Double plasma resonance instability as a source of solar radio zebra emission

Jan Benáček[1,2], Marian Karlický[3], Leonid V. Yasnov[4]

September 8, 2021

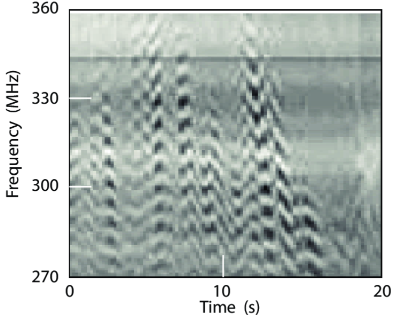
[1] *benacek@tu-berlin.de*, Center for Astronomy and Astrophysics, Technical University Berlin, Germany

[2] Department of Theoretical Physics and Astrophysics, Masaryk University, The Czech Republic

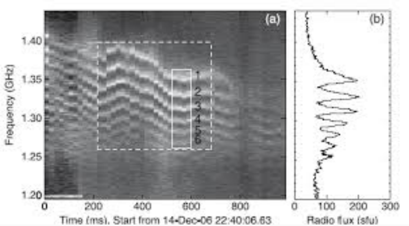
[3] Astronomical Institute, Academy of Sciences of the Czech Republic

[4] St.-Petersburg State University, Russia

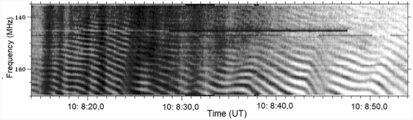
Solar radio zebras



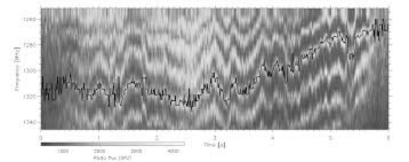
Chernov 2010



Chen et al. 2011



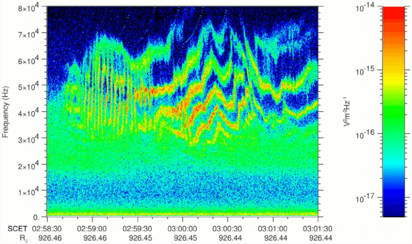
Zlotnik et al. 2003



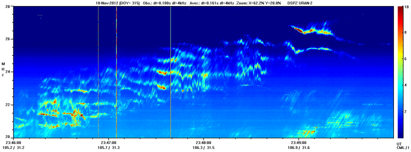
Karlický 2013

Other radio zebra observations

Jupiter

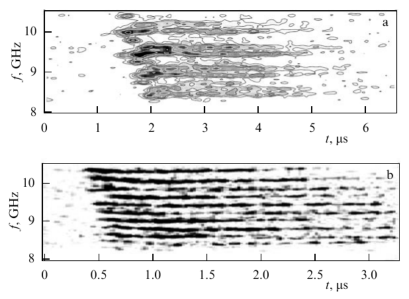


Kurth, Cassini RPWS Team, 2000



Rošker 2015

Pulsar in Crab nebula



Hankins & Eilek 2007

Double plasma resonance (DPR) instability model

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

Resonance

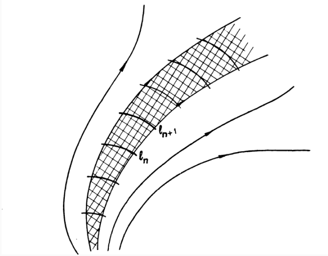
$$\omega_{\mathrm{pe}} - \frac{s\omega_{\mathrm{ce}}}{\gamma_{\mathrm{rel}}} - \frac{v_{\|}k_{\|}}{\gamma_{\mathrm{rel}}} = 0, \quad (1)$$

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

$$\omega_{\mathrm{pe}} \approx s\omega_{\mathrm{ce}} \quad (2)$$

Upper-hybrid waves (Bernstein waves)

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

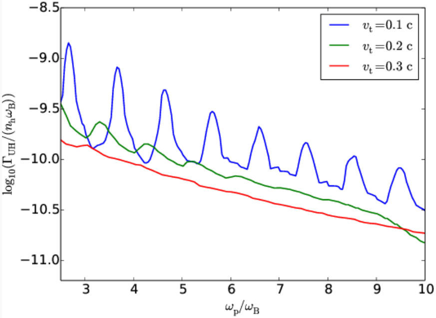


$$E_{\mathrm{E}}(t) \sim \exp(\Gamma t), \quad (4)$$

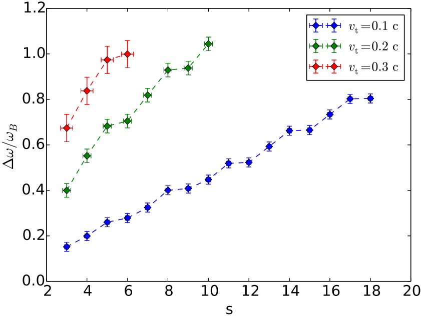
$$\Gamma = \Gamma(\omega_{\mathrm{pe}}, \omega_{ce}, f(\mathbf{v}), n_{\mathrm{h}}) \quad (5)$$

Analytical growth-rates of the upper-hybrid waves

Growth rates



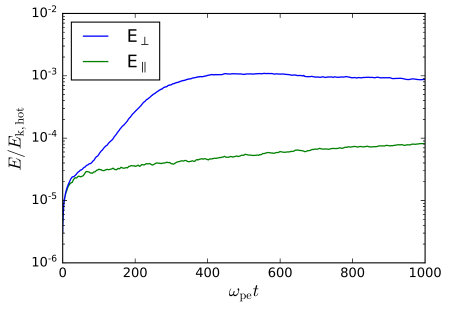
Frequency shifts



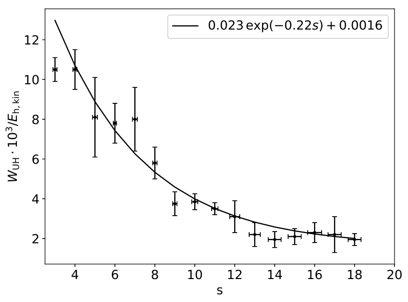
Benáček et al. 2017

PIC simulations of the double plasma resonance instability

Evolution of the electric energy



Saturation energy



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

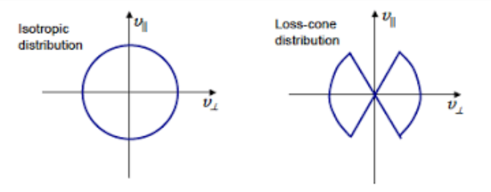
$L \approx 10 - 30$ km.

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

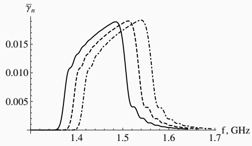
Beháček & Karlický 2018

Growth-rates dependence on the loss-cone angle

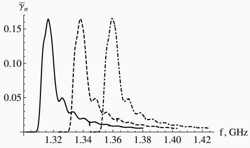
Maxwell, Kappa, and Power-law – loss-cone type of velocity distribution function



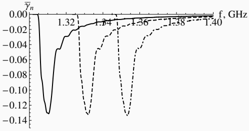
$\theta_\mathrm{c} = 10^\circ$



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



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



Yasnov, Benáček & Karlický 2019

Conclusions

- Radio zebras can be used for estimation of $n_{\mathrm{e}}, \mathbf{B}$.
- We found frequency shifts of the growth rates, $\omega_{\mathrm{pe}} \neq s\omega_{\mathrm{B}}$.
- The growth rates strongly denpends on the loss-cone propeties.
- We used PIC simulations to study the evolution of the DPR instability.
- Estimated the brightness temperatures, electric and electromagnetic energy density.