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*A Vlasov model for the generation of
supra thermal electron tails
in solar wind conditions*

*International workshop in honor of André Mangeney
September 11-14 2007 - Paris Observatory*

Motivations

Space and laboratory collisionless plasmas are most often out of local thermodynamic equilibrium

Their charged particle velocity distributions differ from simple Maxwellian distributions and exhibit a great variety of **anisotropies** and components such as **supra thermal beams and tails**

Solar Wind:

The e.d.f. consist of (at least) three components:

1. A roughly **isotropic, Maxwellian "core"** with density $N_C \sim 10\text{-}40 \text{ cm}^{-3}$ and mean temperature $T_c \sim 10 \text{ eV}$.

2. A diffuse, roughly isotropic **halo** with density $N_H \sim 0.01\text{-}0.03 N_C$ (at energies greater than $\sim 60\text{eV}$ and an equivalent temperature $T_H \sim 7\text{-}8 T_c$.)

3. A beam like population, the **"strahl"** which is superposed on the halo and flows along the local magnetic field.

The situation:

No generally accepted theoretical model

Basic question:

*supra thermal tails are generated
in the solar wind or in the solar corona ?*

Standard interpretation:

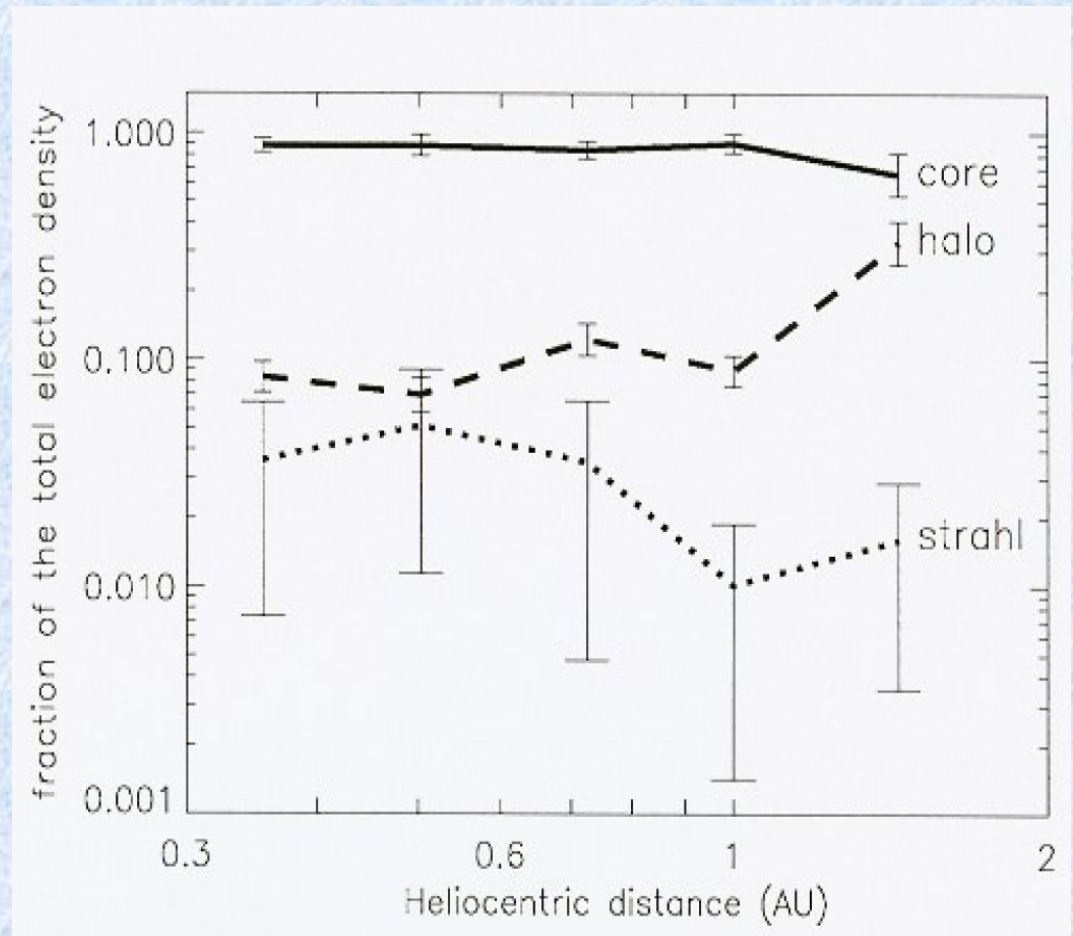
1. **Core electron population:** collisional and bound by the interplanetary electrostatic potential, its properties being regulated locally.
2. **Halo:** scattering of “strahl” electrons over spatial length of the order of many AU.
3. **Strahl electrons:** coronal electrons having velocities large enough to escape without colliding with the background plasma.

Halo results from Coulomb diffusion of strahl electrons ?

The relative number of halo electrons increases while strahl electrons decrease at roughly constant core fraction.

BUT:

1. the strahl fraction is always smaller than halo fraction.
2. also consistent with halo fraction increasing from 0.1 to 0.3 while core electron decrease from 0.9 to 0.6 !



Maksimovic et al, 2005

(combining data from Helios, WIND, Ulysses)

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Problems

If the halo results from Coulomb diffusion of strahl electrons, one should observe a weak halo component when background density decreases.

BUT

supra thermal tails more important in
fast solar winds than in slow wind

whether or not halo electrons result from the scattering
of strahl electrons on the core electrons, not yet settled!

The model

Vlasov - Poisson equations + external forcing

We investigate under what conditions one can generate locally
an

equilibrium between supra thermal electron tails and an

enhanced level of high frequency (Langmuir) waves.
Two main ingredients of collisionless space plasmas:

Electric field generated by charge separation due to thermal noise

high frequency term in electron and proton Vlasov Eqs.

Energy injection from the large scale energy cascade

low frequency term in the proton Vlasov Eq. only

(the electrons response is mainly adiabatic, i.e. no charge separation effects

THE EQUATIONS:

$$\frac{\partial f_e}{\partial t} + v \frac{\partial f_e}{\partial x} - (E + \epsilon \nabla \Psi_{HF}) \frac{\partial f_e}{\partial v} = 0$$

$$\frac{\partial f_p}{\partial t} + v \frac{\partial f_p}{\partial x} + \frac{m_e}{m_p} (E + \mu \nabla \Psi_{LF} + \epsilon \nabla \Psi_{HF}) \frac{\partial f_p}{\partial v} = 0$$

$$\nabla \cdot \mathbf{E} = \int f_p dv - \int f_e dv; \quad \mathbf{E} = -\nabla \Phi$$

Normalized to the electron characteristic scales:

$$V_{th,e}; \lambda_D; \omega_{pe}; M/m = 1836; L_x = 5000 \lambda_D$$

In Eqs. (1-2) Ψ_{LF} and Ψ_{HF} are the potentials of the external forcing varying on a low and high frequency time scale.

Low frequency Force: Space - time gaussian pulses.

$$\Psi_{LF} = A_{LF} \sum_{n=1}^K a_n e^{-(t-t_n)^2/\ell_t} e^{-(x-x_n)^2/\ell_x}$$

A \equiv normalization factor

a_n \equiv random amplitudes

K \equiv total number of "events"

x_k, t_k \equiv random distributed positions

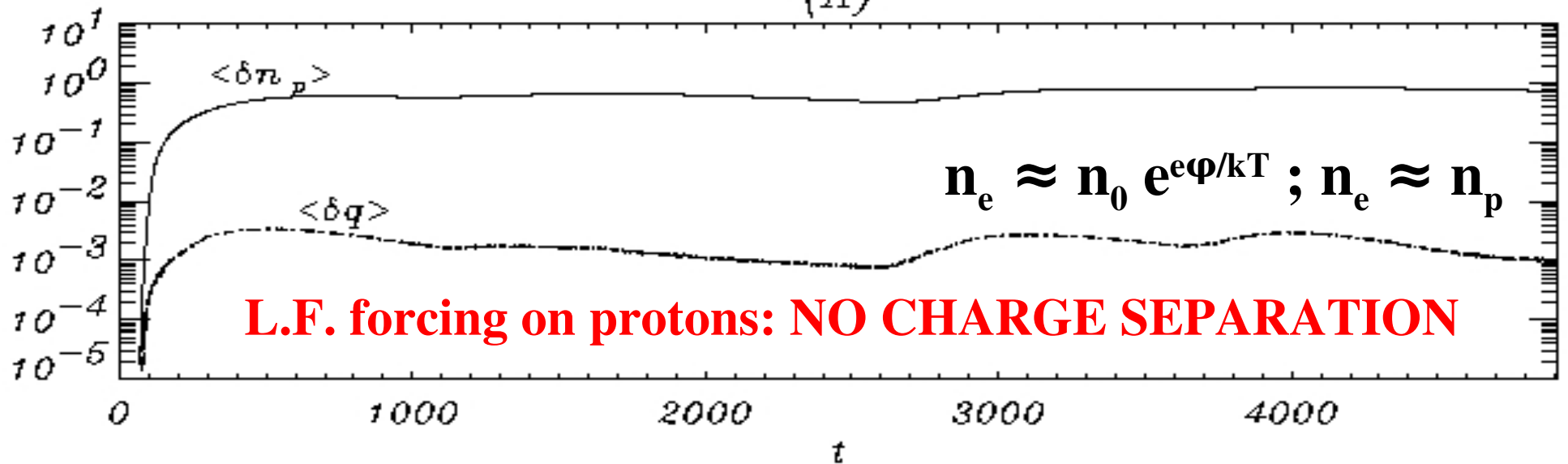
ℓ_x, ℓ_t \equiv characteristic scale lengths.

The gaussian shape drives a number of
spatial plasma compressions or rarefactions.

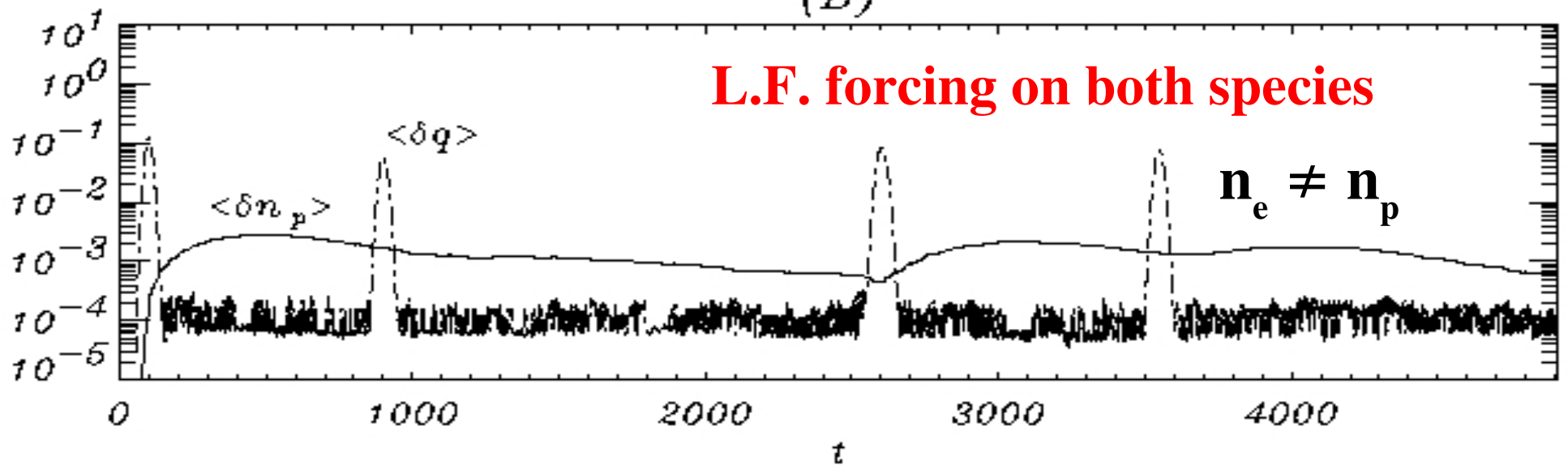
Proton motions driven by any other more complicated analytical forms for Ψ_{LF} can be represented as a sum of plasma compressions and rarefactions on the proton density.

Low frequency forcing (an example with $K=4$)

(A)



(B)



High frequency forcing

Not completely random, but with a certain degree of coherence induced by small scale processes (micro instabilities or kinetic effects) characterized by several high frequency events randomly distributed

$$\Psi_{\text{HF}} = A_{\text{HF}} \sum_{n=1}^N e^{-[(x-x_n)/(h_x(1\pm c_n))]^2} e^{-(t-t_n)/(h_t(1\pm d_n))}$$

where A_{HF} is a normalization factor such, N is the total number of "events", x_n and t_n the random distributed positions, h_x and h_t the characteristic length and time scale, and c_n and d_n random numbers between 0 and 1.

Initial conditions

We take a homogeneous thermal plasma with a single Maxwellian populations for both electrons and protons with the same temperature:

$$f_e(\mathbf{x}, \mathbf{v}_e, t = 0) = \frac{1}{\sqrt{2\pi}} e^{-v_e^2/2}$$

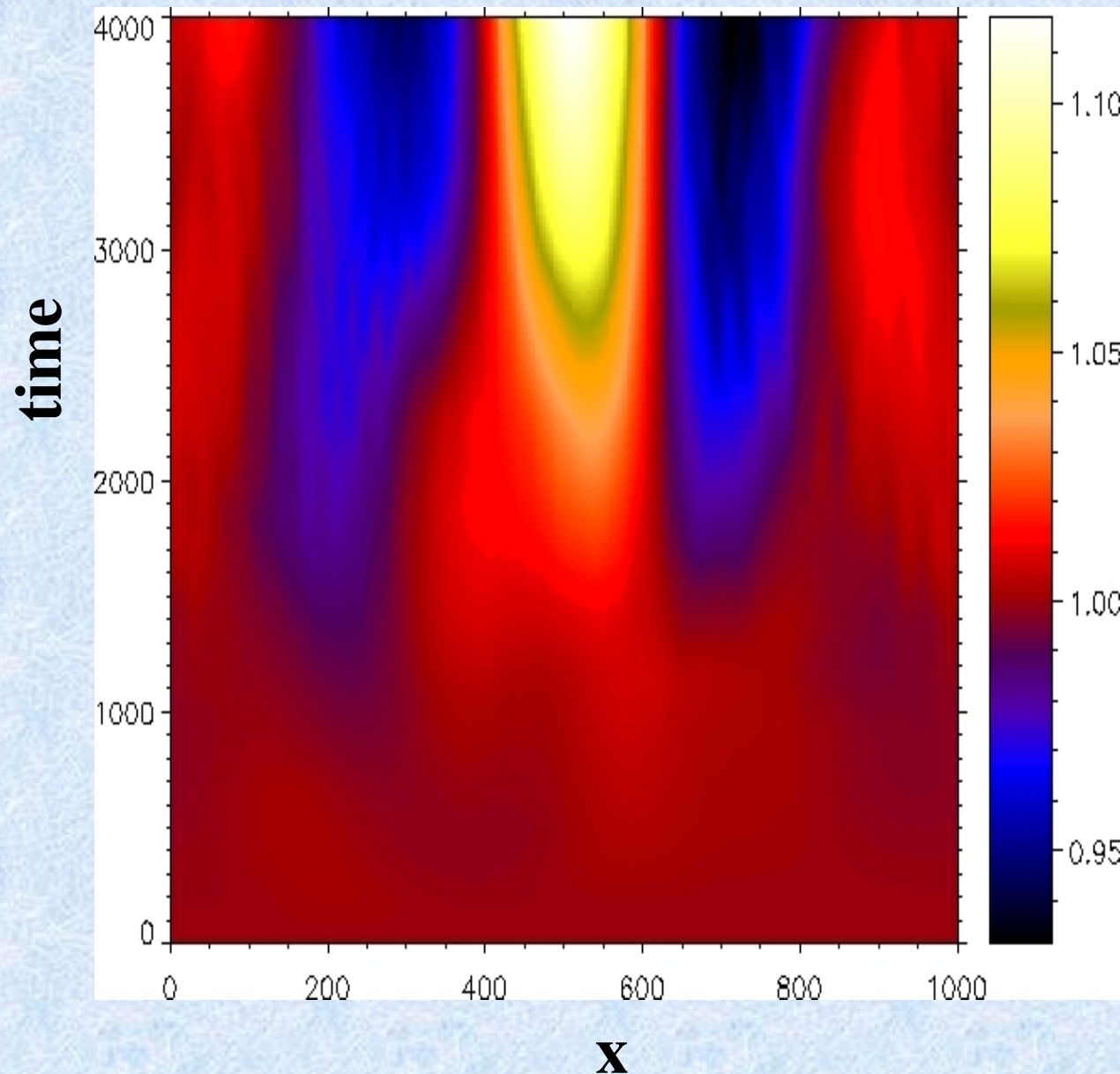
$$f_p(\mathbf{x}, \mathbf{v}_p, t = 0) = \frac{1}{\sqrt{2\pi\mu}} e^{-v_p^2/2\mu}$$

$$n_e = n_p = 1, \quad T_e = T_p = 1$$

RESULTS: $\eta = 0.03$, $\varepsilon = 0.03$

The **LF forcing** generates **proton density fluctuations** with $\delta n_p \approx 0.05$ which can be considered as *consistent with the typical values observed in the solar wind.*

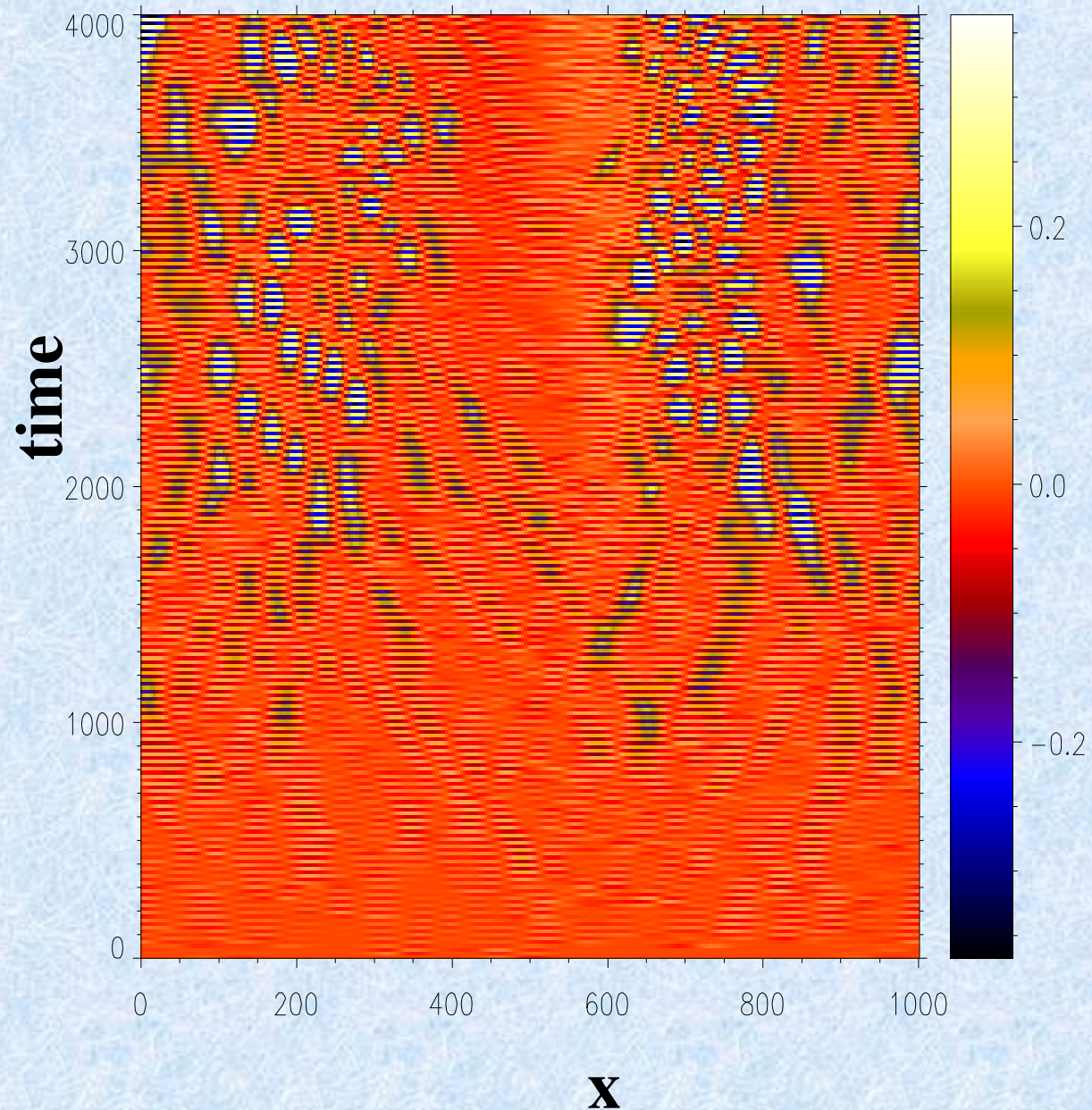
The proton density



RESULTS: $\eta = 0.03$, $\varepsilon = 0.03$

The electric field

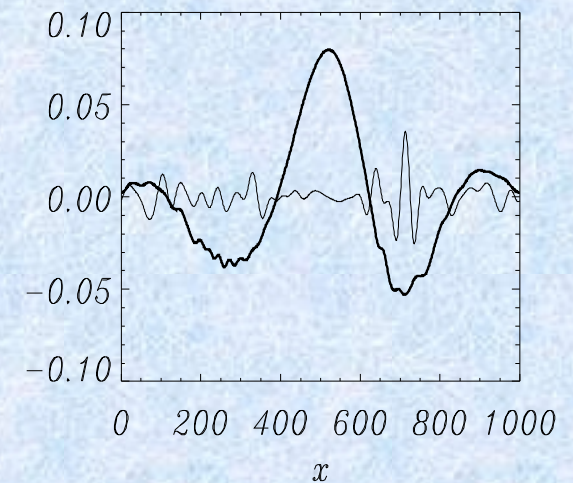
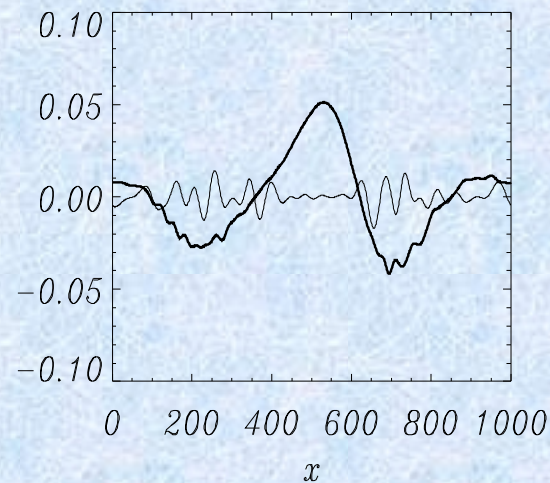
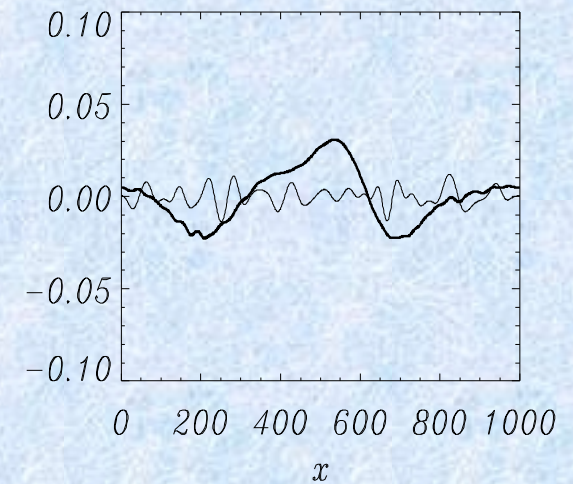
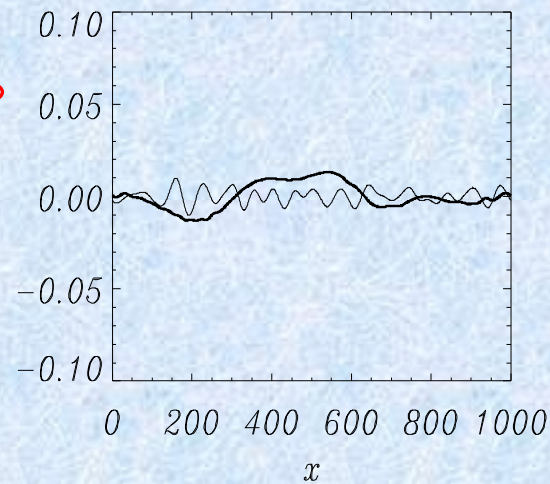
The **HF forcing** generates **plasma oscillations** with $\delta E \approx 0.025$ which **concentrate in the proton cavities** in the form of "*wave trains*", where they are **amplified to much larger values**, $\delta E \geq 0.2$.



RESULTS: $\eta = 0.03$, $\varepsilon = 0.03$

The proton fluctuations and the charge separation

progressive formation of **proton inhomogeneities** accompanied by the smoothing of δq in the central bumped region and by the **concentration and by the amplification of δq** in the cavities.

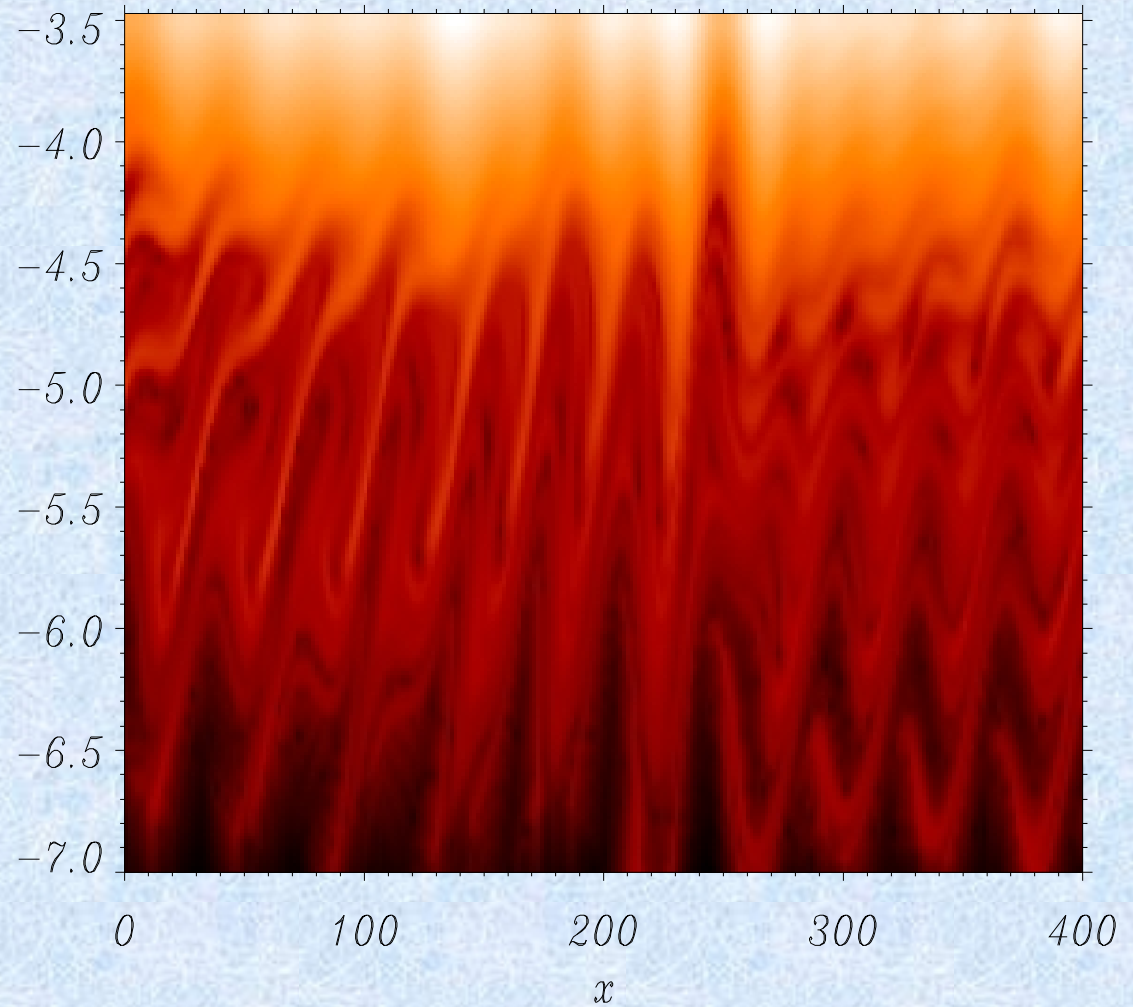


RESULTS: $\eta = 0.03$, $\varepsilon = 0.03$

Iso-contours of the e.d.f. in the phase space strip $0 \leq x \leq 400$, $-7 \leq v \leq -3.5$, $t=4000$.

Due to the presence of plasma density gradients, the plasma oscillations break due to the self-intersection of electron trajectories.

A significant fraction of the **electrons are accelerated** to larger velocity values.

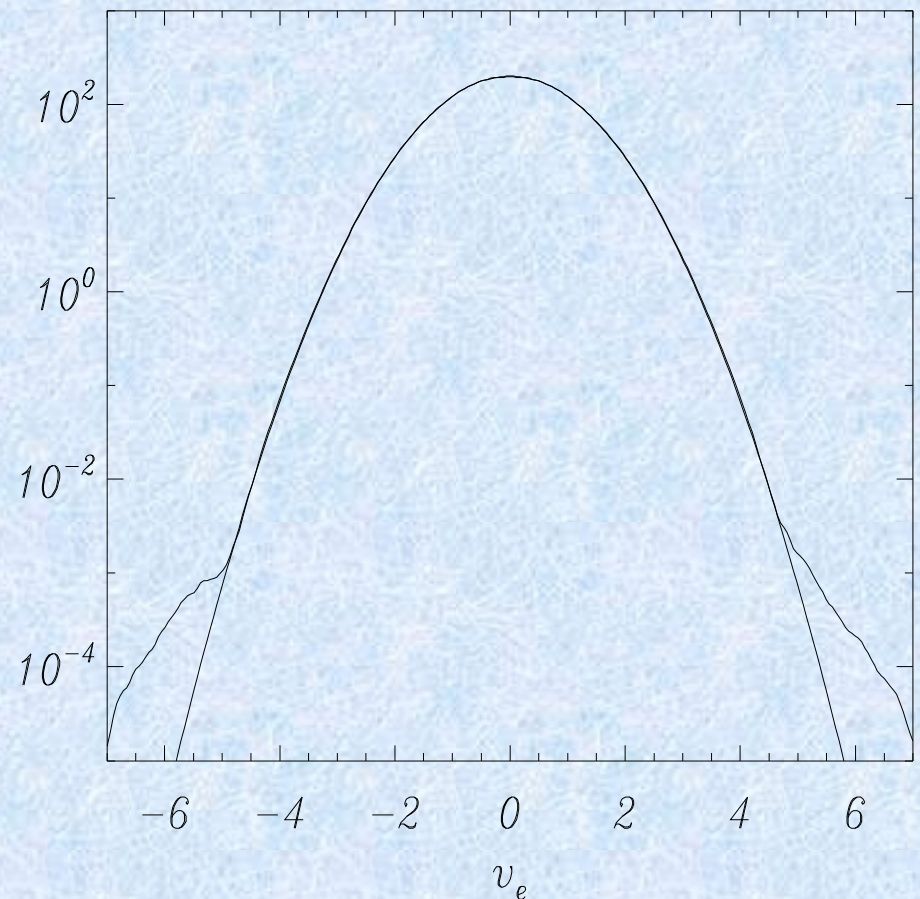


RESULTS: $\eta = 0.03$, $\varepsilon = 0.03$

Formation of a halo for velocity values $v > 5$. According to Bulanov et al. [xxx], the breaking time of plasma oscillations with $\lambda \sim 5-10 \lambda_D$ with an inhomogeneous scale length $\lambda_{inh} \sim 100 \lambda_D$ is of the order of $\tau_{wb} \sim 100 - 1000 \omega_{pe}^{-1}$.

This is consistent with the observed formation time of the halo on the e.d.f. in our simulation.

the e.d.f. averaged in space at $t=0, 4000$



CONCLUSIONS

We take $\delta n_p \sim 10 \text{ cm}^{-3}$, $\lambda_D \sim 10\text{m}$ as typical solar wind values.

Then, we can estimate the corresponding typical **electric field fluctuations induced by charged particles** which turns out to be

$E_* \sim 10^{-3}$ (here $E_* \sim n_D^{-1/3}$ is the electric field induced by the thermal noise)

This value is *just slightly smaller* than that induced by the

HF forcing in our simulation, $\delta E \sim 0.025$ where

a halo is observed to form in the presence of proton fluctuations.

CONCLUSIONS

However, is it reasonable to assume that
the "thermal" solar wind electric field could be enhanced
by the contribution of micro instabilities
developing at the kinetic scales (at least by one order of magnitude).

**We conclude that the mechanism proposed here,
even if in a very simplified form, can be considered as a
good candidate for the local generation of
the electron halo observed in the solar wind.**