Simulation of VLF chorus emissions in the magnetosphere and comparison with THEMIS spacecraft data*

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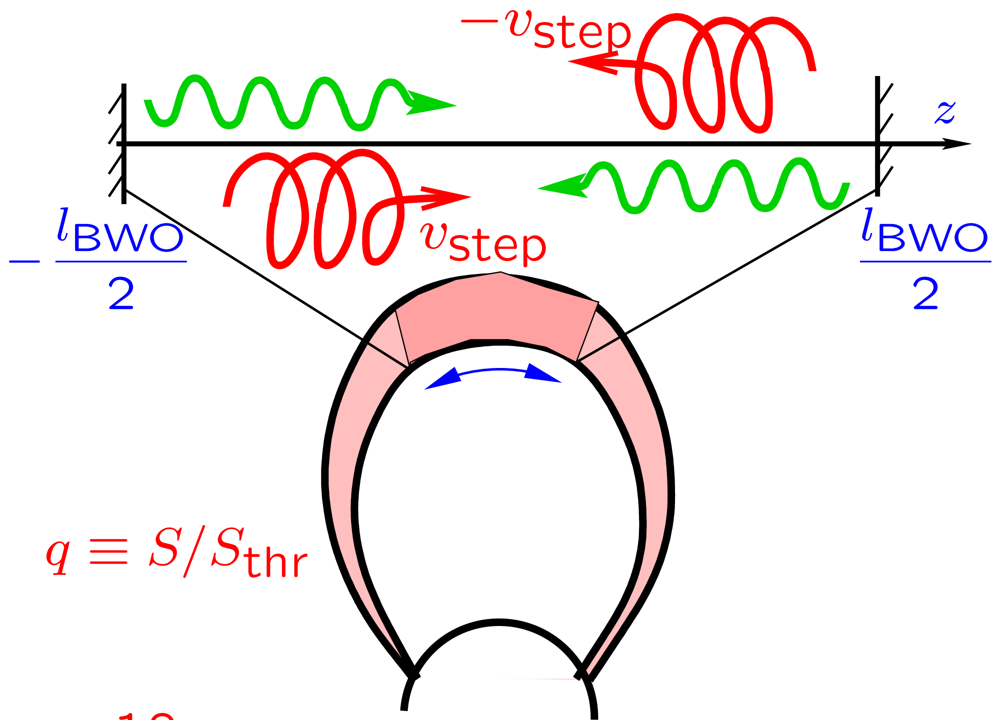
Хоровые излучения: модель лампы обратной волны (ЛОВ)

(*гиро*-ЛОВ = абсолютная *циклотронная* неустойчивость)

Нужна «ступенька» в пространстве скоростей

$$\Delta = \omega - \omega_B - kv_\parallel = 0; \quad kv_\parallel < 0$$



- длина области генерации (размер источника)

  $l_{\rm BWO} \approx (\lambda R_E^2 L^2)^{1/3} \sim 2000$ км

- характерный временной масштаб

  $T_{\rm BWO} \approx l_{\rm BWO}\left(\frac{1}{v_{\rm g}} + \frac{1}{v_{\rm step}}\right) \sim 0.03$ с

- инкремент неустойчивости

  $\gamma_{\rm BWO} \approx \frac{\pi}{T_{\rm BWO}}\left(q^{1/2} - 1\right) \sim 200\ \text{с}^{-1}, \qquad q \equiv S/S_{\rm thr}$

- характерная амплитуда

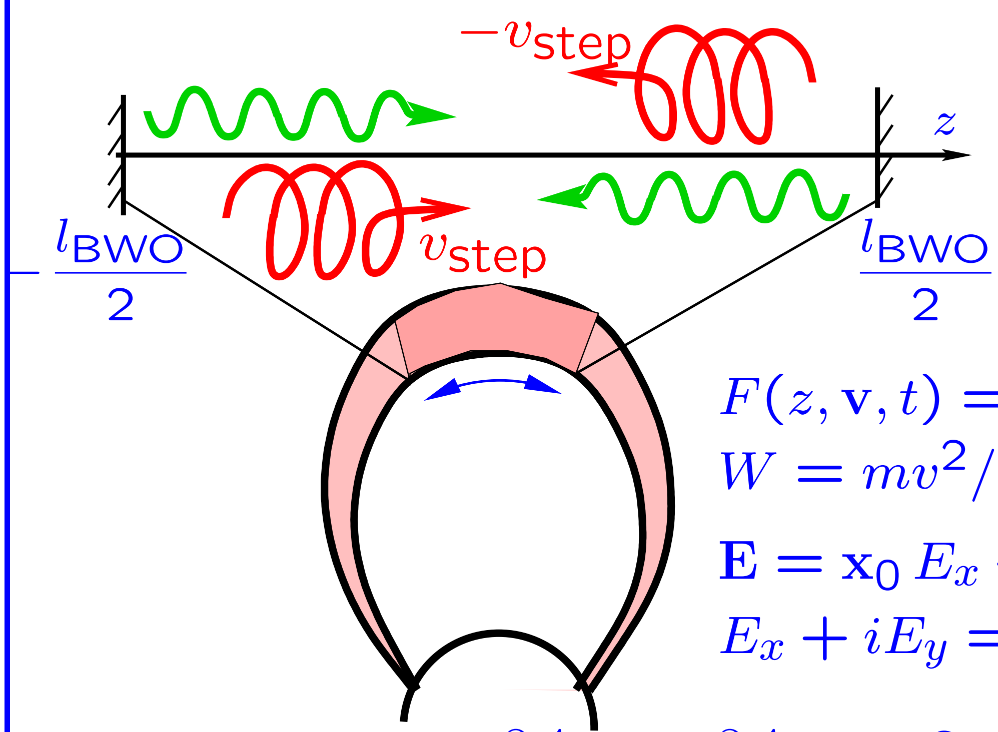
  $\Omega_{\rm tr}^2 = \frac{ekV_\perp B_{\rm w}}{mc} \approx 10\,\gamma_{\rm BWO}^2$, отсюда: $B_{\rm w} \approx \frac{10mc}{ekV_\perp}\gamma_{\rm BWO}^2 \sim 100$ пТл

- скорость дрейфа частоты

  $\frac{\Delta f}{\Delta t} \sim \frac{\Omega_{\rm tr}^2}{4\pi^2} \sim 0.3\,\gamma_{\rm BWO}^2 \sim 1.2 \cdot 10^4$ Гц/с $\approx 0{,}3\,\frac{\pi^2}{T_{\rm BWO}^2}(q^{1/2} - 1)^2$

(Trakhtengerts, 1995; 1999; Trakhtengerts et al., 2004; ср. df/dt с Omura et al., 2008)

Magnetospheric backward-wave oscillator: basic equations



characteristic scales:

$$l_{\rm BWO} = (\lambda R_E^2 L^2)^{1/3} \ll R_E L$$

$$T_0 = l_{\rm BWO}(v_{\rm step}^{-1} + v_{\rm g}^{-1})$$

$F(z,\mathbf{v},t) = F(z,W,I,\varphi,t)$,

$W = mv^2/2$, $I = v_\perp^2/2H$, $\varphi = (\widehat{\mathbf{v}_\perp\mathbf{E}})$.

$\mathbf{E} = \mathbf{x}_0\, E_x + \mathbf{y}_0\, E_y$,

$E_x + iE_y = A(z,t)\exp(i\omega t - ikz)$.

$$\frac{\partial A}{\partial t} + v_{\rm g}\frac{\partial A}{\partial z} = \frac{2\pi c}{v_{\rm g}} J; \qquad J := -e\int F\, v_\perp\, e^{i\varphi}\, \mathrm{d}^3\mathbf{v}$$

$$\frac{\partial F}{\partial t} + v_\parallel\frac{\partial F}{\partial z} = \frac{e}{m}\left(\mathbf{E} + \tfrac{1}{c}[\mathbf{v}\times\mathbf{B}]\right)\frac{\partial F}{\partial \mathbf{v}}$$

Simplification: $F_0 = \mathrm{step}(v_{\parallel\,0\,\rm eq} + V_*)$

$$F \simeq F_0 + \Phi(\varphi,z,t)\cdot\delta(v_{\parallel\,0\,\rm eq} + V_*)\cdot f_\perp(I)$$

Demekhov & Trakhtengerts, Radiophysics & Quantum Electronics, 2005; 2008

Simulations for THEMIS data (1)

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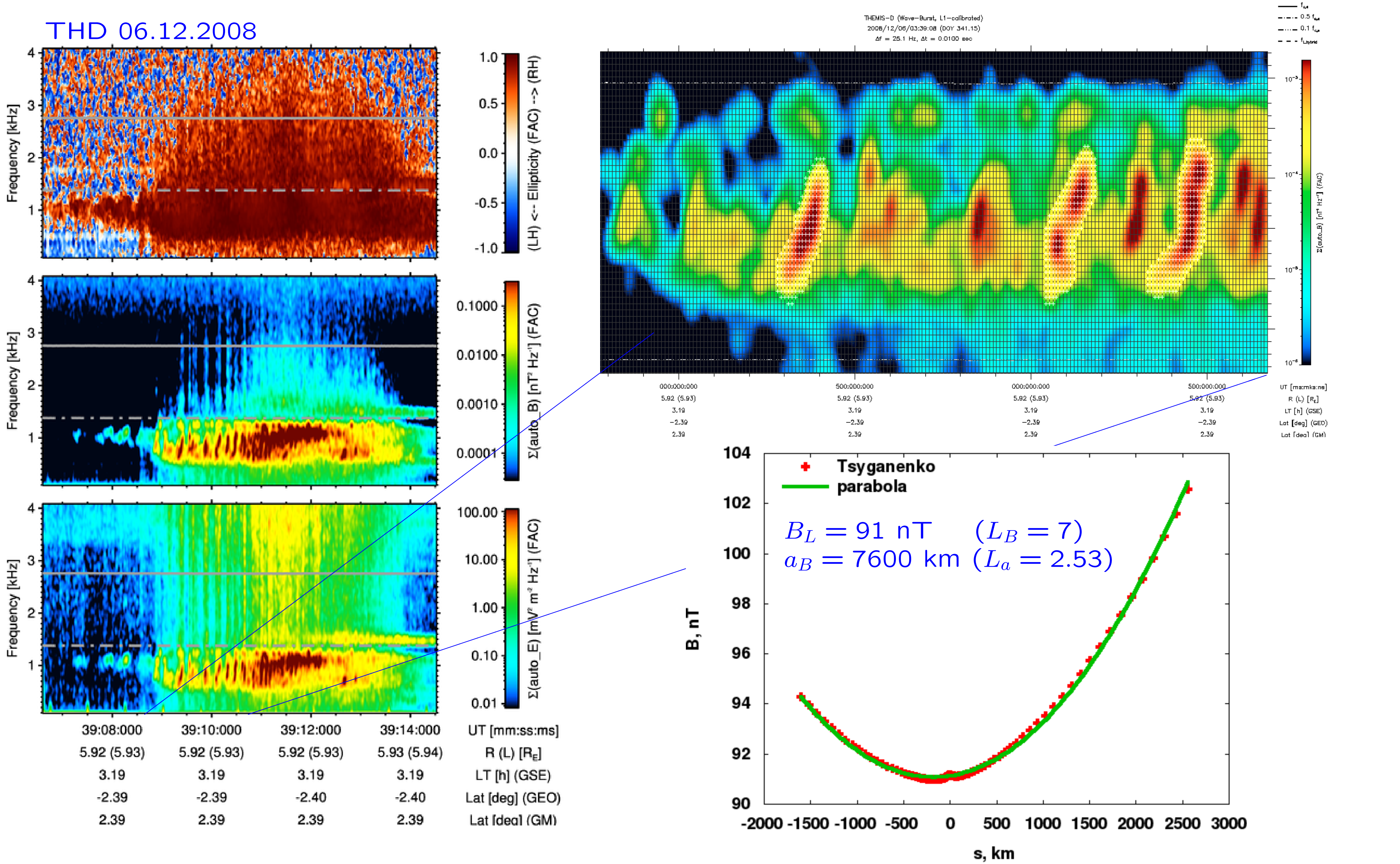
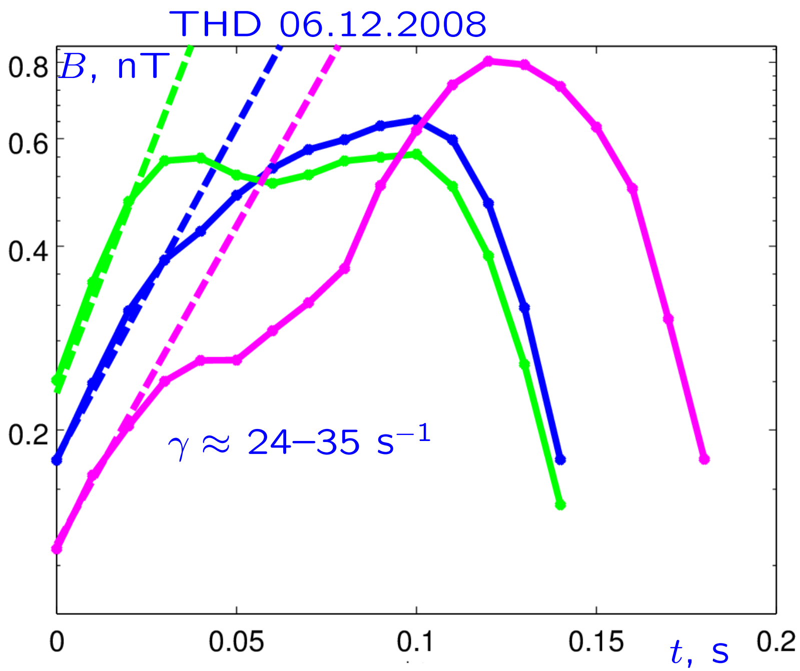
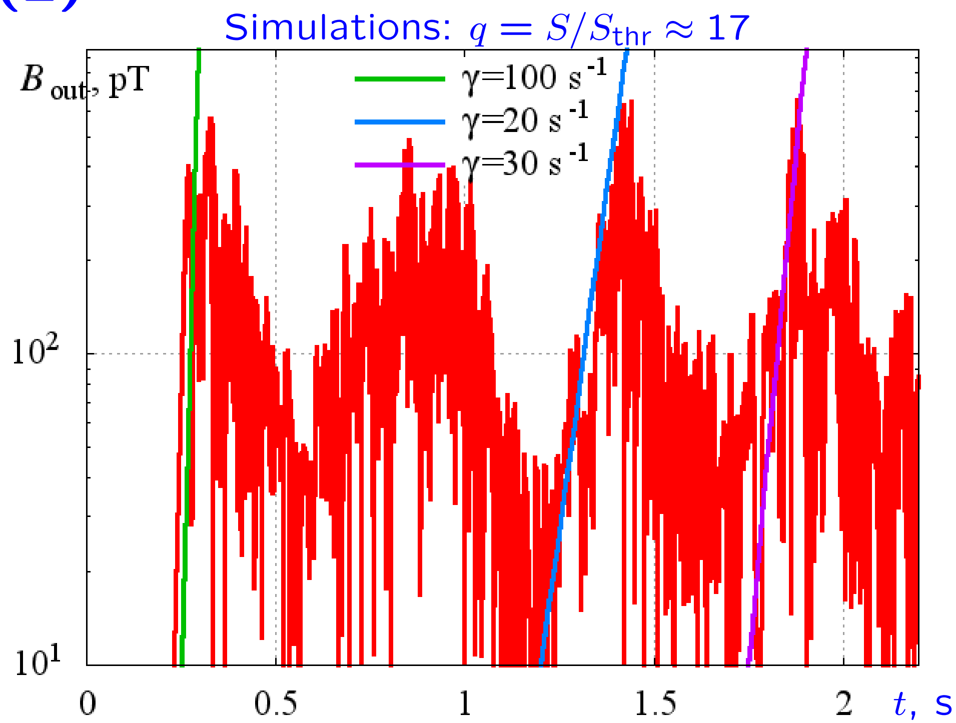


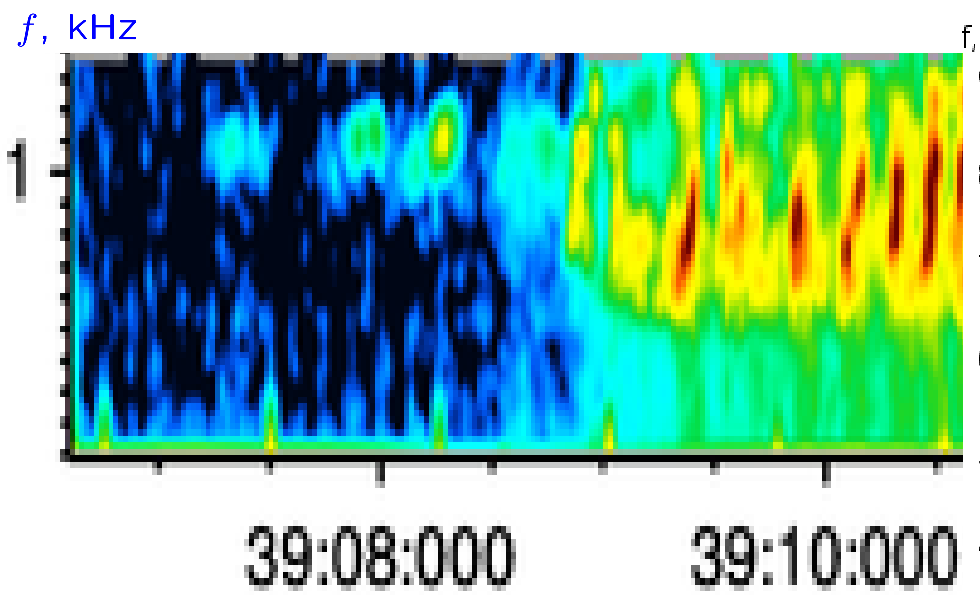
Simulations for THEMIS data (2)

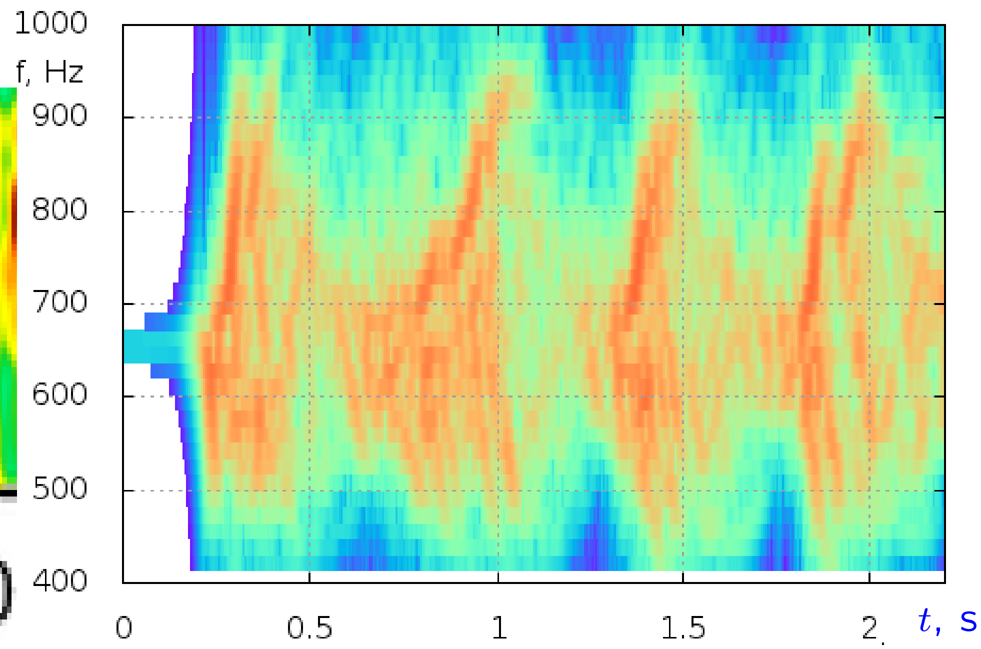




- Data: $L = 7$, $N_c \approx 5$ cm^{-3}, $f/f_B \approx 0.25$
- Choosing $q = S/S_{\mathrm{thr}} \approx 17$ we obtain the amplitude approximately matching the measured ones
- In this case, the simulated growth rate also approximately matches the measured one
- Note that the purely linear growth rate ($\gamma \sim 100$ s^{-1}) is 3–5 times larger than the growth rate of subsequent elements

Simulations for THEMIS data (3)

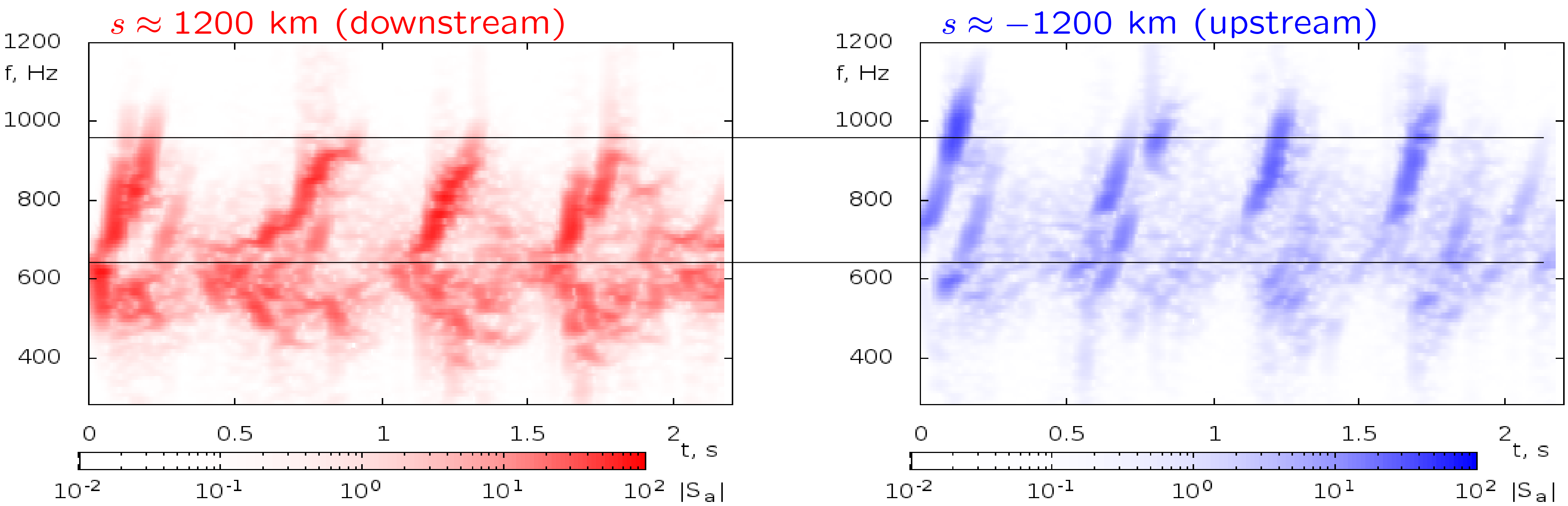




- Simulated and observed chorus elements have similar frequency-time structure
- The interval between the elements is about twice as smaller for the observed chorus than for the simulated signals

Simulations for THEMIS data (4)

Consider the spectra of waves upstream and downstream of equator

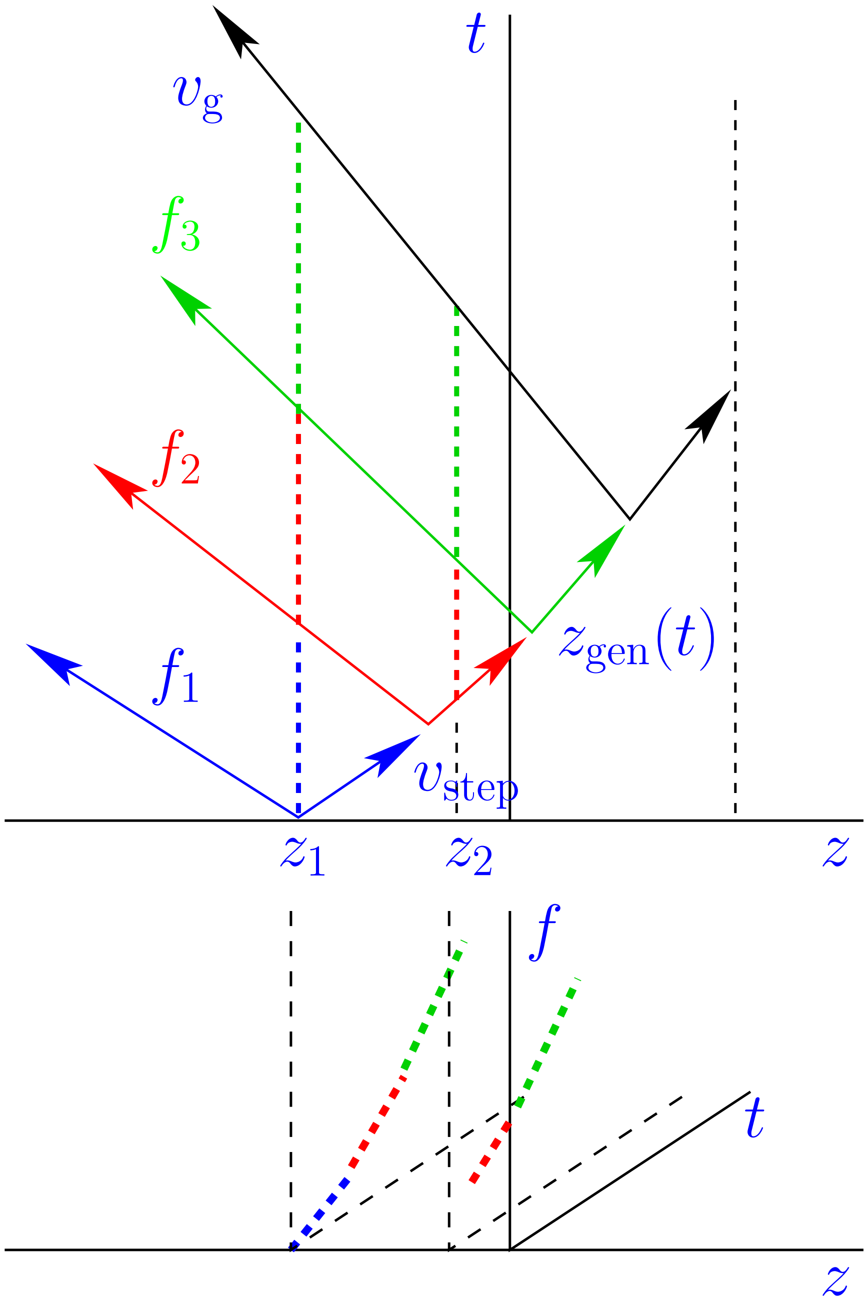


Simulation results show that wave spectra differ downstream and upstream of the equator:

upstream the frequency is higher and the elements are weaker.

This is due to the evolution of the electron distribution function (“step” motion) while electrons move in the generation region.

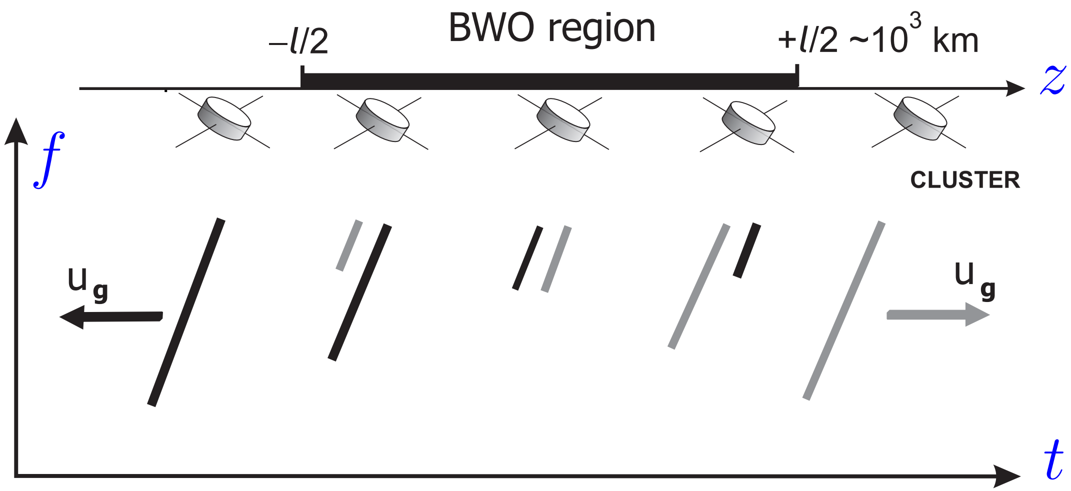
Формирование хорового элемента: качественная картина



$$\frac{\mathrm{d}v_{step}}{\mathrm{d}t} \approx -\frac{\Omega_{tr}^2}{2\pi k} - \frac{v_\perp^2}{2B}\frac{\mathrm{d}B}{\mathrm{d}z}$$

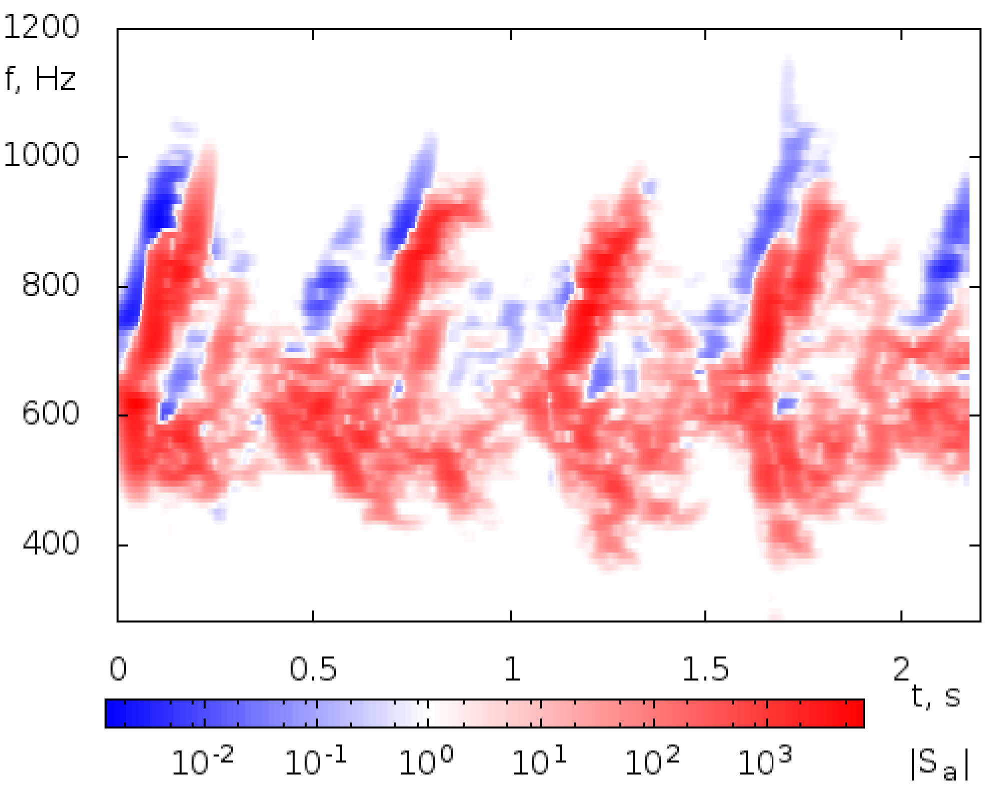
$$\omega_H(z_{gen}) - \omega = k v_{step}(z_{gen})$$

$$t(\omega, z) = \int_z^{z_{gen}} \frac{d\xi}{v_{step}(\xi)} + \int_z^{z_{gen}} \frac{d\xi}{v_g(\omega, \xi)}$$



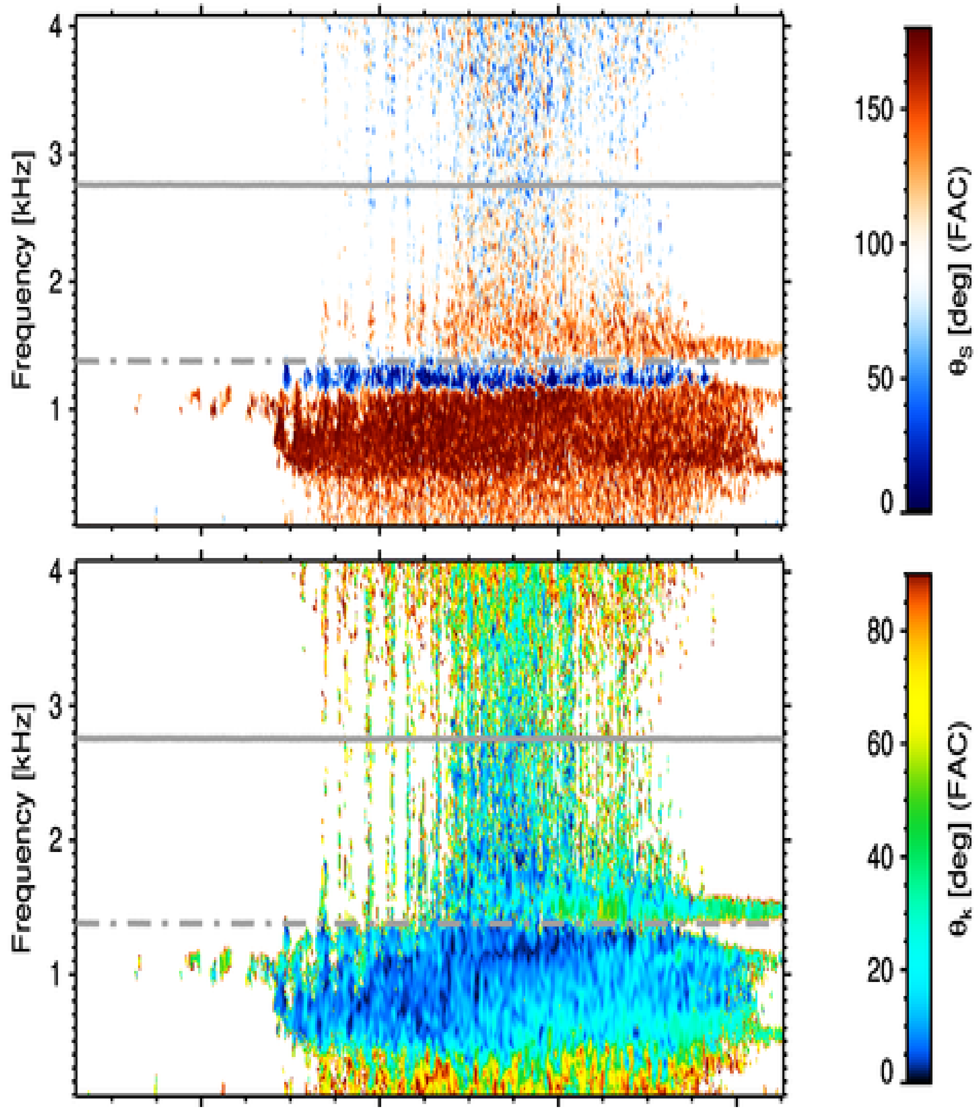
(Trakhtengerts et al, 2007)

Simulations for THEMIS data (5)



Combined picture for both wave directions at $s \approx 1200$ km:

If we distinguish the wave packets by Poynting flux direction, then we can expect higher-frequency and weaker wave packets to go towards the equator.



THEMIS data show an upper band of oppositely propagating waves just below a half of gyrofrequency.

ИПФ РАН

Выводы

- На примере данных THEMIS показано, что на основе данных об амплитуде хоровых ОНЧ излучений и параметрах фоновой плазмы и магнитного поля можно подобрать параметры модели ЛОВ, обеспечивающих воспроизведение инкремента, скорости дрейфа частоты и характерного интервала следования элементов.

- Продемонстрирована зависимость спектра хоровых элементов от положения точки наблюдения относительно экватора; на этой основе предложено объяснение наблюдаемого различия в направлениях распространения хоровых излучений, одновременно наблюдаемых в соседних частотных полосах.