Electromagnetic wave radiation in turbulent magnetized and inhomogeneous plasmas : theory and simulations

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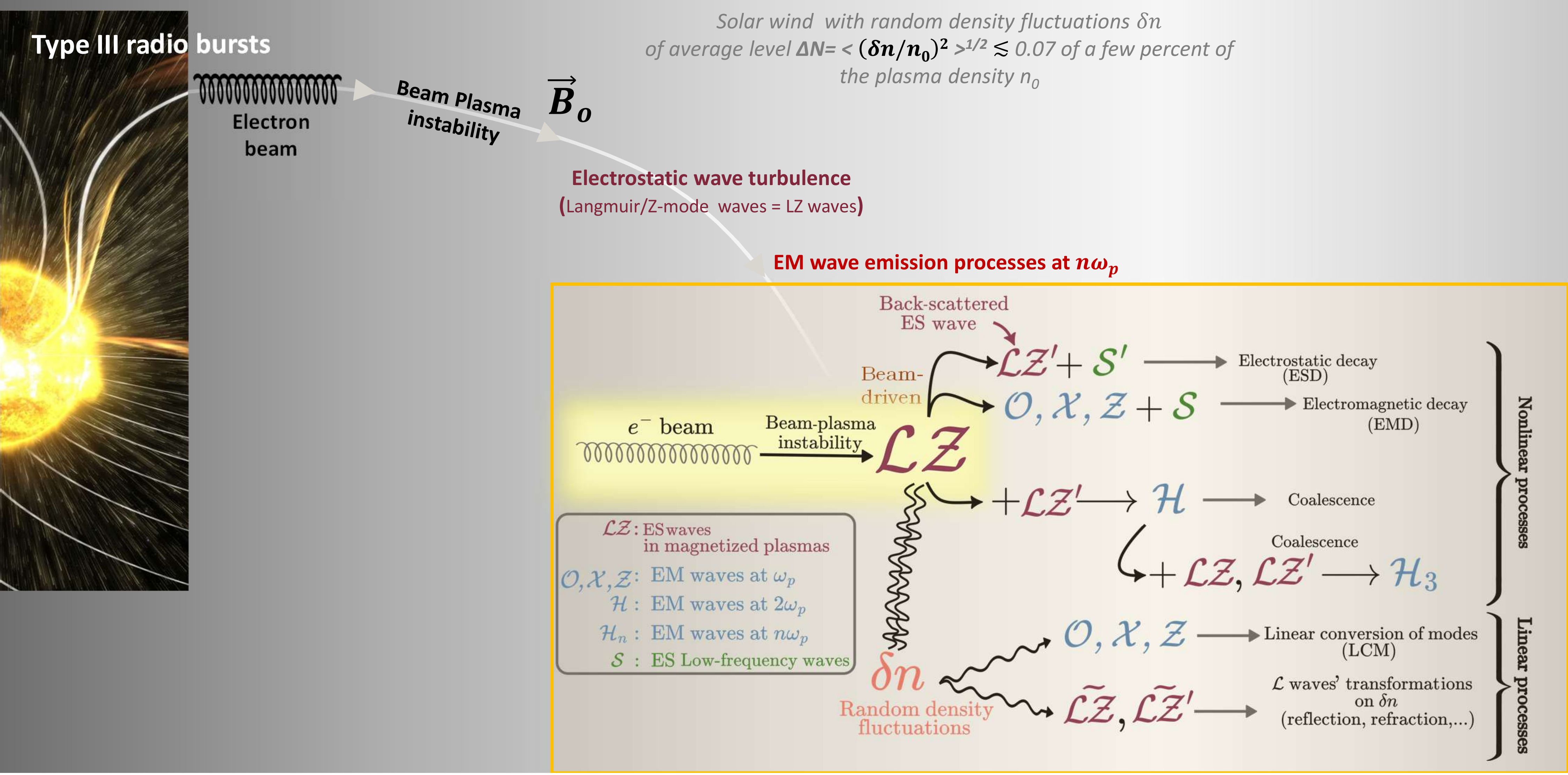
Mechanisms of electromagnetic wave radiation by type III solar radio bursts



Objectives

QUESTIONS

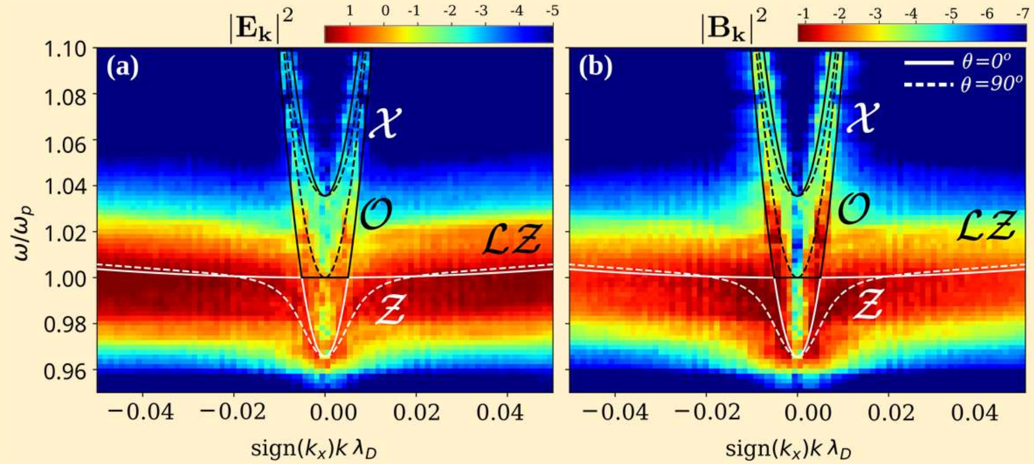
- What are the dominant processes of EM wave radiation at ω_p by beam-driven LZ wave turbulence in weakly to moderately magnetized and randomly inhomogeneous plasmas ?
- What are the radiation rates and energies of EM waves in the modes O, X and Z ?
- What is the impact of density fluctuations and magnetization on EM radiation ?

3 INDEPENDENT METHODS leading to similar results

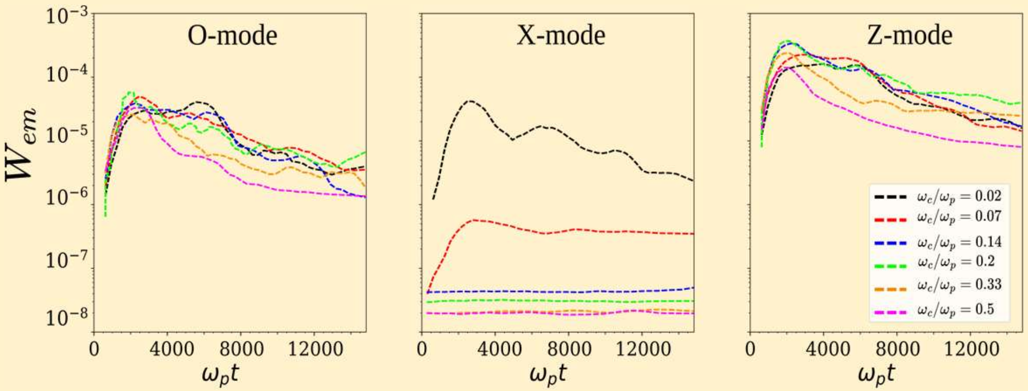
- Large-scale, long-term , and high-resolution 2D/3V PIC simulations
- 2D theoretical and numerical model
- 3D analytical calculations in the framework of weak turbulence theory extended to randomly inhomogeneous plasmas

(with parameters relevant to type III solar radio bursts)

First method : 2D/3V PIC simulations



Dispersion of electric and magnetic spectral energies ($\omega_c/\omega_p = 0.07$ and $\Delta N = 0.025$)



Time variations of energies of O, X and Z modes for $0 \leq \omega_c/\omega_p \leq 0.5$ and $\Delta N = 0.05$ (normalized by the initial beam energy)

LZ wave turbulence

- Spectral broadening of LZ waves : $\Delta\omega \approx \omega_p \Delta N$ due to density fluctuations
- LZ waves follow dispersion curves but are shifted to lower frequencies due to their trapping in density depletions :

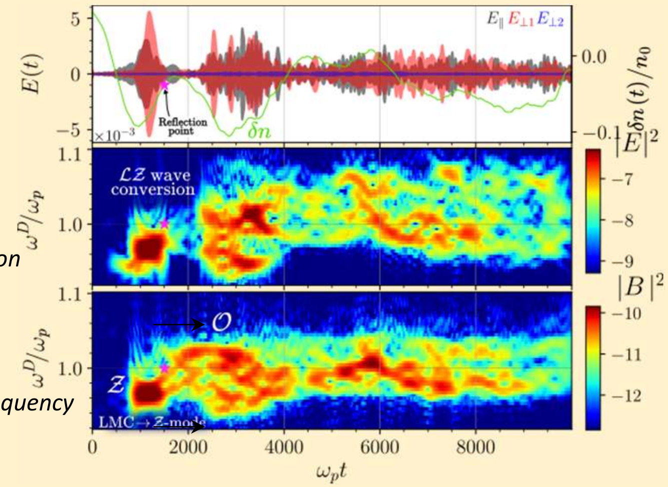
EM waves radiated by LMC process at constant frequency

- Z-mode waves are excited down to their cutoff frequency (100% left-handed polarization)
- Z-mode waves have the largest energies and radiation rates for any $\omega_c/\omega_p \leq 0.5$
- O-mode waves are emitted with energies one order of magnitude below Z-mode waves
- X-mode waves are not excited for $\omega_c/\omega_p > 0.07$
  significantly excited for $\omega_c/\omega_p = 0.02$,

in agreement with our analytical results, i.e. X-mode is emitted only if $\omega_c/\omega_p \lesssim \alpha\Delta N$

LZ wave in density depletion

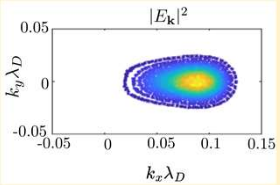
Z-mode wave radiated at same frequency



Example of LMC process in PIC simulations

Second method : New theoretical/numerical model for EM radiation at ω_p

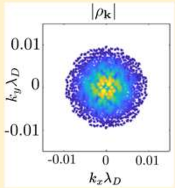
t=0



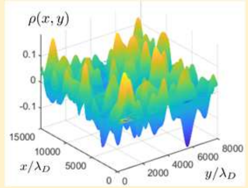
Electric energy spectrum

LZ wave turbulence in a 2D weakly magnetized plasma with applied density fluctuations δn (no beam)

Zakharov equations with $\omega_c > 0$

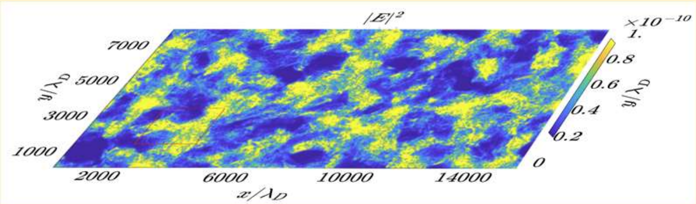


Density fluctuations' spectrum



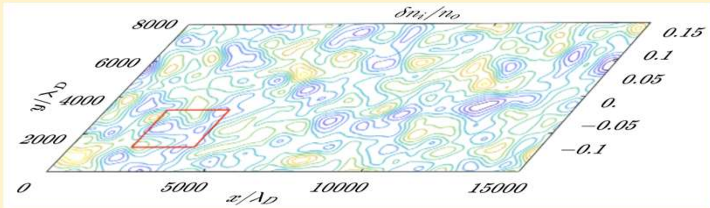
Space distribution of $\delta n(x,y)$

t > 0



Space distribution of electric energy

current $\delta\vec{\mathbf{j}}(\vec{r},t)$ due to LZ waves' transformations on δn



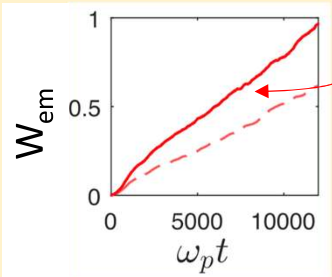
Space distribution of ion density

EM waves

Homogeneous plasma

$$\left(i\frac{\partial}{\partial t}+\frac{\omega_p-\overbrace{\omega_{\mathbf{k}}^{\pm}}^{\text{wave dispersion}}}{\omega_p}\right)\underbrace{B_{\mathbf{k}}^{\pm}}_{\text{Amplitude of wave magnetic field envelope of X (+) and Z (-) modes}}\simeq-\frac{2\pi c}{\omega_p}\underbrace{\mathbf{a}_{\mathbf{k}}^{\pm *}}_{\text{Polarization vector}}\cdot\left(\mathbf{k}\times\underbrace{\delta\mathbf{j}_{\mathbf{k}}^{\pm}}_{\text{depends on } \boldsymbol{E} \text{ and } \delta n}\right)$$

Numerical solutions : time variation of electromagnetic energy W_{em}



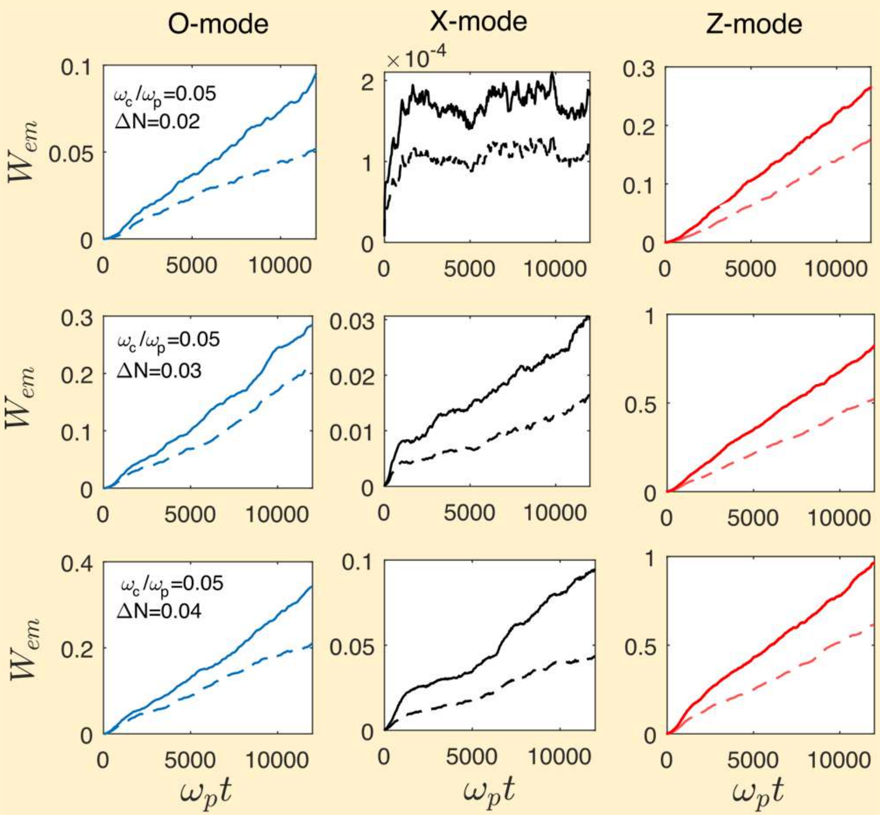
Radiation rate $\mu^{\pm}$

= slope at asymptotic time

Model's main assumptions

- All Transformations of ES waves on δn included with no assumptions (scattering, reflection, refraction, tunneling, linear mode conversion LMC, …)
- No averaging on random wave phases
- Weak ponderomotrice effects
- Non self-consistent model

Theoretical/numerical model : results



Time variations of electromagnetic energy for ω_c/ω_p =0.05 and various ΔN and c/v_T

- Energy and radiation rates of Z-mode waves are the largest ones
- O-mode waves have smaller rates and energies than Z-mode waves
- Upper row : $\omega_c/\omega_p > \alpha\Delta N$: no X-mode emission (α ≈1-2)
  Middle row : $\omega_c/\omega_p \approx \alpha\Delta N$: small X-mode emission
  Bottom row : $\omega_c/\omega_p < \alpha\Delta N$: larger X-mode emission
- Same results with other ω_c/ω_p , *ΔN and c/v_T*
- Same results as PIC simulations

Third method : Analytical calculations in the framework of weak turbulence theory extended to randomly inhomogeneous plasmas (3D geometry)

Necessary condition for X and Z mode radiation via LMC

$$k_{\pm}^2\lambda_D^2 = \frac{2v_T^2}{c^2}\left(3k_2^2\lambda_D^2 \mp \frac{\omega_c}{\omega_p}\right) > 0$$

X (+), Z(-)

$k_-^2 > 0 \longrightarrow$ Z-mode radiation

$k_+^2 < 0 \longrightarrow$ No X-mode radiation for $\frac{\omega_c}{\omega_p} \gtrsim \alpha\Delta N$ (α ~1-2)

$k_+^2 > 0 \longrightarrow$ X-mode radiation for $\frac{\omega_c}{\omega_p} \lesssim \alpha\Delta N$

Radiation rates $\boldsymbol{\mu}^{\pm}$ of X and Z-modes magnetic energy in randomly inhomogeneous and weakly magnetized plasmas with $\omega_c/\omega_p < 0.2$

$\mathbf{k}_2$ (k_2, θ_2, ψ_2) : wavevector of LZ waves

$$\mu^{\pm} \simeq \frac{V}{\pi\lambda_D^3}\left(\frac{v_T}{c}\right)^3 \int_V \frac{d^3\mathbf{k}_2}{(2\pi)^3}\left|\frac{\delta n_{-\mathbf{k}_2}(t)}{n_o}\right|^2 \left|\mathbf{E}_{\mathbf{k}_2}(t)\right|^2 \left(3k_2^2\lambda_D^2 \mp \frac{\omega_c}{\omega_p}\right)^{\frac{3}{2}} \left(\sin^2\theta_2\left(1 \pm 2\frac{\omega_c}{\omega_p}\right) + \frac{\cos^2\theta_2}{15}\right)$$

temperature scaling — *spectrum of density fluctuations* — *spectrum of LZ wave energy*

$\cos\theta_2 = \boldsymbol{B}_0 \cdot \boldsymbol{k}_2 / \mathrm{B}_0 \mathrm{k}_2$

The radiation rates can be calculated by numerical integration if both LZ wave energy and density fluctuation spectra are known.

Conclusions

The three independent methods used converge to the same results, which are :

- LMC is the dominant process of EM radiation at ω_p by beam-generated LZ wave turbulence in randomly inhomogeneous and weakly magnetized plasmas (0.1-1 au).
- Most important part of EM radiation at ω_p is emitted in the Z-mode, at frequencies $\omega_{cZ} \lesssim \omega \lesssim \omega_p$ down to the cutoff ω_{cZ}, where polarization is 100% left-handed ; this radiation remains inside or close to the radio source.
- Only about 10% or less of EM energy radiated is escaping from the radio source, in the form of O-mode waves mainly.
- X-mode waves are only emitted in plasmas with $\omega_c/\omega_p \lesssim \alpha\Delta N$.
- Radiation rates are determined analytically and computed numerically using LZ waves' and density spectra.
- This work can provide strong support to interpretation of observations by spacecraft as Solar Orbiter and Parker Solar Probe.
- Results can help to localize radio sources or diagnose solar wind plasmas.

C. Krafft et al., Nature Astronomy, in press, 2025

Thanks for your attention