emission | falling tone



- Frequency chirping
- Power gap at about $0.5f_{ce}$

Frequency chirping

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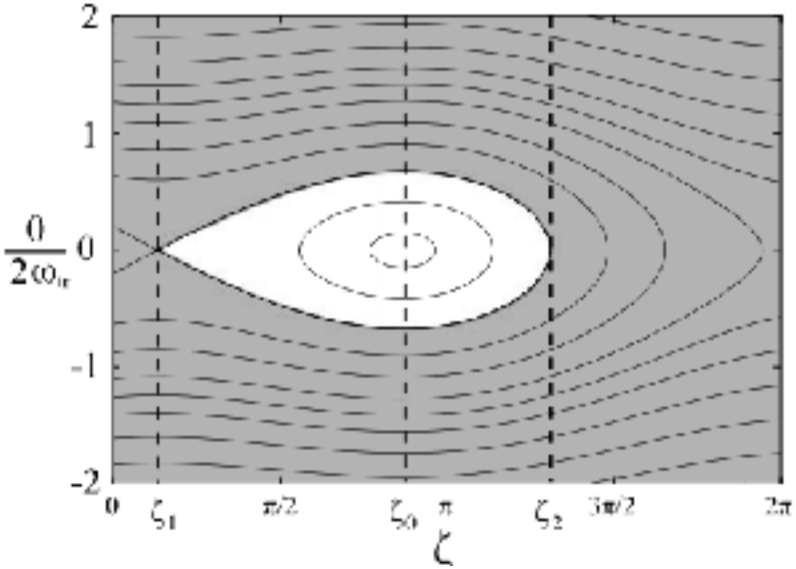
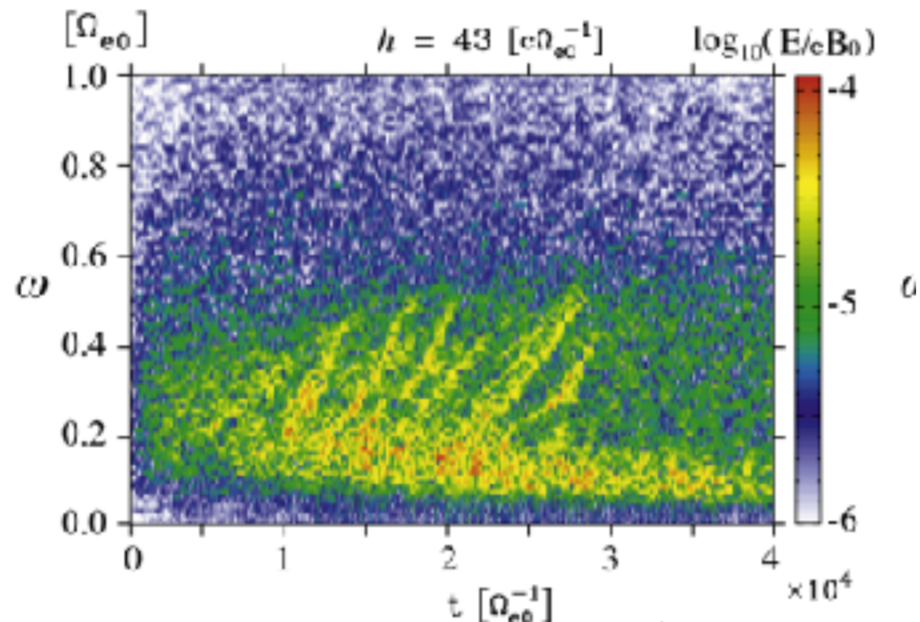
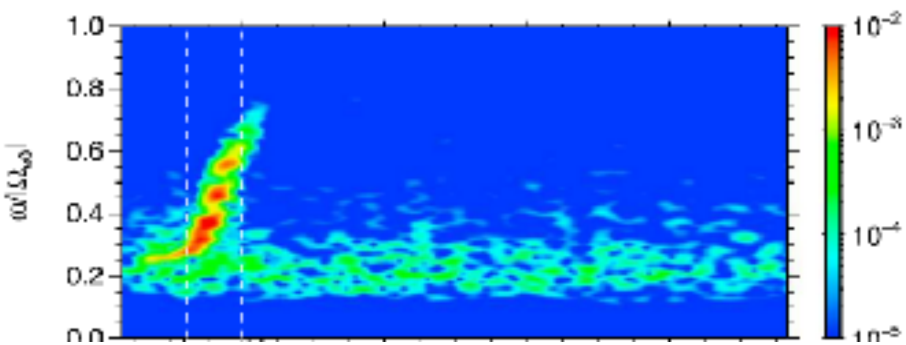
Nonlinear trapping

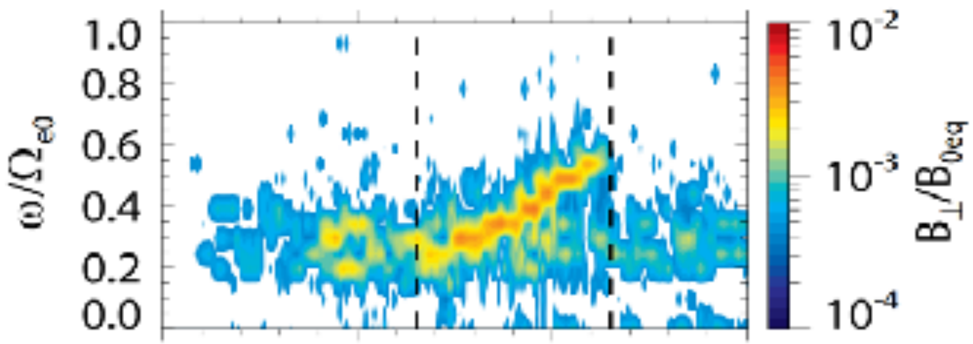




[Omura et al., 2008]



[Tao, 2014]



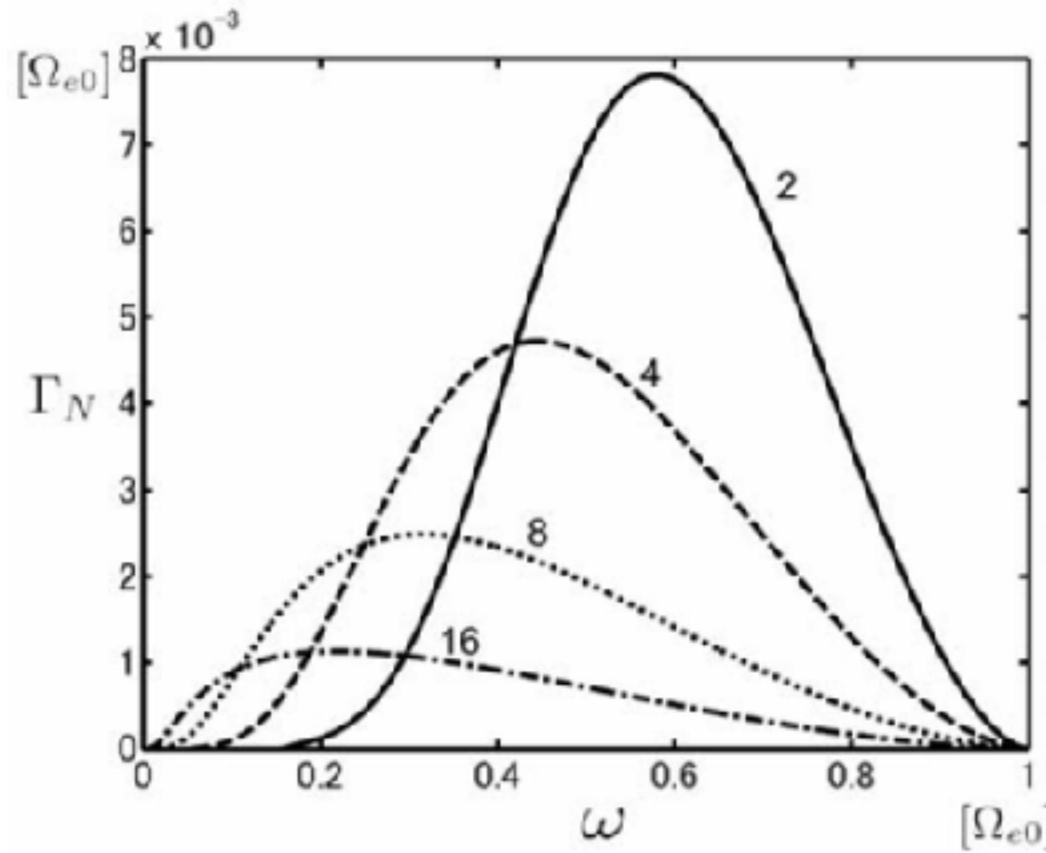
[Ke et al., 2017]

Generation of upper-band chorus

Nonlinear growth rate (taking into account of the inhomogeneous of background magnetic field):

$$\Gamma_N = \frac{Q\omega_{ph}^2}{2}\left(\frac{\xi}{\Omega_w \omega}\right)^{1/2}\frac{V_g}{U_{t\parallel}}\left(\frac{V_{\perp 0}\delta}{c\pi\gamma}\right)^{3/2}\exp\left(-\frac{\gamma^2 V_R^2}{2U_{t\parallel}^2}\right)$$

Upper band wave is just the extension of lower band.

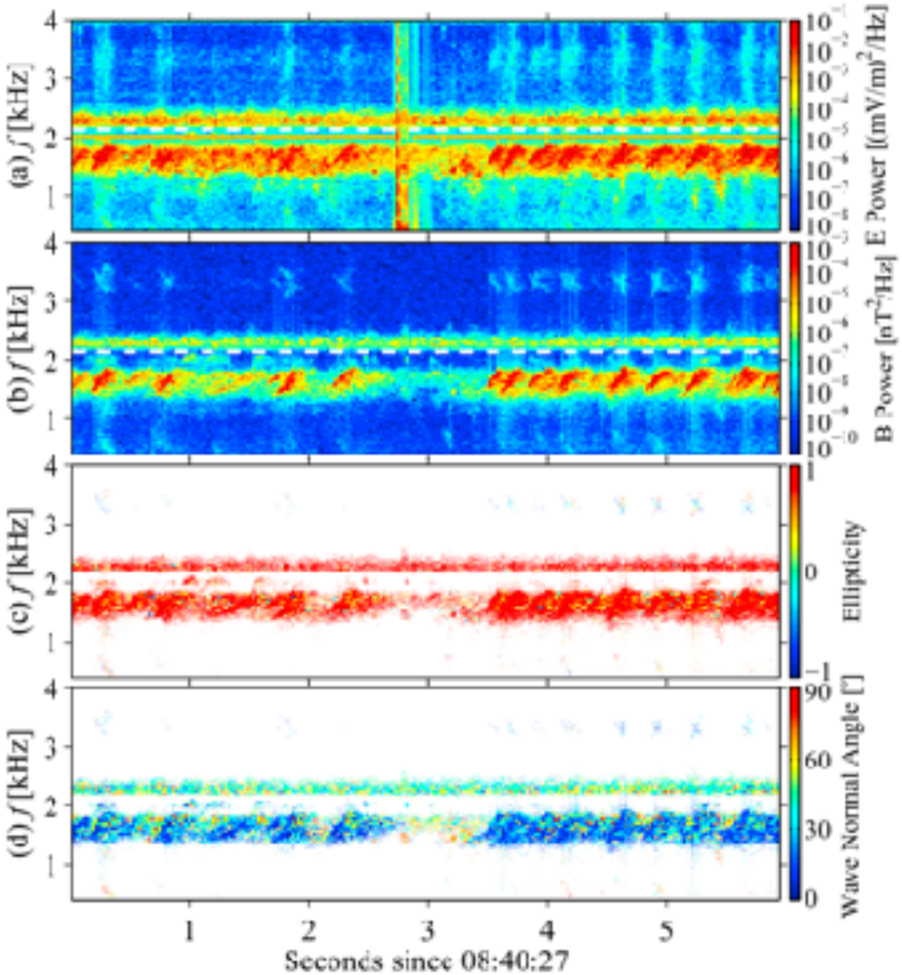


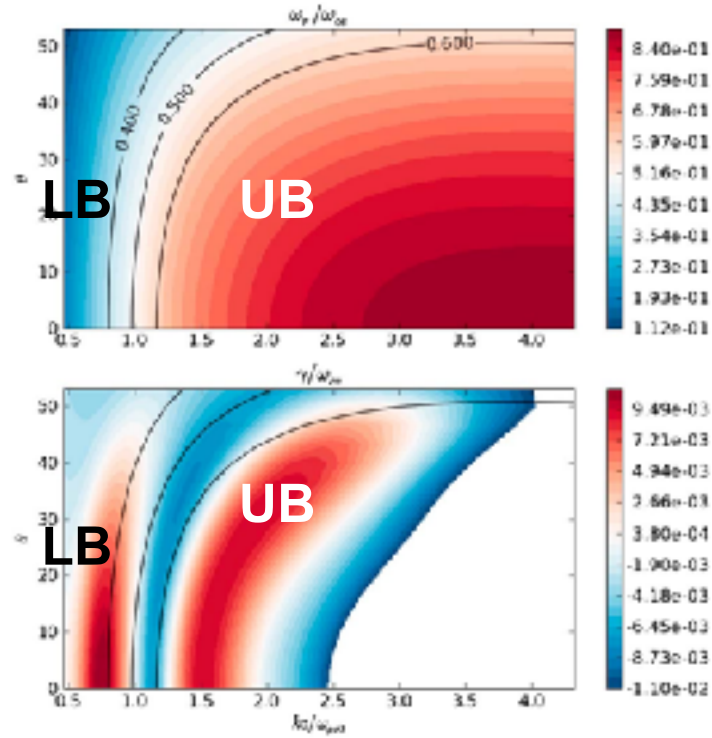
$\omega_{pe}/\Omega_{e0} = 2,\ 4,\ 8, 16$

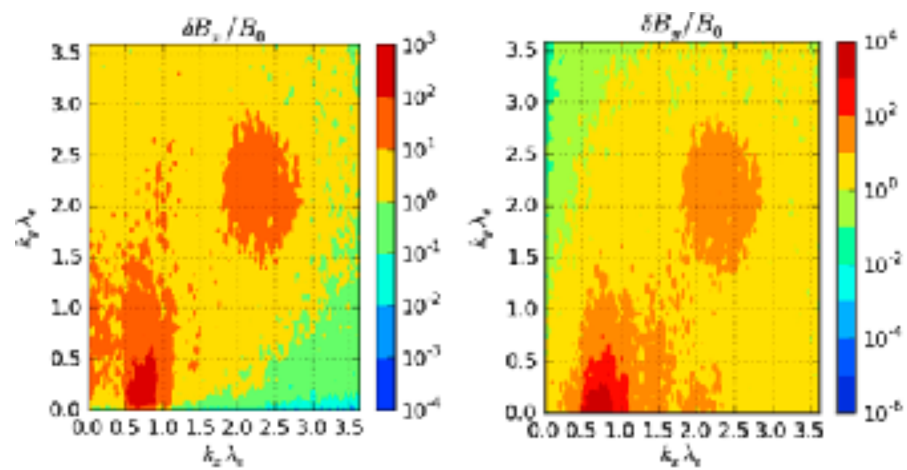
[Omura et al., 2009]

Generation of upper-band chorus

RBSP-A







[Fu et al., 2014]

Generation of upper-band chorus

Power gap

↓

Discrete power distribution in frequency

↙ ↘

EMIC waves
MS waves

Chorus waves

Multiband chorus: THEMIS observation

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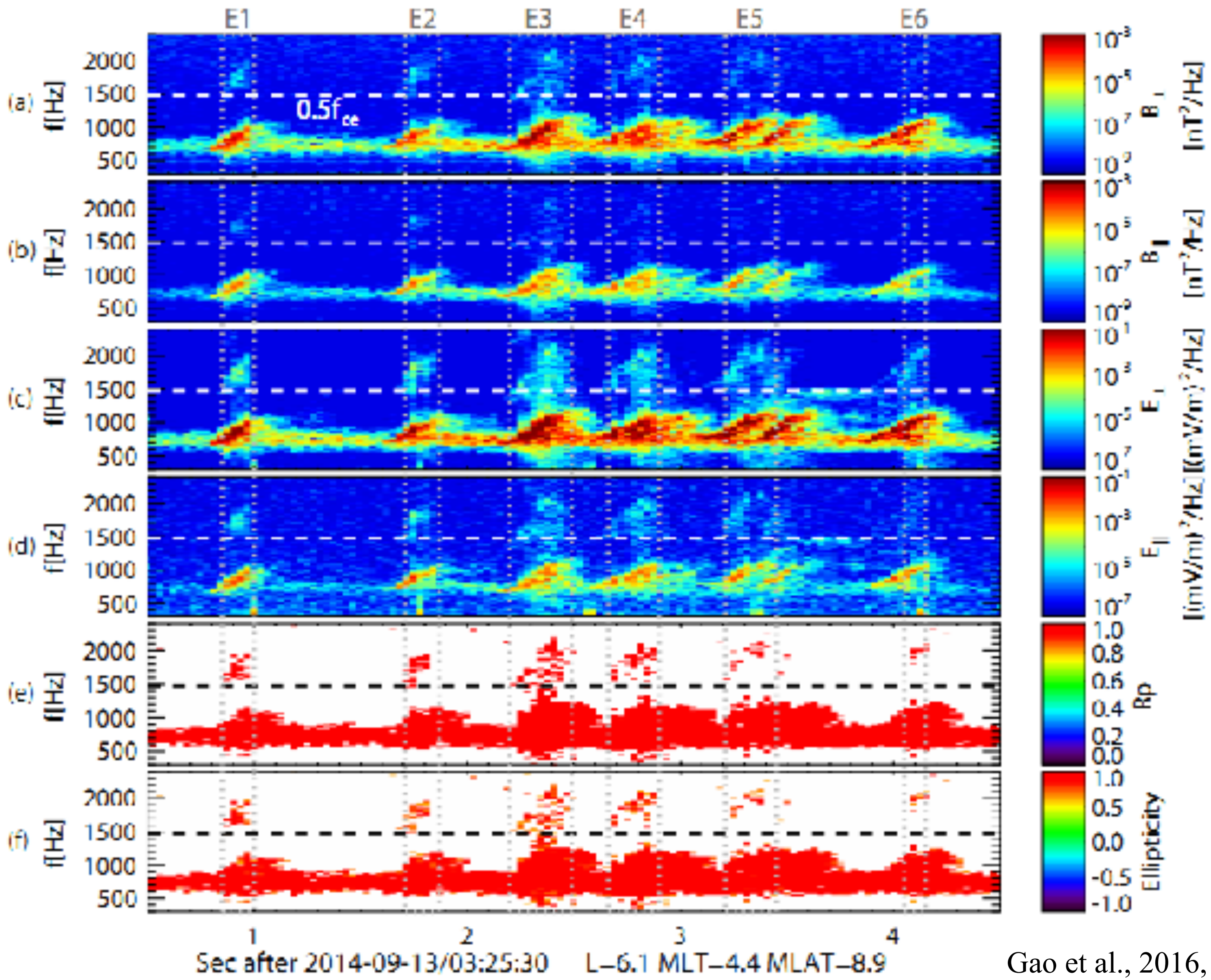
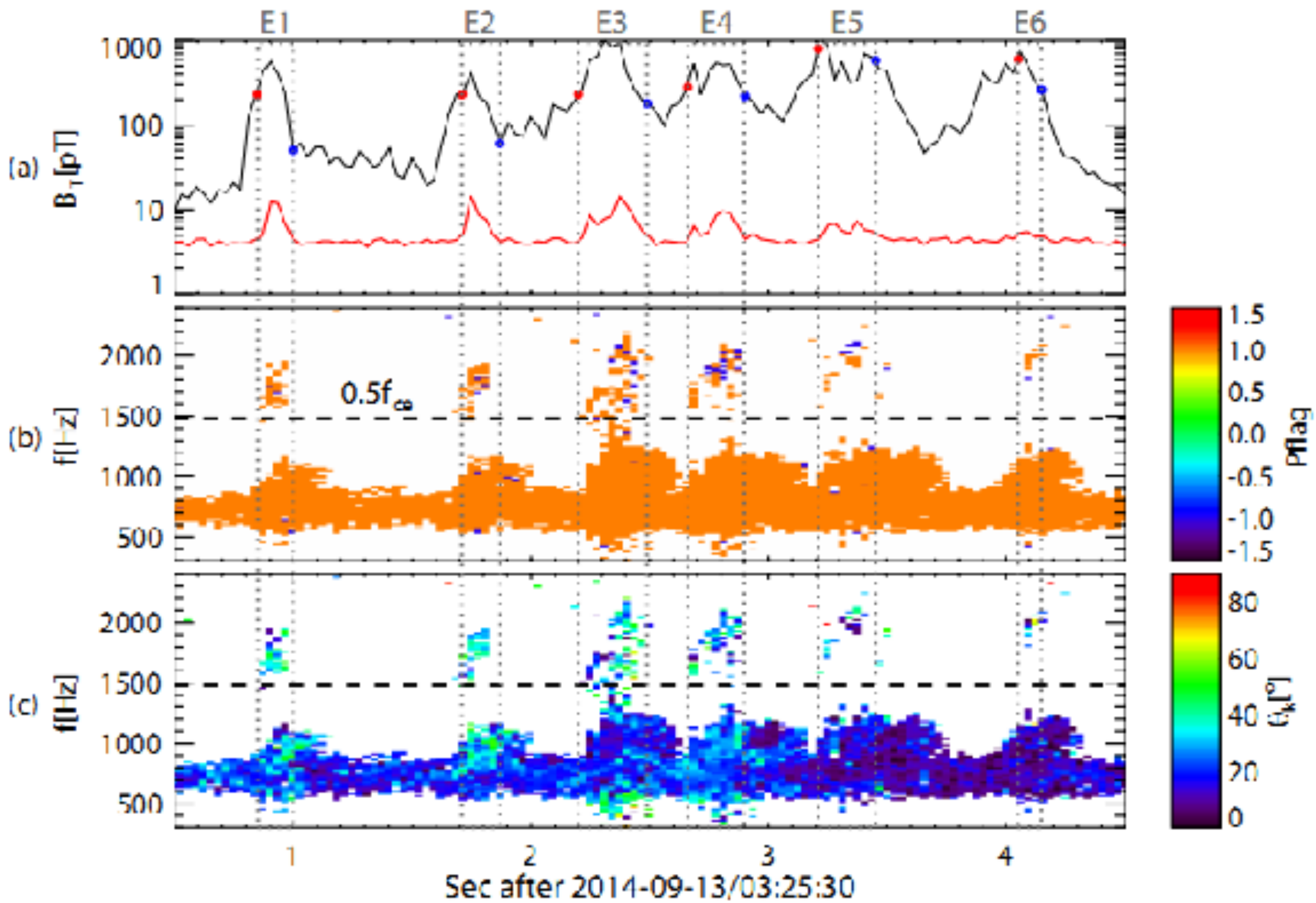


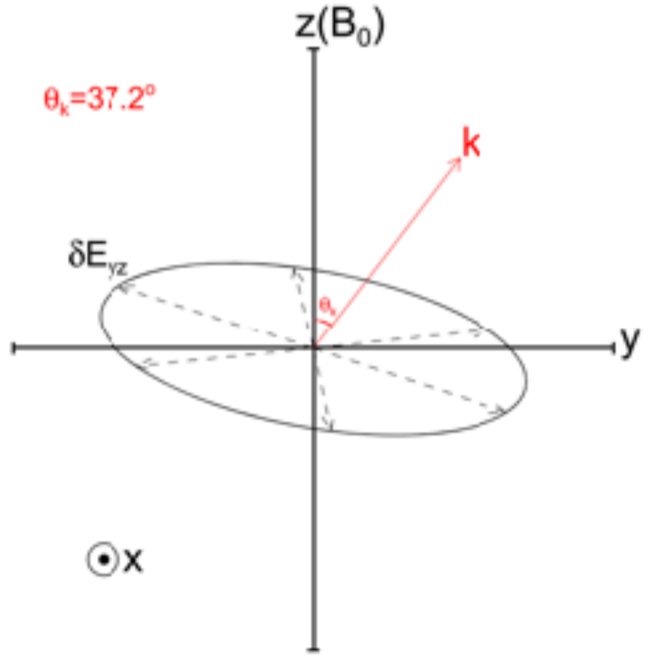
Gao et al., 2016, GRL

Lower band cascade



Gao et al., 2016, GRL

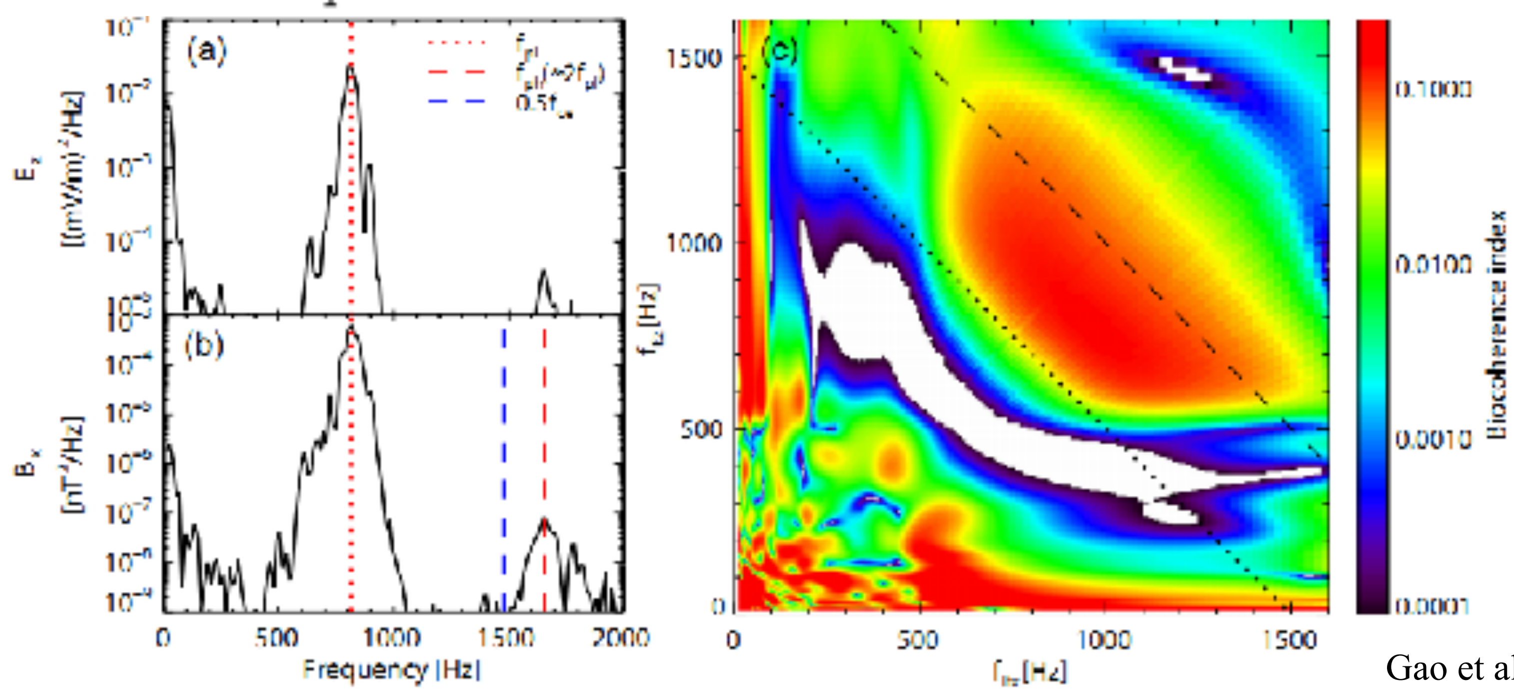
Lower band cascade



Bicoherence index: measure the amount of phase coupling that occurs among three wave modes.

$$\left|\left\langle E_z(f_1)B_x(f_2)B_x^*(f_3)\right\rangle\right|^2 / \left\langle \left|E_z(f_1)B_x(f_2)\right|^2\right\rangle \left\langle \left|B_x^*(f_3)\right|^2\right\rangle$$

where $f_3 = f_1 + f_2$



Gao et al., 2016, GRL

Multiband chorus:1-D PIC Simulation

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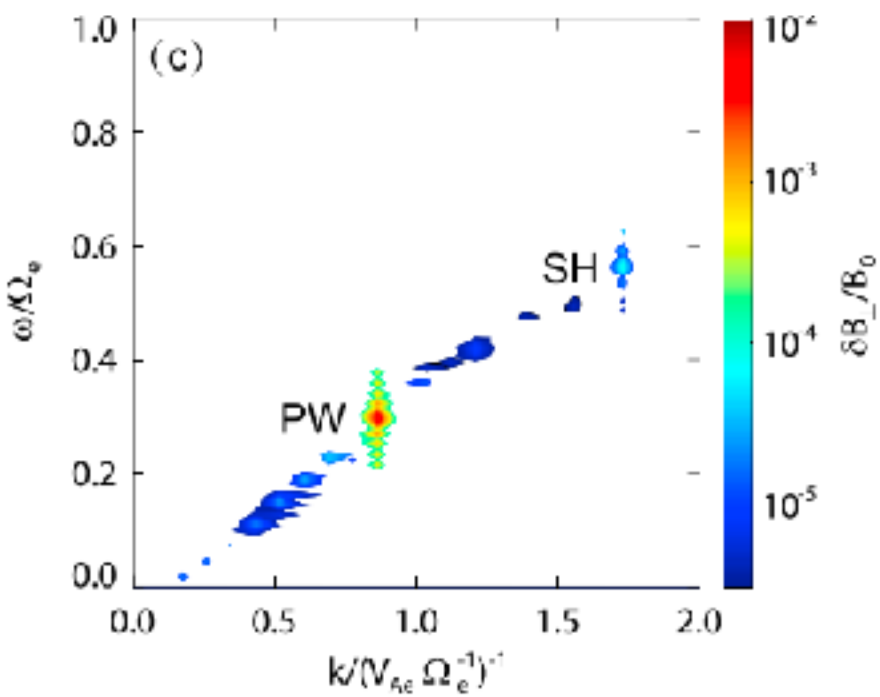
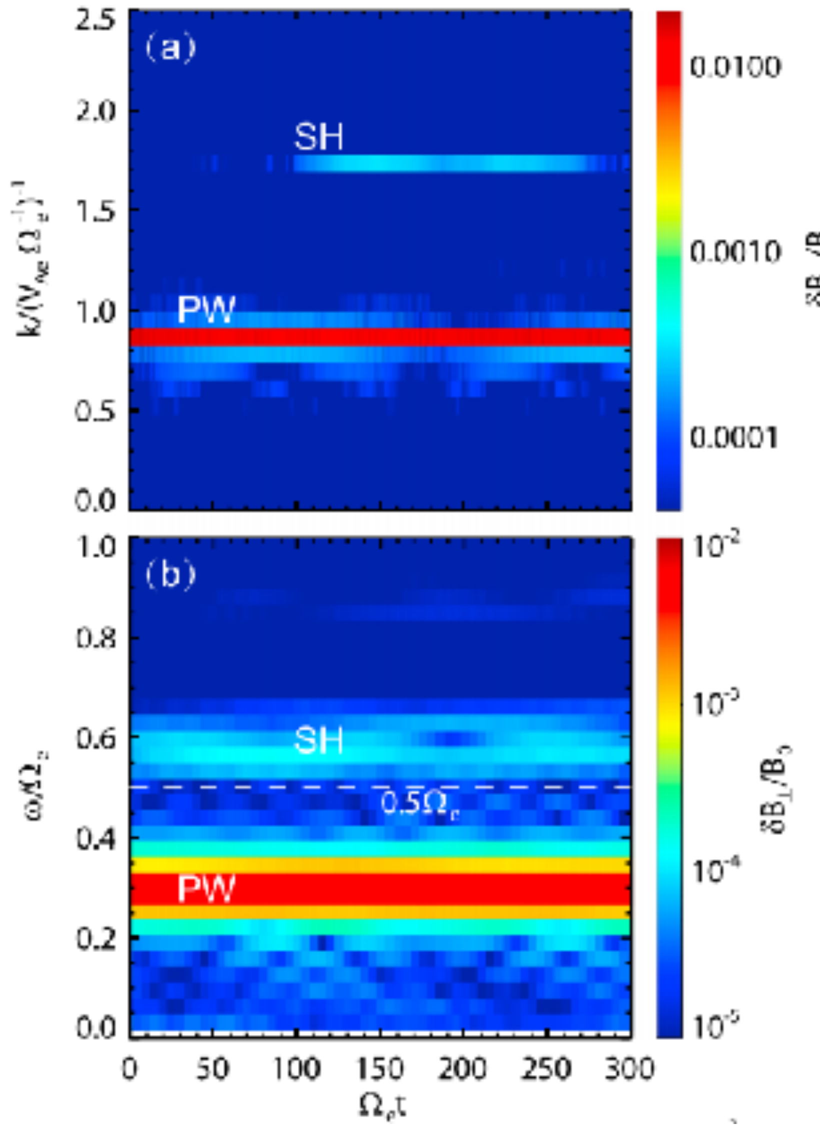
Table 1. Some Initial Parameters in the Simulation Model[a]

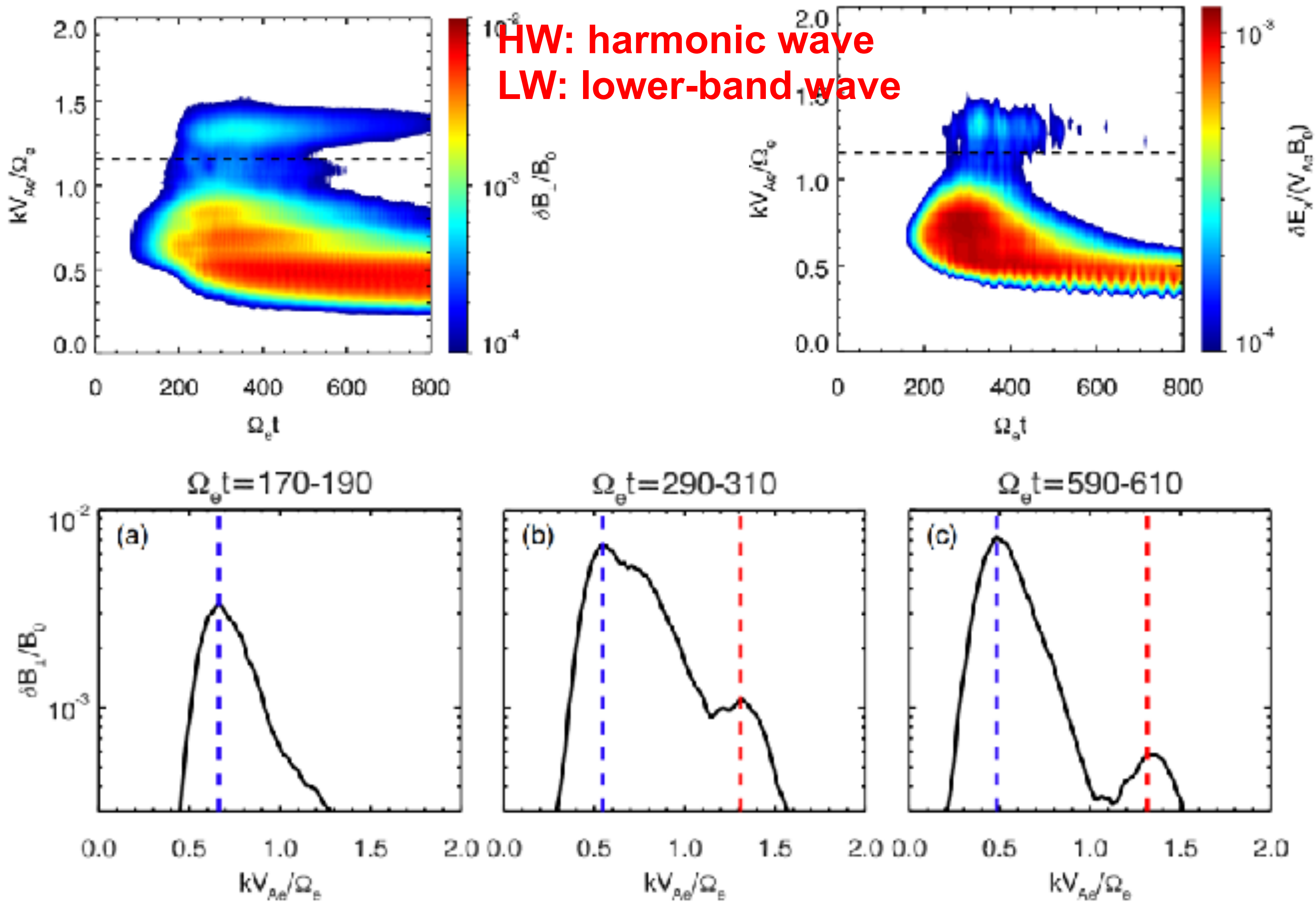
Parameter	Value	Parameter	Value
n_c/n_0	0.9	m_p/m_e	1836
v_{tc}/V_{Ae}	6×10^{-2}	ω_0/Ω_e	0.3
n_h/n_0	0.1	k_0V_{Ae}/Ω_e	0.86
v_{th}/V_{Ae}	0.4	θ	45°
v_{tp}/V_{Ae}	1.4×10^{-3}	$\delta B_{yz}/B_0$	0.02





Gao et al., 2017, GRL

1-D PIC: anisotropic hot electrons



Chen, Gao et al., 2017, JGR

Theoretical analysis: electron fluid

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$$\partial_t n_e + \nabla \cdot (n_e \mathbf{v_e}) = 0$$

$$m_e(\partial_t \mathbf{v_e} + \mathbf{v_e} \cdot \nabla \mathbf{v_e}) = -e(\mathbf{E} + \mathbf{v_e} \times \mathbf{B})$$

$$\nabla \cdot \mathbf{E} = -\frac{1}{\varepsilon_0}(n_e - n_0)e$$

$$\nabla \times \mathbf{B} = -\mu_0 n_e e \mathbf{v_e} + \frac{1}{c^2}\partial_t \mathbf{E}$$

$$\nabla \times \mathbf{E} = -\partial_t \mathbf{B}$$

Linearized but keep up to the second order

$$\begin{cases} n_e = n_0 + (\delta n' + \delta n'') \\ \mathbf{v_e} = (\delta v'_{\parallel} + \delta v''_{\parallel})\hat{\mathbf{x}} + (\delta v'_{\perp y} + \delta v''_{\perp y})\hat{\mathbf{y}} + (\delta v'_{\perp z} + \delta v''_{\perp z})\hat{\mathbf{z}} \\ \mathbf{E} = (\delta E'_{\parallel} + \delta E''_{\parallel})\hat{\mathbf{x}} + (\delta E'_{\perp y} + \delta E''_{\perp y})\hat{\mathbf{y}} + (\delta E'_{\perp z} + \delta E''_{\perp z})\hat{\mathbf{z}} \\ \mathbf{B} = B_0(\cos\theta\hat{\mathbf{x}} + \sin\theta\hat{\mathbf{y}}) + (\delta b'_{\perp y} + \delta b''_{\perp y})\hat{\mathbf{y}} + (\delta b'_{\perp z} + \delta b''_{\perp z})\hat{\mathbf{z}} \end{cases}$$

Dispersion relation of whistler with θ

$$\left(\frac{1}{c^2\Omega_e}\omega^2 k - \frac{\Omega_e}{V_{Ae}^2}k\right)\left[\left(\cos\theta k^2 - \frac{\cos\theta}{c^2}\omega^2\right)^2 - \left(\frac{1}{c^2\Omega_e}\omega^3 - \frac{1}{\Omega_e}\omega k^2 - \frac{\Omega_e}{V_{Ae}^2}\omega\right)^2\right]$$
$$-\left(\sin\theta k^2 - \frac{1}{c^2}\sin\theta\omega^2\right)\frac{1}{c^2}\sin\theta\omega k\left(\frac{1}{c^2\Omega_e}\omega^3 - \frac{1}{\Omega_e}\omega k^2 - \frac{\Omega_e}{V_{Ae}^2}\omega\right) = 0$$

Gao et al., 2018, AIP Adv

Theoretical analysis: electron fluid

$$
\begin{bmatrix}
i\dfrac{8}{c^2\Omega_e}\omega^2 k - i\dfrac{2\Omega_e}{V_{Ae}^2}k & 4\sin\theta k^2 - \dfrac{4}{c^2}\sin\theta\omega^2 & 0 \\
0 & 4\cos\theta k^2 - \dfrac{4\cos\theta}{c^2}\omega^2 & \begin{bmatrix} -i\dfrac{8}{c^2\Omega_e}\omega^3 + i\dfrac{8}{\Omega_e}\omega k^2 \\ +i\dfrac{2\Omega_e}{V_{Ae}^2}\omega \end{bmatrix} \\
\dfrac{4}{c^2}\sin\theta\omega k & \begin{bmatrix} i\dfrac{8}{c^2\Omega_e}\omega^3 - i\dfrac{8}{\Omega_e}\omega k^2 \\ -i\dfrac{2\Omega_e}{V_{Ae}^2}\omega \end{bmatrix} & 4\cos\theta k^2 - \dfrac{4\cos\theta}{c^2}\omega^2
\end{bmatrix}
\begin{bmatrix} \delta E''_{\parallel} \\ \delta b''_{\perp y} \\ \delta b''_{\perp z} \end{bmatrix} = NL
$$

$$
NL = \begin{bmatrix}
\begin{bmatrix} -2\dfrac{B_0}{V_{Ae}^2}k^2\left(\delta v'_{\parallel}\delta v'_{\parallel}\right) + i2\dfrac{\Omega_e}{V_{Ae}^2}k\left(\delta v'_{\perp y}\delta b'_{\perp z} - \delta v'_{\perp z}\delta b'_{\perp y}\right) \\ +i2\dfrac{B_0}{n_0}\dfrac{\Omega_e}{V_{Ae}^2}\sin\theta k\left(\delta n'\delta v'_{\perp z}\right) - 4\dfrac{B_0}{n_0}\dfrac{1}{V_{Ae}^2}\omega k\left(\delta n'\delta v'_{\parallel}\right) \end{bmatrix} \\
\begin{bmatrix} 2\dfrac{B_0}{V_{Ae}^2}k^2\left(\delta v'_{\parallel}\delta v'_{\perp y}\right) + i2\dfrac{\Omega_e}{V_{Ae}^2}k\left(\delta b'_{\perp z}\delta v'_{\parallel}\right) \\ +i2\dfrac{B_0}{n_0}\dfrac{\Omega_e}{V_{Ae}^2}\cos\theta k\left(\delta n'\delta v'_{\perp z}\right) + 4\dfrac{B_0}{n_0}\dfrac{1}{V_{Ae}^2}\omega k\left(\delta n'\delta v'_{\perp y}\right) \end{bmatrix} \\
\begin{bmatrix} 2\dfrac{B_0}{V_{Ae}^2}k^2\left(\delta v'_{\parallel}\delta v'_{\perp z}\right) - i2\dfrac{\Omega_e}{V_{Ae}^2}k\left(\delta b'_{\perp y}\delta v'_{\parallel}\right) + 4\dfrac{B_0}{n_0}\dfrac{1}{V_{Ae}^2}\omega k\left(\delta n'\delta v'_{\perp z}\right) \\ +2i\dfrac{B_0}{n_0}\dfrac{\Omega_e}{V_{Ae}^2}k\left(\delta n'\delta v'_{\parallel}\sin\theta - \delta n'\delta v'_{\perp y}\cos\theta\right) \end{bmatrix}
\end{bmatrix}
$$

Gao et al., 2018, AIP adv

Two types of MBC

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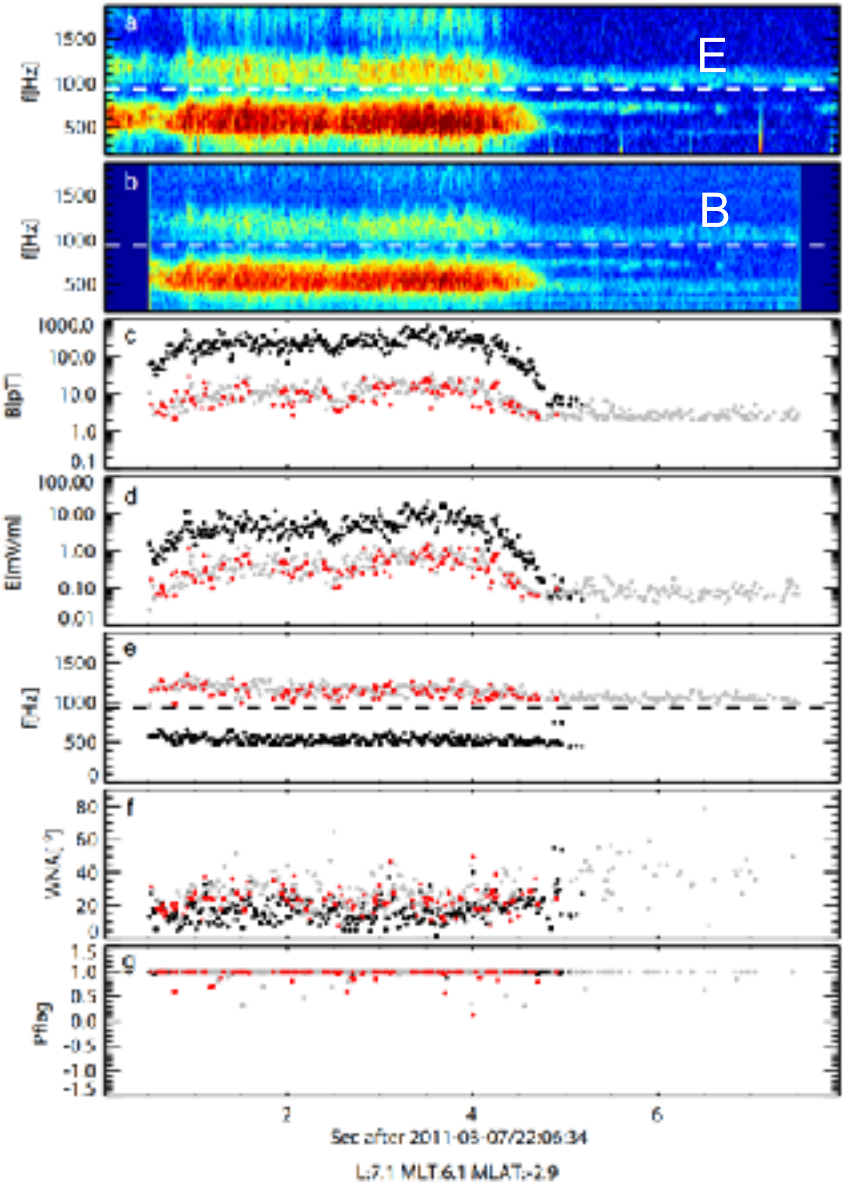
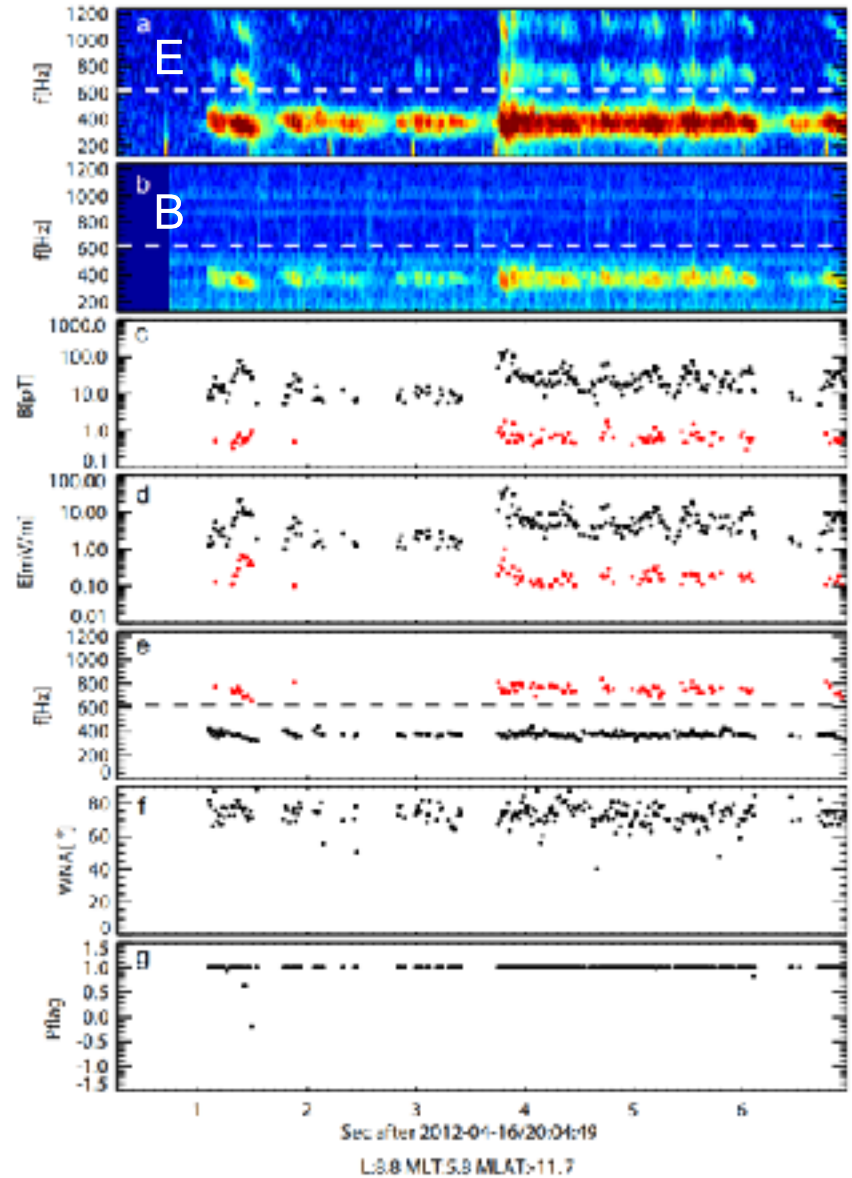
ElectroMagnetic MBC: EM-MBC

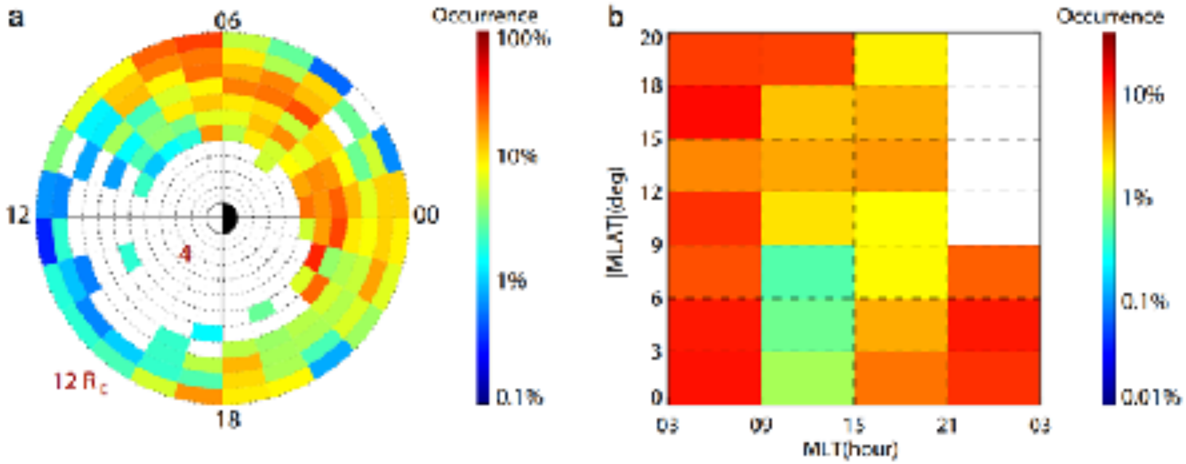


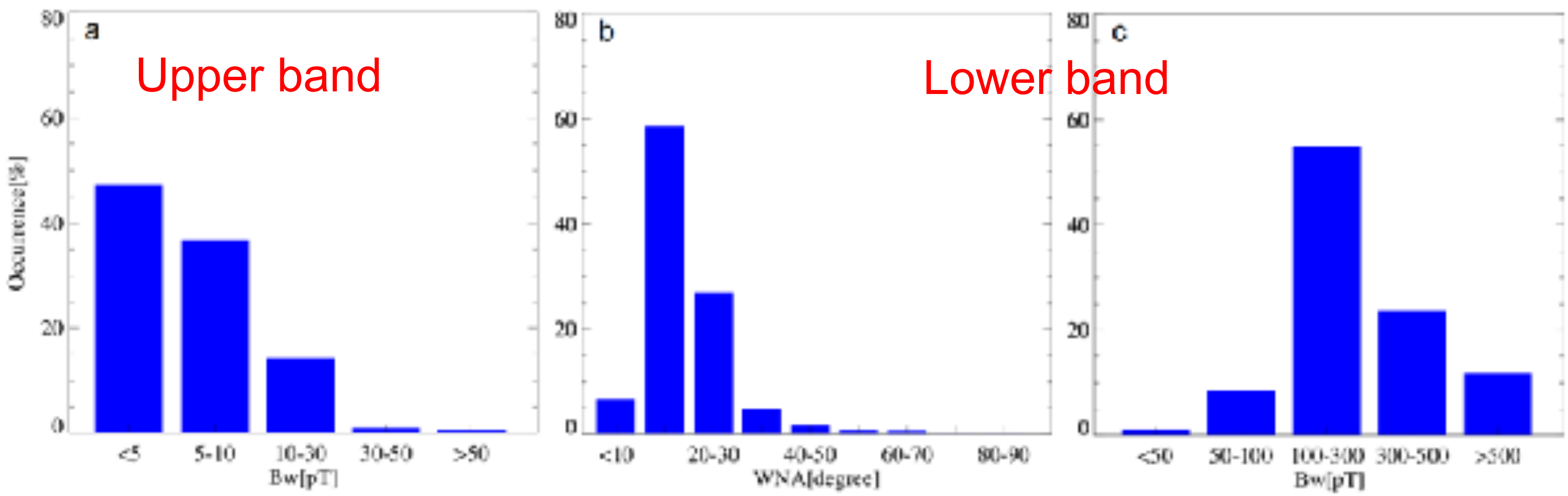
Quasi-Electrostatic MBC: QE-MBC



Gao et al., 2018, JGR

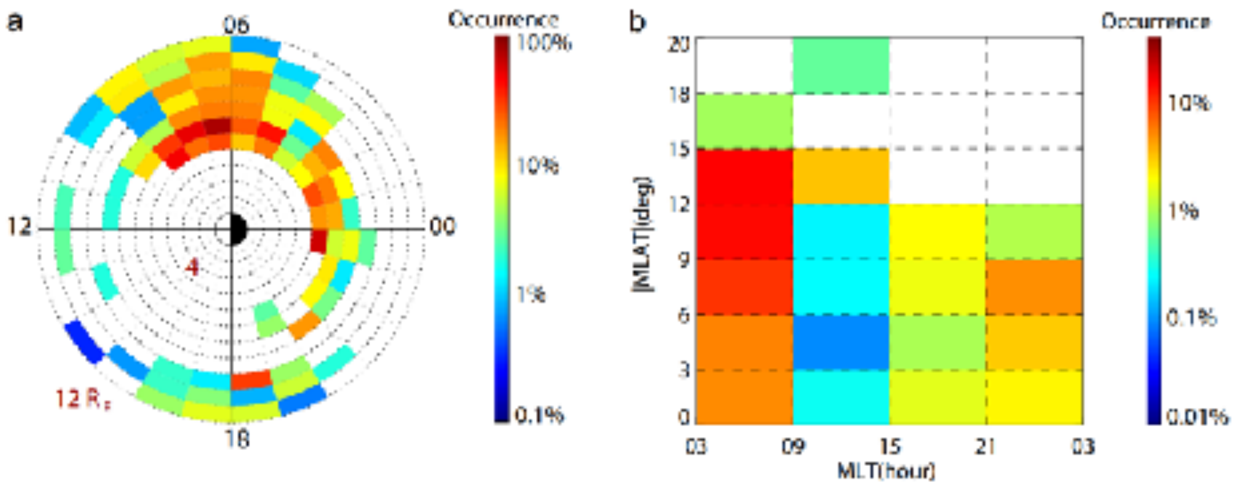
Statistical results of EM-MBC

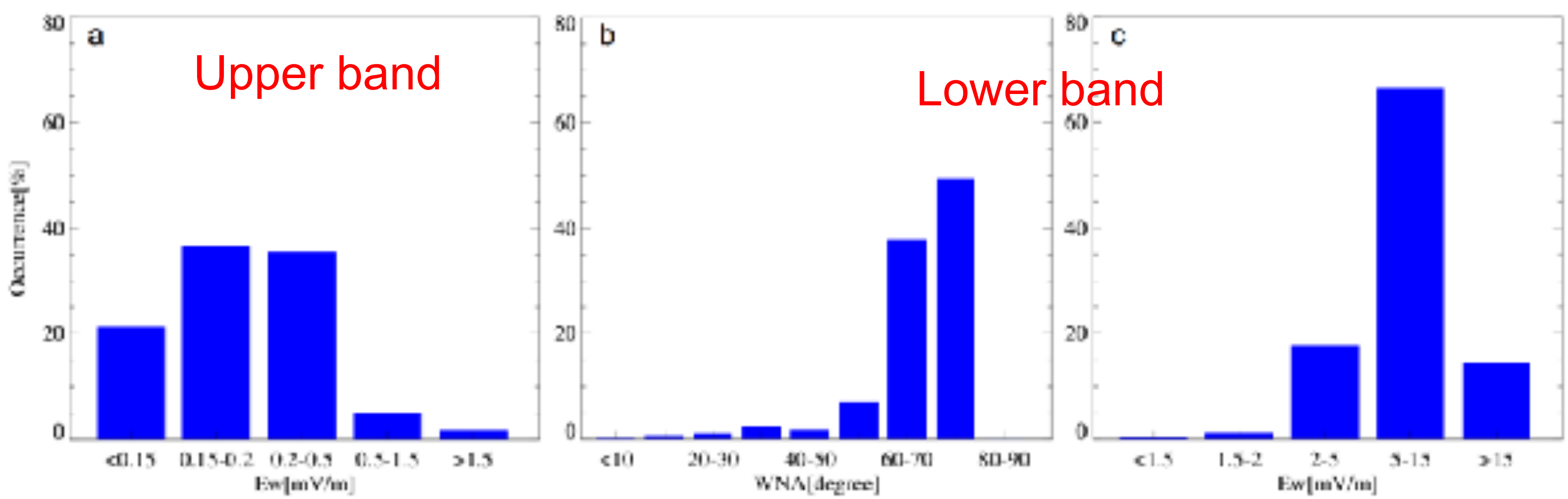




Gao et al., 2018, JGR

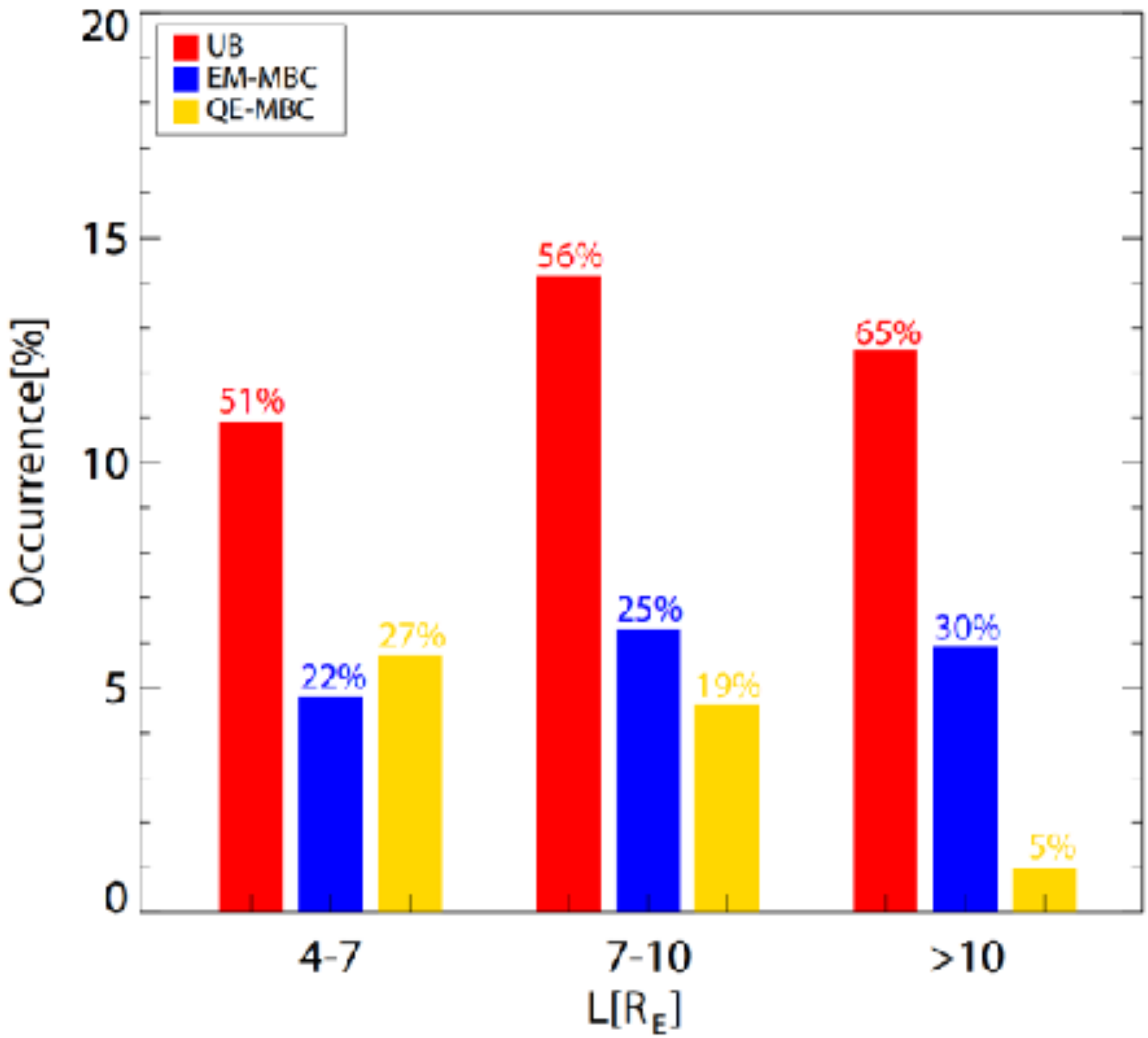
Statistical results of QE-MBC





Gao et al., 2018, JGR

Statistical results of MBC



Gao et al., 2018, JGR

- ➢Multiband chorus --- lower band cascade, reported by THEMIS and reproduced by PIC.
- ➢Multiband chorus (EM-MBC and QE-MBC) have occupied a very large population in upper-band chorus in the magnetosphere.
- ➢The significant role of the lower band cascade in generating upper-band chorus waves.

Thanks for your attention!