NONLINEAR COUPLING BETWEEN DENSITY STRUCTURES AND FEEDBACK-UNSTABLE ULF WAVES IN THE IONOSPHERE

Anatoly V. Streltsov

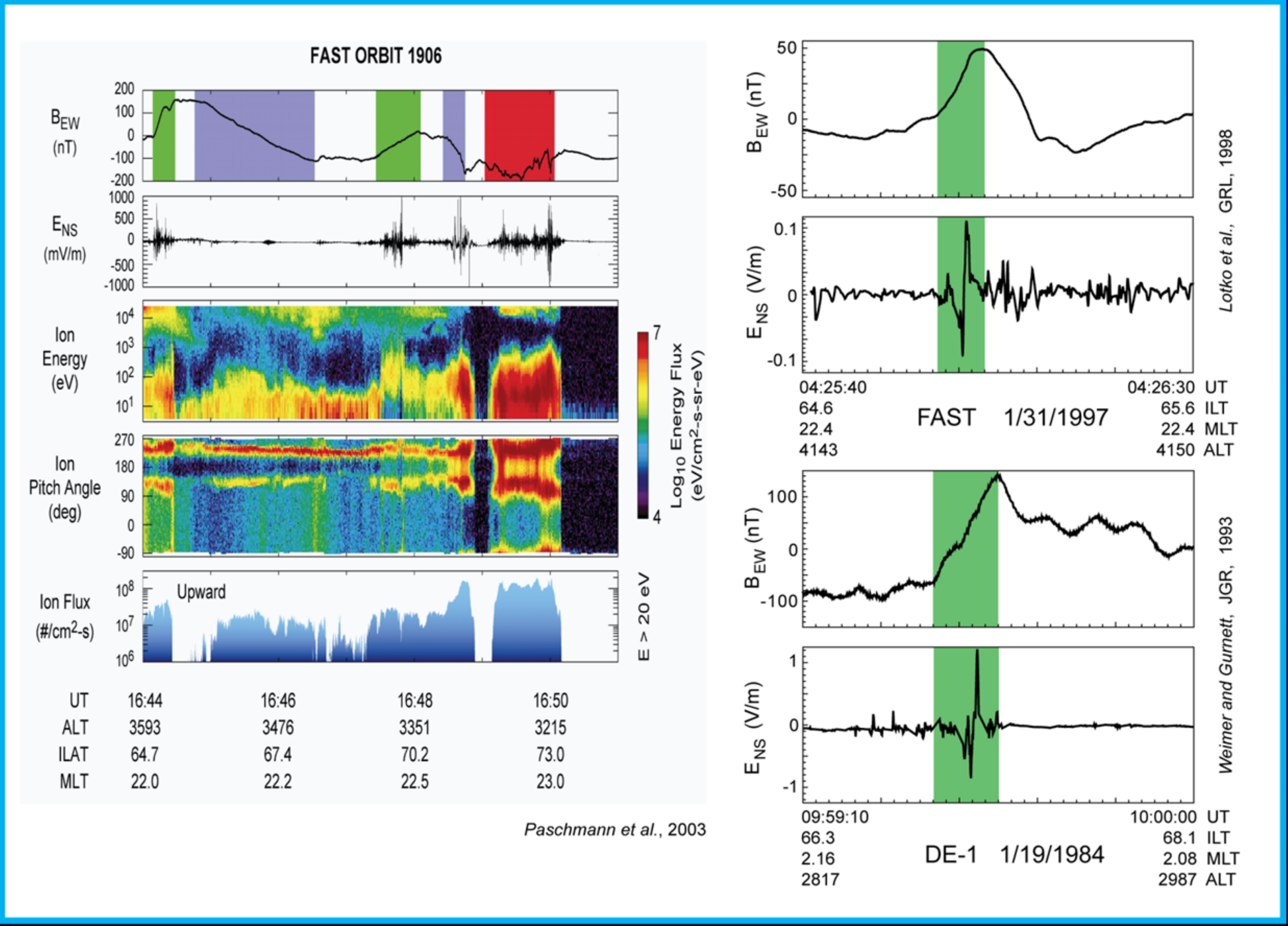
Thayer School of Engineering, Dartmouth College, USA

Modern Challenges in Nonlinear Plasma Physics

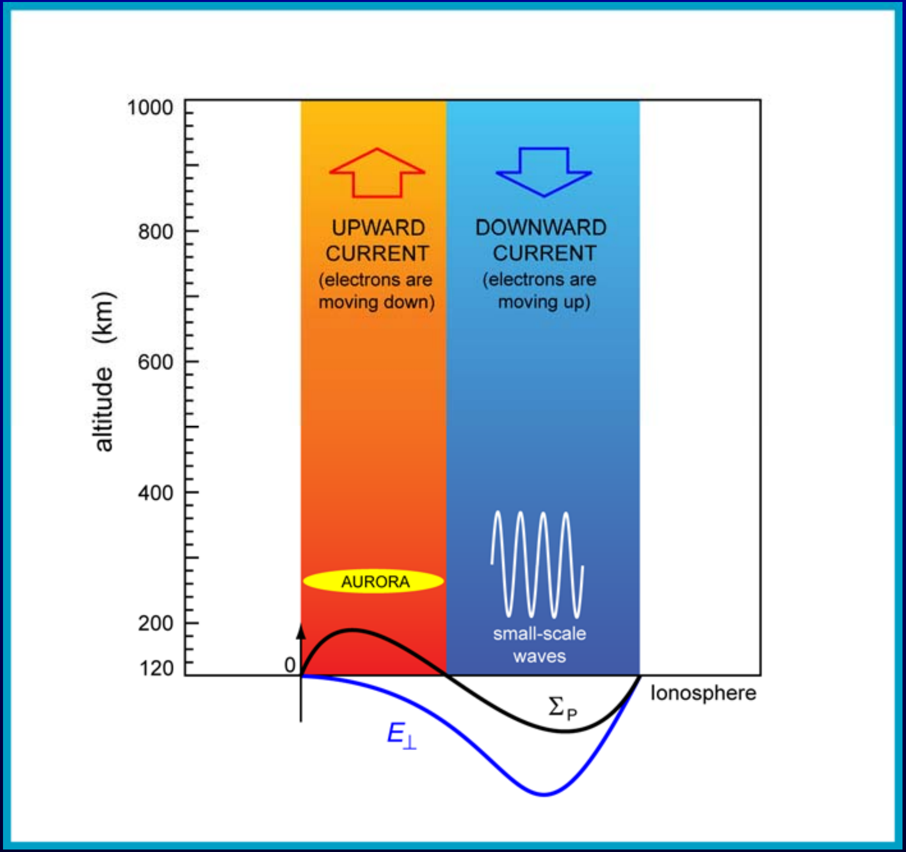
June 15-19, 2008

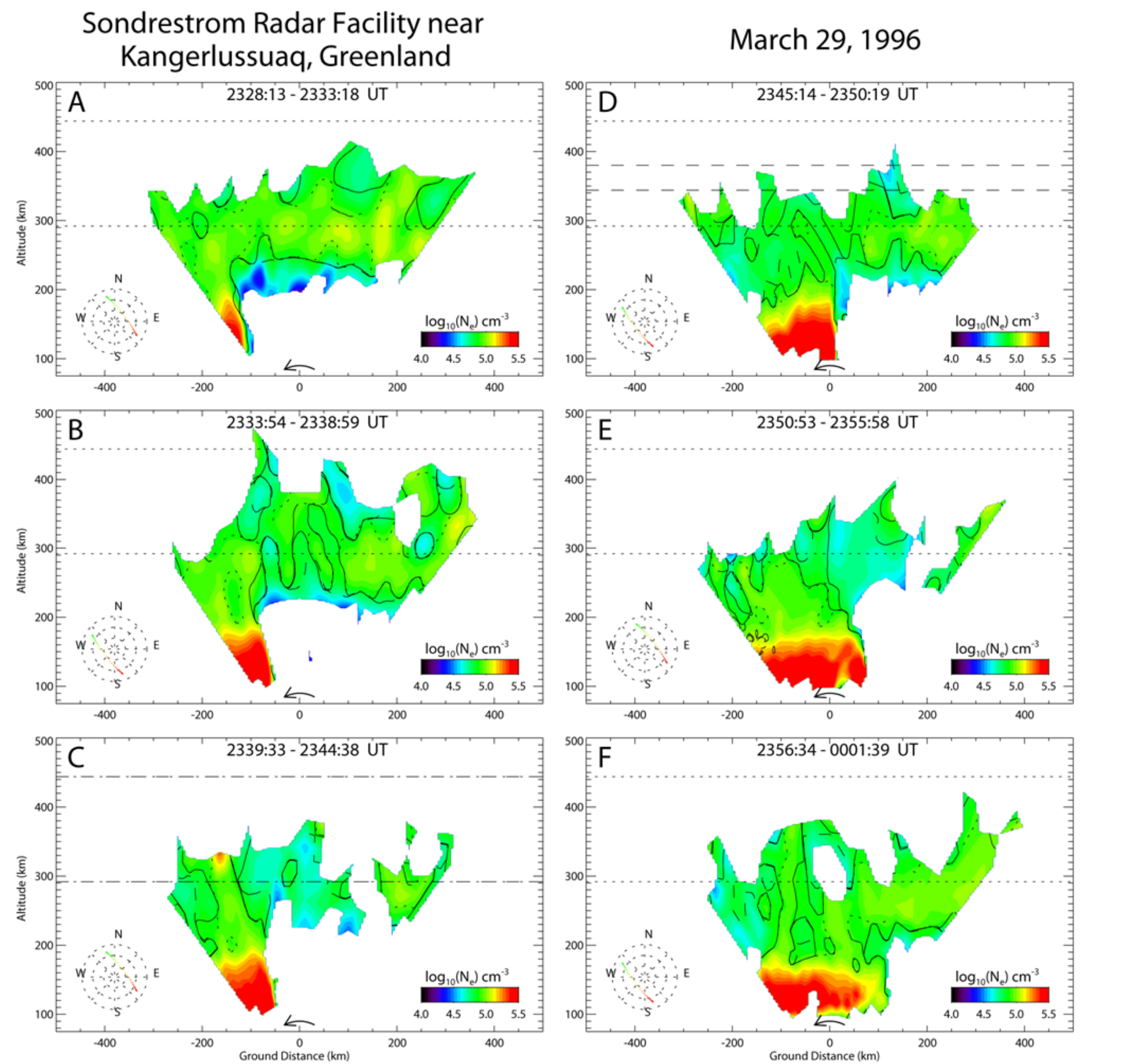
Halkidiki, GREECE

Observations of intense, small-scale ULF waves at low altitudes



Interaction of two FACs with the ionosphere

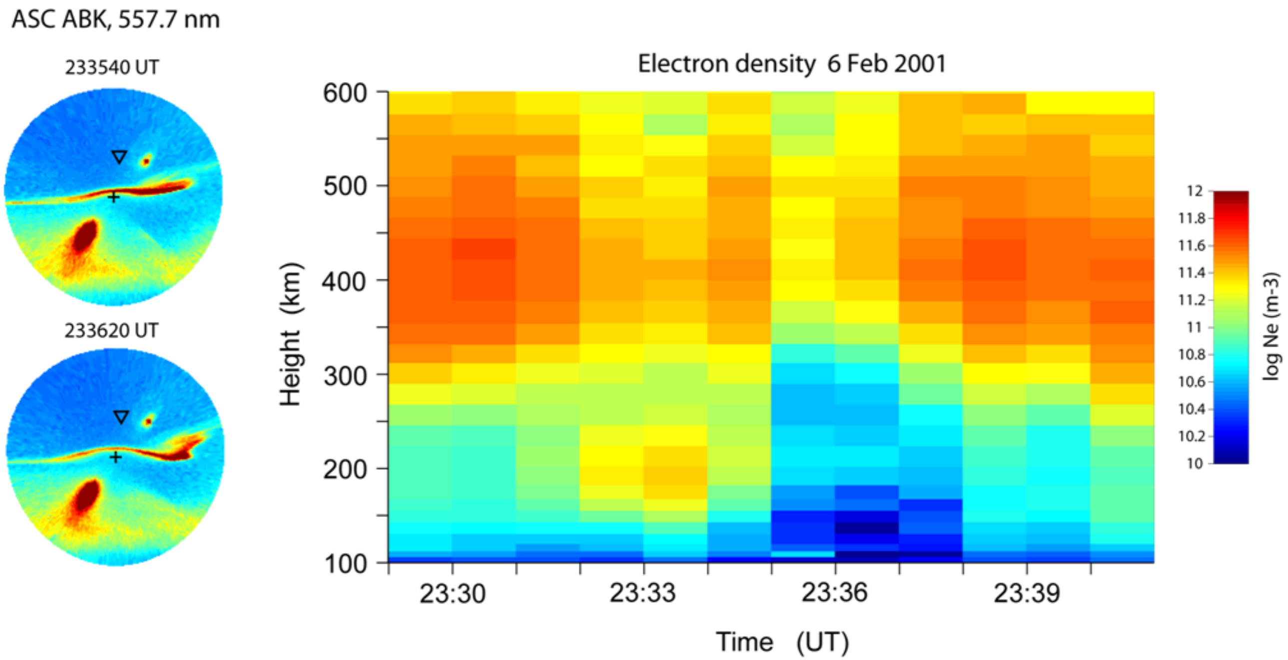




Shepherd et al. [1998]

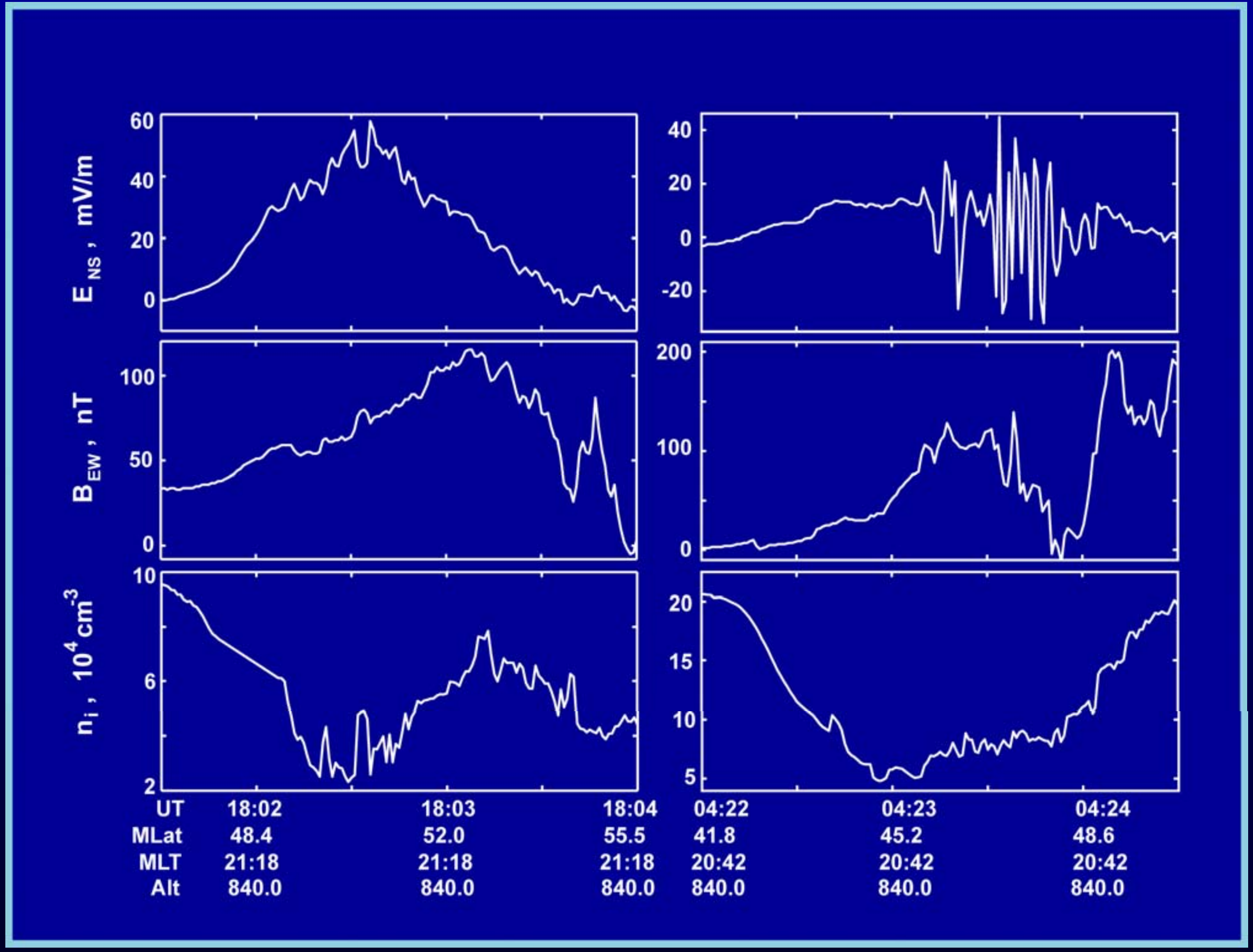
Interaction of FACs with the ionosphere

EISCAT measurement from the downward FAC region poleward of the arc.
[from *Aikio et al.*, 2004]



Observations of EM waves and density cavities at low altitudes

(DMSP F15 11-06-2001)



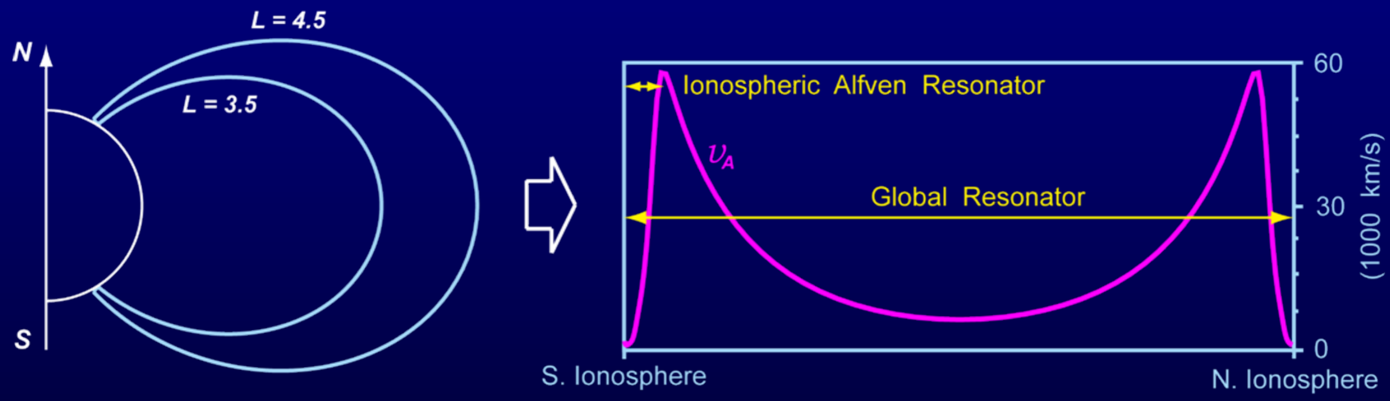
Mishin et al. [2003]

Ionospheric Feedback Mechanism (IFM)

$$\nabla \cdot (\Sigma_P \mathbf{E}_\perp) = -j_\parallel, \quad \text{where} \quad \Sigma_P \propto n$$

$$\frac{\partial n}{\partial t} = \frac{j_\parallel}{eh} + \alpha \left(n_0^2 - n^2\right)$$

IFM + $E_\perp$ + cavity = Ionospheric Feedback Instability (IFI)



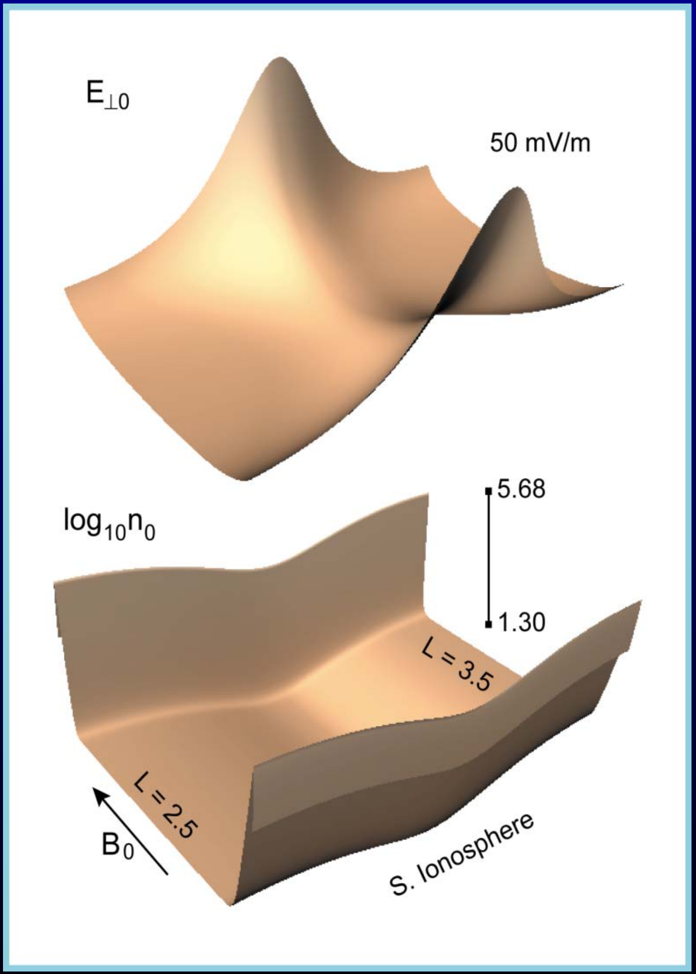
IFI growth rate is large when

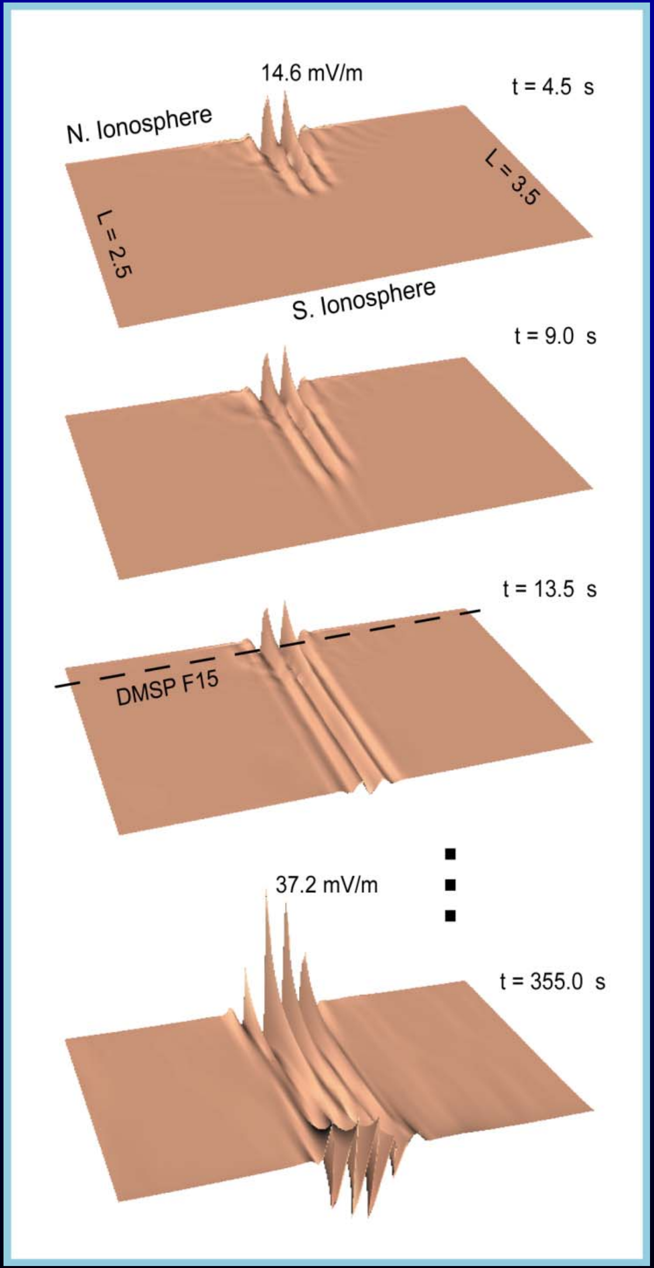
Σ_P is small, $E_\perp$ is large and $k_\perp$ is large

Simulations (FLR)

$$\nabla\cdot[(\Sigma_{P0}+\delta\,\Sigma_P)\,\mathbf{E}_{\perp 0}] = -\delta\, j_{\parallel}$$

Background Parameters

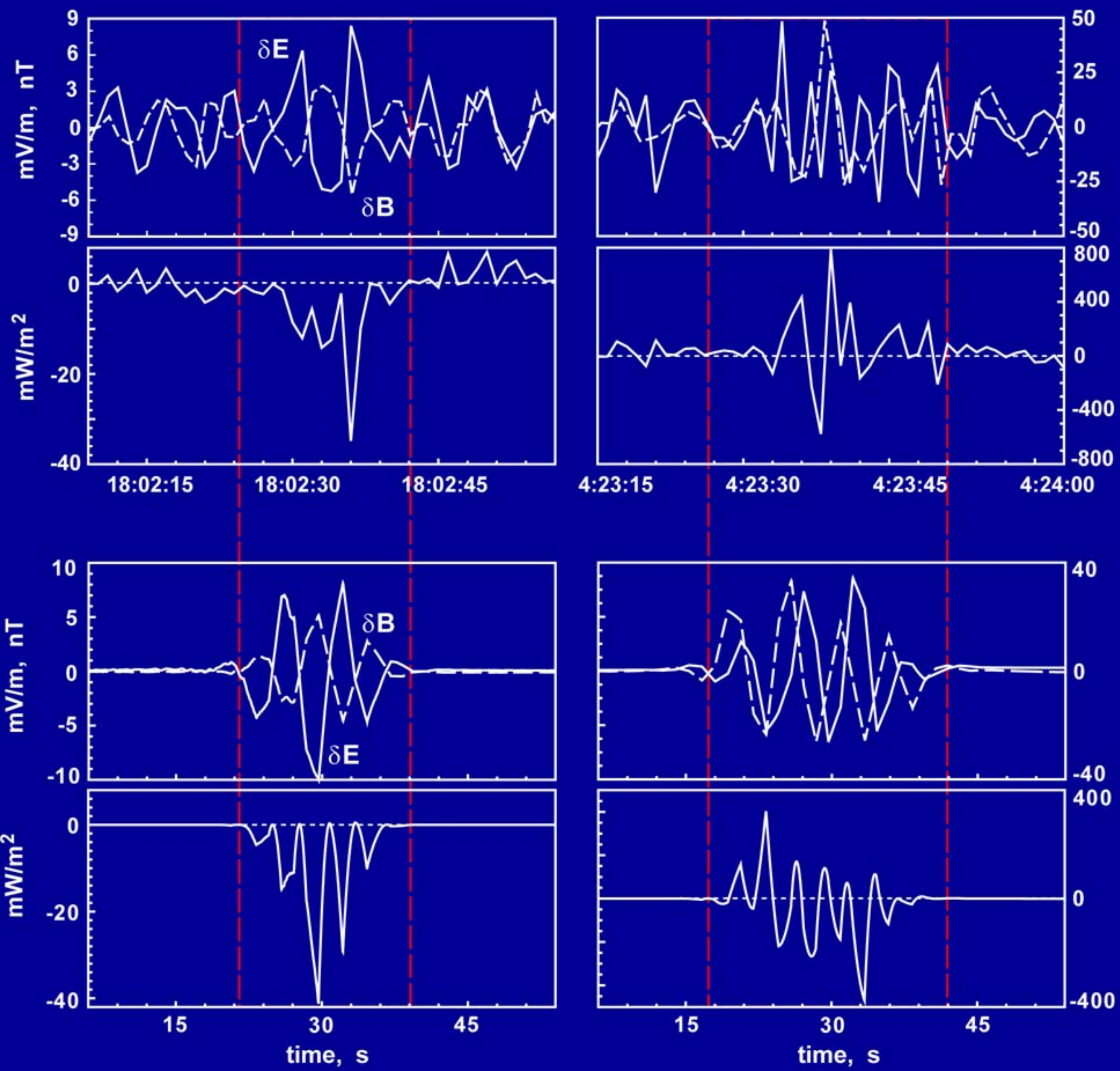




Streltsov and Mishin, 2004

DMSP F15 data

Simulations



[*Streltsov and Mishin,* 2004]

"Two-Field" Reduced MHD Model

electron momentum:

$$\frac{\partial j_{\|e}}{\partial t} + \nabla \cdot (\mathbf{j}_{\|e} \mathbf{v}_{\|e}) = \frac{e n}{m_e} E_{\|}$$

current continuity:

$$\nabla \cdot \left[\left(\frac{1}{v_A^2} + \frac{1}{c^2} \right) \frac{\partial \mathbf{E}_{\perp}}{\partial t} + \mu_0 \mathbf{j}_{\|e} \right] = 0$$

$$\mathbf{E}_{\perp} = -\nabla_{\perp}\varphi \ , \quad E_{\|} = -\nabla_{\|}\varphi - \frac{\partial A_{\|}}{\partial t} \ , \quad \mathbf{j}_{\|e} = -en\mathbf{v}_{\|e} = -\frac{1}{\mu_0}\nabla \times \nabla \times \mathbf{A}_{\|}$$

$$n_e \approx n_e \equiv n(x)$$

“Three-Field” MHD Model

electron momentum:

$$\frac{\partial j_{\|e}}{\partial t} + \nabla \cdot (\mathbf{j}_{\|e} \mathbf{v}_{\|e}) = \frac{e n}{m_e} E_{\|} + \frac{1}{m_e} \nabla_{\|} p_e$$

current continuity:

$$\nabla \cdot \left[\left(\frac{1}{v_A^2} + \frac{1}{c^2} \right) \frac{\partial \mathbf{E}_{\perp}}{\partial t} + \mu_0 \mathbf{j}_{\|e} \right] = 0$$

density continuity:

$$\frac{\partial n}{\partial t} + \nabla \cdot (n \, \mathbf{v}_e) = 0$$

$$p_e = n T_e \;; \qquad T_e(t, x) = T_e(x)$$

"Four-Field" MHD Model

Ohm's law:

$$\frac{\partial j_{\|}}{\partial t} + \nabla \cdot (\mathbf{j}_{\|i}\mathbf{v}_{\|i} - \mathbf{j}_{\|e}\mathbf{v}_{\|e}) = \frac{en}{m_e}E_{\|} + \frac{1}{m_e}\nabla_{\|}p_e$$

current continuity:

$$\nabla \cdot \left[\left(\frac{1}{v_A^2} + \frac{1}{c^2} \right) \frac{\partial \mathbf{E}_{\perp}}{\partial t} + \mu_0 \mathbf{j}_{\|} \right] = 0$$

density continuity:

$$\frac{\partial n}{\partial t} + \nabla \cdot (n\,\mathbf{v}_i) = 0$$

parallel ion momentum:

$$\frac{\partial j_{\|i}}{\partial t} + \nabla \cdot (\mathbf{j}_{\|i}\mathbf{v}_{\|i}) = \frac{e}{m_i} j_{\perp i} B_{\perp} - \frac{1}{m_i}\nabla_{\|}(p_e + p_i) + \mathbf{g}n$$

$$j_{\|} = j_{\|i} - j_{\|e} = en\left(v_{\|i} - v_{\|e}\right)$$

parallel ion momentum:

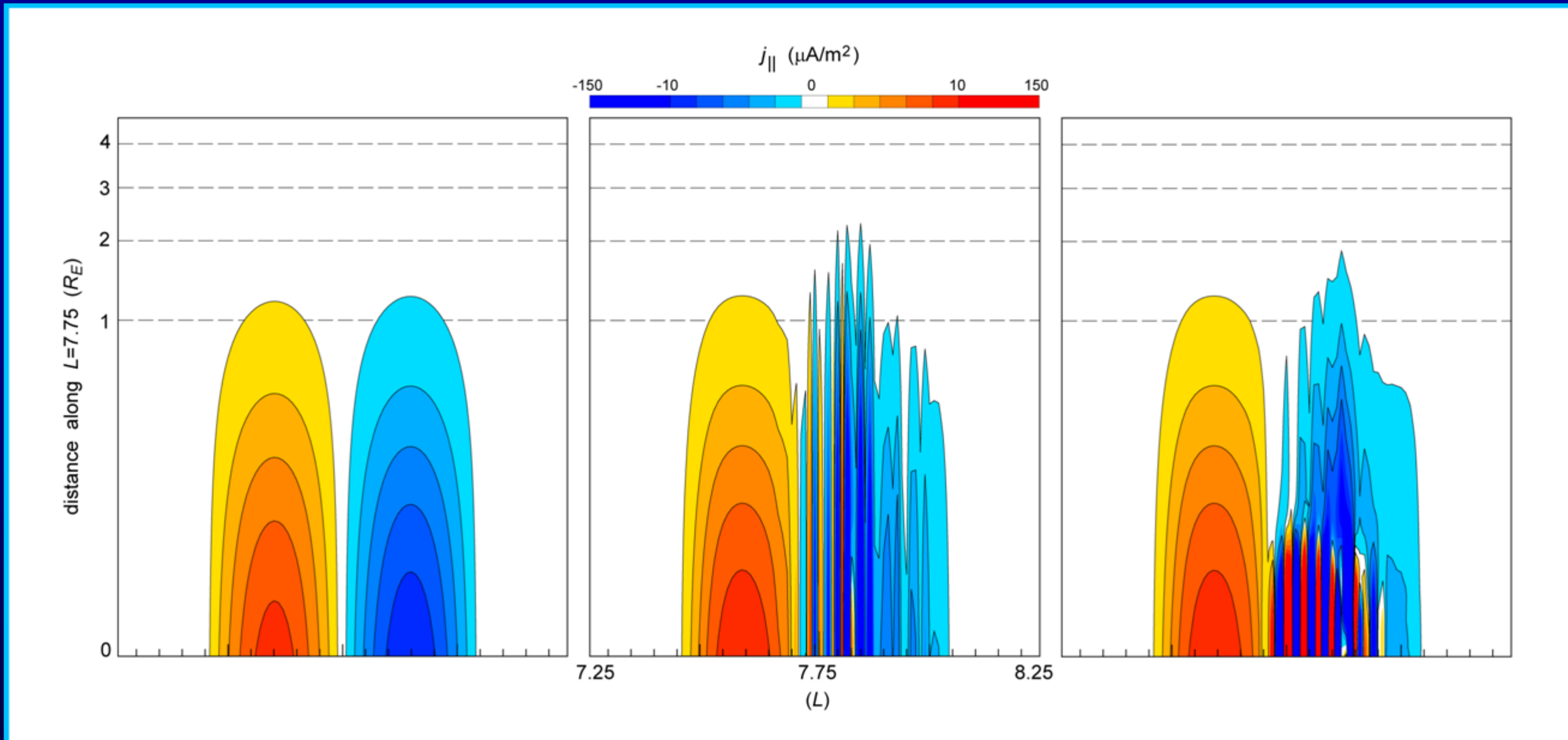
$$\frac{\partial j_{\parallel i}}{\partial t} + \nabla \cdot (\mathbf{j}_{\parallel i} \mathbf{v}_{\parallel i}) = \frac{e}{m_i} j_{\perp i} B_\perp - \frac{1}{m_i} \nabla_\parallel (p_e + p_i) + \mathbf{g} n$$

$$j_{\perp i} = n \frac{m_i}{B_0^2} \frac{\partial E_\perp}{\partial t}$$

$$\frac{\partial j_{\parallel i}}{\partial t} \propto B_\perp \frac{\partial E_\perp}{\partial t}$$

Ponderomotive term

Interactions of two FACs with the ionosphere



$\Sigma_P \equiv$ constant

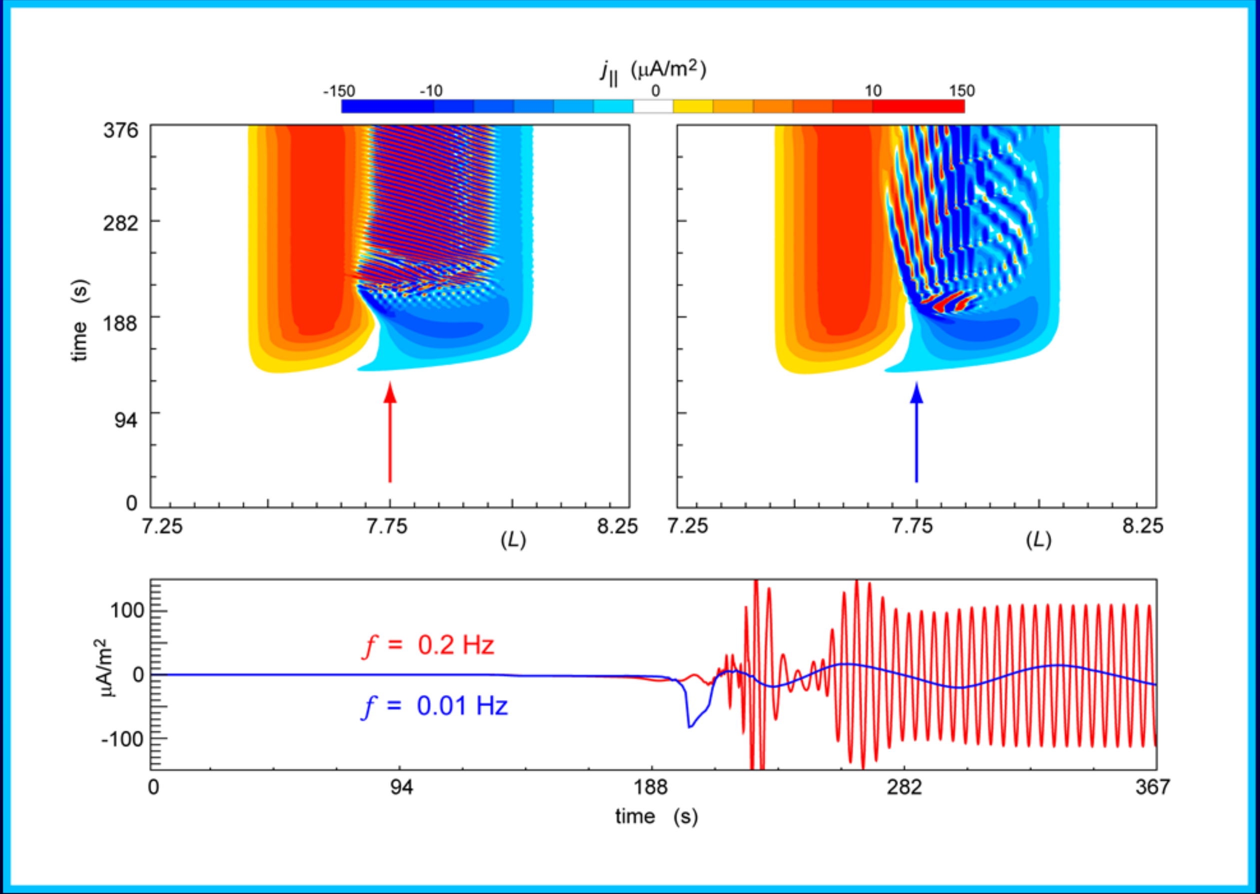
$\Sigma_{P0} >> \Sigma_A$

2 mho 0.16 – 0.39 mho

$\Sigma_{P0} \approx \Sigma_A$

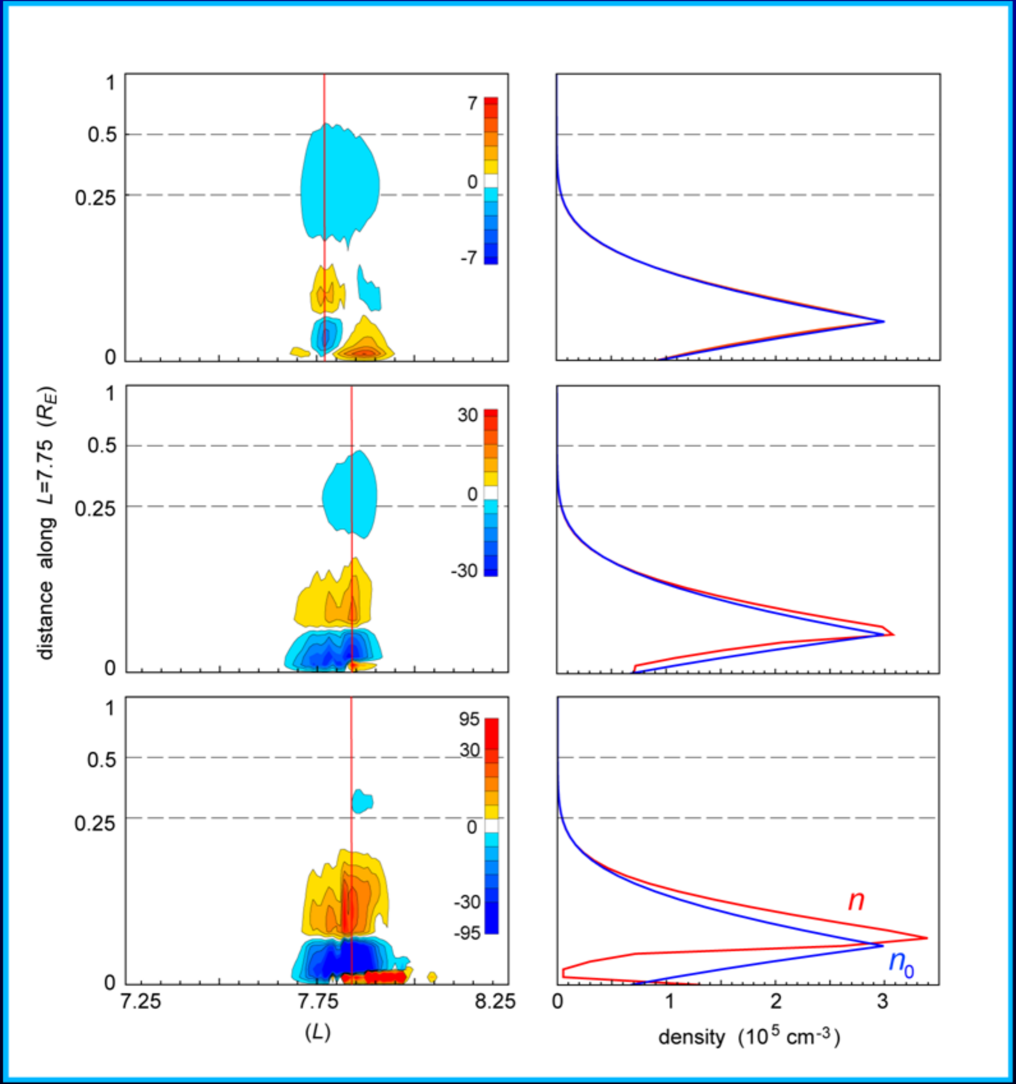
2 mho 0.91 – 2.11 mho

FACs at low altitude with (left) and without (right) IAR



[*Streltsov and Lotko,* 2008]

Density structures inside IAR



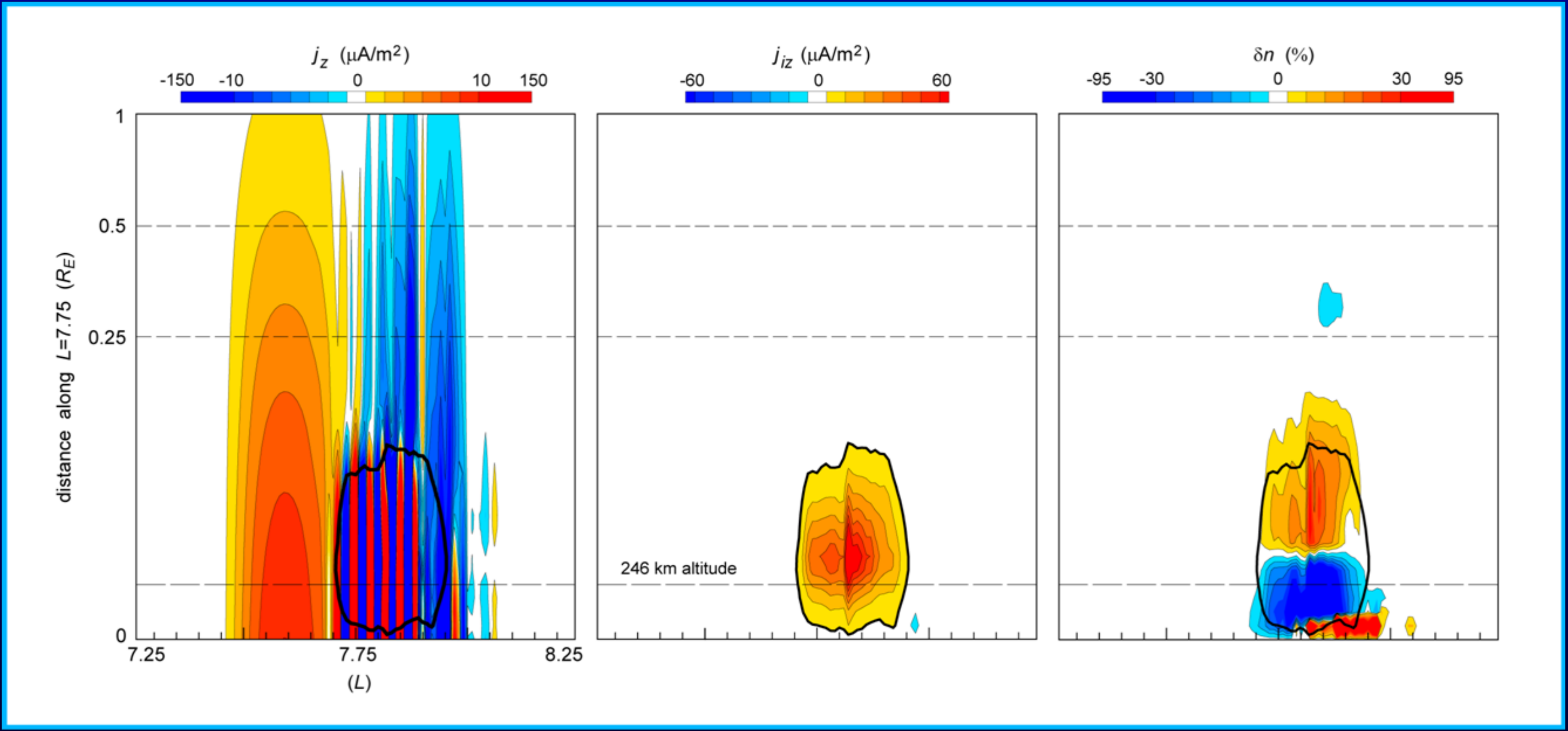
$n_E = 6\times10^4\ \mathrm{cm}^{-3}$
$M_P = 10^4\ \mathrm{m}^2/\mathrm{sV}$
$\Sigma_{P0} = 2\ \mathrm{mho}$

$n_E = 3\times10^4\ \mathrm{cm}^{-3}$
$M_P = 10^4\ \mathrm{m}^2/\mathrm{sV}$
$\Sigma_{P0} = 1\ \mathrm{mho}$

$n_E = 3\times10^4\ \mathrm{cm}^{-3}$
$M_P = 2\times10^4\ \mathrm{m}^2/\mathrm{sV}$
$\Sigma_{P0} = 2\ \mathrm{mho}$

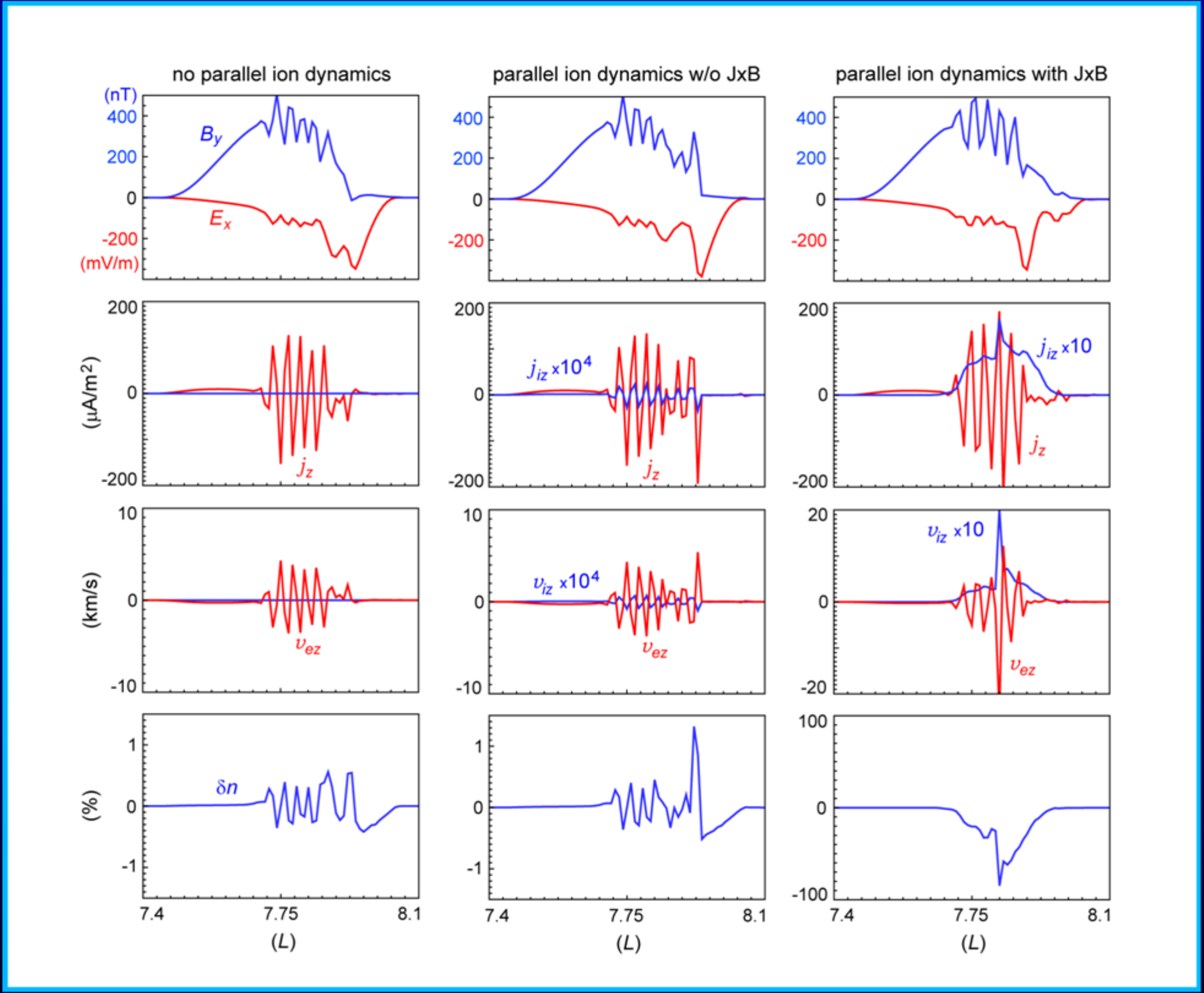
[*Streltsov and Lotko,* 2008]

FAC, ion parallel current, and density disturbances inside the IAR



[*Streltsov and Lotko,* 2008]

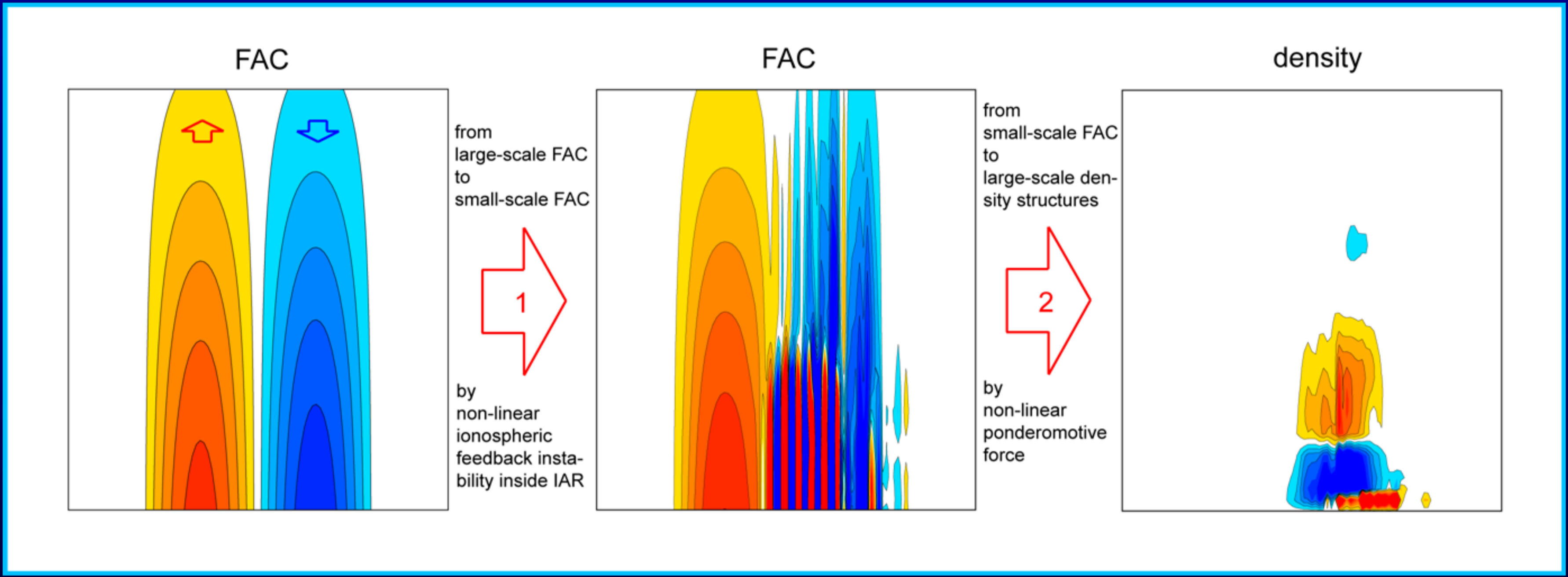
Structure of fields and current at the altitude 246 km



[*Streltsov and Lotko*, 2008]

Conclusion

Large-scale, ULF shear Alfven waves (FACs) can cause significant density disturbances at low altitude in the following 2-step process:

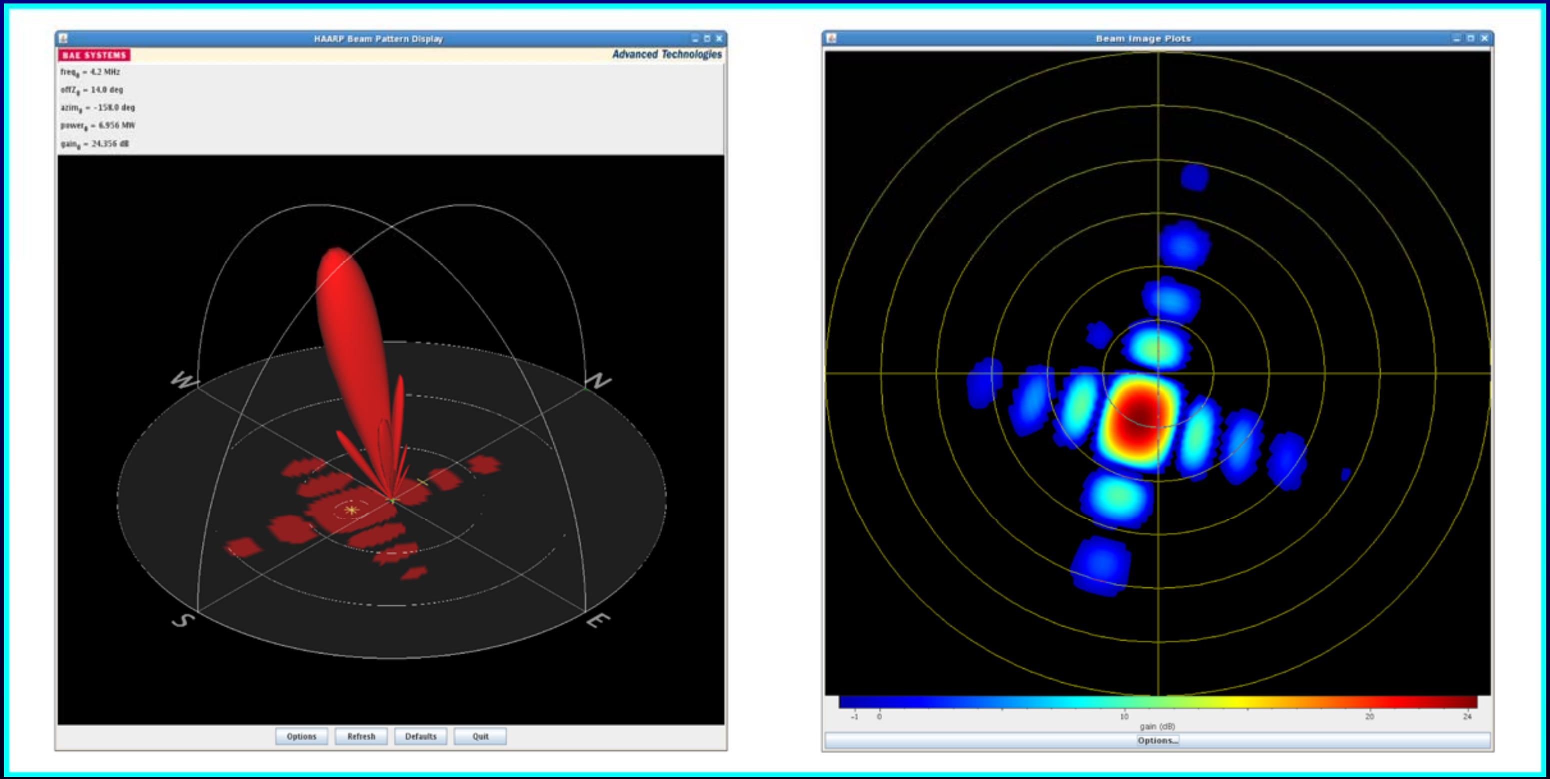


Ionospheric Feedback Instability (IFI) plays the central role in generation of density structures.

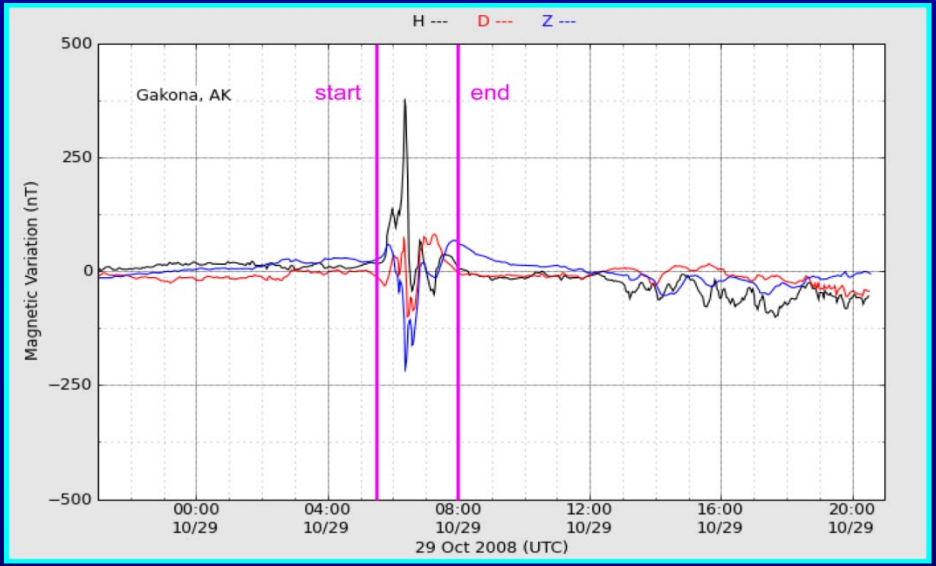
Excitation of IFI with HAARP

The experiment was conducted from 05:30 to 08:00 UT on 29 October and 1 November 2008.

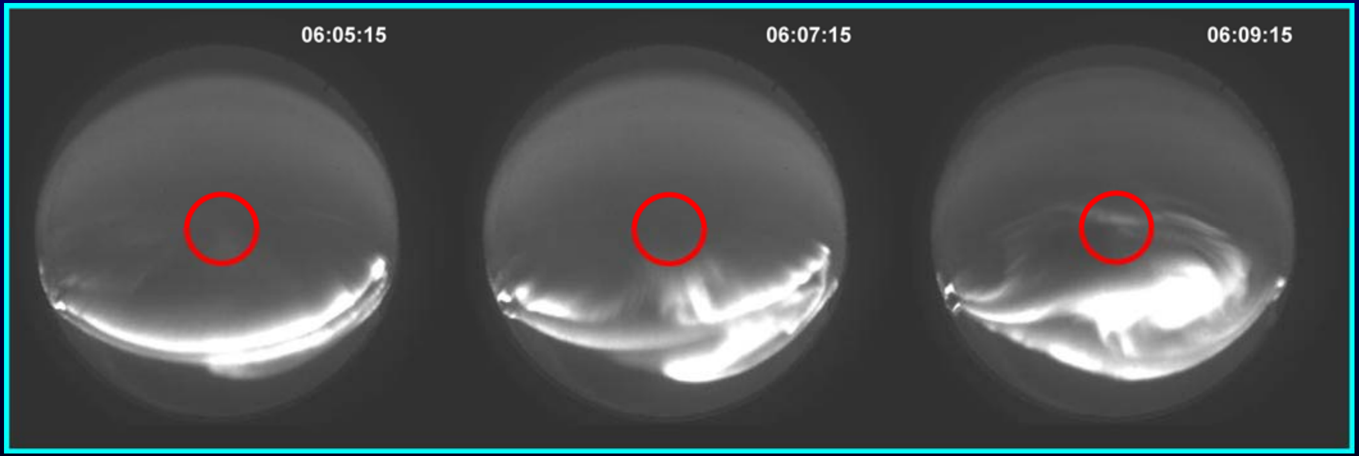
The E-region was heated with 4.5 MHz X-mode waves focused to a 20 km spot in the direction of the magnetic zenith and vertically.



Ionospheric Feedback Instability and Substorm

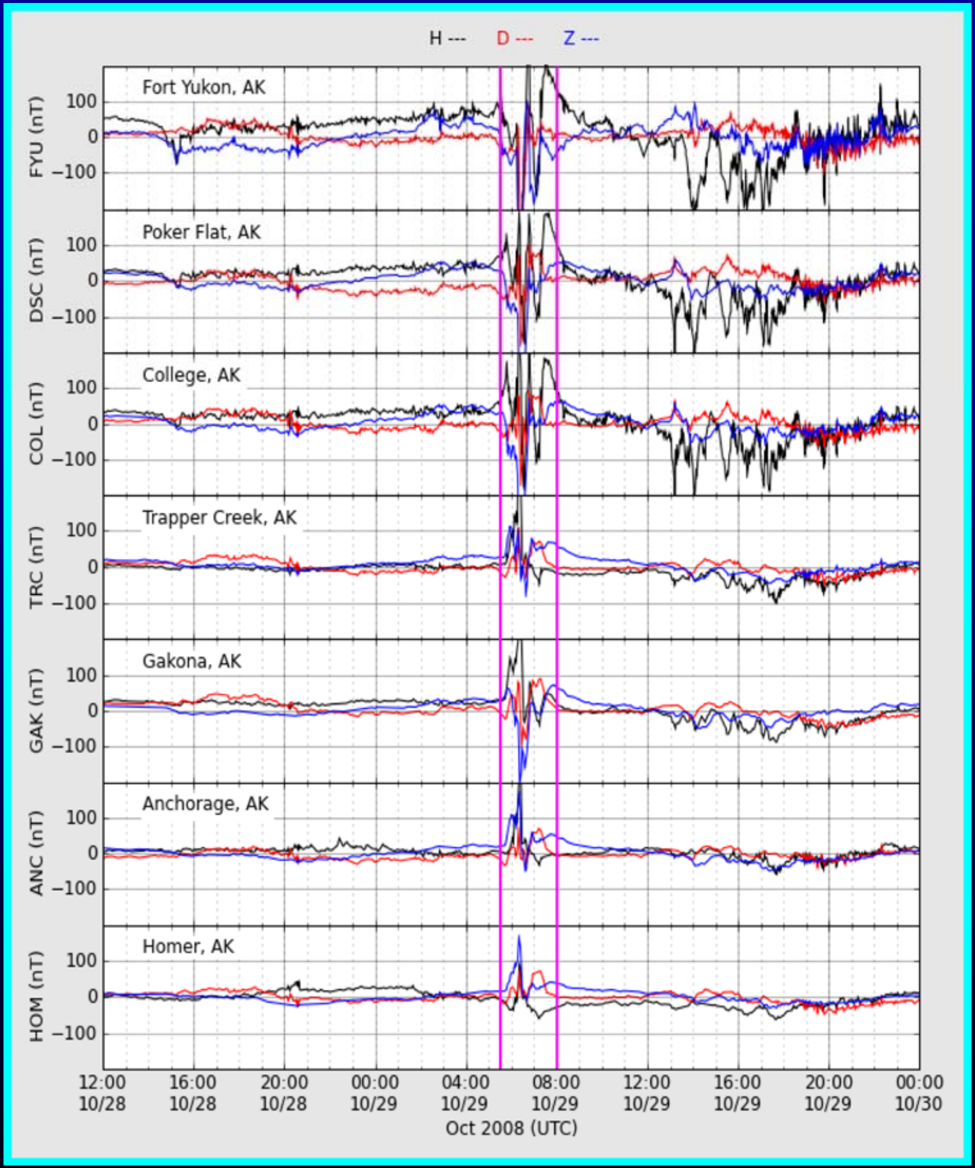


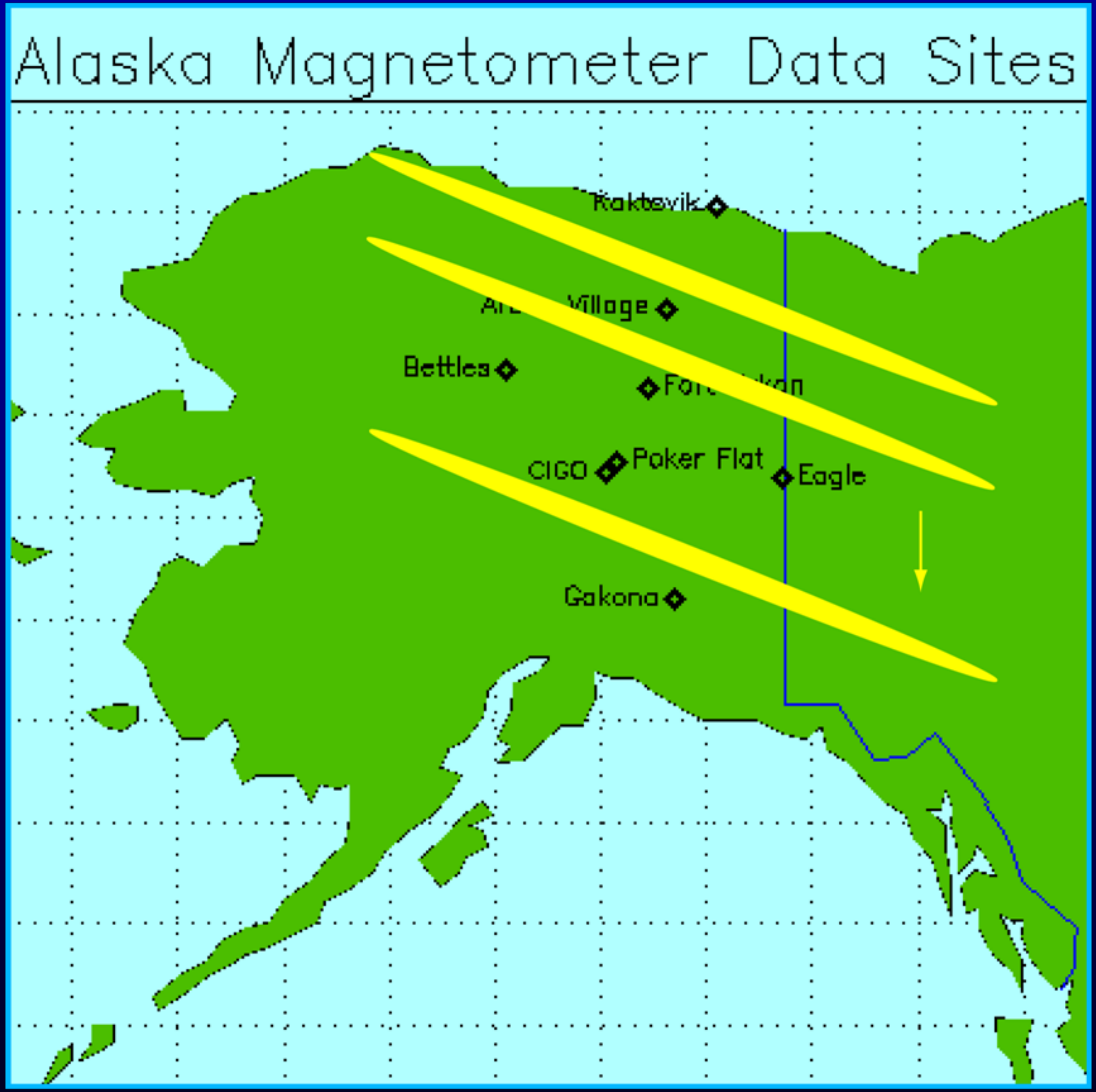
HAARP (Gakona) Fluxgate Magnetometer

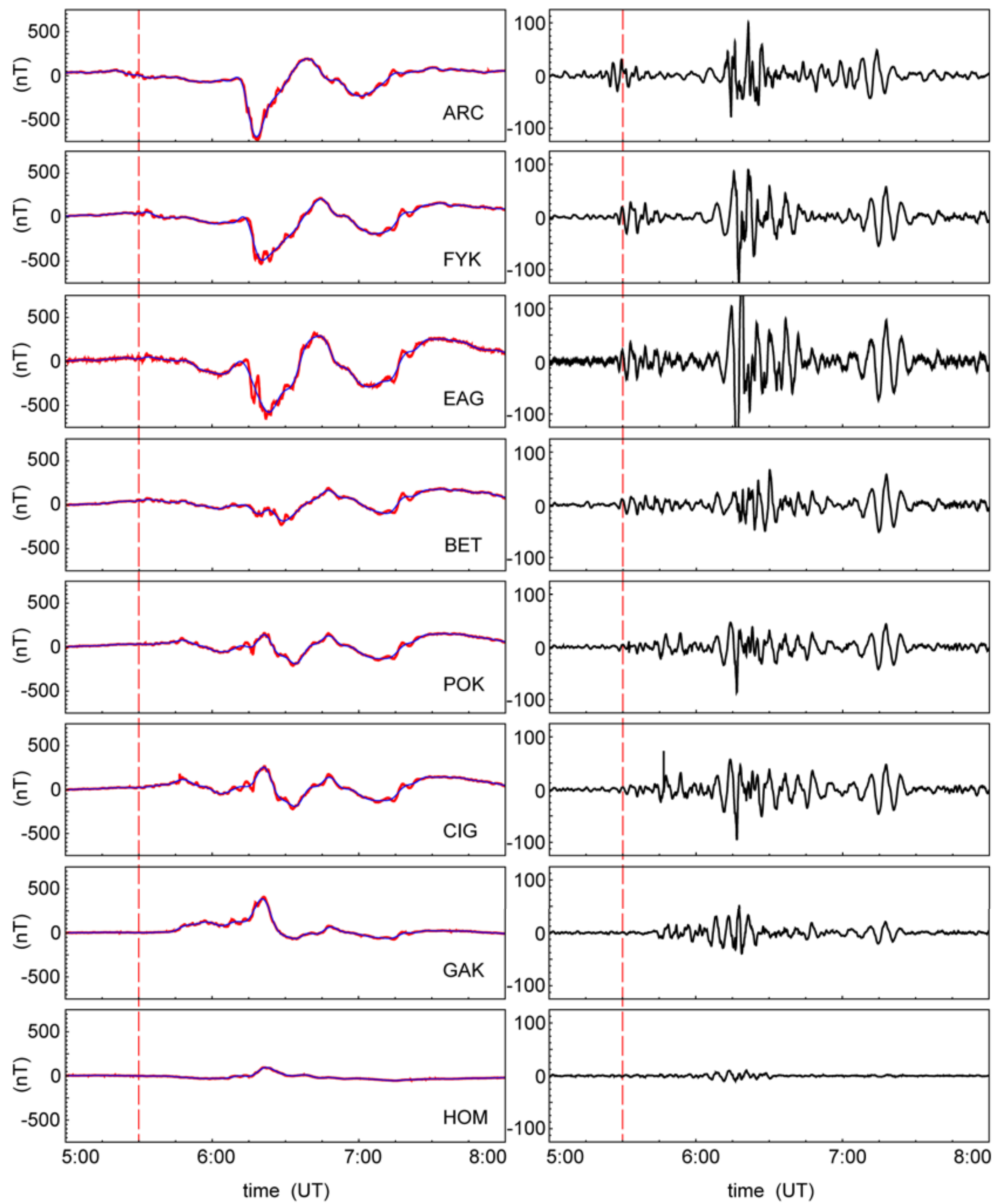


HAARP all-sky imager (Todd Pedersen)

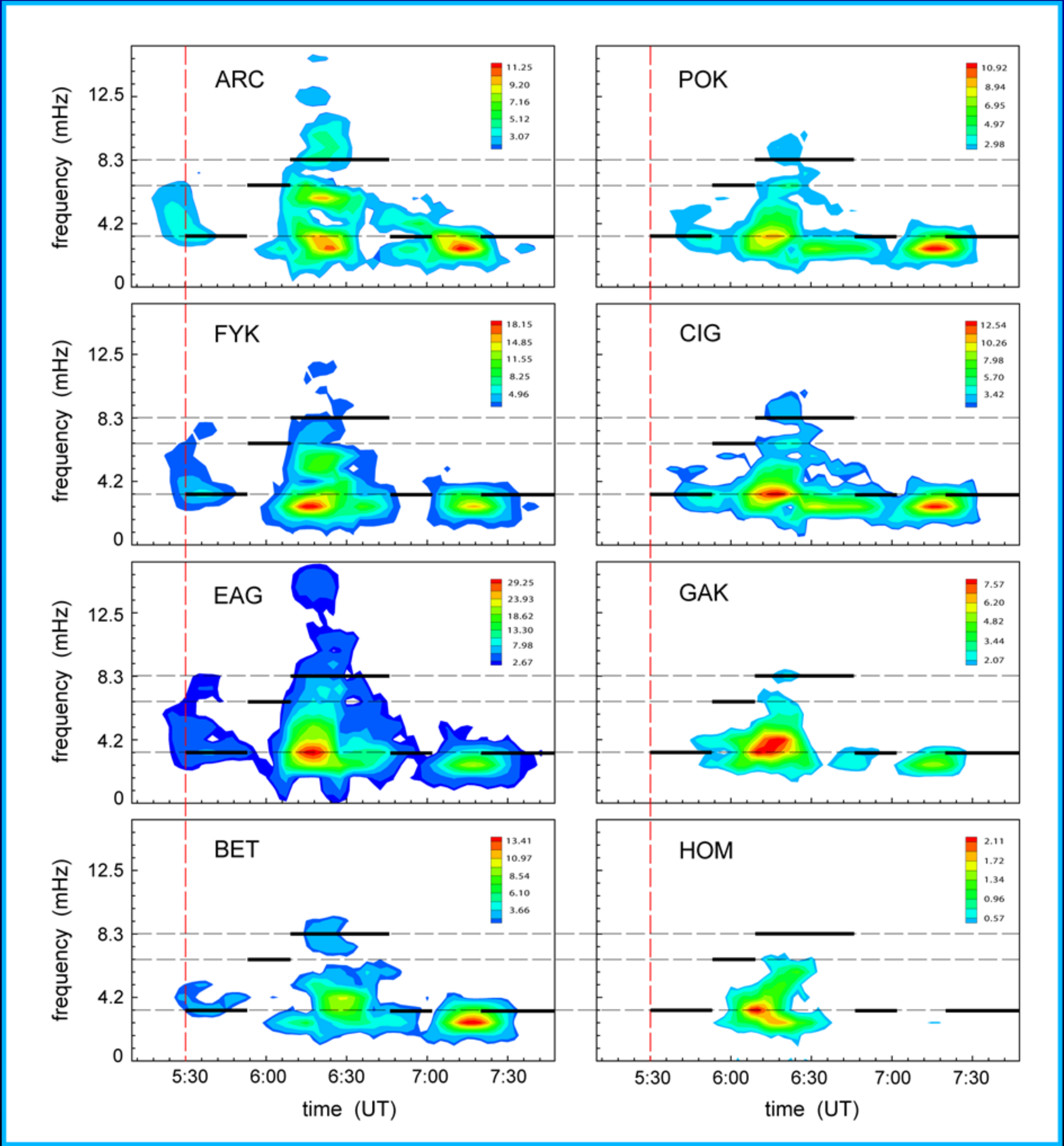
UAF/GI magnetometer array




Alaska Magnetometer Data Sites
Kaktovik
Village
Bettles
CIGO
Poker Flat
Eagle
Gakona



ARC
FYK
EAG
BET
POK
CIG
GAK
HOM
(nT)
500
0
-500
100
0
-100
5:00
6:00
7:00
8:00
time (UT)


ARC
POK
FYK
CIG
EAG
GAK
BET
HOM
frequency (mHz)
12.5
8.3
4.2
0
5:30
6:00
6:30
7:00
7:30
time (UT)
11.25
9.20
7.16
5.12
3.07
10.92
8.94
6.95
4.97
2.98
18.15
14.85
11.55
8.25
4.96
12.54
10.26
7.98
5.70
3.42
29.25
23.93
18.62
13.30
7.98
2.67
7.57
6.20
4.82
3.44
2.07
13.41
10.97
8.54
6.10
3.66
2.11
1.72
1.34
0.96
0.57