Solar radio zebra emission as a probe for plasma properties during solar flares

Jan Benáček[1,2], Marian Karlický[3]

1. Center for Astronomy and Astrophysics, Technical University of Berlin, Germany
2. Department of Theoretical Physics and Astrophysics, Masaryk University, Brno, Czech Republic
3. Astronomical Institute of the Czech Academy of Sciences, Ondřejov, Czech Republic

Introduction

Solar radio zebras are Type IV fine structure radio bursts. They are observed as frequency-narrow bands in radio spectrograms. They are assumed to be generated by plasma emission mechanism at harmonics of cyclotron frequencies,

They allow *precise estimations of plasma density and magnetic field* in the solar corona.

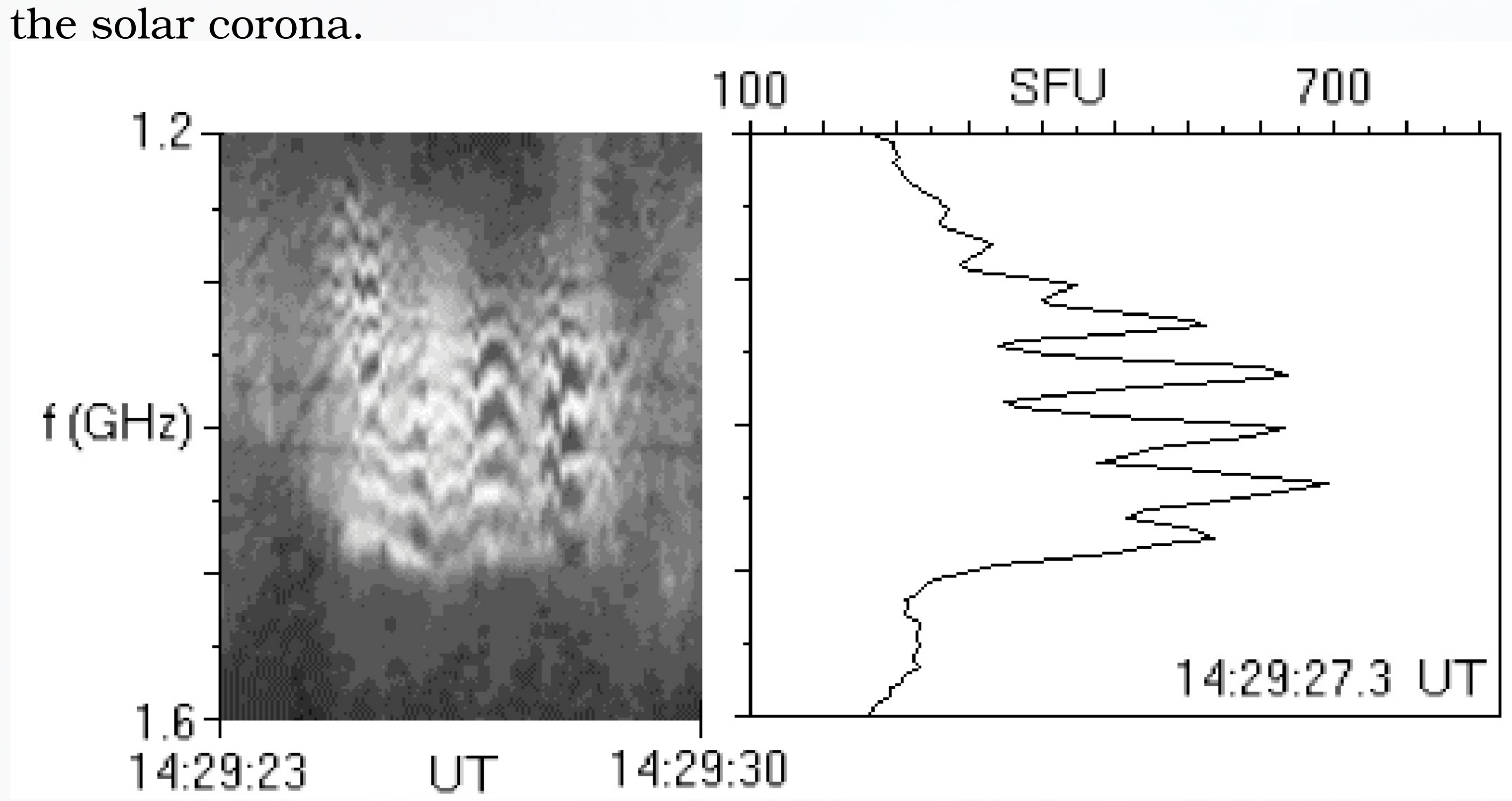

Figure 1: *Left*: An example of the zebra pattern observed during the 2 May 1998 solar flare. *Right*: The radio-flux profile as a function of frequency.

The double plasma resonance model assumes resonance between cyclotron and plasma frequencies, and generation of electrostatic waves with frequency ω and wavevector $\mathbf{k} = (k_\parallel, k_\perp)$

$$\omega - \frac{k_\parallel u_\parallel}{\gamma} - \frac{s\omega_B}{\gamma} = 0, \qquad (1)$$

where $u_\parallel$ is the parallel electron velocity, ω_B is the electron cyclotron frequency, and $\gamma = \sqrt{1 + u^2/c^2}$ is the Lorentz factor.

In plasma, consisting of the loss-cone type distribution of hot electrons with density n_h and much denser and colder background plasma with density n_e, this instability generates the Bernstein waves. Consequently, these waves are transformed into the electromagnetic waves and observed as radio zebras.

Model

We use fully electromagnetic relativistic PIC code TRISTAN with periodic boundary conditions. The model size was $\lambda\Delta \times \lambda\Delta \times 32\Delta$, where λ is the wavelength of the longest unstable wave generating instability. Usually $\lambda = 24 - 44$. Magnetic field is in z- direction and time step $\omega_{pe}\Delta t = 0.025$.

Background electrons have density $n_e = 1920$ PPC and Maxwellian distribution function for temperature $v_{tb} = 0.03$ c. Hot electrons have loss-cone DGH type of distribution

$$f_{hot}(u_\perp, u_\parallel) = \frac{u_\perp^2}{2(2\pi)^{3/2} v_t^5} \exp\left(-\frac{u_\perp^2 + u_\parallel^2}{2v_t^2}\right). \qquad (2)$$

with thermal velocity $v_t = 0.2$ c.

Results

We found that the saturation energy as well as the growth rates are proportional to the initial hot electron density (Figure 2).

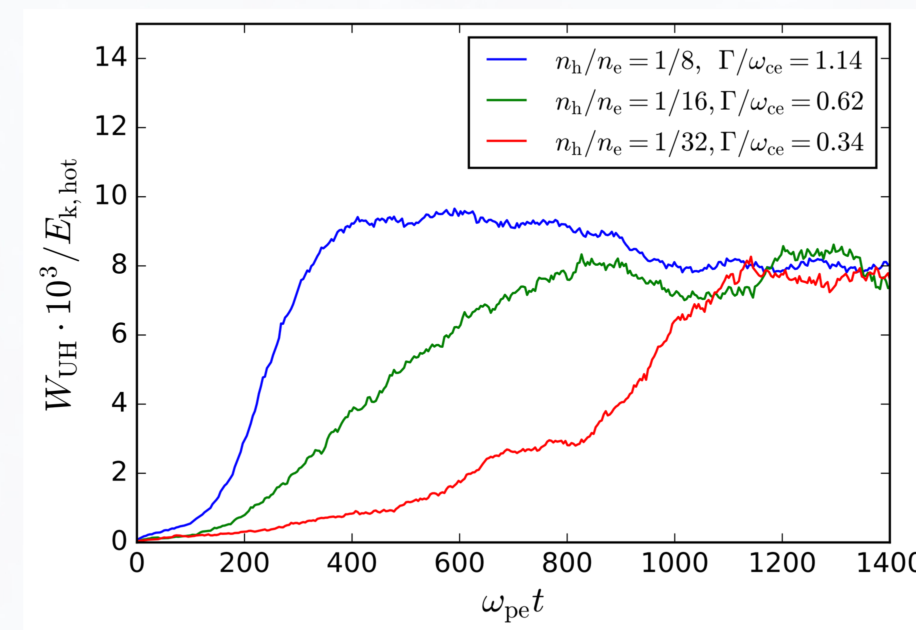

Figure 2: Time evolution of electric energy density for three different n_h/n_e ratios and for $\omega_{ce}/\omega_{pe} = 0.190$.

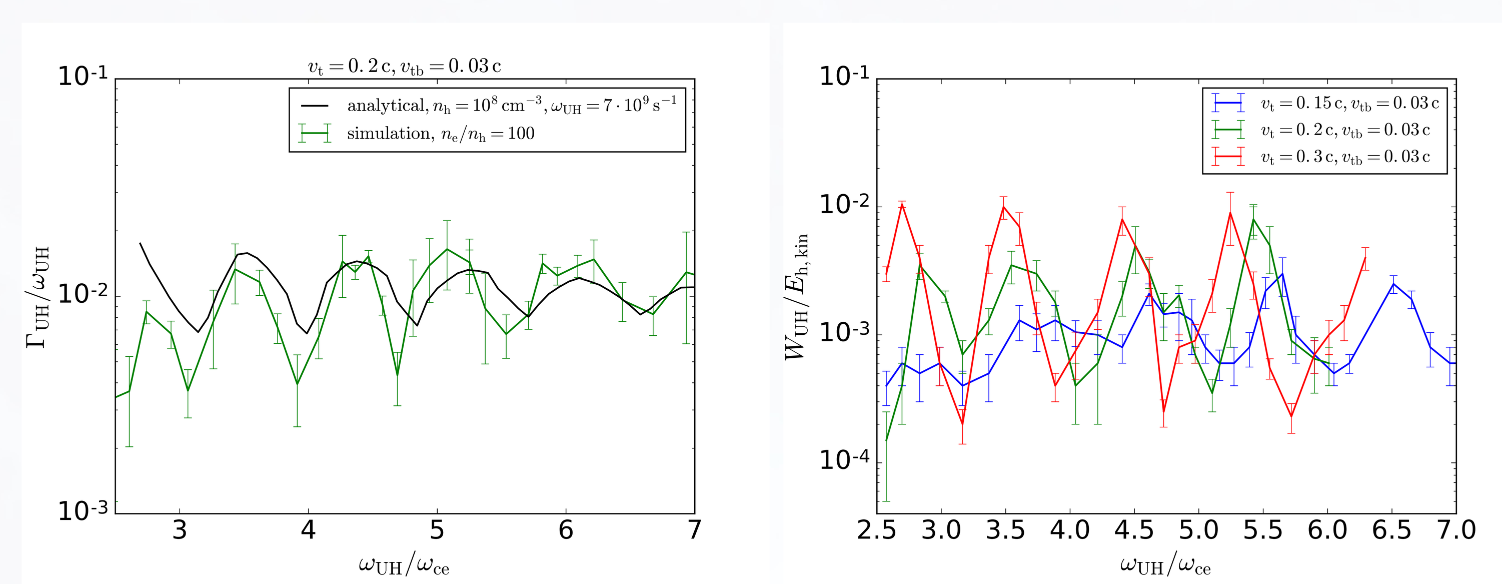

Figure 3: Left: Comparison of growth rates computed analytically and with usage PIC models. Right: Saturation energies normalized to initial kinetic energy of hot electrons for three different thermal velocities.

We compared growth rate computed analytically and those by PIC simulation in Figure 3 Left. Both the results show good conformance for broad range of frequency ratios.

We analyzed saturation energies that cannot be predicted by analytical theory from series of models for three hot electron thermal velocities in range $v_t = 0.15, 0.2, 0.3$ c, each for $\omega_{pe}/\omega_{ce} = 2.5 - 7$ (Figure 3 Right). The evolution of velocity distribution is on Figure 4.

All these findings are used for estimation of radio source properties for 2 May 1998 event. We assume that the region has angular size 2 arcsec and corona scale height 1 Mm. The estimated observed electromagnetic energy density and electrostatic energy density from the simulation allowed us to estimate conversion efficiency of this instability. Selected properties are summarized in Table 1.

SolFER Spring 2021 Meeting, 24 - 26 May 2021, Virtual

Contact: benacek@tu-berlin.de

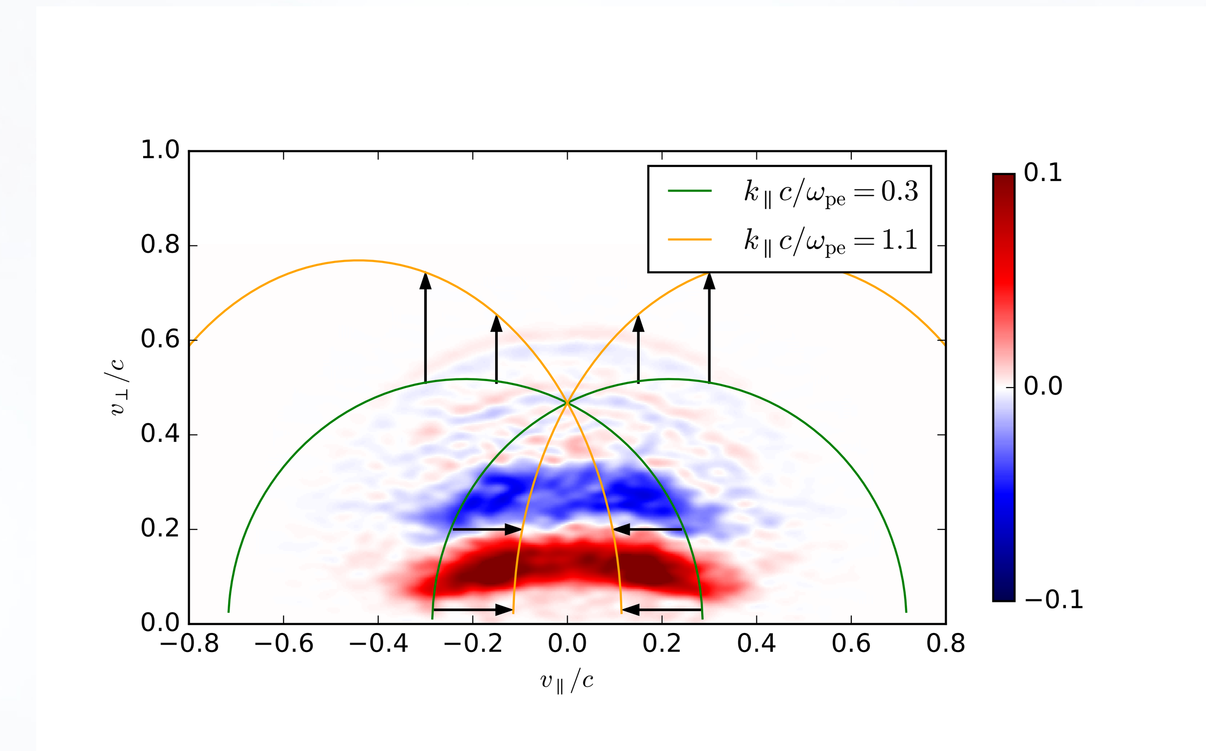

Figure 4: Difference between final and initial velocity distribution. Red regions: Distribution increases. Blue regions: Distribution decreases. The lines represent resonance ellipses. Arrows indicate shifts of ellipses with increasing wavenumber $k_\parallel$.

Table 1: Found source parameters for event from Figure 1.

		ZP 2 May 1998
Event location		S15W15
Radio flux	[sfu]	650
Frequency	[GHz]	1.45
Harmonic number		21
Emission angle	[arcsec]	2.70
Source length	[km]	23
Source height	[km]	28
Plasma density	[cm^{-3}]	2.6×10^{10}
Hot electron density	[cm^{-3}]	1.28×10^{13}
Magnetic field	[G]	2.3
T_b	[K]	8.3×10^{15}
W_{elm}	[J m^{-3}]	2.57×10^{-9}
W_{UH}	[J m^{-3}]	5.41×10^{-5}
Conversion efficiency		4.75×10^{-5}

References

Benáček, J., Karlický, M., Yasnov, L. V. 2017, A&A, 598, A106
Benáček, J., Karlický, M., 2018, A&A, 611, A60
Benáček, J., Karlický, M. 2019, ApJ, 881, 21.
Yasnov, L. V., Benáček, J., Karlický, M. 2017, Sol. Phys., 292, 163
Yasnov, L.V., Benáček, J., Karlický, M.: 2019, Sol. Phys., 294, 29.
Zhelezniakov, V. V., Zlotnik, E. I. 1975, Sol. Phys., 43, 431