Low Frequency Waves in HF Heating of Mid-latitude Ionosphere

Surja Sharma, Bengt Eliasson*, Xi Shao, Gennady Milikh and Dennis Papadopoulos

University of Maryland, College Park
*University of Strathclyde, Glasgow, UK

IES 2015
Alexandria, VA

Supported by NSF Grant AGS-1158206
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
\[
\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E} \quad \quad \nabla \times \mathbf{B} = \mu_0 e n_0 (\mathbf{v}_i - \mathbf{v}_e)
\]

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: $T_e = T_{mod} \text{tanh}^2 \left( \frac{t}{D_t} \right) \cos (\omega \ t) \exp \left[ - \frac{r_{0}^2}{D_{r0}^2} - \frac{(h-h_{max})^2}{D_h^2} \right]$, 

$B_0$

Heated region

Weakly collisional ($\omega > v_{in}$)
F-region
Alfvén waves
Diffusive ($v_{in} > \omega$)
($\sigma_p > \sigma_H$)
Helicon waves
E-region ($\sigma_H > \sigma_p$)

Free space

Conducting ground

$z$ (km)

$x$ (km)

$z \ (R_E)$

$x \ (R_E)$
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 \( E_{\text{par}} \) and \( B_n \)
- Conducting ground:
  no \( E_{\text{par}} \) and \( B_n \)
Low Frequency Waves

- Dispersion relation
  \[ \omega \ll \omega_{ce}, \quad \omega \ll c k_\parallel \]

\[
\omega^2 + v_A^2 k_\parallel^2 \frac{\omega}{\omega_{ci}} - v_A^2 k_\parallel^2 = 0
\]

L-Mode/EMIC (+) waves

- Whistler/helicon mode

Obliquely propagating Alfvén waves:
\[ \text{EMIC} + \text{Whistlers/MS} \]

\[
(\omega^2 - v_A^2 k_\perp^2) \left(\omega^2 - v_A^2 k_\parallel^2\right) - \frac{\omega^2}{\omega_{ci}^2} v_A^2 k_\parallel^2 k_\perp^2 = 0.
\]

Magnetosonic (MS) waves:
\[ \omega^2 - v_A^2 k_\parallel^2 = 0, \quad \text{for} \quad k_\parallel = 0. \]
Simulation Results: 2Hz (Movie)
Simulation Results 10Hz (Movie)

$B_x$ t=0.192 s

$z(\text{R}_E)$

$x(\text{R}_E)$

$B_y$

$z(\text{R}_E)$

$x(\text{R}_E)$

$B_y$
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.
\( f = 2 \text{ Hz} \)
Conversion MS -> Whistler + EMIC

$B_x \ t=6.504 \ s$

$f = 10 \ Hz$

$z (R_E)$

$x (R_E)$

$B_y$

$z (R_E)$

$x (R_E)$

$B_y$
ELF waves for different modulation frequencies

2 Hz

10 Hz
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
- Realistic 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:


$f = 5 \text{ Hz}$
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 relativistic electrons