Low Frequency Waves in HF Heating of Mid-latitude Ionosphere

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HF Heating in the Ionosphere:
Excitation of waves in D/E region

Heating in the D/E region (~80 km)
  -Expts at Tromso, Sura

ELF/ULF generated by variations in the auroral electrojet current

Modified current flow due to local heating:
  Polar Electrojet (PEJ) antenna

Fast cooling due to inelastic processes (vibrational and rotational)

PEJ mechanism requires electrojet

HF Heating in the Ionosphere:
Excitation of waves in F region

Heating in the F region (~300 km)
 -Expts at HAARP

Magnetosonic (MS) waves excited by diamagnetic current due to heating

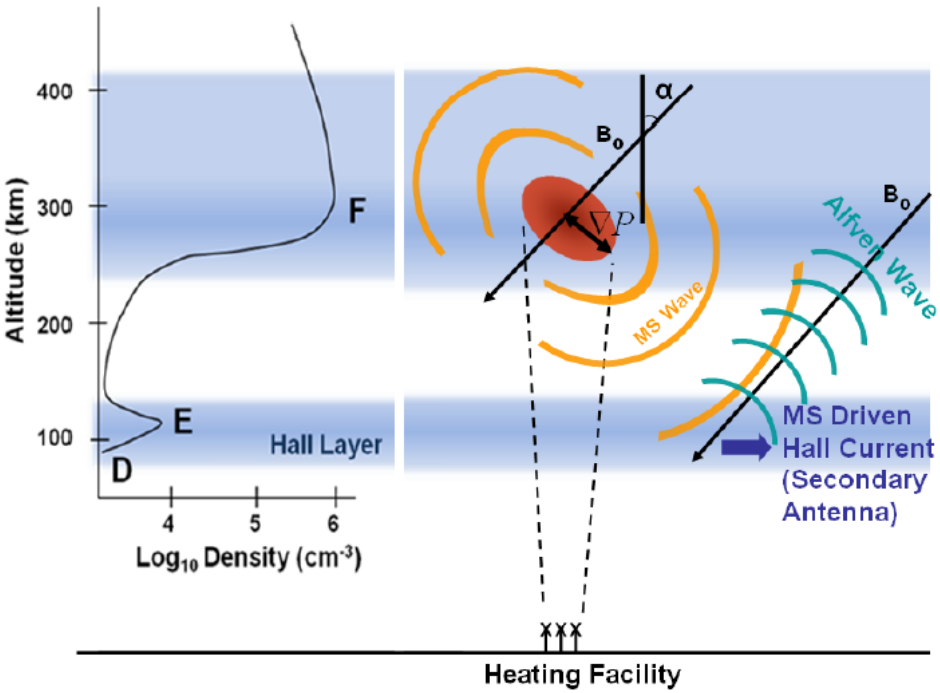
Shear Alfven (SA) waves generated by MS waves in the Hall layer

Propagation of Alfven waves to the ground and the magnetosphere

ELF waves generation without electrojet

ELF Waves in HF heating:
High-latitude Ionosphere

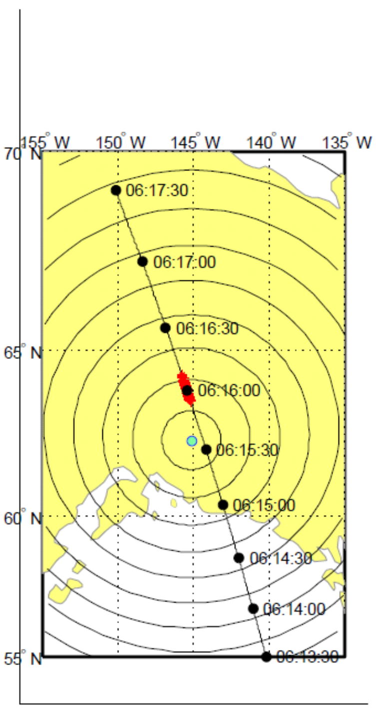
Physical mechanism

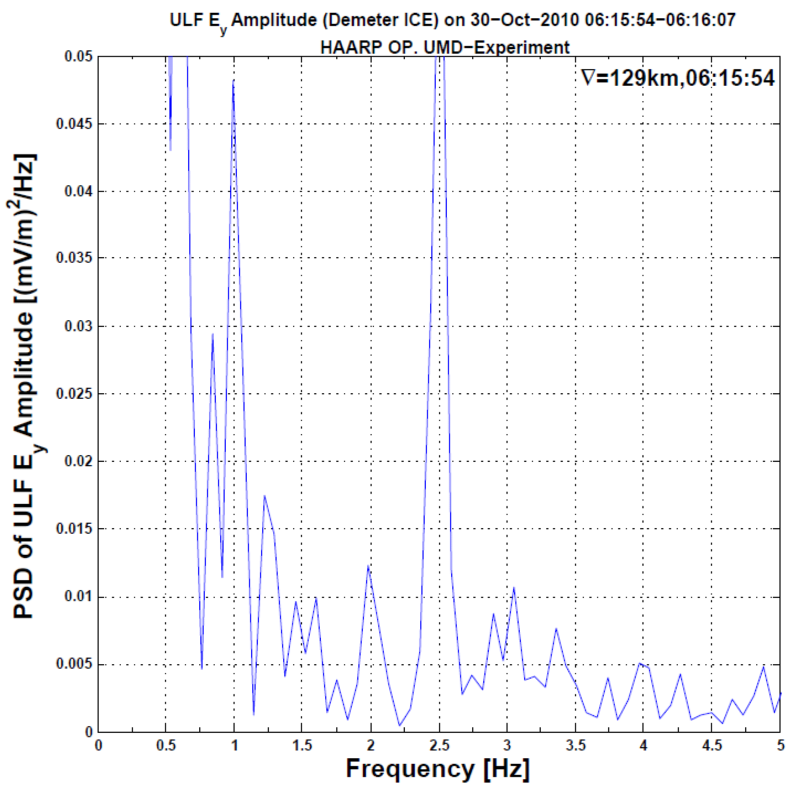


Papadopoulos et al., GRL 2011

ELF Waves in HF heating:
High-latitude Ionosphere

DEMETER Observations of Shear Alfvén waves (2.5 Hz): HAARP expt





Eliasson et al., JGR 2012

Simulation Model: Collisional Hall-MHD

Collisional Hall-MHD model

Faraday's and Ampère's laws

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E} \qquad \nabla \times \mathbf{B} = \mu_0 e n_0 (\mathbf{v}_i - \mathbf{v}_e)$$

Ion momentum equation

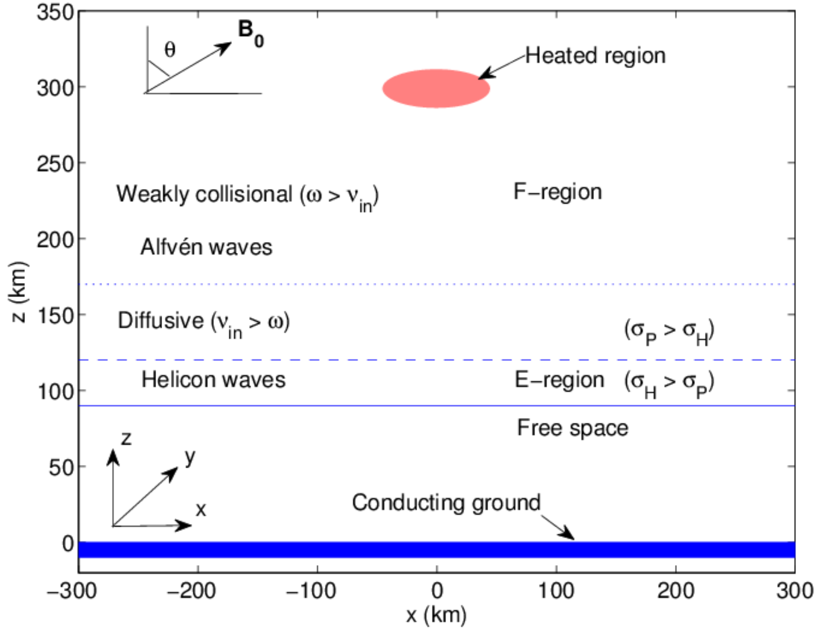
$$\frac{\partial \mathbf{v}_i}{\partial t} = \frac{e}{m_i}(\mathbf{E} + \mathbf{v}_i \times \mathbf{B}_0) - \nu_{in}\mathbf{v}_i$$

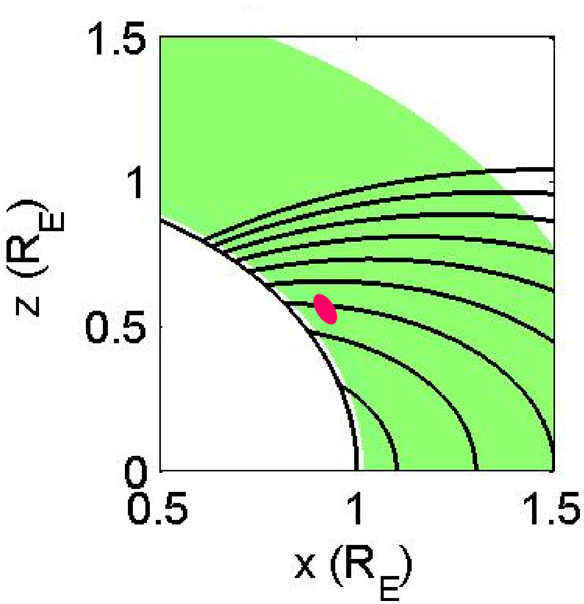
Momentum equation for inertial-less electrons

$$0 = -\frac{e}{m_e}(\mathbf{E} + \mathbf{v}_e \times \mathbf{B}_0) - \nu_{en}\mathbf{v}_e - \frac{\nabla P_e}{m_e n_0}$$

Electron pressure P_e modulated by RF wave

Ionospheric profile and geometry





Weakly collisional F region

Diffusive Pedersen layer 120-150 km (equal electron and ion drifts)

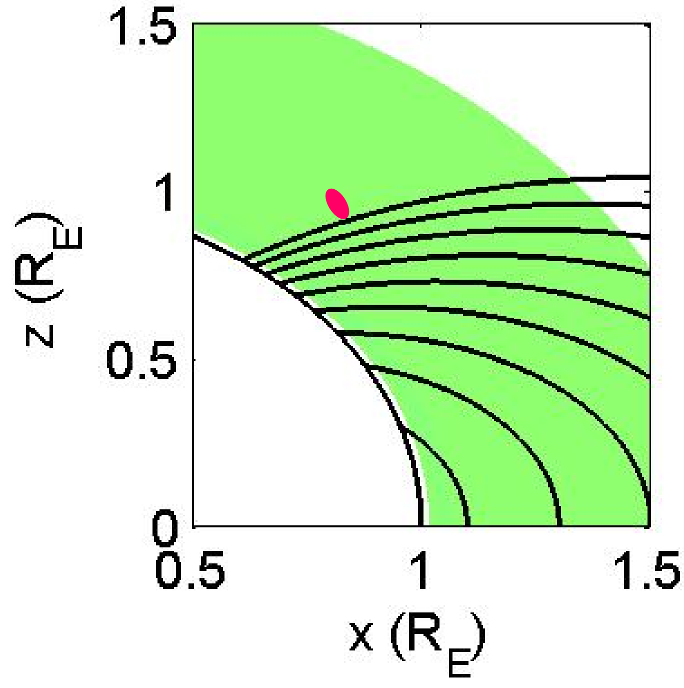
E-region below 120 km (Hall region), free space below 90 km

Conducting ground

Dipole magnetic field in polar coordinates

Heated Region: $T_e = T_{mod}\tanh^2\left(\frac{t}{D_t}\right)\cos(\omega\, t)\exp\left[-\frac{r_\theta^2}{D_{r\theta}^2} - \frac{(h-h_{max})^2}{D_h^2}\right]$,

Simulation Setup

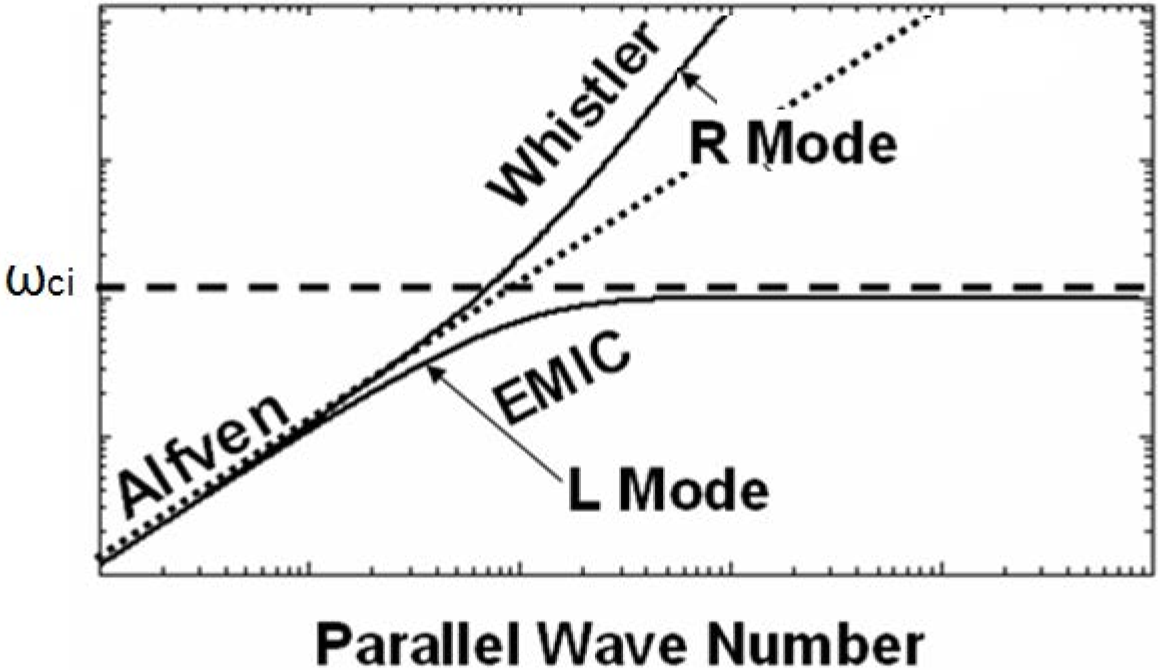


- Source location

  L =1.6, Altitude = 300 km
- Source dimension 40 x 80 km
- ELF/ULF waves: 2, 10 Hz
- Ionosphere conditions
  - Chapman density profile
  - Dipole magnetic field
- Free space below 90 km: Continuity of E_{par} and B_n
- Conducting ground:

  no E_{par} and B_n

Low Frequency Waves



- Dispersion relation
  $\omega << \omega_{ce}$, $\omega << ck_{||}$

$$\omega^2 \mp v_A^2 k_{||}^2 \frac{\omega}{\omega_{ci}} - v_A^2 k_{||}^2 = 0$$

L-Mode/EMIC (+) waves

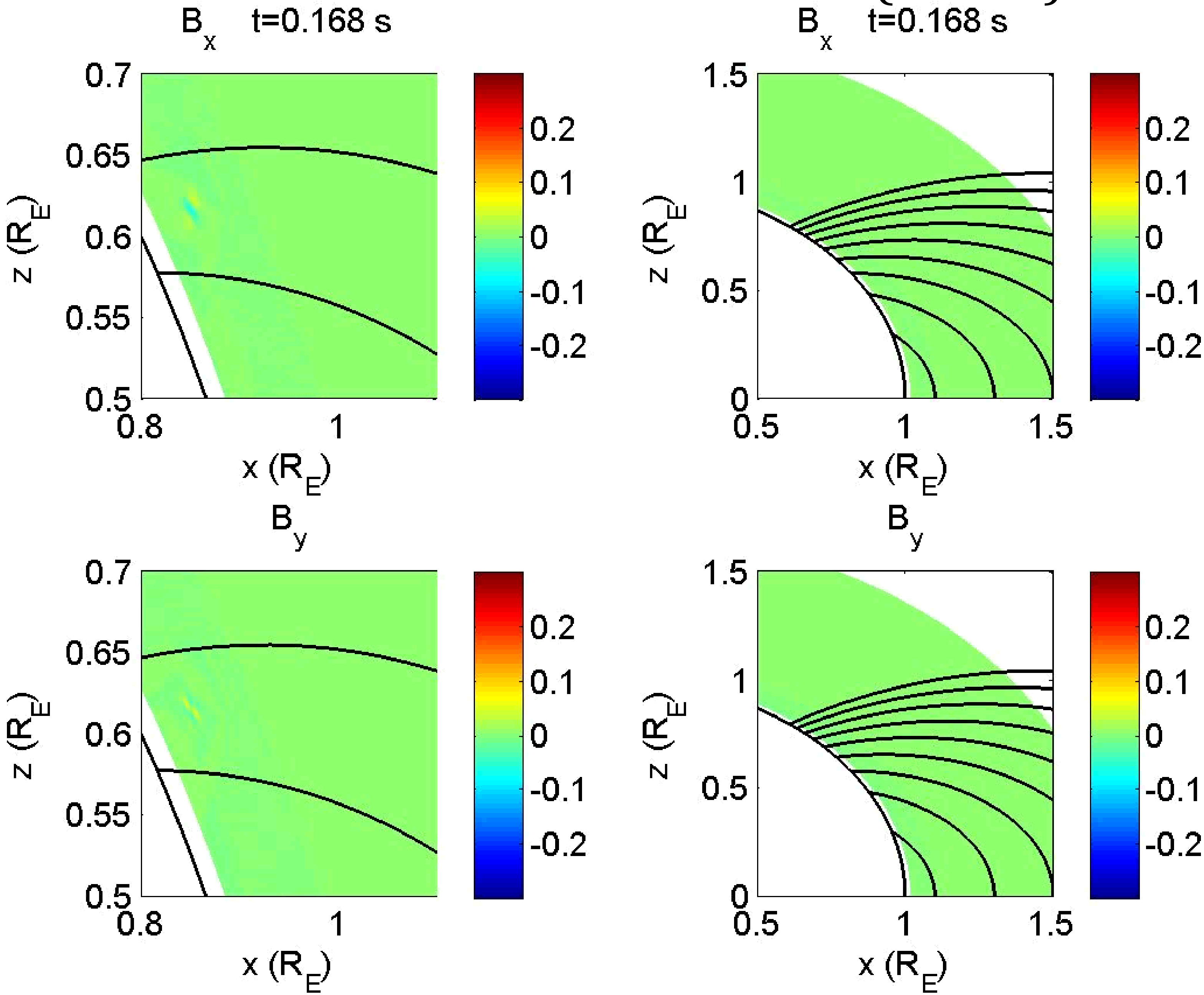
- Whistler/helicon mode

Obliquely propagating Alfvén waves:
EMIC + Whistlers/MS

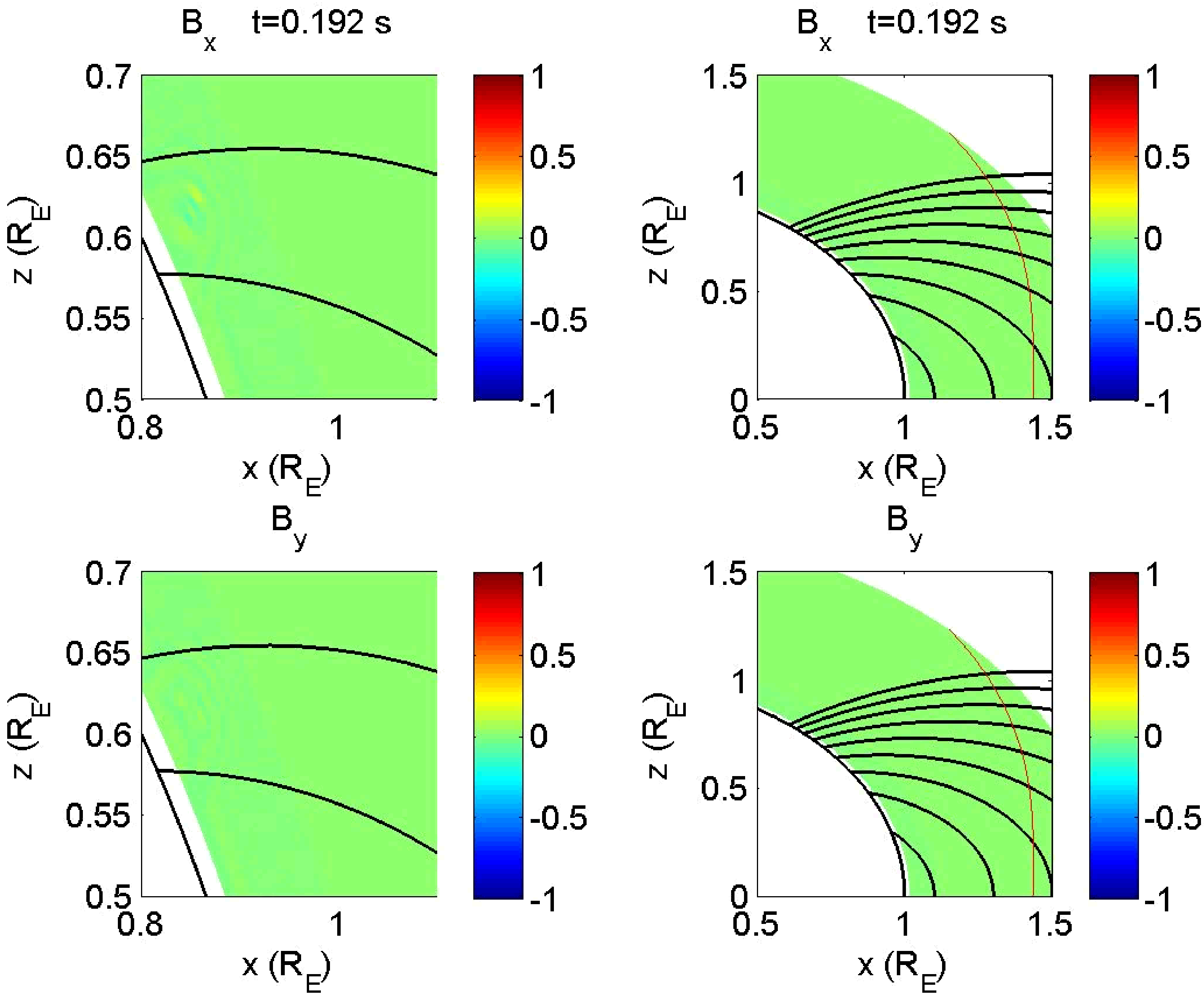
$$\left(\omega^2 - v_A^2 k^2\right)\left(\omega^2 - v_A^2 k_{||}^2\right) - \frac{\omega^2}{\omega_{ci}^2} v_A^4 k^2 k_{||}^2 = 0 \qquad k^2 = k_{||}^2 + k_{\perp}^2$$

Magnetosonic (MS) waves: $\omega^2 - v_A^2 k^2 = 0$, for $k_{||}^2 = 0$

Simulation Results: 2Hz (Movie)

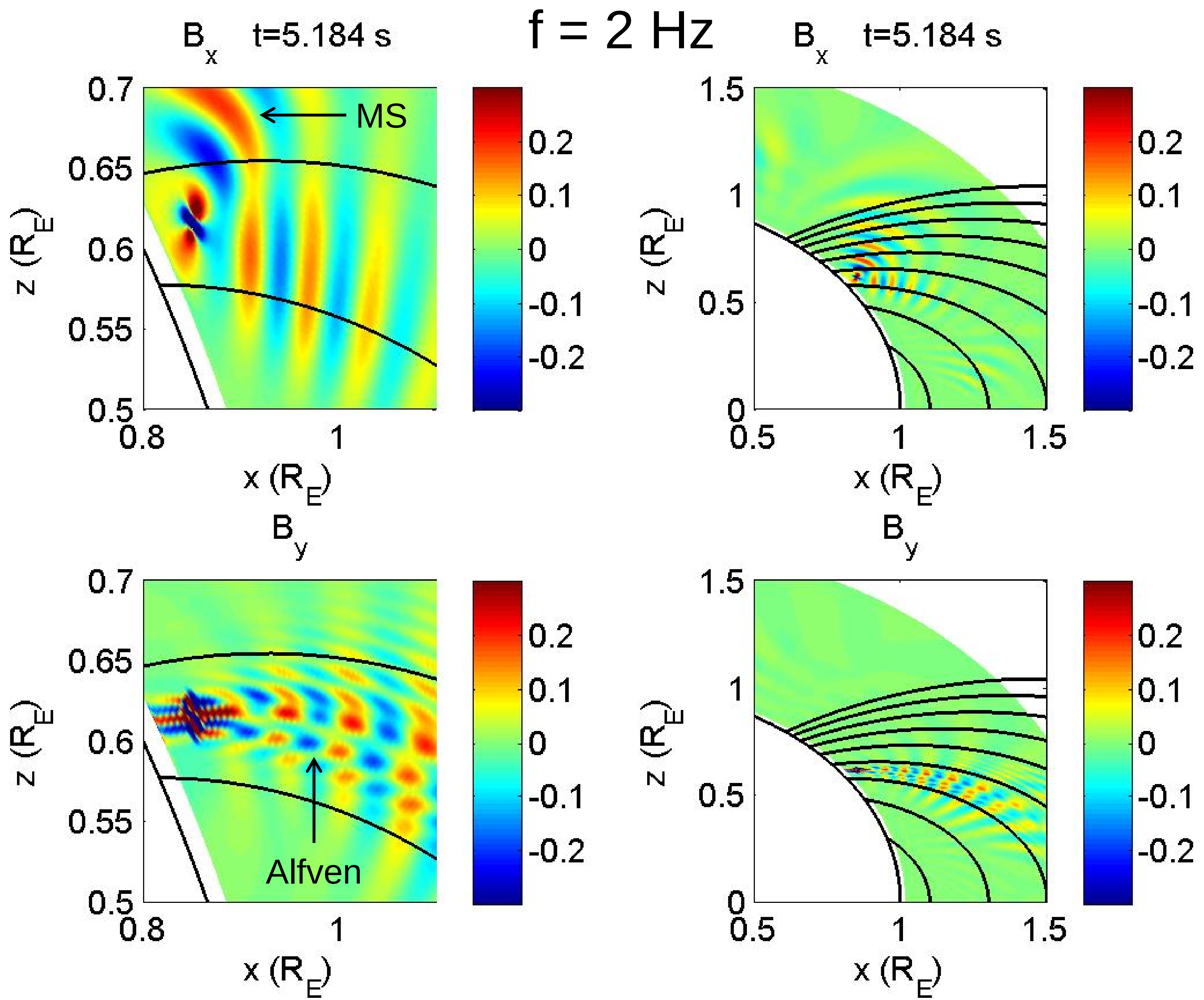


Simulation Results 10Hz (Movie)

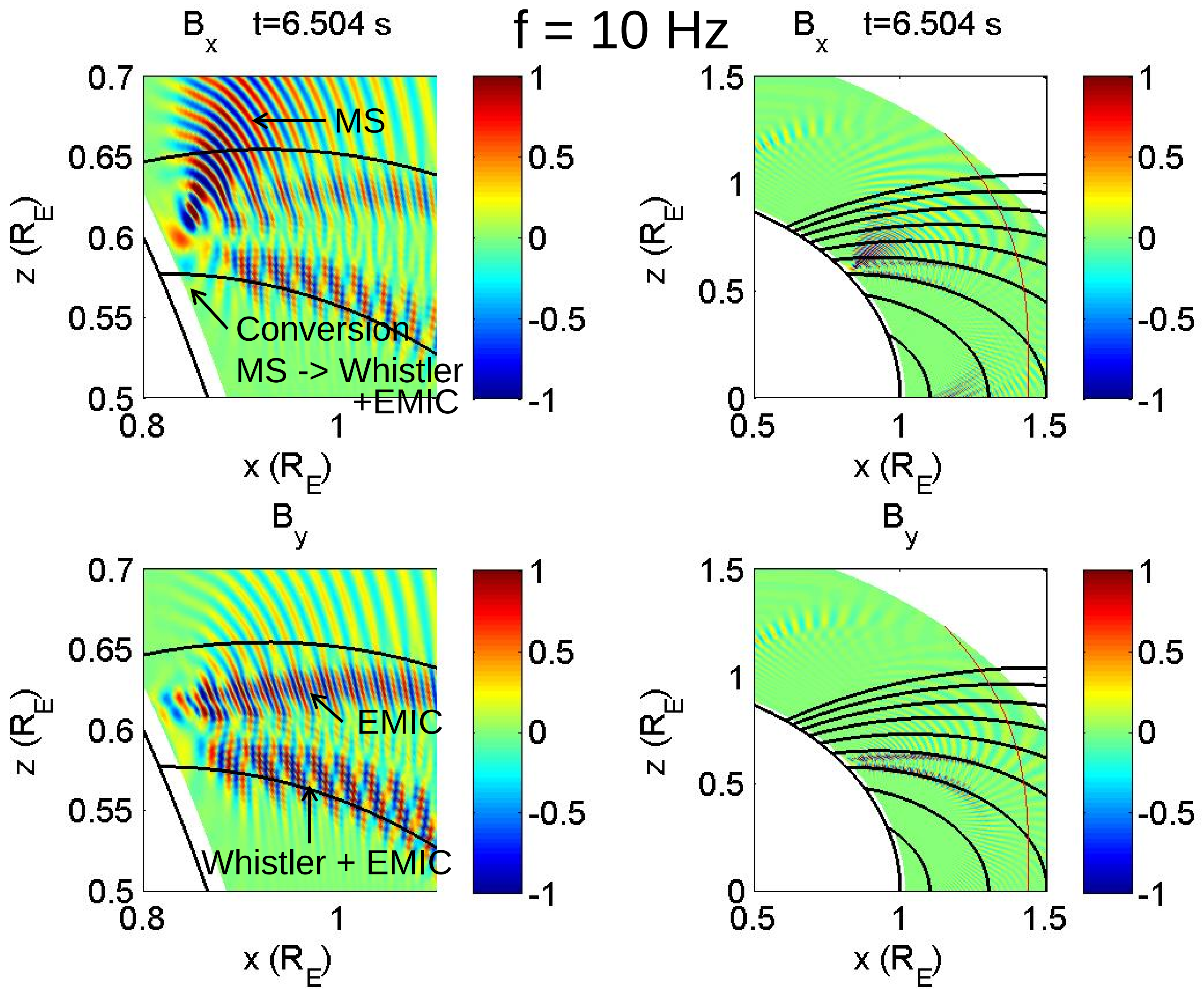


Main features

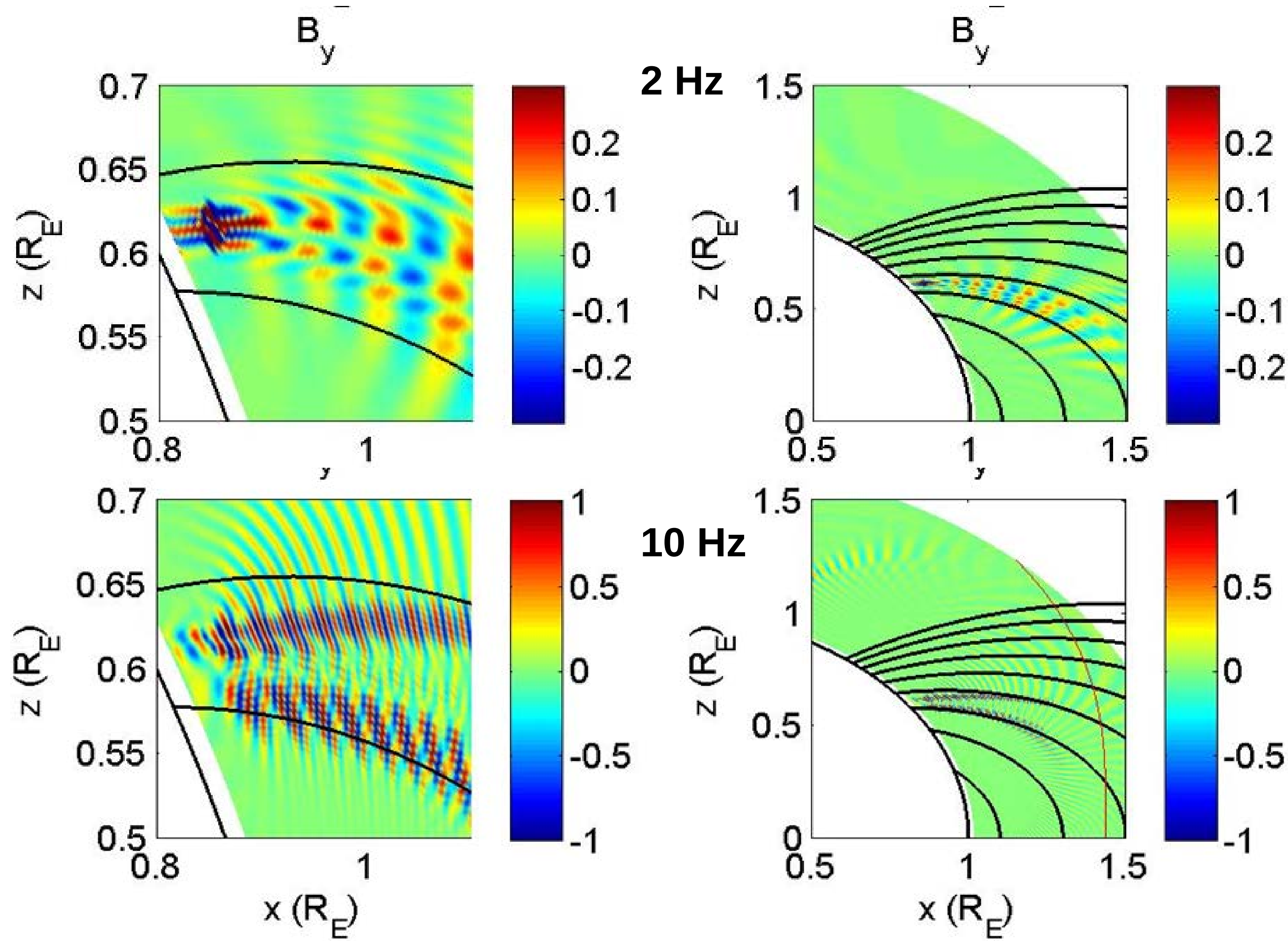
- Magnetosonic waves are created by HF heating and propagate at large angles to magnetic field lines.
- Whistlers (R-mode) and EMIC (L-mode) waves propagate mainly along magnetic field lines
- Direct generation of EMIC waves at the source region
- Generation of EMIC and whistlers via mode conversion of MS waves in the E-region.
- 10Hz: EMIC wavelength and propagation speed significantly smaller than for Whistlers.



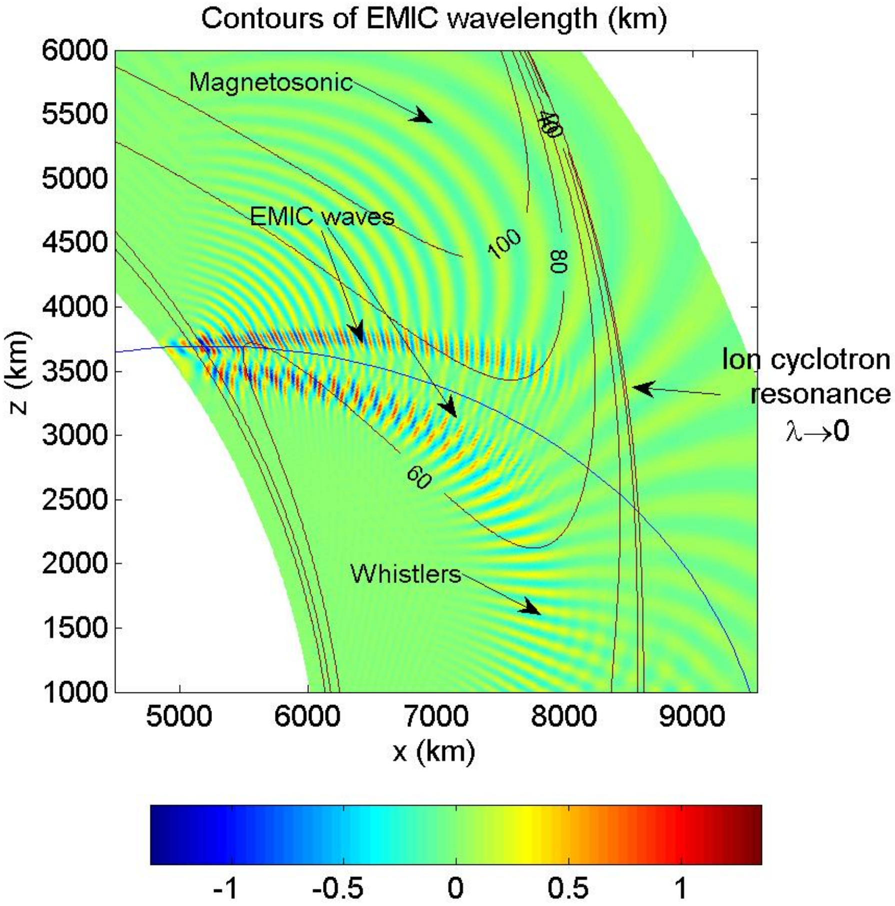
f = 2 Hz
B x t=5.184 s
B x t=5.184 s
MS
B y
B y
Alfven
z (R E)
x (R E)
0.7
0.65
0.6
0.55
0.5
0.8
1
1.5
0
0.2
0.1
-0.1
-0.2

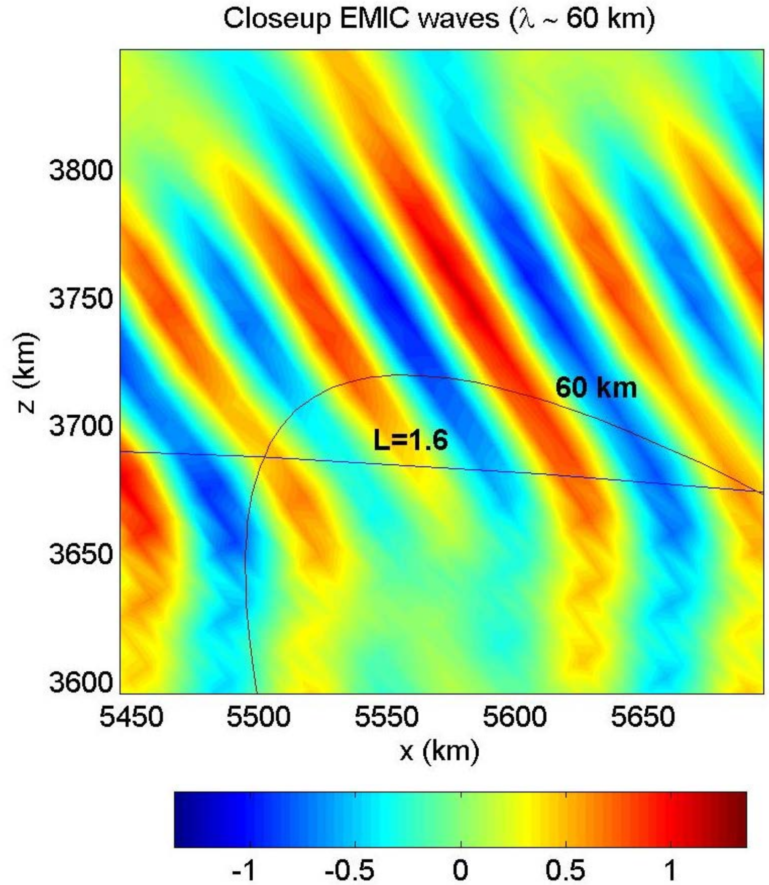

f = 10 Hz
B_x t=6.504 s
B_x t=6.504 s
MS
Conversion
MS -> Whistler
+EMIC
B_y
B_y
EMIC
Whistler + EMIC
z (R_E)
x (R_E)
0.7
0.65
0.6
0.55
0.5
0.8
1
1.5
0.5
0
-0.5
-1

ELF waves for different modulation frequencies



EMIC Waves and Whistlers (10 Hz)





Whistler / EMIC features

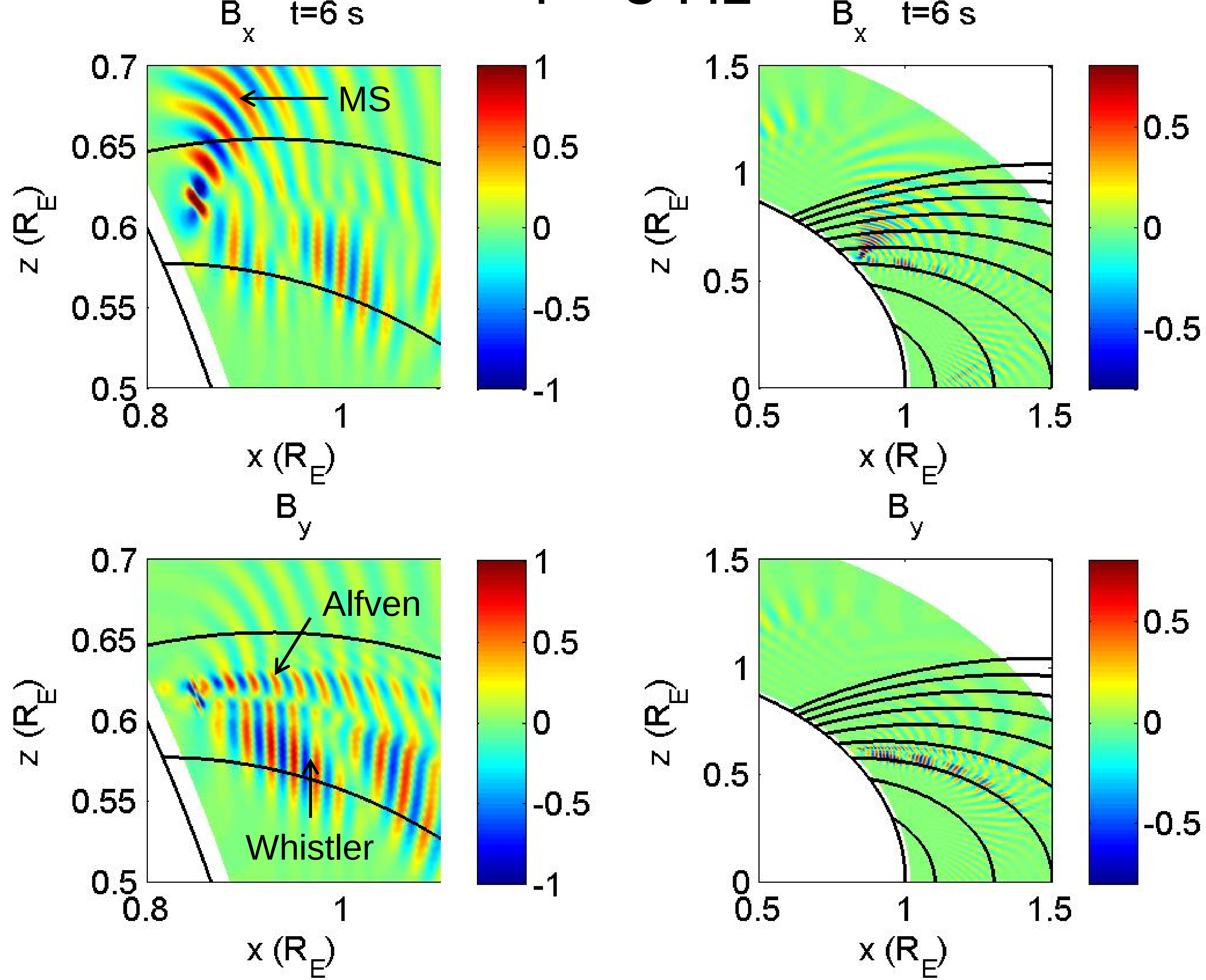
- Magnetosonic waves (shown by Bx) are created by HF heating and propagate upwards to the magnetosphere and downwards to E-region, where they convert to whistlers and EMIC waves.
- EMIC waves also generated at the source region
- EMIC and Whistler waves (shown by By and Bx) propagate along magnetic field lines
- 10 Hz: EMIC waves cannot propagate beyond ion cyclotron resonance layer where their wavelength goes to zero
- EMIC relatively short wavelength compared to whistlers

Summary

- Generation of ELF waves by HF heating in the F region - in the absence of an electrojet
- Realisitic ionospheric profile, collisionality and dipole magnetic field geometry
- Direct generation of EMIC waves in source region, mode conversion of MS waves via Hall currents in the E-region
- Provides features for comparison with satellite data during passes over the heating site.
- Low frequency waves (plasma eigenmodes) in HF heating with no modulation

- References:
- B. Eliasson, C.-L. Chang, and K. Papadopoulos (2012), Generation of ELF and ULF electromagnetic waves by modulated heating of the ionospheric F2 region, J. Geophys. Res., 117, doi:10.1029/2012JA017935
- Papadopoulos, K., N. A. Gumerov, X. Shao, I. Doxas, and C. L. Chang
- (2011), HF-driven currents in the polar ionosphere, Geophys. Res. Lett.,
- 38, L12103, doi:10.1029/2011GL047368.
- Papadopoulos, K., C.-L. Chang, J. Labenski, and T. Wallace (2011), First
- demonstration of HF-driven ionospheric currents, Geophys. Res. Lett., 38,
- L20107, doi:10.1029/2011GL049263.

f = 5 Hz



Motivation and observation

- **Ionospheric ULF Wave Generation without Electrojet** [Papadopoulos et al., 2011a,b; Eliasson, Chang and Papadopoulos, 2012]
  - Both simulation and experiments
  - Up to 50 Hz
  - Ionospheric current drive (ICD) in F layer
  - Predictable and repeatable signal generation on daily basis
  - Viable technique in low latitude regions with robust F
- **ICD-driven ULF Wave generation and injection in EIW and the radiation belt**
  - A comprehensive simulation model is needed
- **Inducing energetic particle precipitation from radiation belt through resonant pitch angle scattering**
  - Pitch angle scattering protons with Alfven waves [Shao et al., 2009]
  - EMIC waves interact resonantly with relatvisitc electrons