Whistler-mode generation threshold in multicomponent plasma: THEMIS statistics and theoretical model

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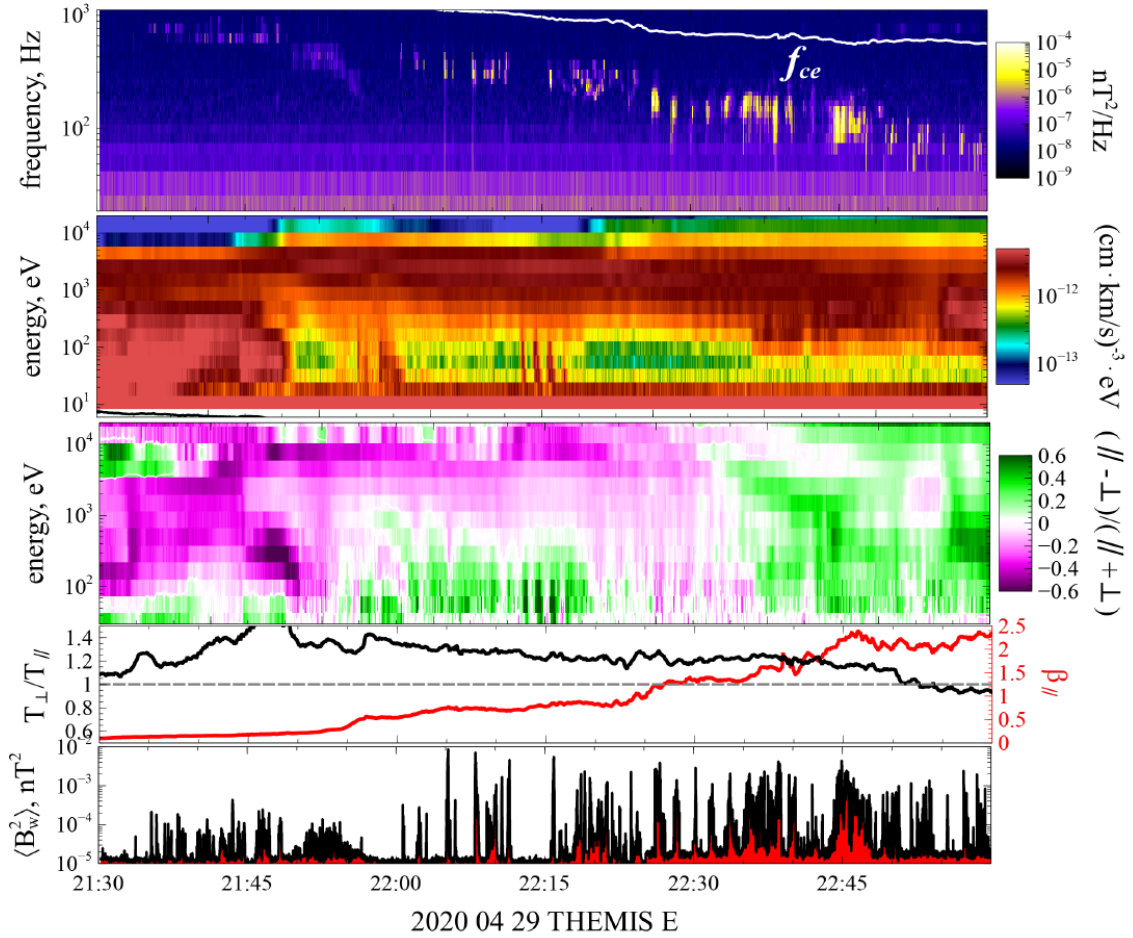
Motivation: As whistler-mode wave generation is controlled by electron temperature anisotropy (often estimated as the ratio of transverse and parallel electron temperature components, $T_{||}/T_{\perp}$) and electron flux magnitude (often estimated as the ratio of electron thermal pressure and magnetic field pressure, $\beta_{||}=8\pi n T_{||}/B^2$), two parameters $T_{||}/T_{\perp}$, β can characterize the free energy available for wave generation. For Maxwellian electron distributions the threshold of wave generation is determined by (see Gary & Wang 1996):

$$T_{\perp}/T_{||} = 1 + S_g/\beta_{||}^{A_g}$$

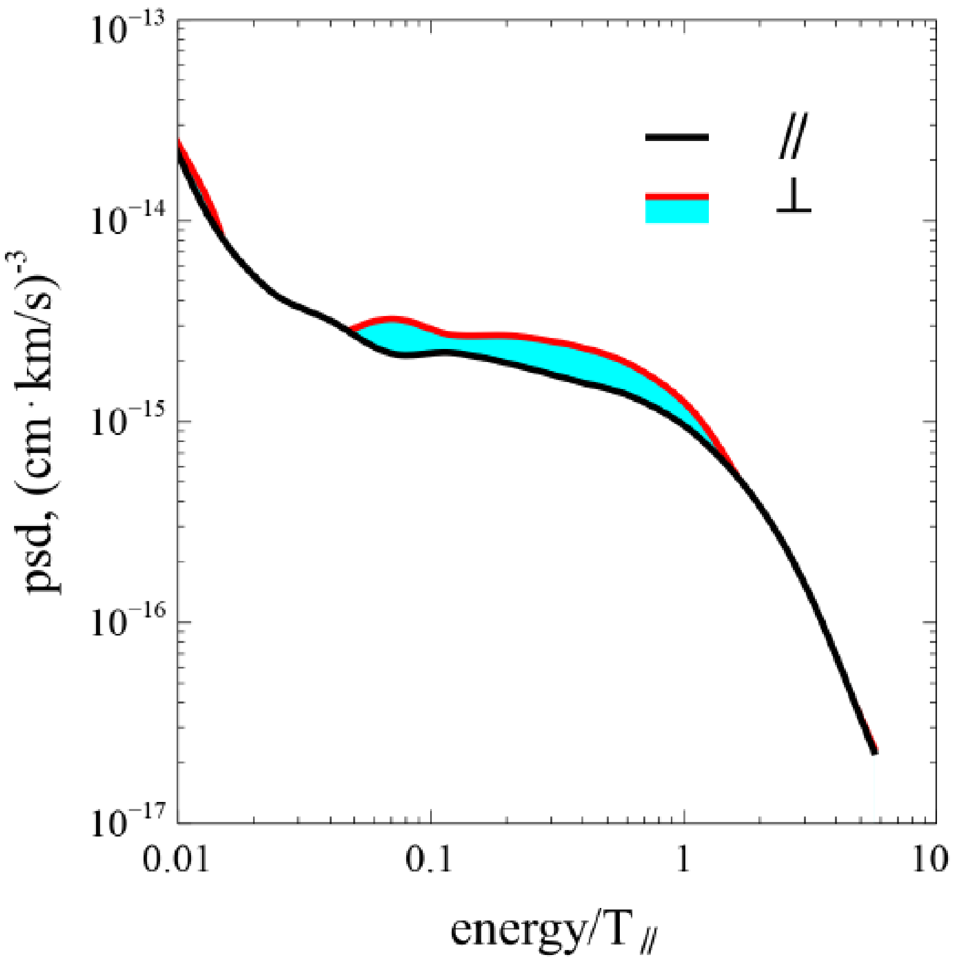
We aim to show the electron distributions associated with whistler-mode wave generation are multicomponent and then generalized the wave generation threshold for such realistic electron distributions.

THEMIS observations of electron distributions associated with whistler-mode waves in plasma sheet

The example of electron distribution observed around plasma injection region. Although thermal anisotropy is small, there is a certain energy range of anisotropic electrons that are likely responsible for generation of intense whistlers.



Flux anisotropy is present at a certain energy range, whereas cold and hot electron populations remain isotropic, or even parallel anisotropic.



Wave generation threshold for multicomponent plasma

$$\omega^2 = k^2c^2 + 2\pi\omega \sum_\alpha \omega_{p\alpha}^2 \iiint dv_\parallel dv_\perp \frac{v_\perp^3}{kv_\parallel - \omega + \Omega_{c\alpha}} \left[\frac{\partial f_{\alpha 0}}{\partial v_\perp^2} \left(1 - \frac{kv_\parallel}{\omega} \right) + \frac{\partial f_{\alpha 0}}{\partial v_\parallel^2} \frac{kv_\parallel}{\omega} \right]$$

$$\chi_r^2 = K^2 - \sum_\alpha \frac{\omega_{p\alpha}^2}{\Omega_c^2} \left(\varkappa_\alpha + \chi_r \frac{W_\alpha}{K a_\alpha} Z(\xi_\alpha) \right)$$

$$\chi_i = -\frac{\sqrt{\pi} \sum_\alpha \frac{\omega_{p\alpha}^2}{\Omega_c^2} \frac{W_\alpha}{K a_\alpha} e^{-\xi_\alpha^2}}{1 + \frac{K^2}{\chi_r^2} + \sum_\alpha \frac{\omega_{p\alpha}^2}{\Omega_c^2} \left(\frac{W_\alpha Z'(\xi_\alpha)}{K^2 a_\alpha^2} + \frac{\varkappa_\alpha}{\chi_r^2} \left(\frac{Z(\xi_\alpha)}{K a_\alpha} - 1 \right) \right)}$$

$$\varkappa_\alpha = \frac{T_{\perp\alpha}}{T_{\parallel\alpha}} - 1, \quad W_\alpha = 1 + \varkappa_\alpha \left(1 - \frac{1}{\chi_r} \right)$$

$$K = \frac{kc}{\Omega_c}, \; \chi_r = \frac{\omega_r}{\Omega_c}, \; \chi_i = \frac{\omega_i}{\Omega_c}, \; a_\alpha = \sqrt{\frac{2k_B T_{\parallel\alpha}}{m_e c^2}}$$

$$\beta_{\parallel\alpha} = \frac{n_\alpha k_B T_{\parallel\alpha}}{B_0^2/8\pi} = \frac{\omega_{p\alpha}^2}{\Omega_c^2} a_\alpha^2 \qquad N_\alpha = \frac{n_\alpha}{n}$$

$$\boxed{\begin{array}{l} \dfrac{T_\perp}{T_\parallel} - 1 = G \dfrac{\beta_\parallel - \beta_c - \beta_h}{\beta_\parallel} \\ G = \dfrac{S}{\beta_\parallel^A} \quad \begin{array}{l} S \approx S_g(1 - aN_c^b - c\beta_c) \\ A \approx A_g \end{array} \end{array}}$$

Conclusions

There are a lot of whistler-mode wave observations well within the stable region delimited by the threshold in anisotropic Maxwellian electron distribution (black curve), whereas a modified threshold equation (white curve) for multicomponent electron distribution more properly categorizes these observations for typical characteristics of cold electrons and beta of anisotropic electron population.

Whistler waves in the parametrical space where wave generation is impossible in anisotropic Maxwellian plasma, but is possible in multicomponent plasma.

(black curve)

$$\frac{T_\parallel}{T_\perp} = 1 + \frac{S_g}{\beta_\parallel^{A_g}}$$

(white curve)

$$\frac{T_\parallel}{T_\perp} = 1 + \frac{S_g}{\beta_\parallel^{A_g}} \cdot \left(1 - \frac{\beta_c + \beta_h}{\beta_\parallel}\right) \cdot \left(1 - aN_c^b - c\beta_c\right)$$

the occurrence rate of whistler-mode waves with an amplitude above 3pT