Electron Cyclotron Maser Model of Solar Radio Zebras

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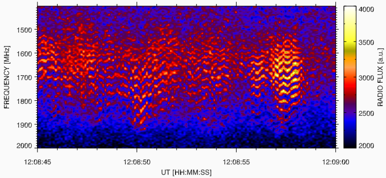
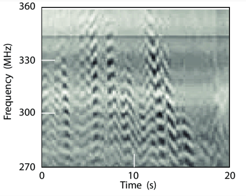
Solar radio zebras and spikes

Zebras

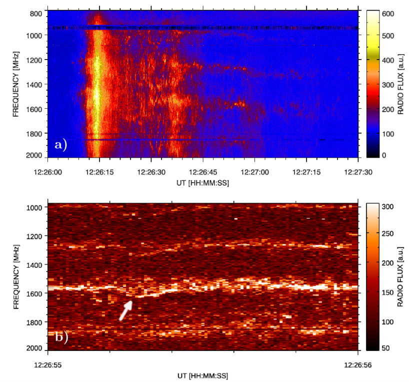


Jiřička & Karlický(2008)



Chernov (2010)

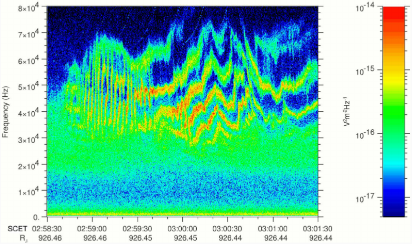
Spikes



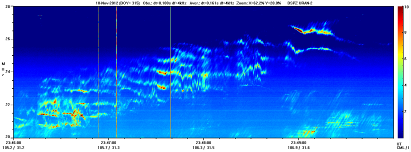
Karlický et al. (2021)

Radio zebra observations by space objects

Jupiter

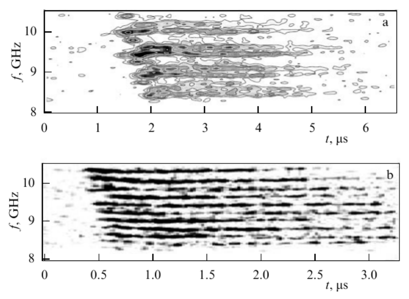


Kurth, Cassini RPWS Team, 2000



Rošker 2015

Pulsar in Crab nebula



Hankins & Eilek 2007

Electron-cyclotron maser (double plasma resonance)

Resonance between electron plasma and cyclotron frequency with presence of loss-cone unstable distribution.

Resonance

$$\omega_{\mathrm{pe}} - \frac{s\omega_{\mathrm{ce}}}{\gamma_{\mathrm{rel}}} - \frac{v_{||} k_{||}}{\gamma_{\mathrm{rel}}} = 0, \qquad (1)$$

which reduces for $v_{||} \to 0$, $\gamma \to 1$

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Upper-hybrid waves
(Bernstein waves)

$$\omega^2 = \omega_{\mathrm{pe}}^2 + \omega_{\mathrm{ce}}^2 + 3k_{\perp}^2 v_{\mathrm{tb}}^2 \quad (3)$$

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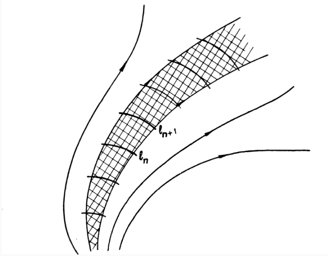


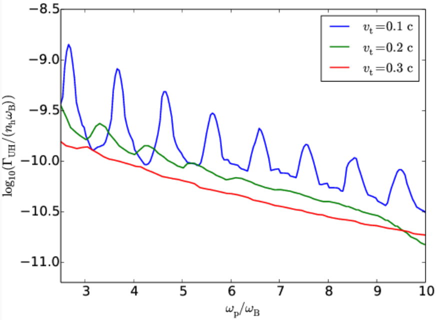
$$E_{\mathrm{E}}(t) \sim \exp(\Gamma t), \quad (4)$$

$$\Gamma = \Gamma(\omega_{\mathrm{pe}}, \omega_{ce}, f(\mathbf{v}), n_{\mathrm{h}}) \quad (5)$$

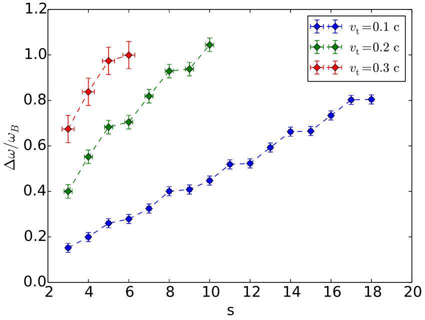
Zhelezniakov & Zlotnik (1975), Benáček & Karlický (2017)

Analytical growth-rates of the upper-hybrid waves

Growth rates



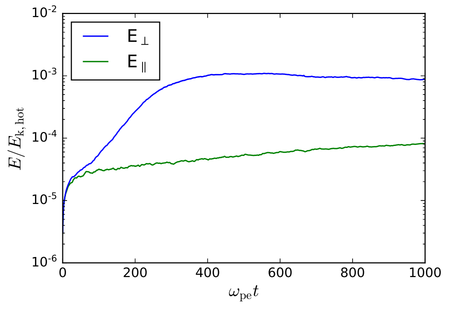
Frequency shifts



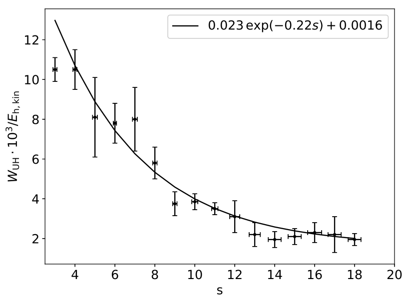
Benáček et al. 2017

PIC simulations of the double plasma resonance instability

Evolution of the electric energy



Saturation energy



$T_b \approx 10^{15} - 10^{17}$ K.

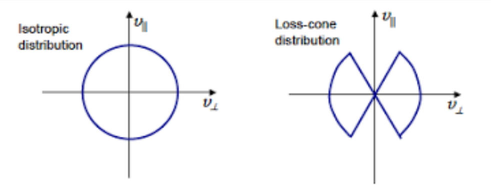
$L \approx 10 - 30$ km.

$\epsilon \approx 10^{-4} - 10^{-6}$ (Electrostatic $\rightarrow$ Electromagnetic)

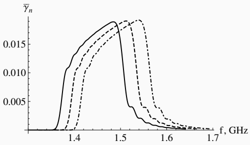
Beňáček & Karlický 2018

Growth-rates dependence on the loss-cone angle

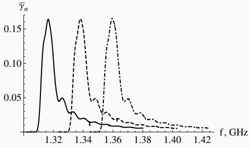
Maxwell, Kappa, and Power-law – loss-cone type of velocity distribution function



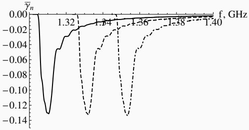
$\theta_{\rm c} = 10^{\circ}$



$\theta_{\rm c} = 50^{\circ}$



$\theta_{\rm c} = 80^{\circ}$



Yasnov, Benáček & Karlický 2019

Conclusions

- Radio zebras can be used for estimation of $n_{\mathrm{e}}, \mathbf{B}$ during zebra and spike events
- Main model is based on electron-cyclotron maser (double plasma resonance)
- We found frequency shifts of the growth rates, $\omega_{\mathrm{pe}} \neq s\omega_{\mathrm{B}}$.
- We used PIC simulations to study the evolution of the DPR instability and estimated electrostatic and electromagnetic energy density and emission power.