Kinetic simulation of the electron-cyclotron maser instability: *effect of a finite source size*

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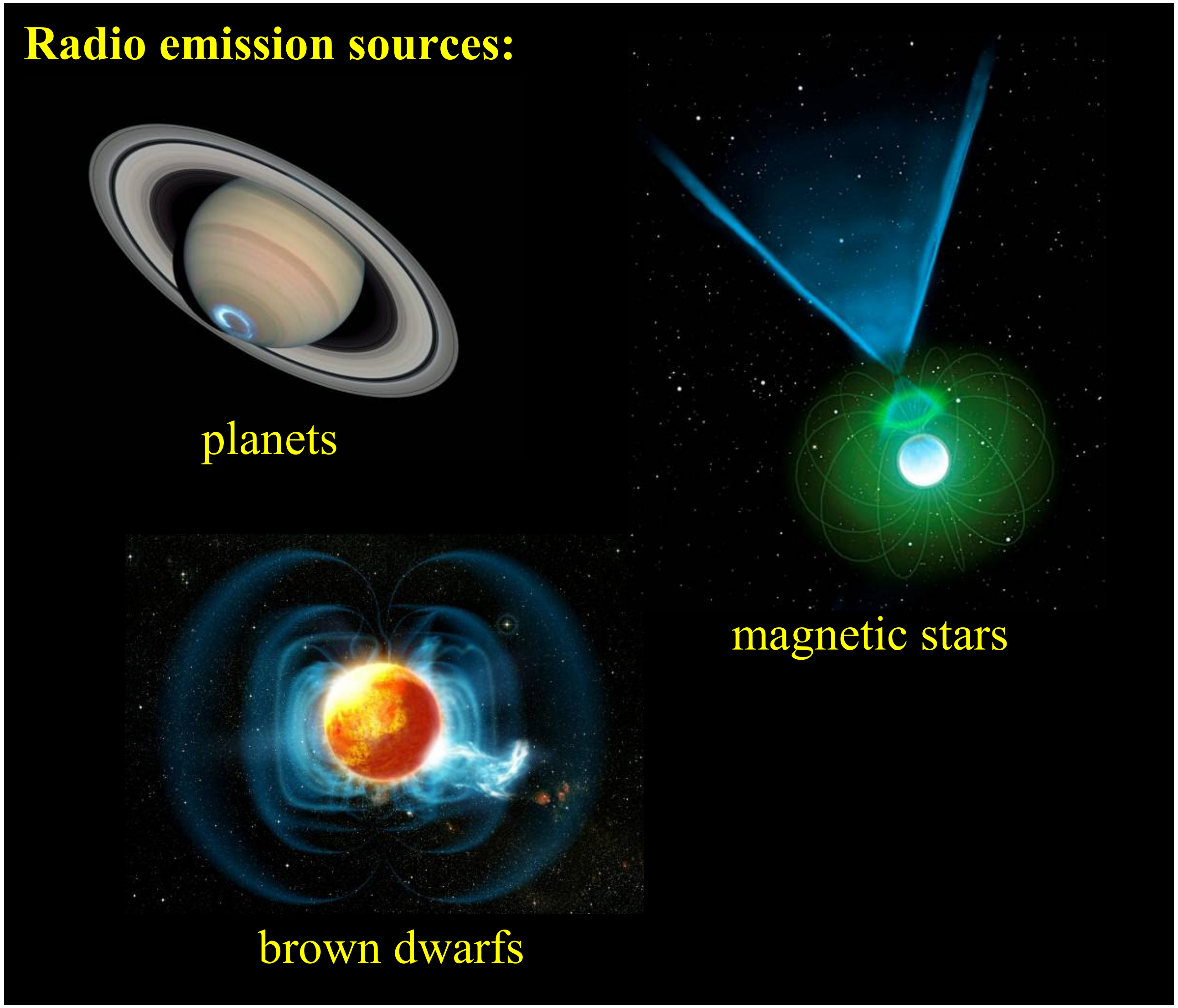
Electron-cyclotron maser instability



Emission characteristics:

- high brightness temperature;
- high circular polarization;
- narrow directivity;
- emission frequency ≈ electron cyclotron frequency.

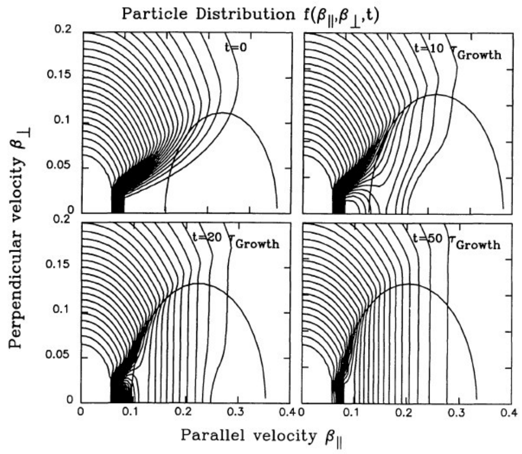
Emission intensity depends nonlinearly on the source parameters.

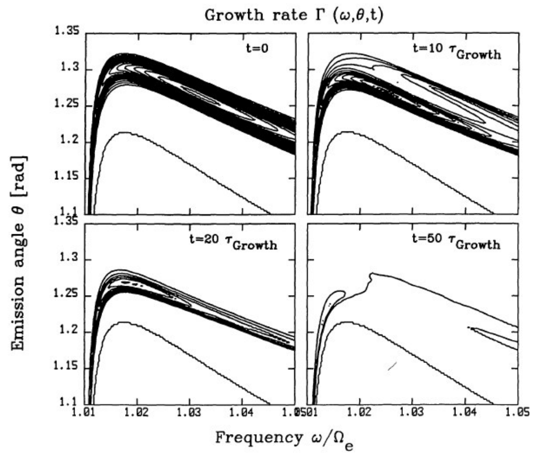
Nonlinear simulations of the co-evolution of the energetic electrons and electromagnetic waves are required.

Previous simulations

“Strong diffusion” limit: spatial movement of waves and particles is ignored.

Kinetic simulation in the strong diffusion limit (Aschwanden 1990) →

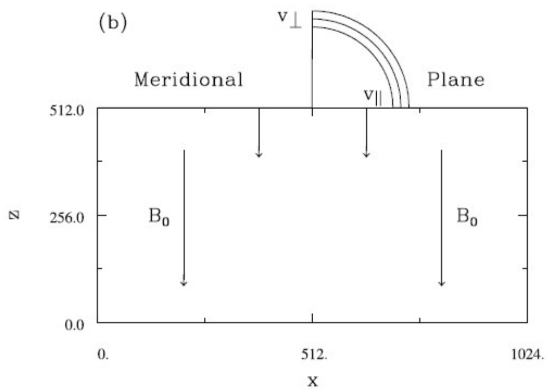


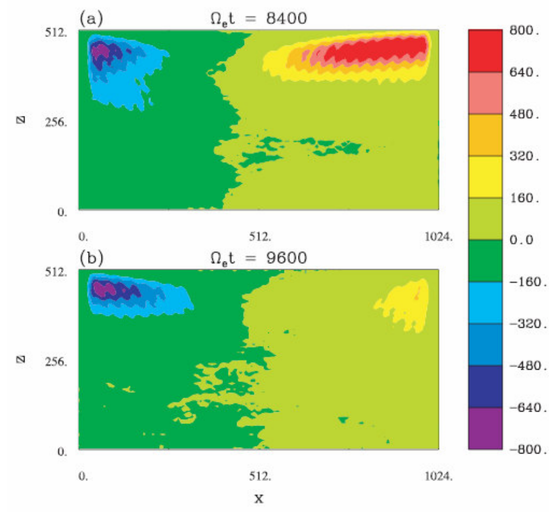


Escape of the waves and particles from the emission source can limit significantly the maser efficiency!

More advanced simulations: account for the radiation escape and particle flow.

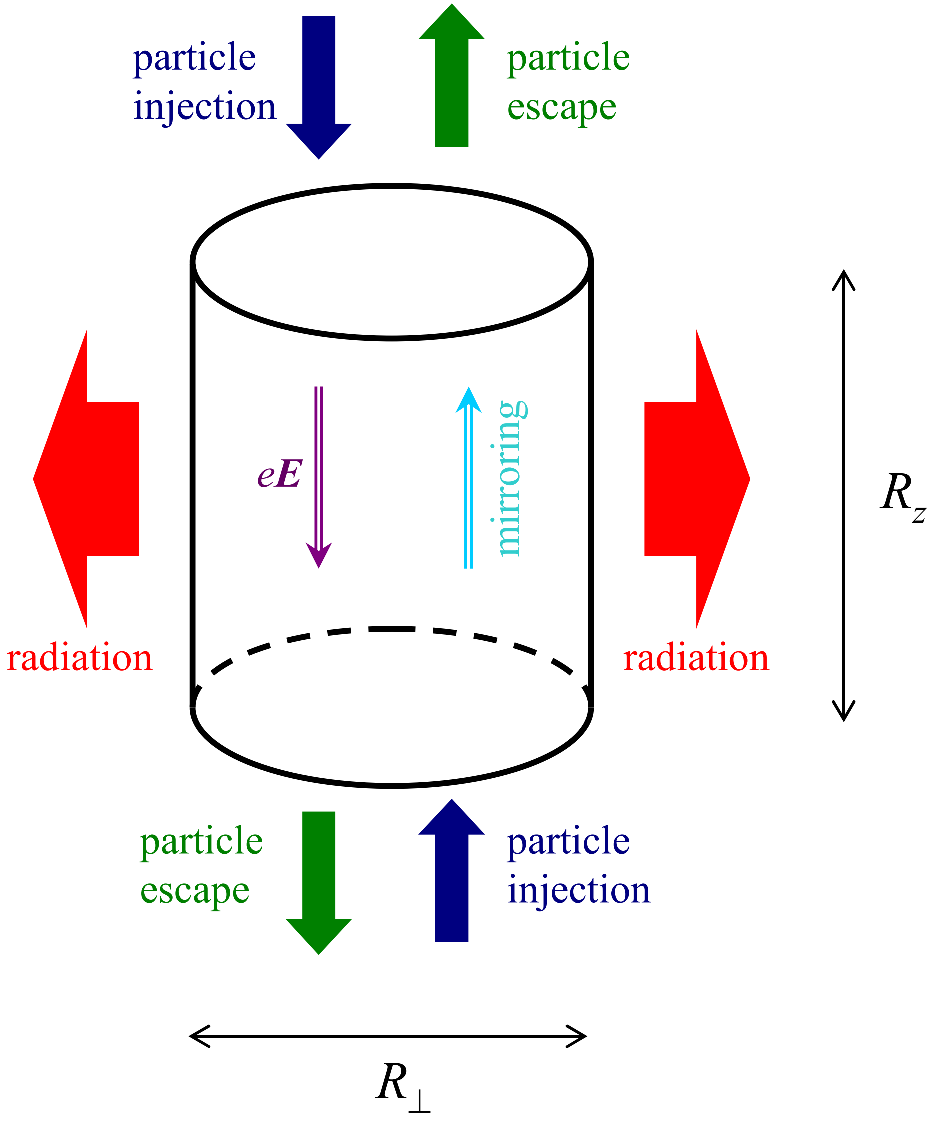
PIC-simulation of the electron-cyclotron maser in a finite auroral cavity (Pritchett et al. 2002) →





A comprehensive PIC-simulation requires a lot of computational resources.

Our model



*f = f(**p**, t)* – spatially averaged electron distribution function

$$\frac{\partial f}{\partial t} = \left(\frac{\partial n}{\partial t}\right)_{\text{inj}} \tilde{f}_{\text{inj}} - \frac{f}{\tau_{\text{esc}}} + \frac{\partial}{\partial p_i}\left(D_{ij}\frac{\partial f}{\partial p_j}\right)$$

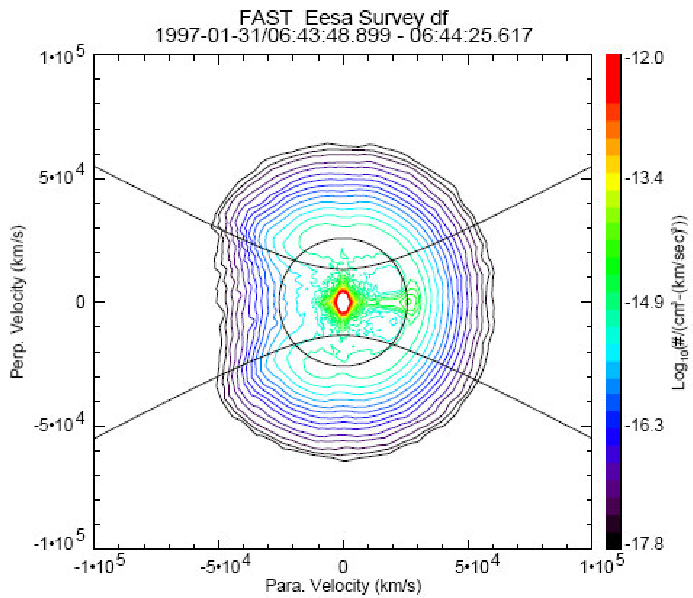
- particle injection ($F_{\text{injection}\downarrow} + F_{\text{injection}\uparrow}$); assumed to be constant.
- particle escape ($F_{\text{escape}\downarrow} + F_{\text{escape}\uparrow}$); $\tau_{\text{esc}} \sim R_z / v_b$.
- wave-particle interactions; $D_{ij} = D_{ij}(W)$.

*W = W(**k**, t)* – spatially averaged wave energy density

$$W \approx \max W = W_0 \exp(\gamma \Delta t)$$

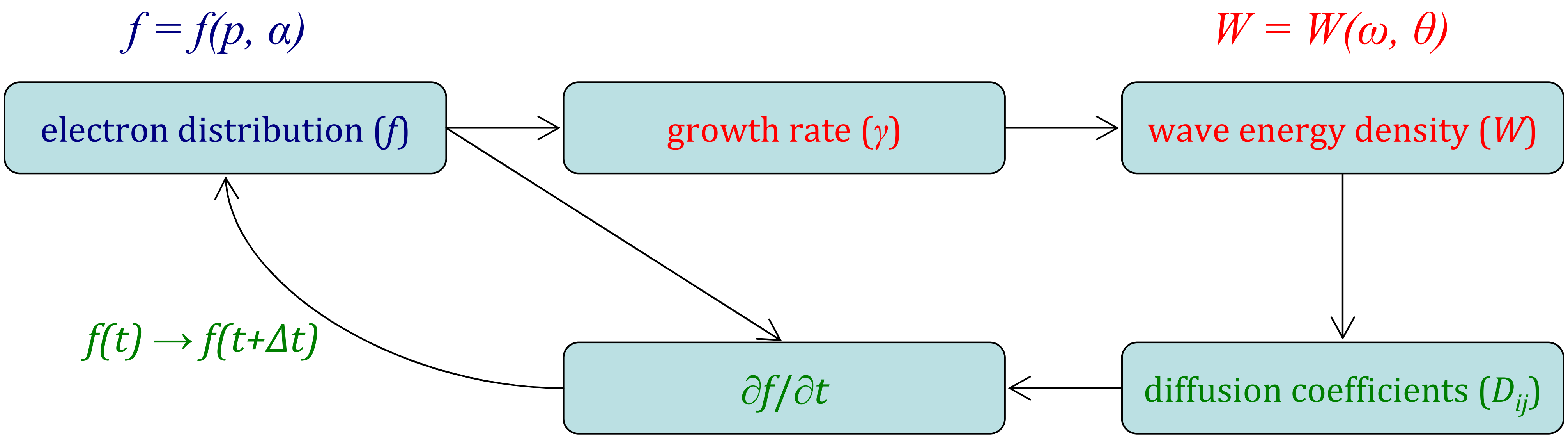
$$\Delta t \sim \frac{R_\perp}{v_{\text{gr}} \sin\theta}, \qquad \gamma = \gamma(f).$$

Simulation parameters

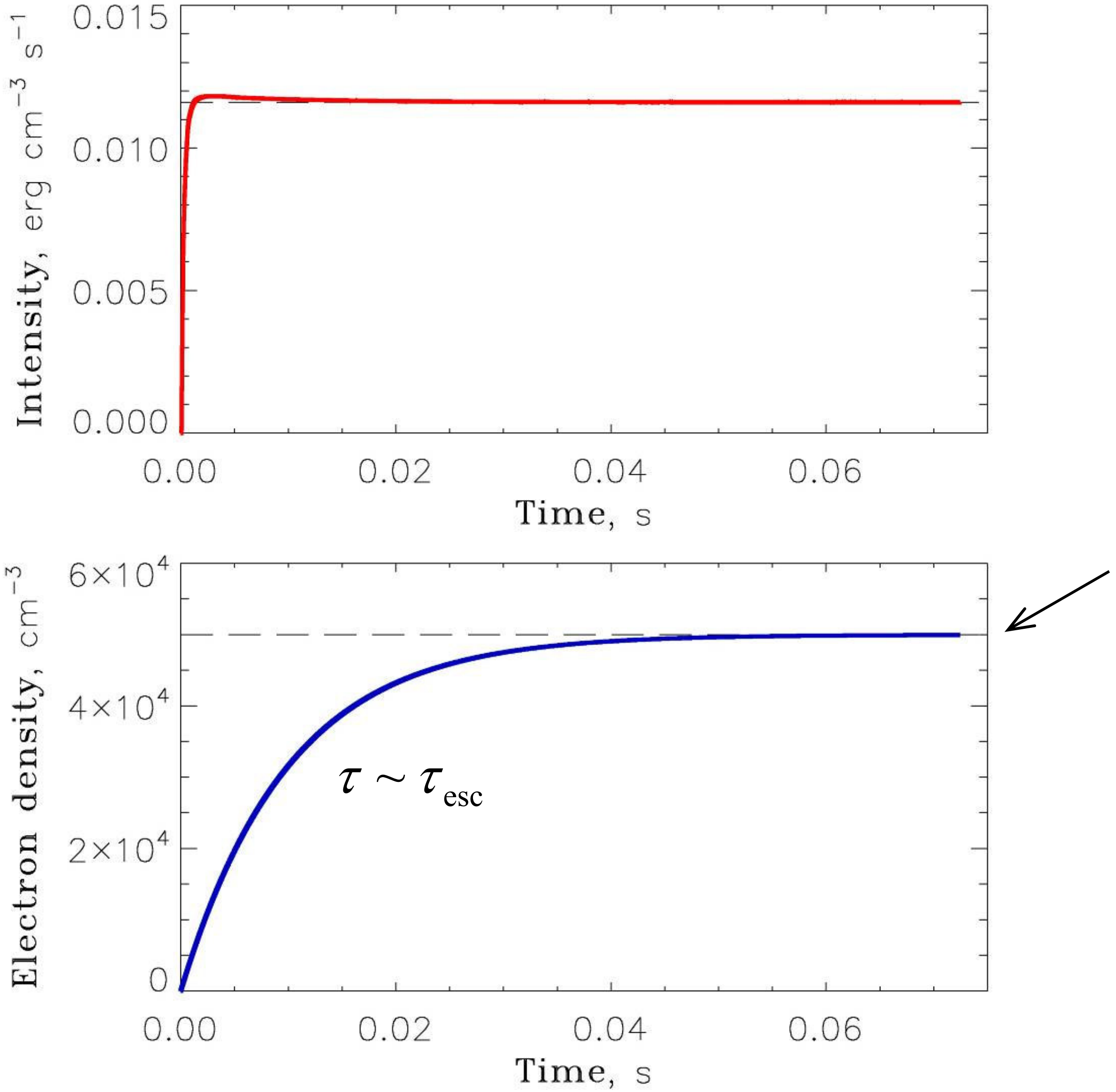


- Injected electrons' distribution: horseshoe-like.
- Very low plasma density ($\omega_p << \omega_B$).
- No background (thermal) electrons.
- Vacuum-like dispersion relation ($N \approx 1$, $v_{gr} \approx c$).

← "Horseshoe" electron distribution (Strangeway et al. 2001).



Simulation results: time history



Simulation results for the magnetosphere of a brown dwarf.

- Fundamental extraordinary mode strongly dominates.
- A quasi-stationary state is reached in a few particle escape timescales (τ_{esc}).

$$n_\infty \approx (\partial n / \partial t)_{inj} \tau_{esc}$$

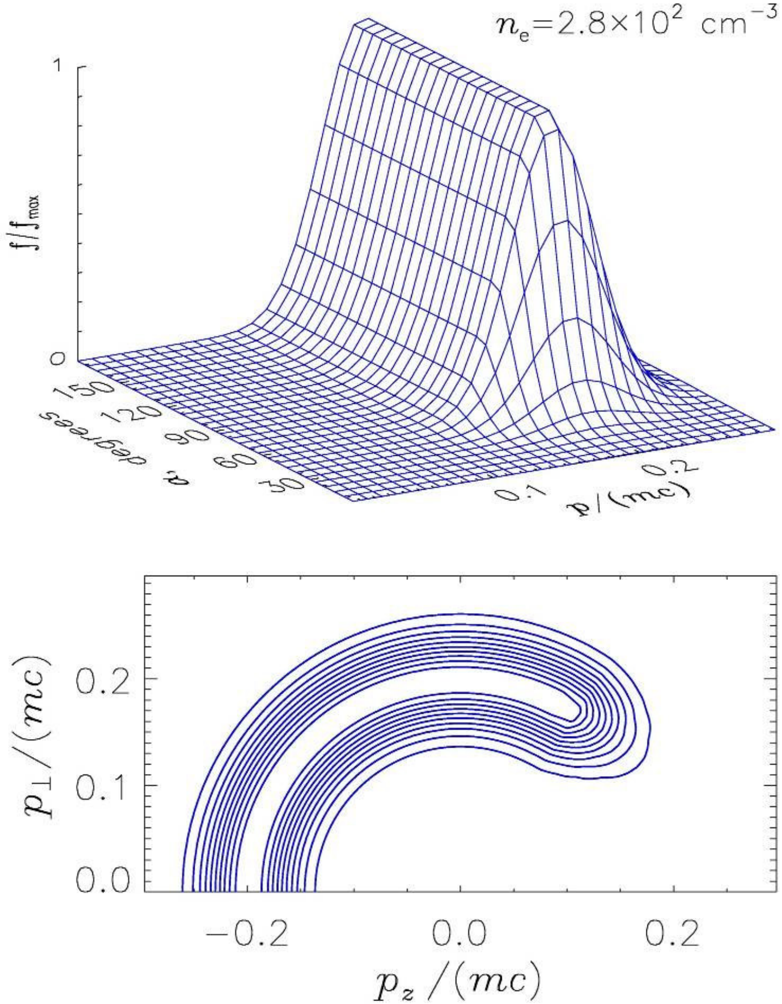
For the terrestrial magnetosphere,

$$\tau_{esc} \sim \frac{\Delta z}{v_b} \sim 0.05 \text{ s}$$

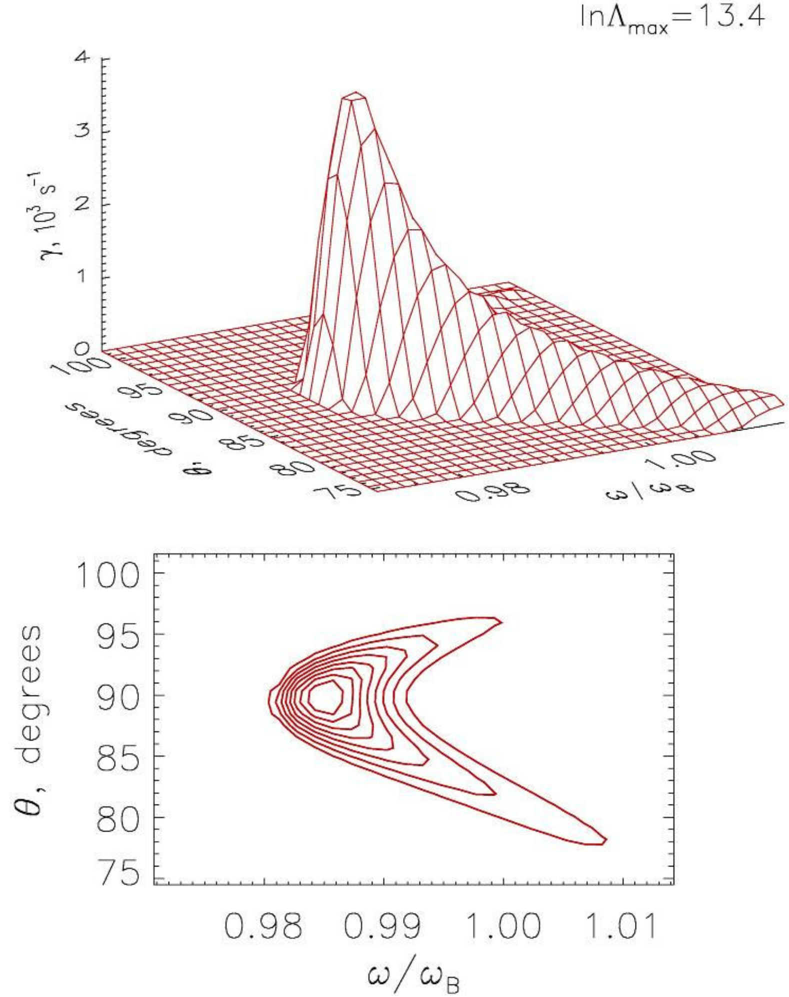
$\Rightarrow$ for the bursts with timescales of ≥ 1 s, the system should be in a stationary state.

Simulation results: the case of weak relaxation (low particle injection rate)

Stationary distribution function



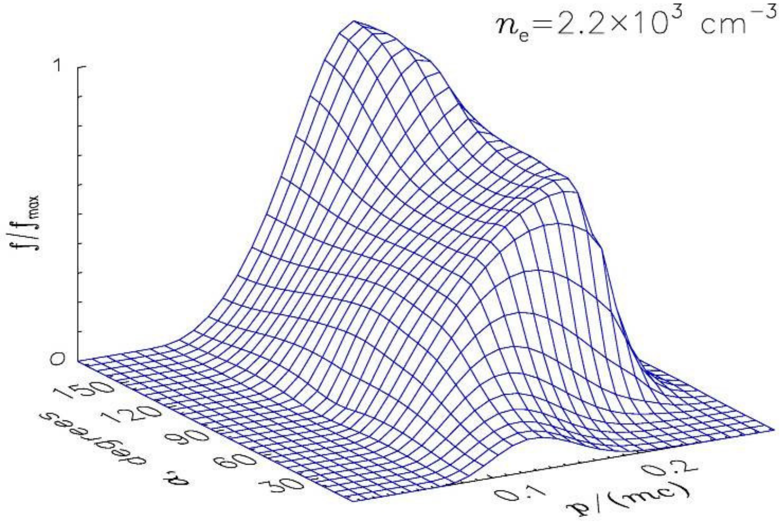
Stationary growth rate

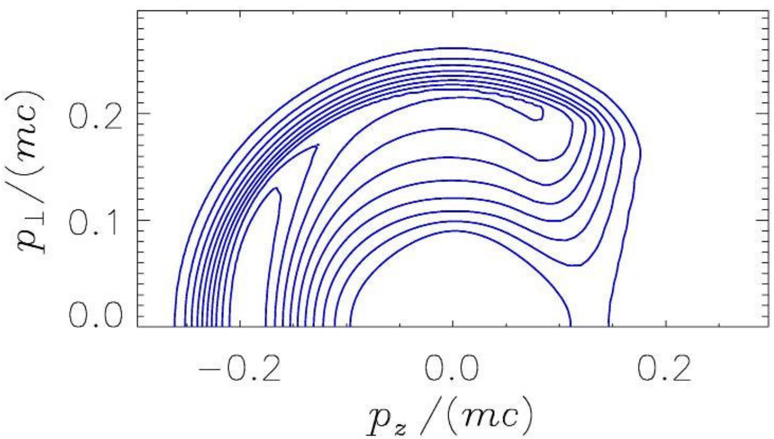


Conversion efficiency of the particle energy flux into waves: $\boldsymbol{\eta \sim 10^{-5} \ll 1}$.

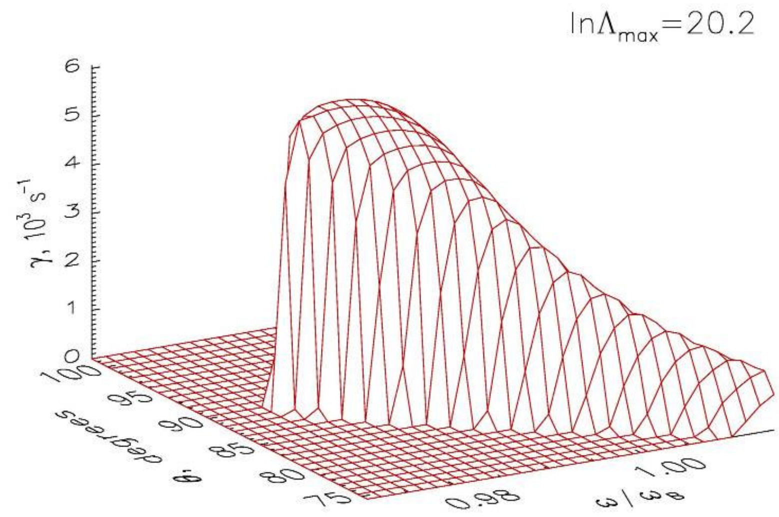
Simulation results: the case of moderate relaxation (moderate particle injection rate)

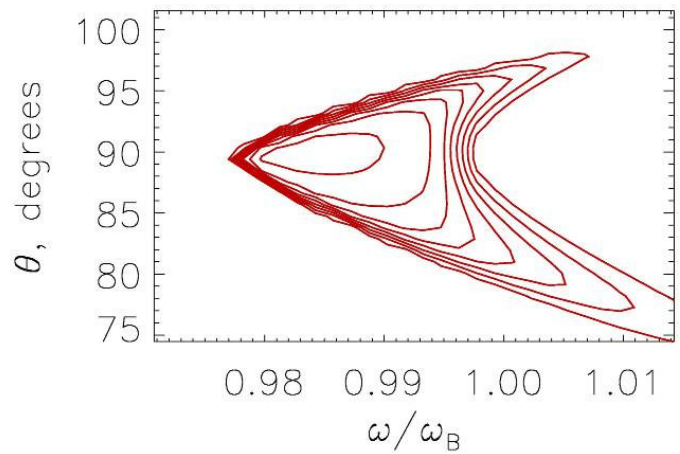
Stationary distribution function





Stationary growth rate

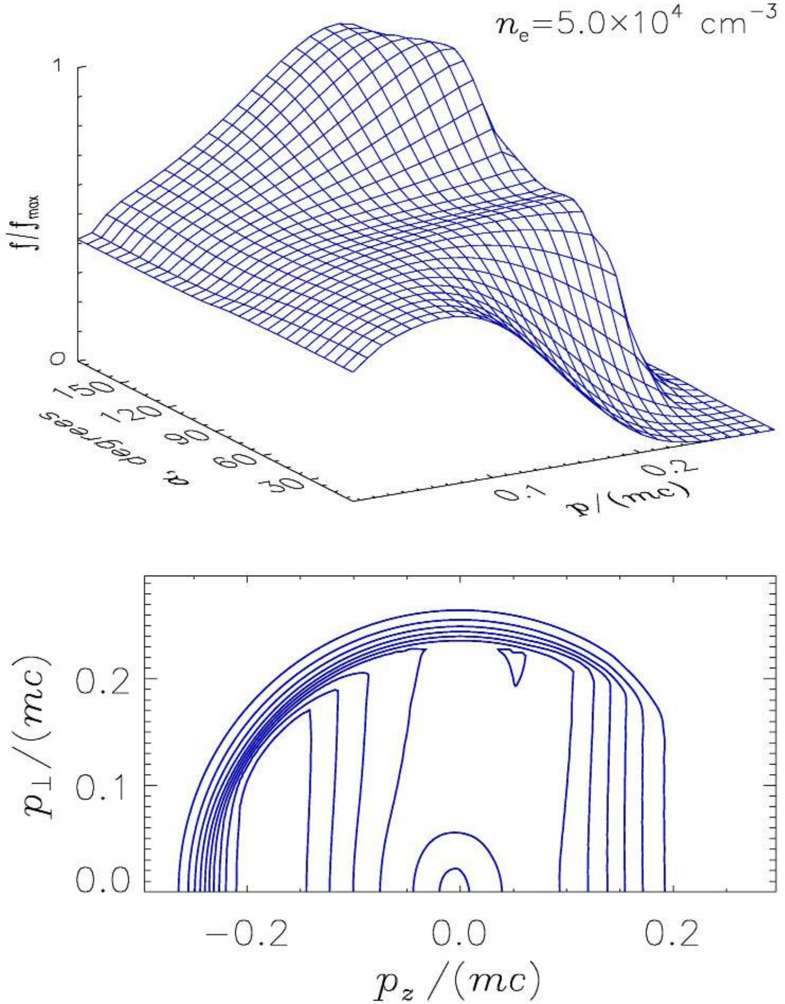




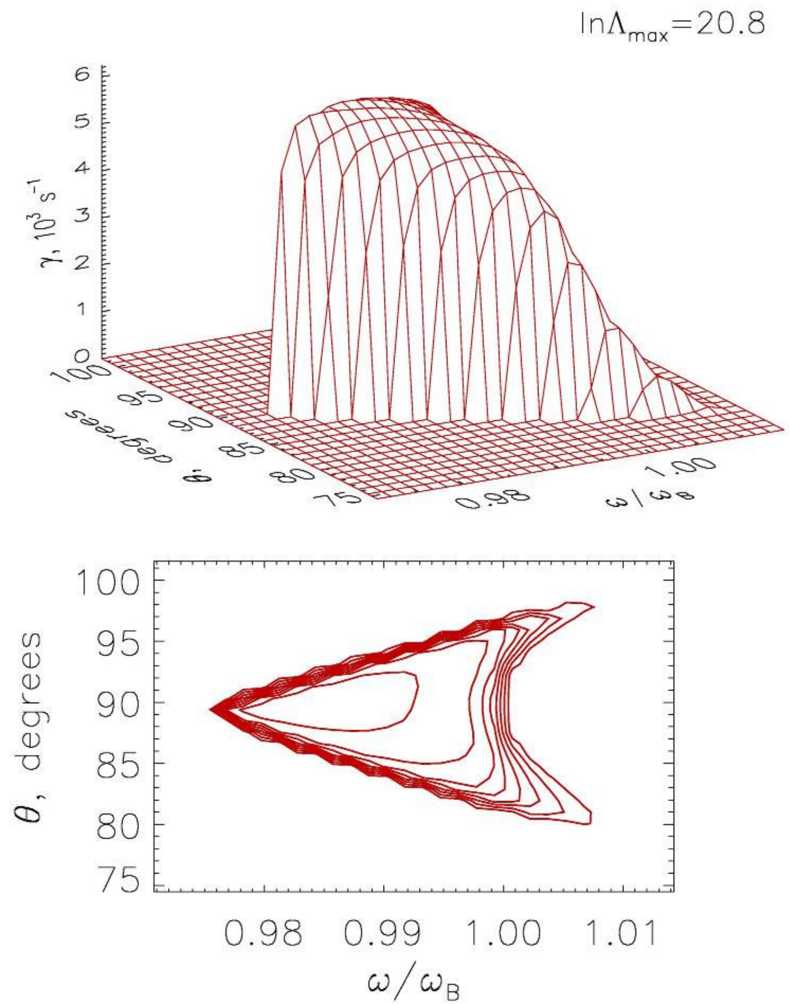
Conversion efficiency of the particle energy flux into waves: ***η* ≈ 6.8%**.

Simulation results: the case of strong relaxation (high particle injection rate)

Stationary distribution function

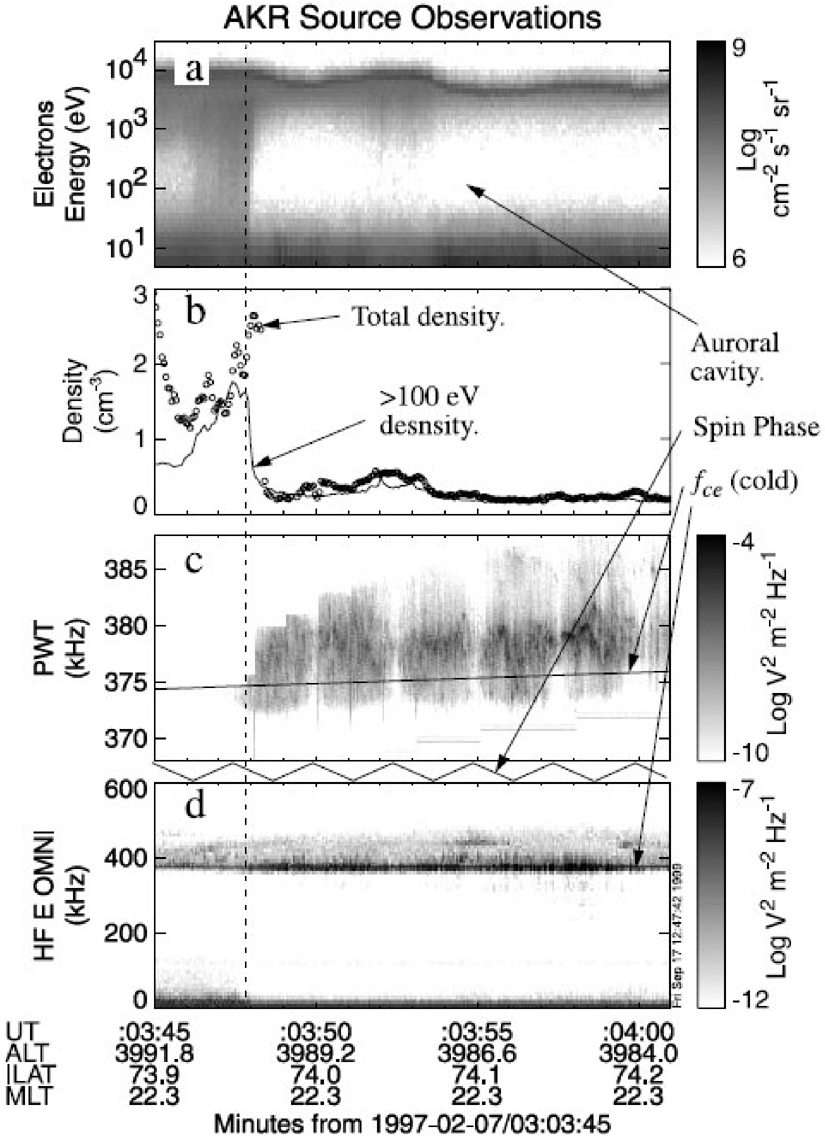


Stationary growth rate

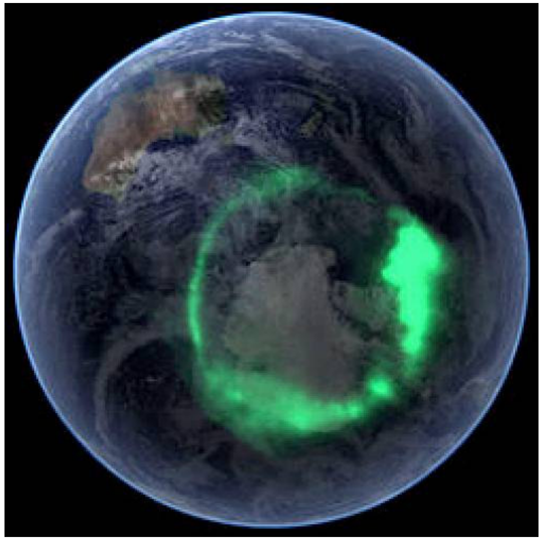


Conversion efficiency of the particle energy flux into waves: ***η* ≈ 14.5%**.

Auroral kilometric radiation of the Earth: observations



FAST observations (Ergun et al. 2000).



AKR characteristics (Zarka 1998)**:**

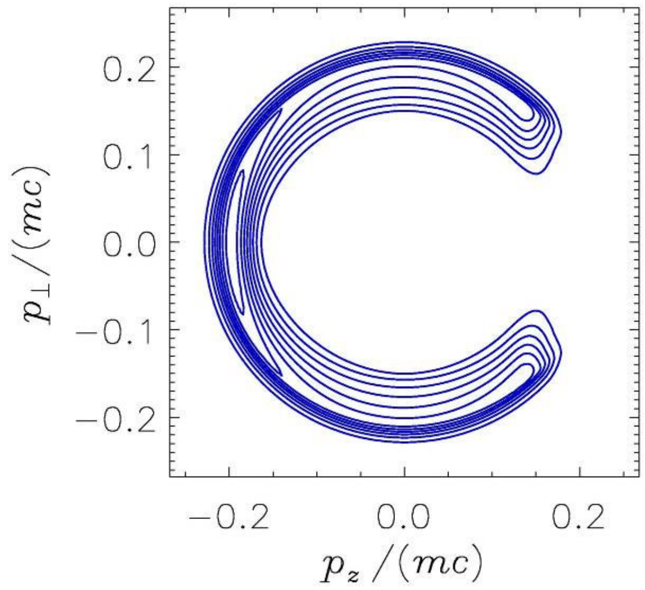
- Emission frequency: ~ 30 – 800 kHz.
- Emission source size: $R_\perp$ < 100 km.
- Source plasma density: n < 1 cm^{-3}.
- Source electron energy: E ~ 1 – 10 keV.
- Emission intensity (at 1 AU distance): ~ 5×10^{-21} W m^{-2} Hz^{-1} or higher.

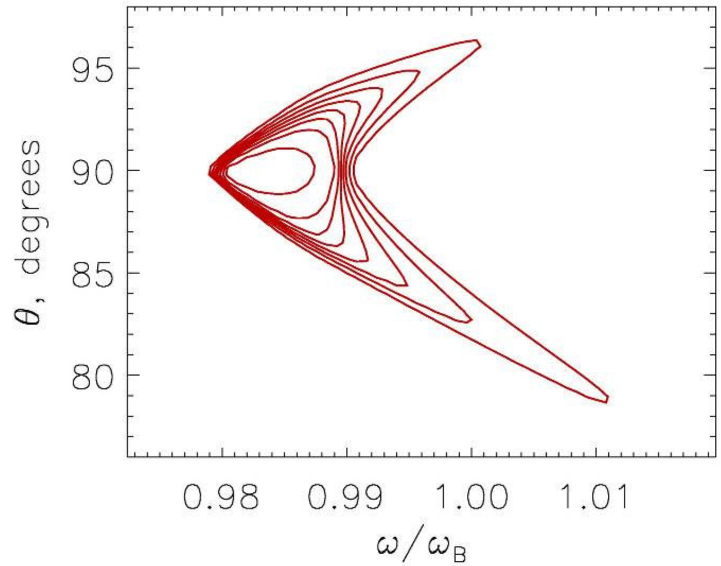
Auroral kilometric radiation of the Earth: simulation results

Simulation parameters:

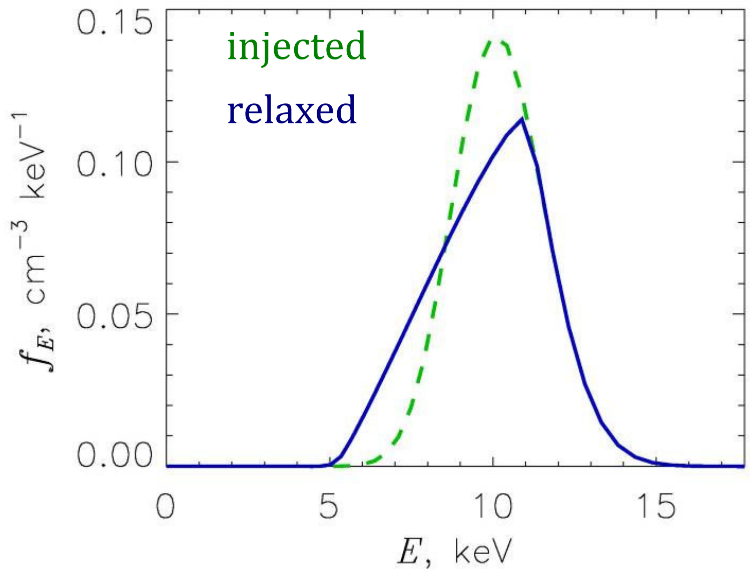
- $f_B = 400$ kHz
- $R_z = 2100$ km ($\tau_{esc} \approx 0.036$ s)
- $R_\perp = 100$ km ($\Delta t \approx 0.0003$ s)
- $E_b = 10$ keV, $\alpha_c = 45°$
- $n_\infty = 0.5$ cm^{-3}

$\Rightarrow I_{1AU} \approx 1.5\times10^{-20}$ W m^{-2} Hz^{-1}, $\boldsymbol{\eta} \approx 3\%$.



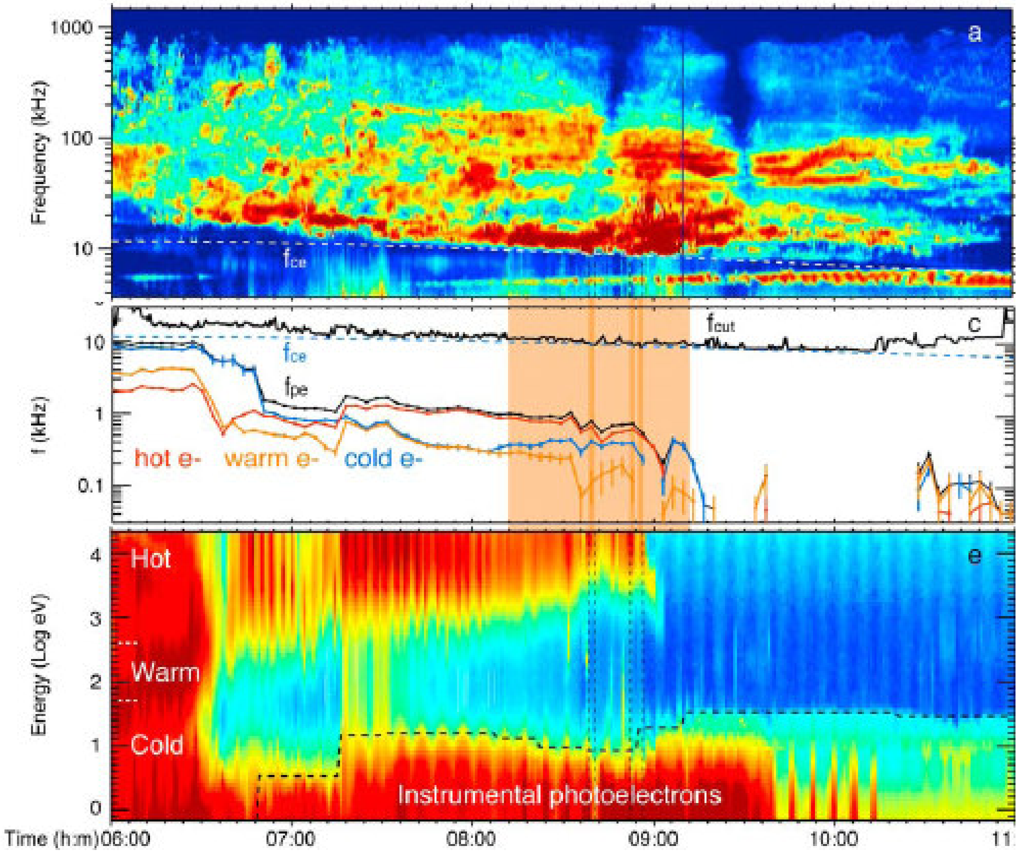


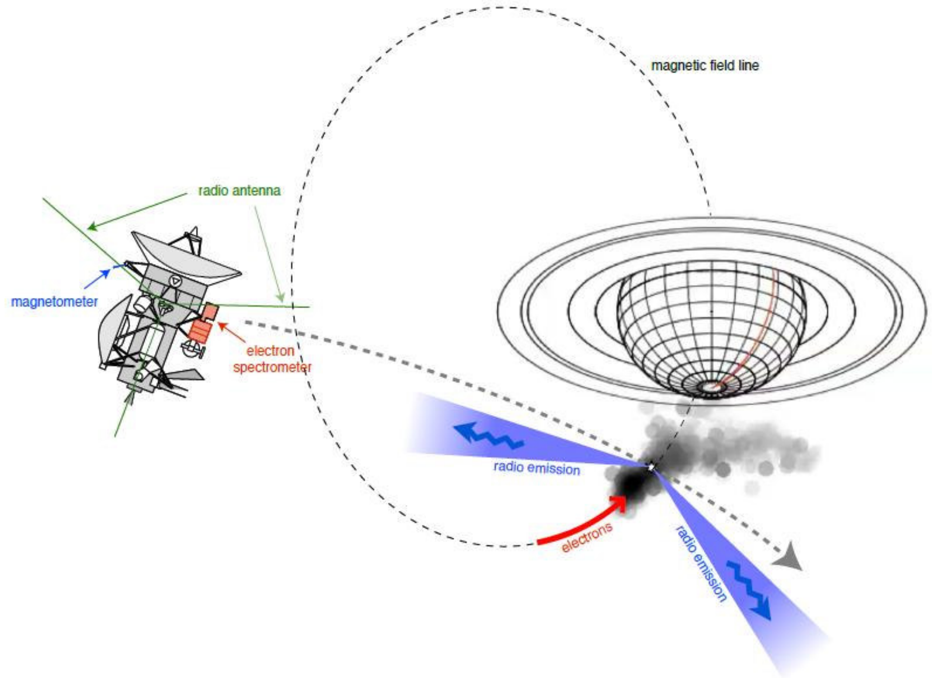
Stationary growth rate



Stationary distribution function

Auroral kilometric radiation of Saturn: observations





Cassini observations (Lamy et al. 2010).

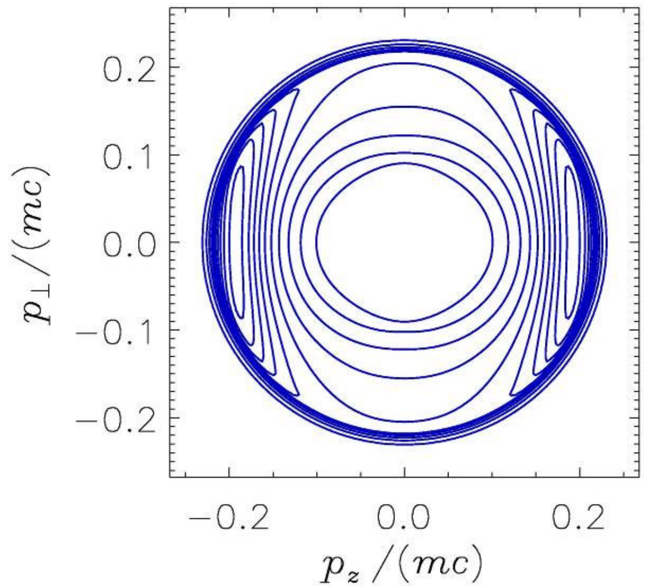
- Emission source size: $R_{\perp} \sim 1000$ km.
- Source plasma density: $n \approx 0.003 - 0.01$ cm^{-3}.
- Source electron energy: $E \sim 10$ keV.
- Emission intensity (at 10 kHz and 1 AU distance): $\sim 10^{-18}$ W m^{-2} Hz^{-1}.

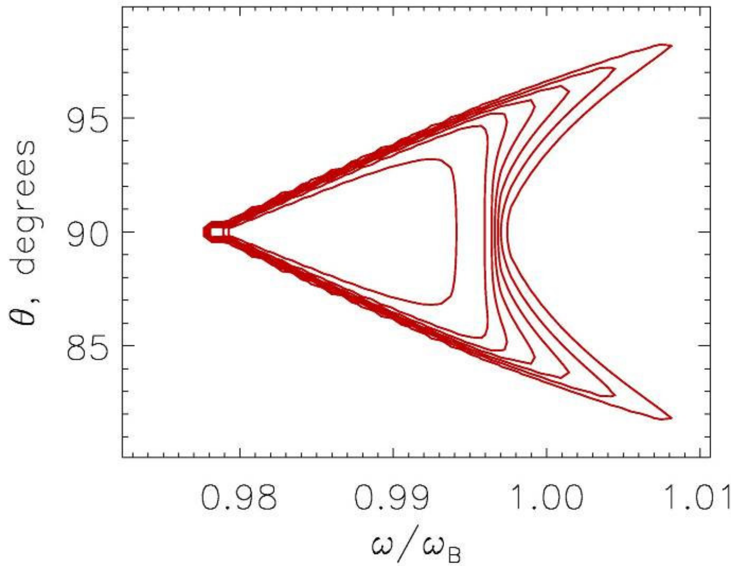
Auroral kilometric radiation of Saturn: simulation results

Simulation parameters:

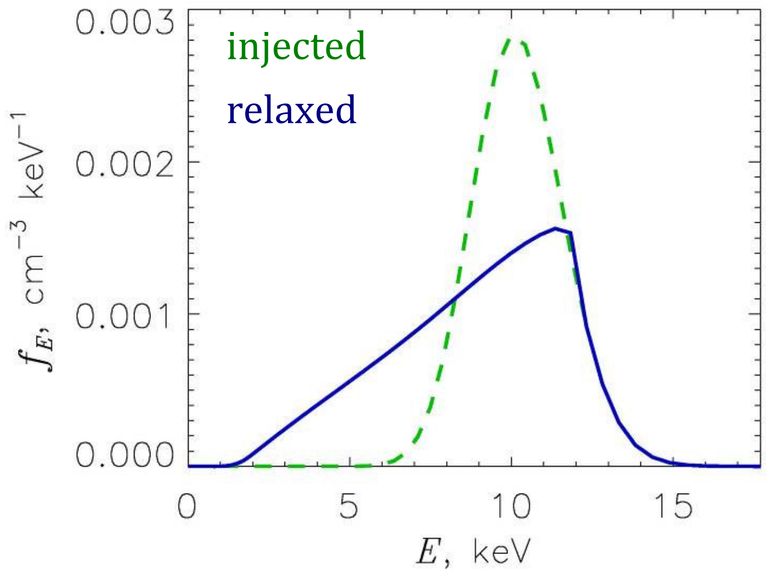
- $f_B = 10$ kHz
- $R_z = 200\,000$ km ($\tau_{esc} \approx 3.4$ s)
- $R_\perp = 1000$ km ($\Delta t \approx 0.003$ s)
- $E_b = 10$ keV, $\alpha_c = 5°$
- $n_\infty = 0.01$ cm^{-3}

$\Rightarrow I_{1AU} \approx 1.2\times10^{-18}$ W m^{-2} Hz^{-1}, $\boldsymbol{\eta} \approx 13\%$.



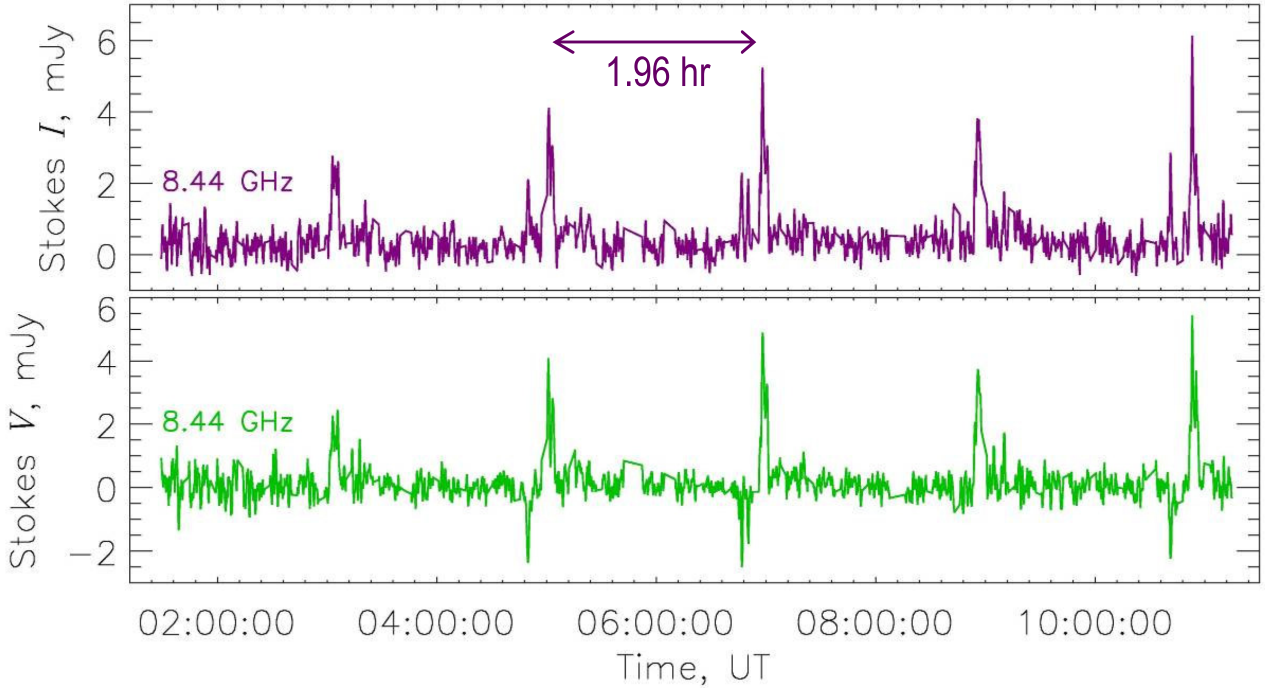


Stationary growth rate

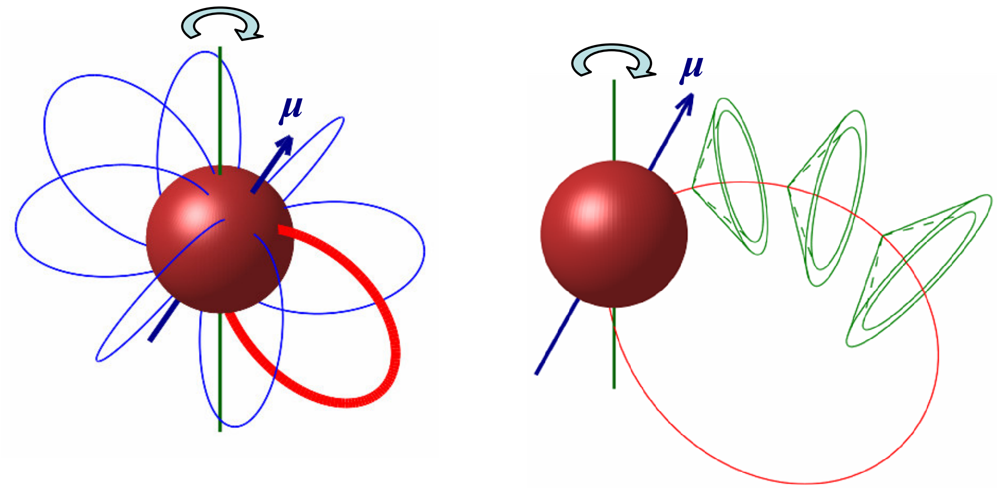


Stationary distribution function

Radio emission from ultracool dwarfs: observations



Radio light curves of the M9 dwarf TVLM 513-46546 (VLA observations) →



Radio source model (Kuznetsov et al. 2012).

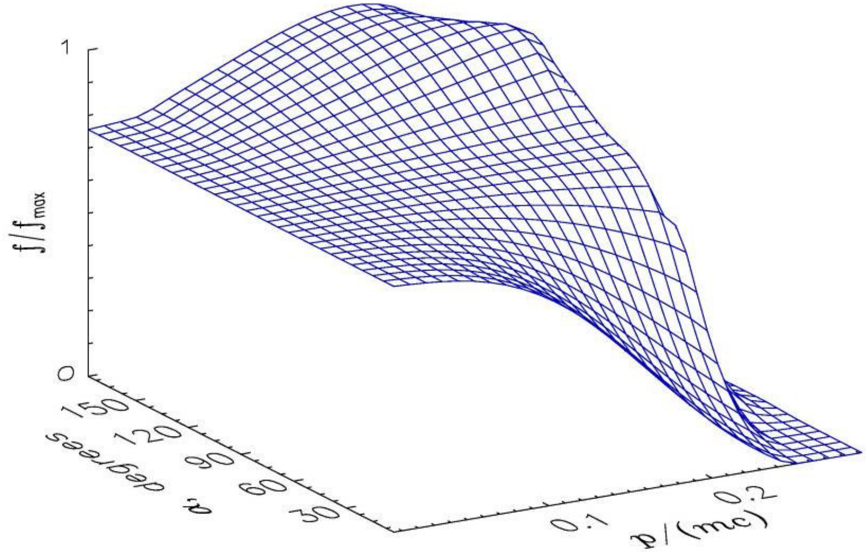
- Emission frequency: ~ 1 – 10 GHz.
- Emission intensity (at 1 AU distance): up to 10^{-15} W m^{-2} Hz^{-1} (10^7 sfu).
- Radio luminosity: $L_{\mathrm{TVLM513}} / L_{\mathrm{Jupiter}} \sim 10^4$.
- Polarization degree: ~ 100%.
- Beam width: ≤ 5°.
- Required magnetic field: ≥ 3000 G.

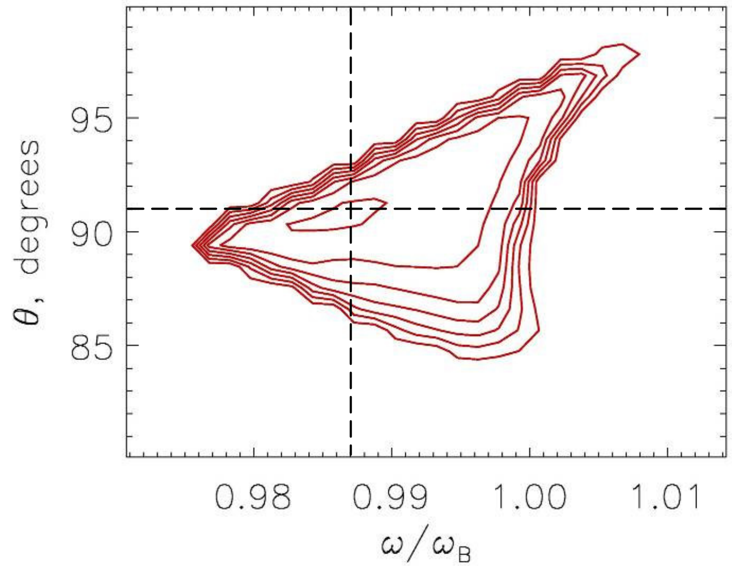
Radio emission from ultracool dwarfs: simulation results

Simulation parameters:

- f_B = 4.5 GHz
- R_z = 4900 km ($\tau_{esc} \approx 0.084$ s)
- $R_\perp$ = 1000 km ($\Delta t \approx 0.003$ s)
- E_b = 10 keV, α_c = 60°
- $n_\infty = 4.2\times10^5$ cm^{-3} ($\omega_p / \omega_B \approx 10^{-3}$)

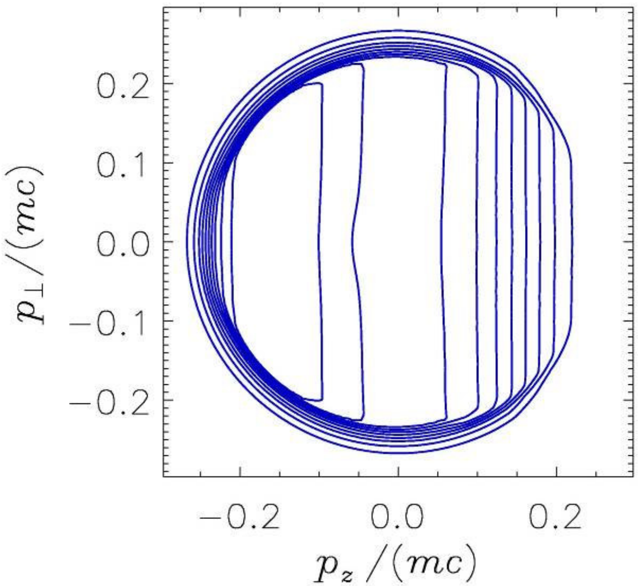
$\Rightarrow I_{1AU} \approx 1.1\times10^{-15}$ W m^{-2} Hz^{-1}, $\boldsymbol{\eta} \approx 13\%$.





$\theta_{max} \approx 91°$

Stationary growth rate



Stationary distribution function

Conclusion

- The produced radio emission:
  - corresponds to the fundamental extraordinary mode;
  - has a frequency slightly below the electron cyclotron frequency;
  - propagates nearly perpendicular to the magnetic field.
- In the planetary magnetospheres:
  - the maser efficiency is limited by the emission escape from the source region;
  - the stationary electron distributions are similar to those of the injected electrons;
  - the energy conversion efficiency is typically a few percent.
- In the magnetospheres of ultracool dwarfs:
  - the stationary electron distributions are strongly relaxed and nearly flat;
  - the energy conversion efficiency can exceed 10%;
  - the energetic electrons with a relatively low density ($\omega_p / \omega_B \approx 10^{-3}$) are able to provide the observed emission intensity.

For more details, see A&A, 539, A141, 2012.