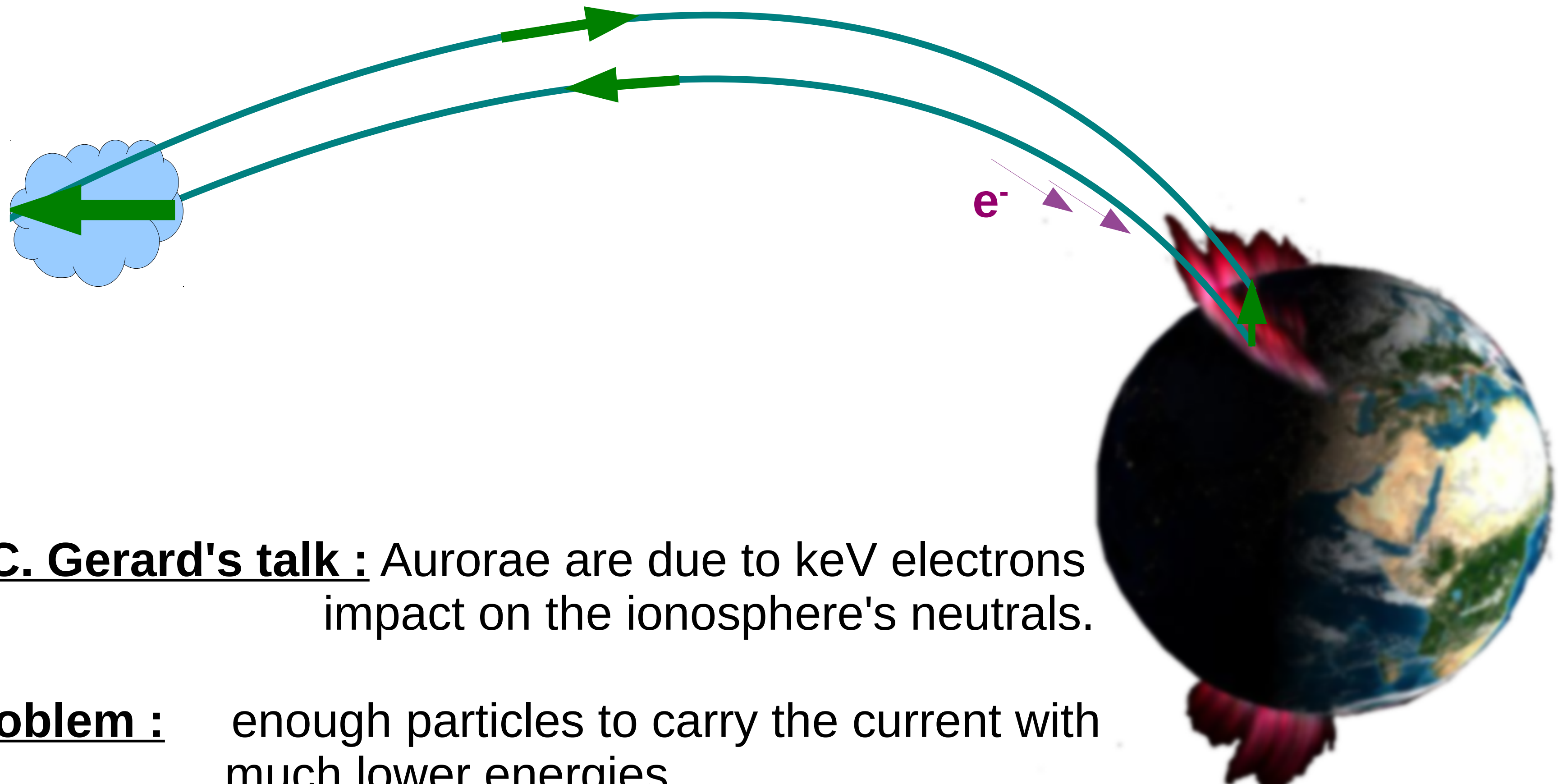
Aurora - acceleration processes

S. L. G. Hess

LATMOS – IPSL/CNRS, Université Versailles St Quentin, France

M. Kivelson's talk : Plasma moves in the magnetosphere.

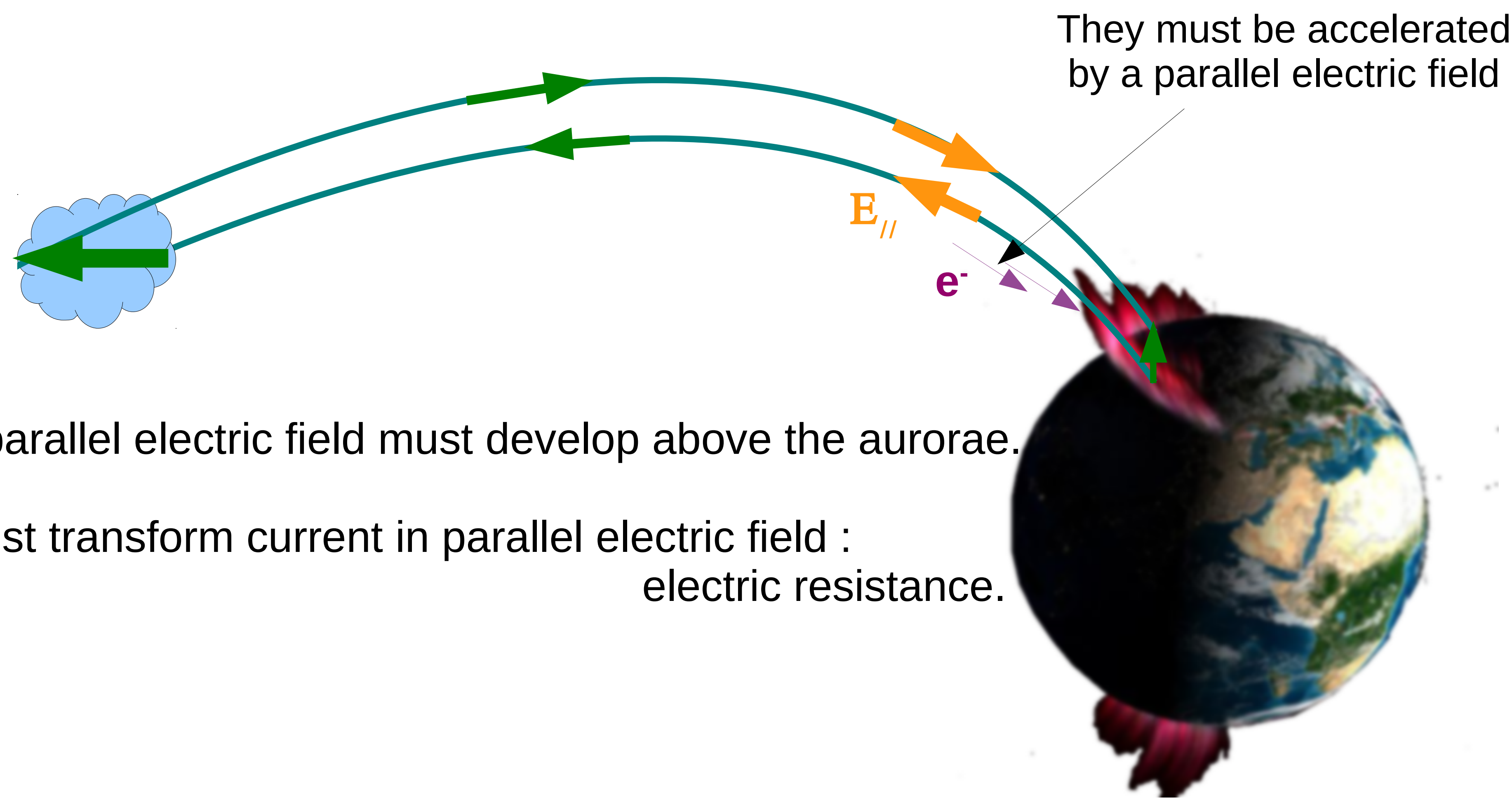
M. Galand's talk : This generates currents which close in the planet's ionosphere.



J-C. Gerard's talk : Aurorae are due to keV electrons
impact on the ionosphere's neutrals.

Problem : enough particles to carry the current with
much lower energies.

Present talk : Why and how do the precipitating electrons reach a keV energy ?



A parallel electric field must develop above the aurorae.

Must transform current in parallel electric field :
electric resistance.

Adiabatic motion of a particle in a magnetic field :

Conservation of the energy (v^2)

and of the magnetic moment ($\mu = v_\perp^2/B$)

Slow down the particles moving toward the planet : $v_{//}^2 = v^2 - \mu B$

Equivalent to a rotation in the velocity frame :

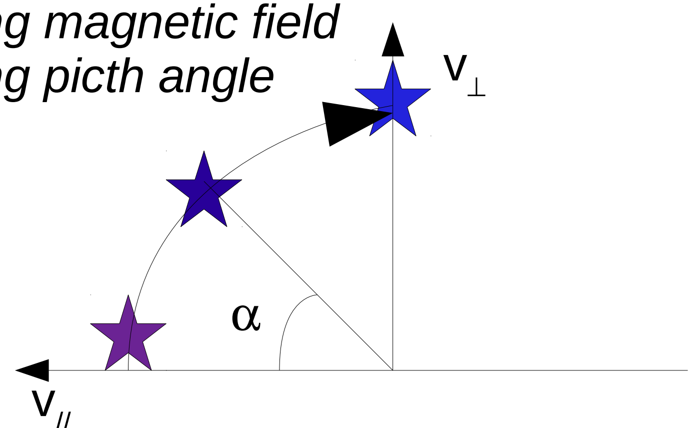
$$\alpha = \text{atan}\frac{v_{//}}{v_\perp} \text{ = pitch angle.}$$

When $\alpha = 90^o$ ($v_{//} = 0$) the particle is reflected: magnetic mirroring.

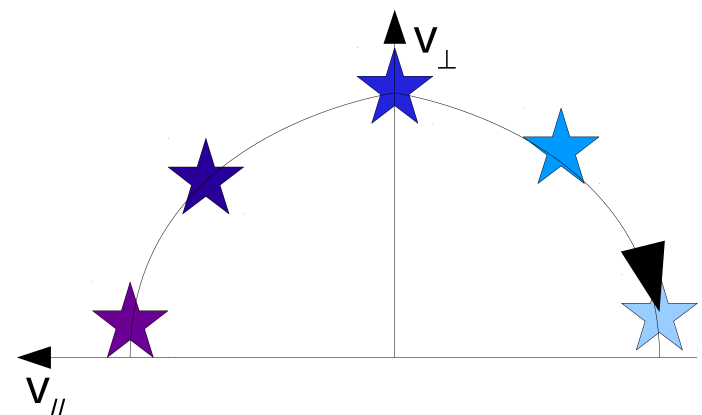
Particle moving toward the planet :

Increasing magnetic field

Increasing picth angle



Magnetically mirrored particle :

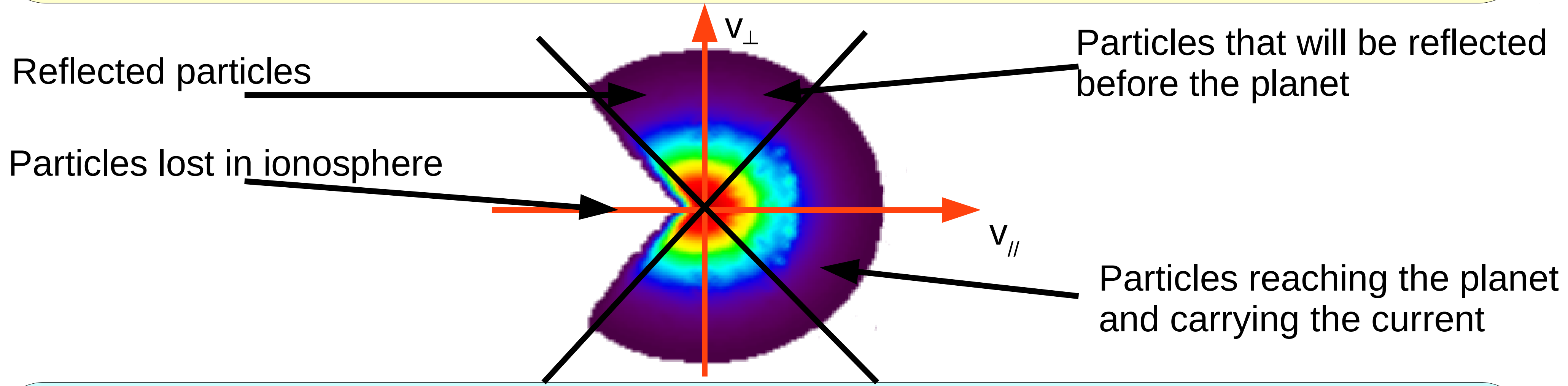


Magnetic mirroring resists to the electron motion

⇒ Resistance to the current

The electrons are reflected for different value of the magnetic field strength, depending on their initial picth angle.

Only the particle not reflected before the ionosphere carry the current to the planet. These particles are lost by collision in the ionosphere and are not reflected at all.
⇒ loss-cone distribution



To increase the current, increase the number of particle in the loss-cone.

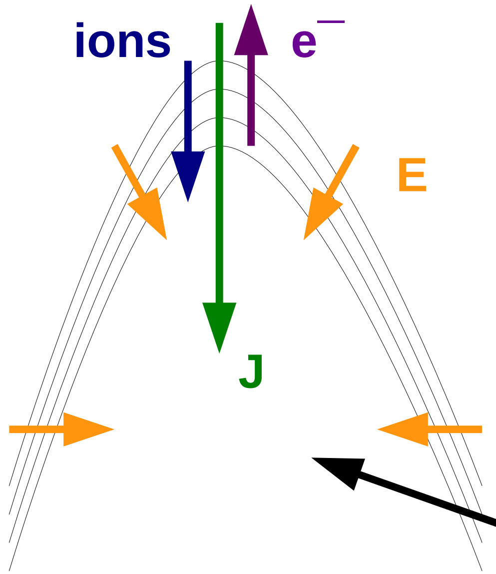
⇒ Knight relation [Knight, 1973]

+ Later refinements to the Knight computation, e.g. Ray et al. 2010.

The potential drop is not continuous : localized potential jump, double layers,...

Perpendicularely : finite size of the flux tube carrying the current.

⇒ « Inverted V » structure.

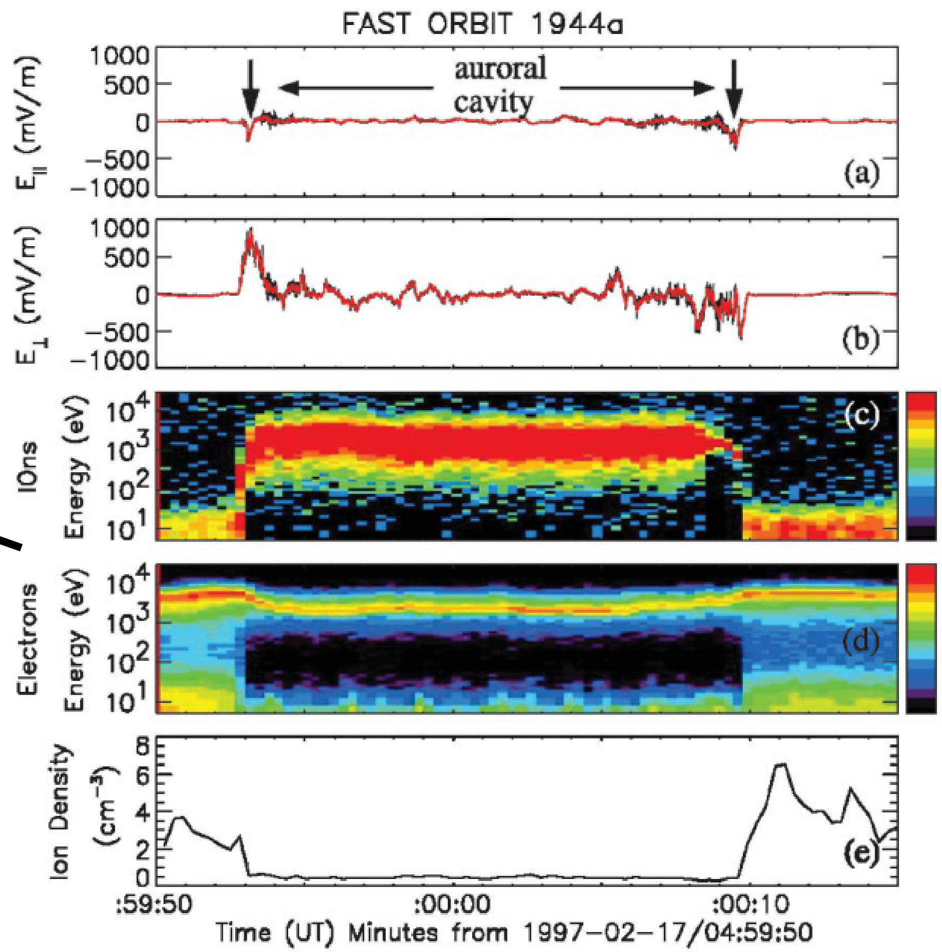


Along the field line :

Multiple accelerations by potential jumps.

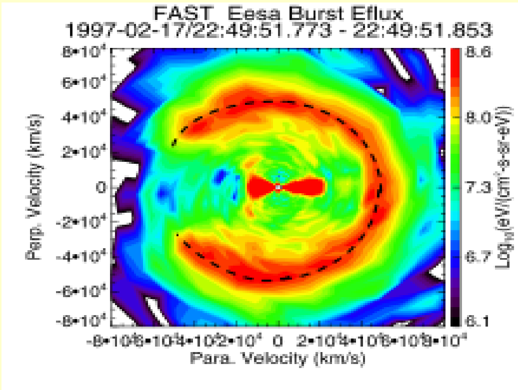
In between, no cold background plasma : only tenous and warm electrons.

⇒ Auroral cavities.



[Main et al., 2006]

Acceleration by potential drops : electron distribution function shifted in energy.



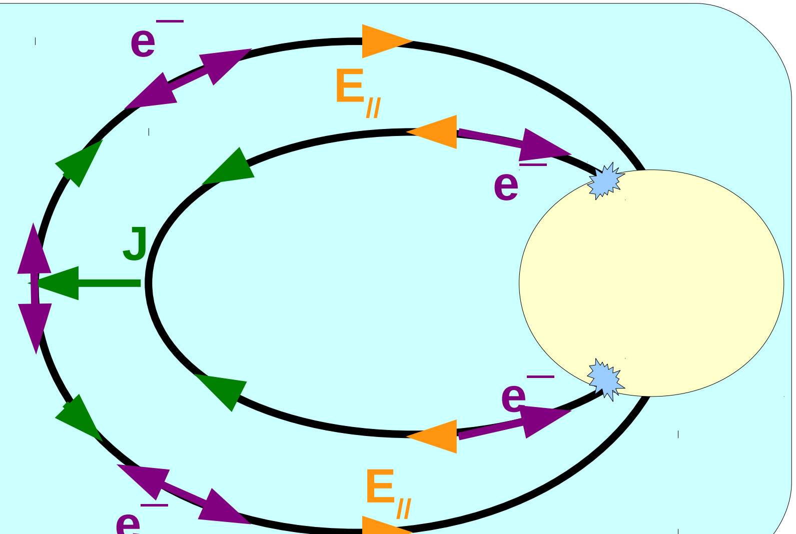
+ pitch angle scattering by magnetic mirroring
= shell distribution.

[Su et al., 2008]

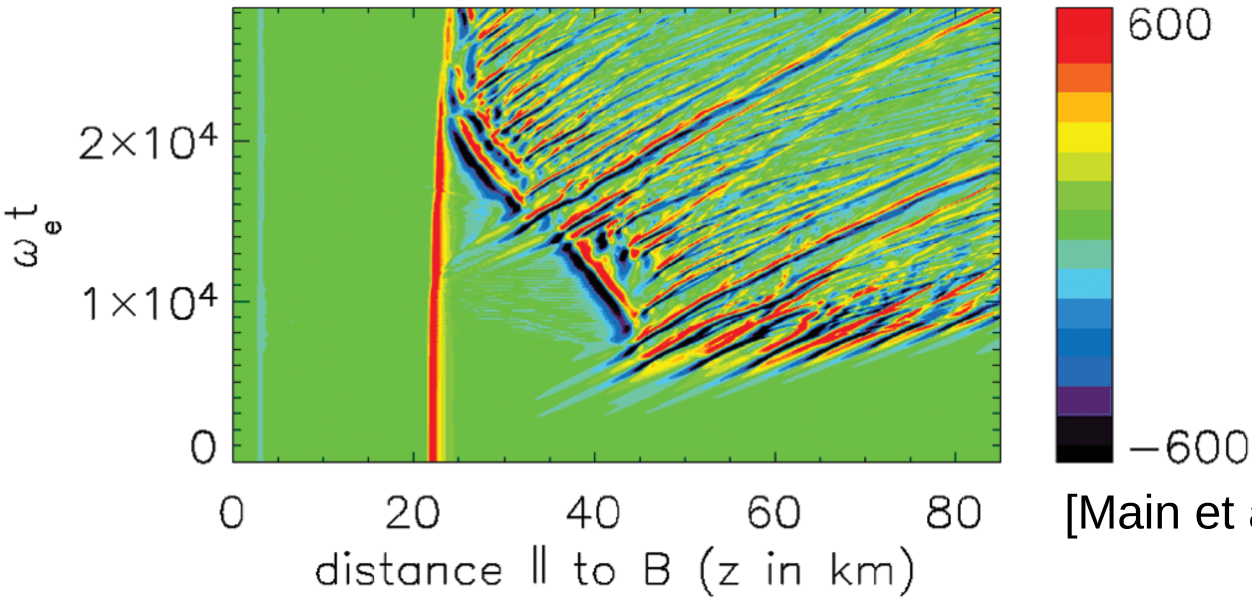
~ monoenergetic keV electrons ⇒ deep auroral emission in a limited range of altitude

Shell distribution + auroral cavities
⇒ efficient radio emission by Maser Cyclotron Instability.

Mono-directional electrons and ion beams
⇒ aurorae only in upward current region
Equatorial electron beams in downward region

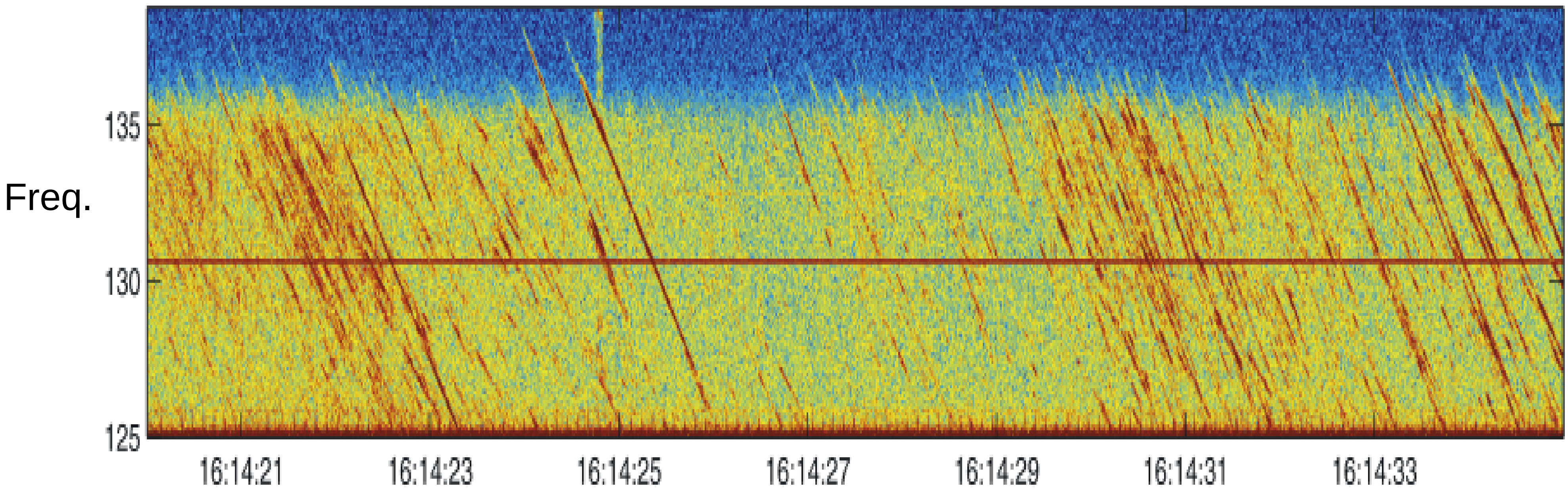


Large potential drops can generate weaker ones.



[Main et al., 2006]

These small electrostatic structures are micro-cavities, suitable for radio emissions.



[Mutel et al. 2006]

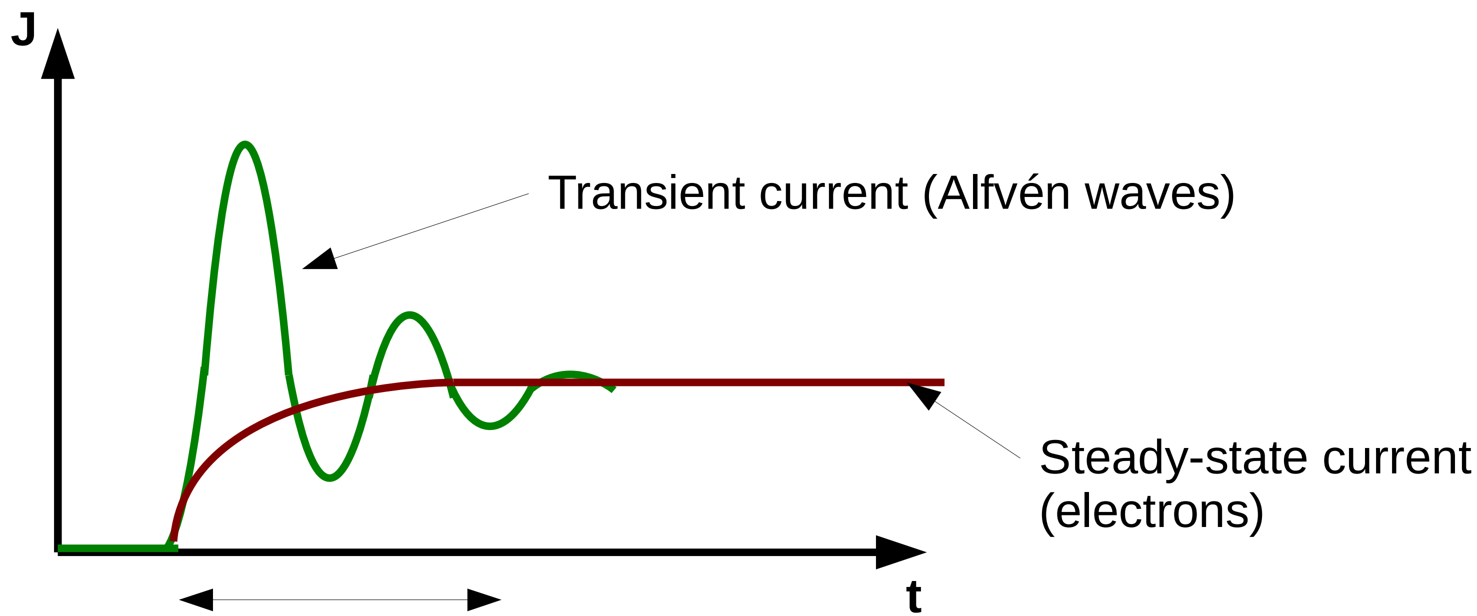
Up to now : A quasi-static overview.

Let's talk about real things !

The current circuits may be (VERY) large.

The information about the current modification is carried by Alfvén waves.

These waves have a finite traveling time between the interaction region and the ionosphere (from a few minutes to several hours) ⇒ **Transient currents**



Mostly transient current systems :

The satellite-magnetosphere interactions

Io example :

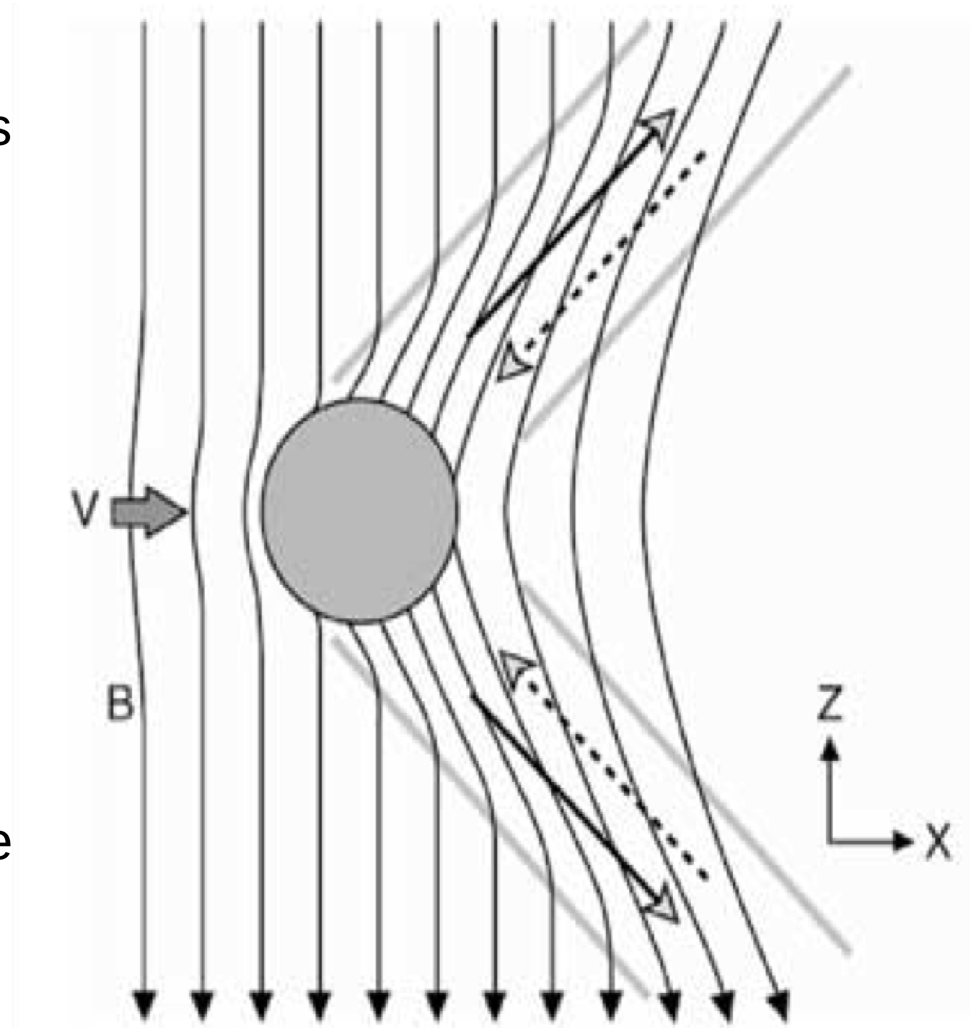
Alfven one-way travel time > 8 min.

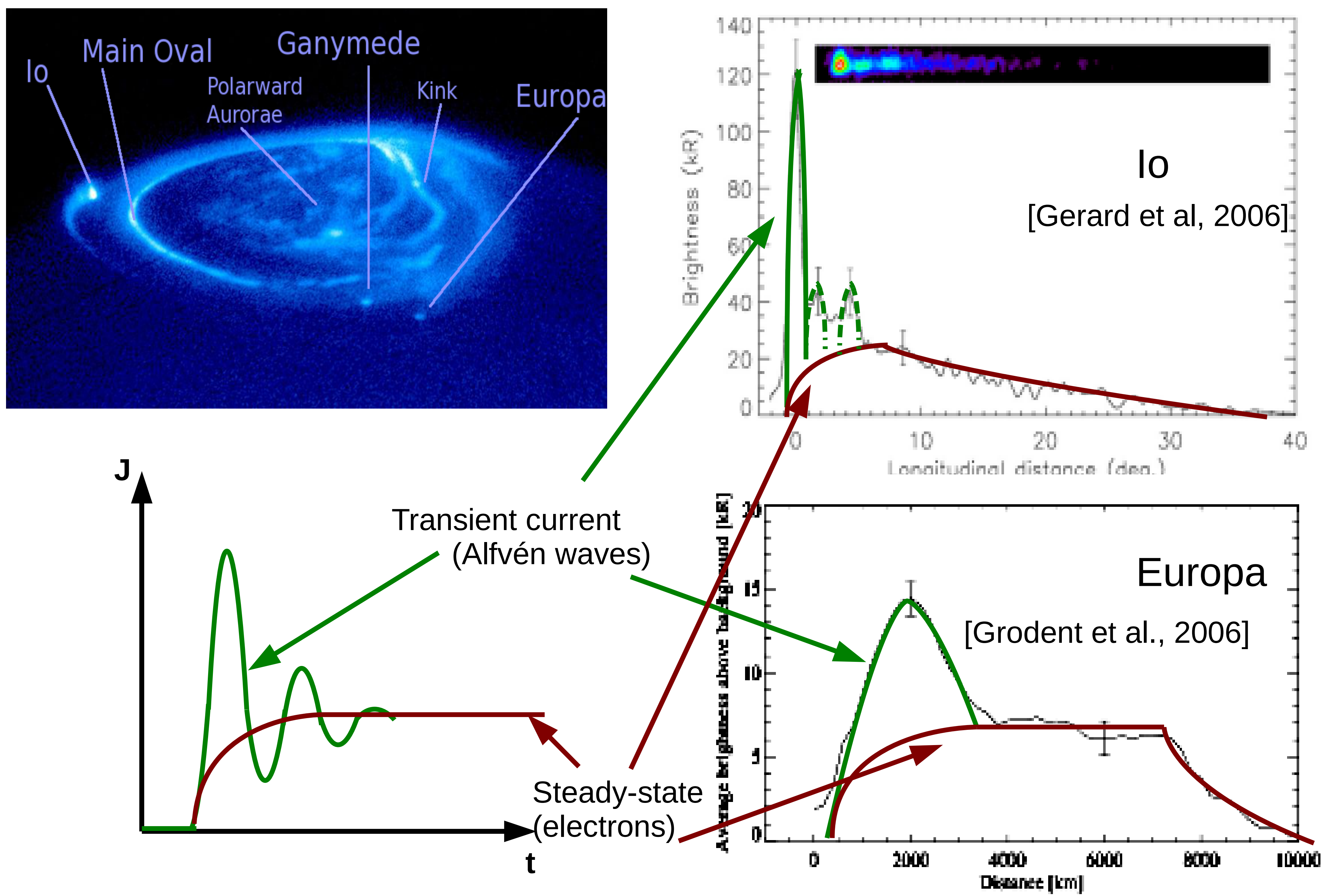
Time for a field line to pass Io ~ 1 min.

No steady-state possible.

The current « closes » in the Alfvén wave packets.

The intensity does not depend on the planet ionosphere conductivity (causality problem).





Io
Main Oval
Polarward Aurorae
Ganymede
Kink
Europa
Brightness (kR)
Longitudinal distance (deg.)
Io
[Gerard et al, 2006]
J
t
Transient current
(Alfvén waves)
Steady-state
(electrons)
Europa
[Grodent et al., 2006]
Average brightness above background [kR]
Distance [km]

Alfvén waves develop a parallel electric field if their perpendicular wavelength is close to the electron inertial length :

$$\delta E_{//} = \omega_a k_\perp \lambda_e^2 \delta B_\perp \qquad \text{[Lysak et al. 2003]}$$

<u>Possible acceleration processes :</u>

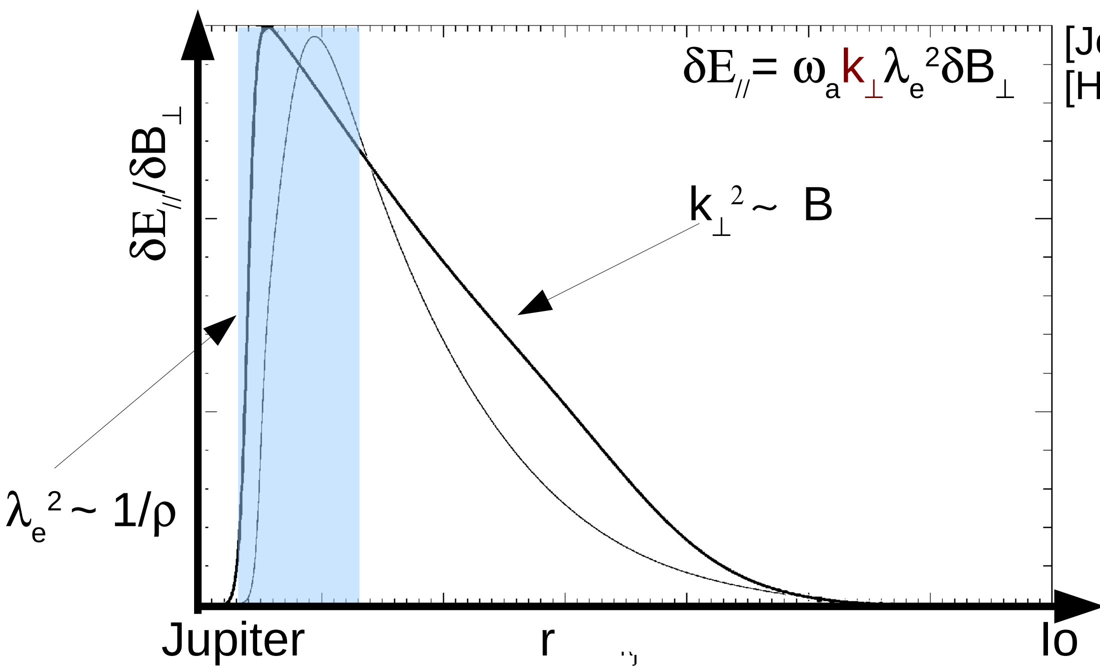
« Resonant » acceleration : Electrons trapped, $v_e \sim v_a$

« Fermi-like » acceleration : Electrons hit the potential wall of the wave : $v_e \sim 2v_a$

⇒ acceleration in a given direction (direction of propagation of the wave)

⇒ need either slow Alfvén waves and/or large electric fields.

Work at Earth, probably not at Jupiter and Saturn ($v_a \sim c$, where non-negligible $E_{//}$).

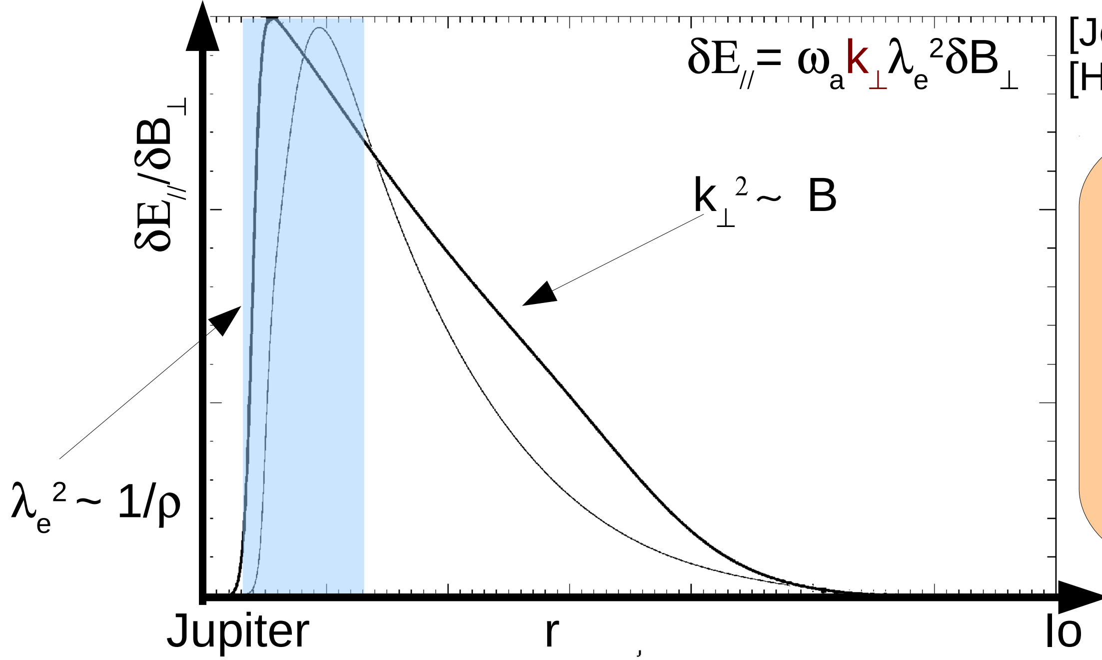


[Jones and Su, 2008]
[Hess et al., 2010]

Narrow region of large $E_{//}$

⇒ electrons see a pulsed electric field.

⇒ acceleration in both directions, depending of the wave phase.



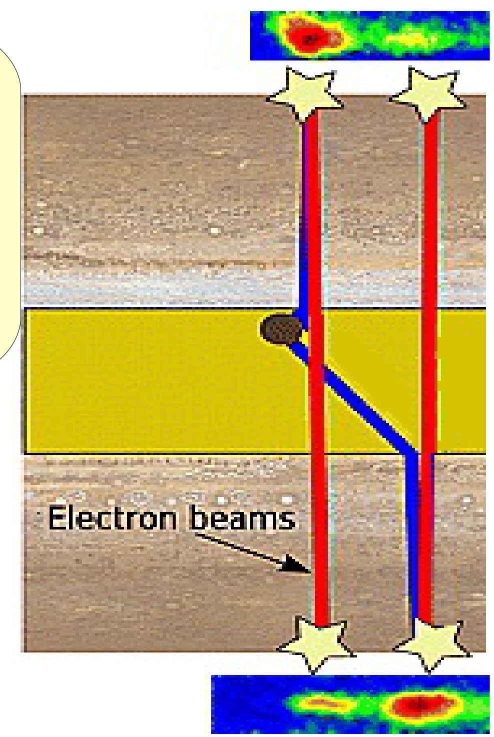
[Jones and Su, 2008]
[Hess et al., 2010]

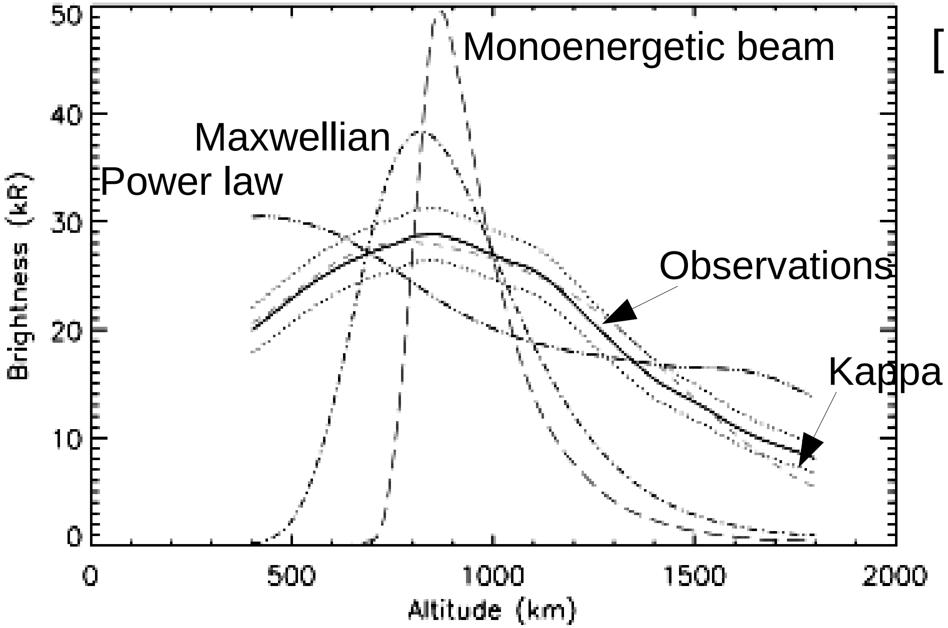
Narrow region of large $E_{//}$
⇒ electrons see a pulsed electric field.

⇒ acceleration in both directions, depending of the wave phase.

keV electrons observed in the equatorial plan behind Io [Frank, Paterson, Mauk, Williams ~2000] and Enceladus [Pryor, Rymer et al. 2011].

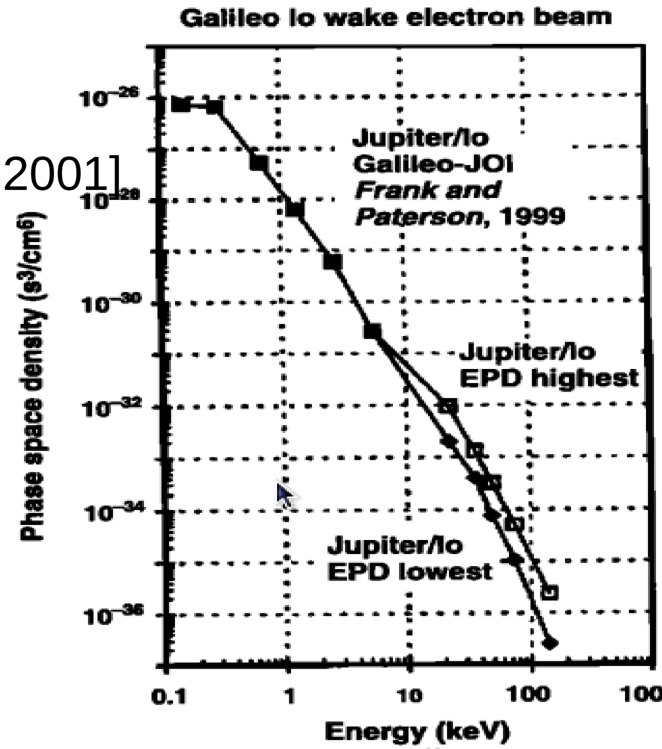
Causes conjugate UV aurorae [Bonfond et al. 2008]





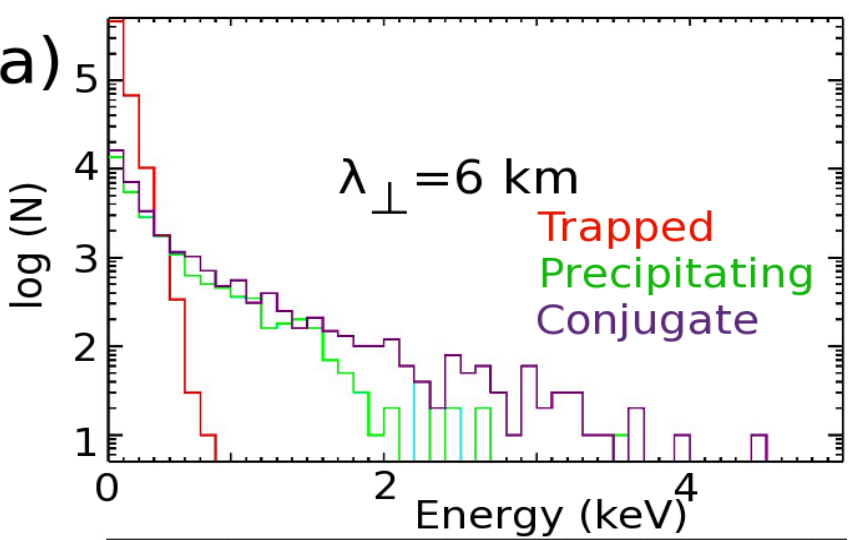
[Bonfond et al., 2010]

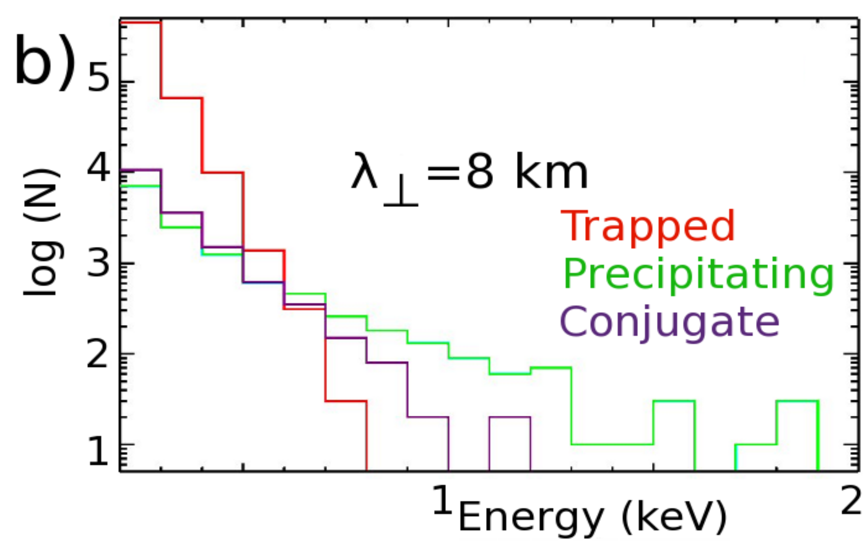
[Mauk et al., 2001]



UV brightness profile : Precipitating electron have a Kappa-like distribution
Equatorial electron: anti-planetward electron have a Kappa-like distribution

Simulations : electrons are accelerated in both directions with a Kappa-like distribution





$\delta E_{//} = \omega_a k_\perp \lambda_e^2 \delta B_\perp$

Need small wavelengths

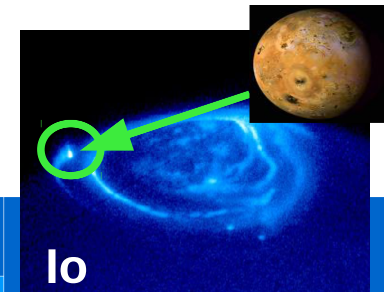
[Swift, 2007]

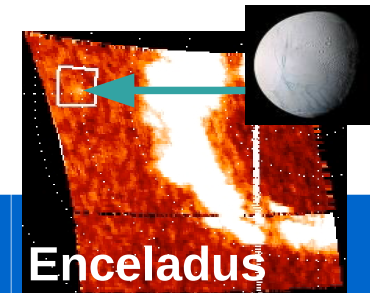
$$\delta E_{//} = \omega_a k_\perp \lambda_e^2 \delta B_\perp$$

↓

Need small wavelengths

In order to transfer enough power to the electrons, the Alfvén waves must be filamented [Hess et al., 2010].





Satellite	Io	Europa	Enceladus
Wavevector distribution			
Satellite scales	~5 10^7 W	~10^6 W	120 W
Filamented (k^{-2})	~10^{10} W	~2 10^9 W	6 10^7 W
From observations	A few 10^{10} W	A few 10^9 W	10^7-10^8 W

Filamentation observed near Io [Chust et al. 2005].
k^{-2} spectrum observed at Saturn [Saur et al., 200].

Small parallel wavelength also needed to avoid strong reflections at the borders of the equatorial plasma sheet.

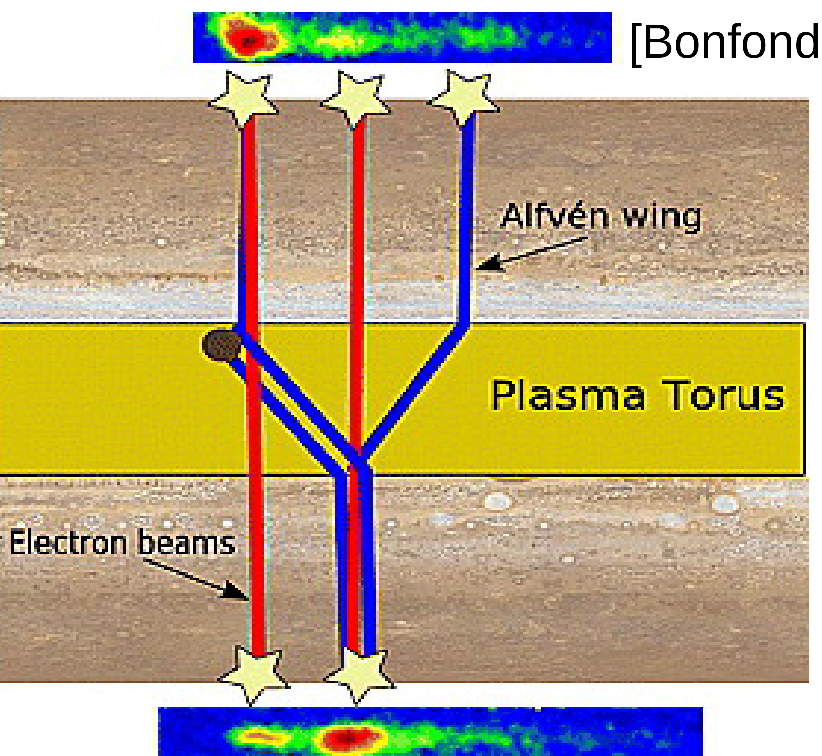
Non-linearities in transient current system :
1) reflections and interferences.

Current is carried by Alfvén waves,

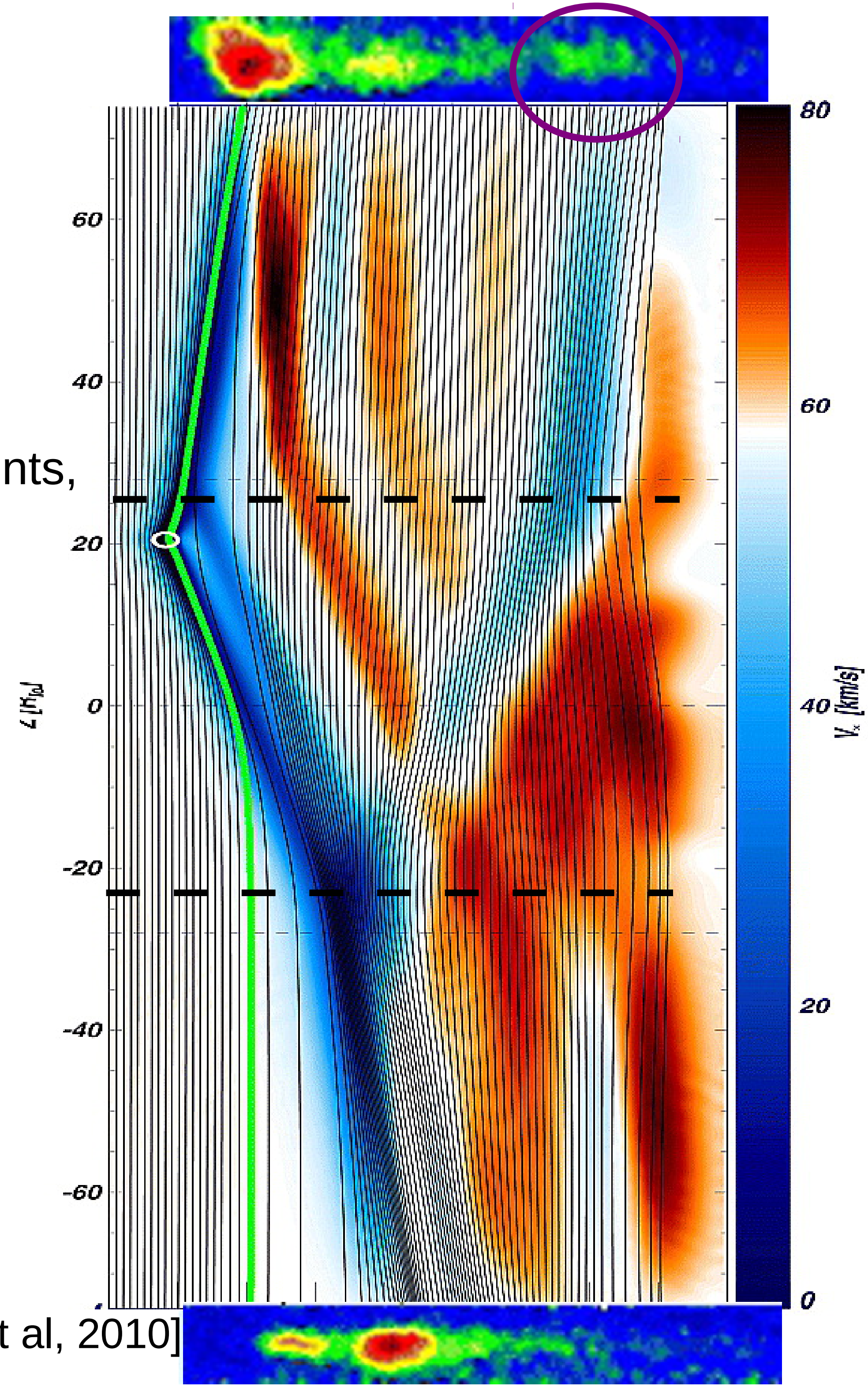
So it behaves like waves.

In particular there can be reflections on gradients, leading to complex interference patterns.

Non-trivial substructures in the UV and radio observations.



[Bonfond et al., 2008]



[Jacobsen et al, 2010]

Non-linearities in transient current system :

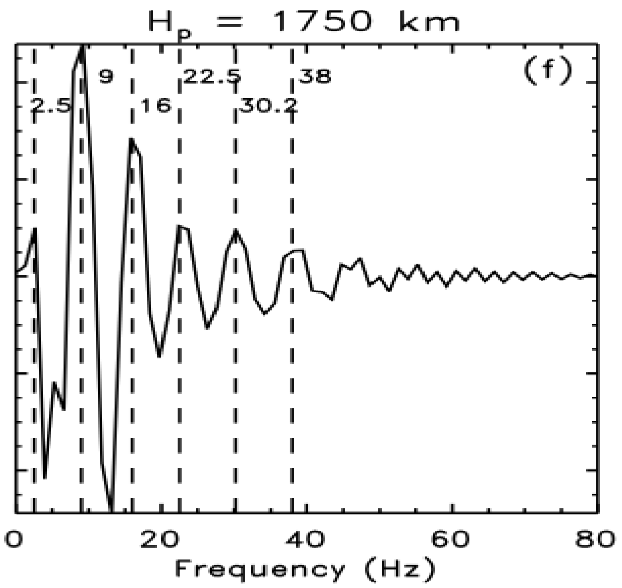
2) Wave trapping and resonance

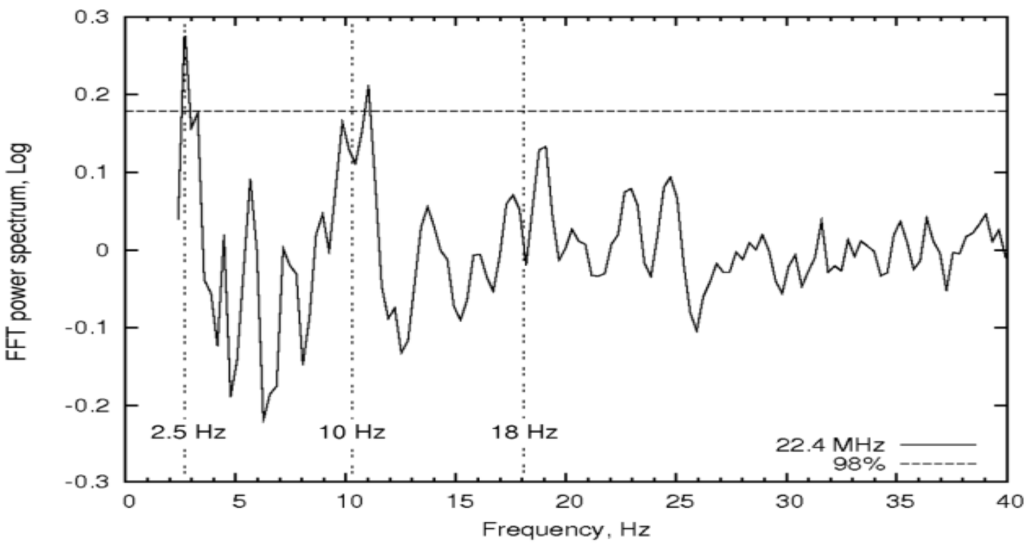
Example : Ionospheric resonantor

Trapping between conductive ionosphere and the Alfvén velocity drop above it [Lysak et al., 1991]

At Jupiter :

Theoretical computation by Su et al., 2006 Measurements by Koshida et al., 2011



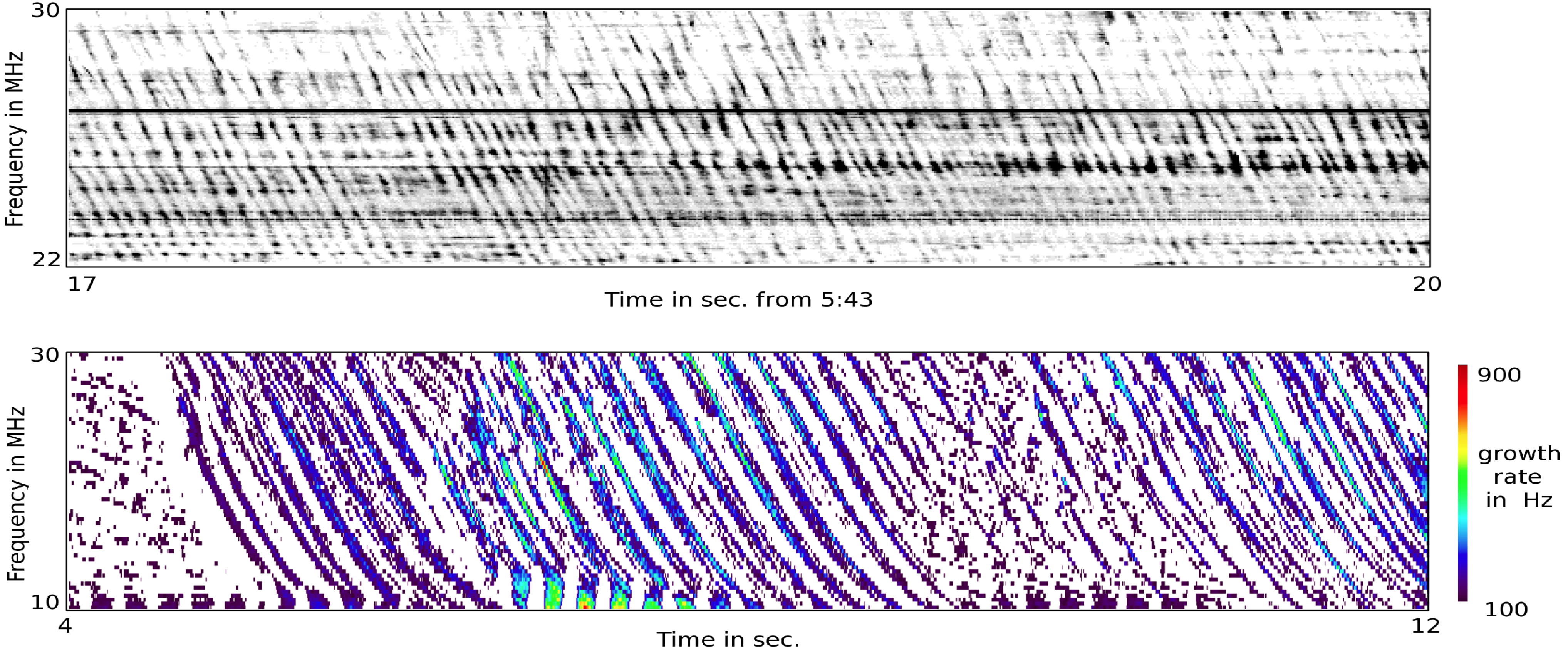


Results in a pulsed electron acceleration and auroral fine structures

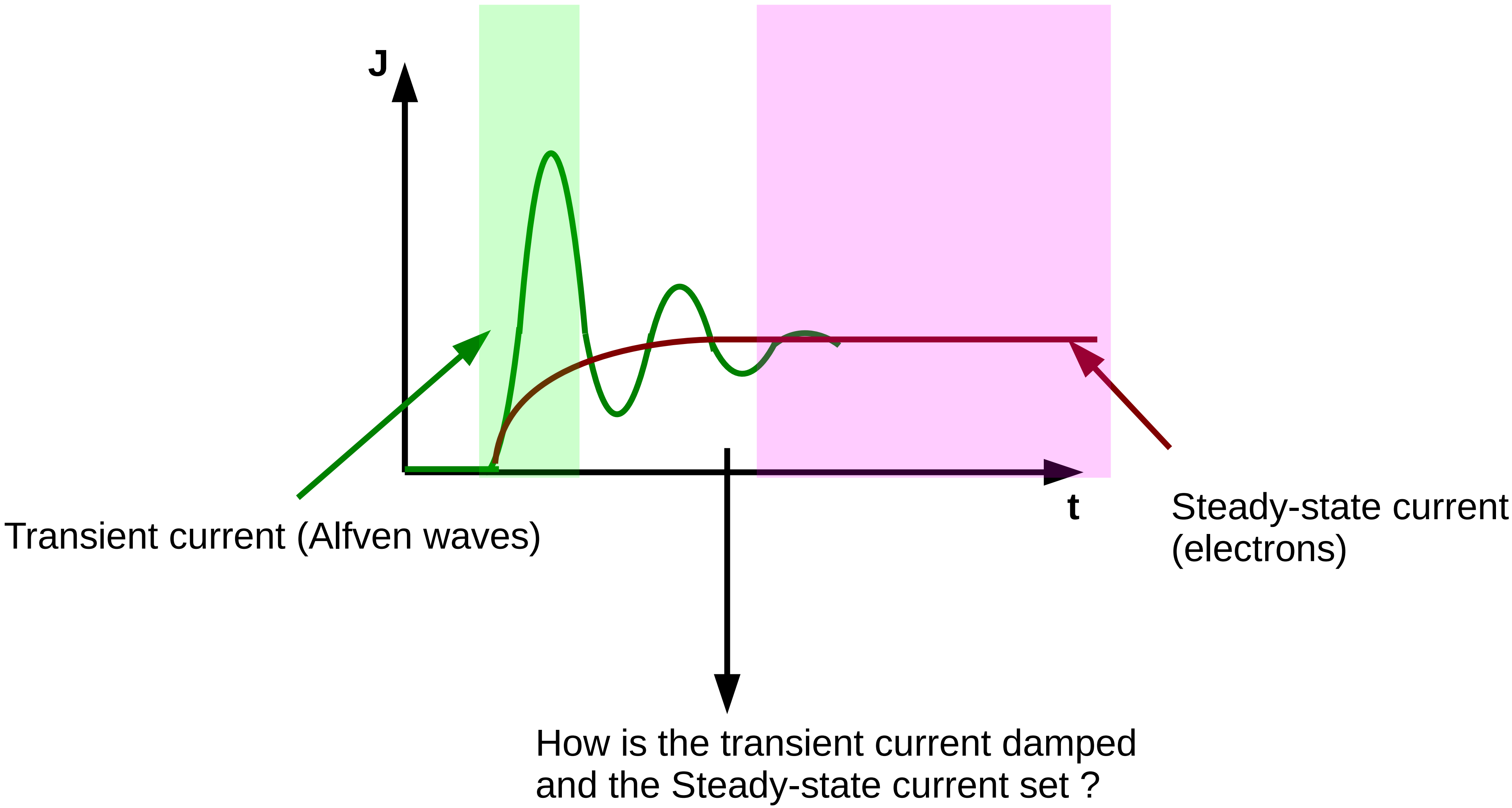
Explains the Jovian S-bursts.

Radio burst with a typical occurrence frequency of 15±10 Hz

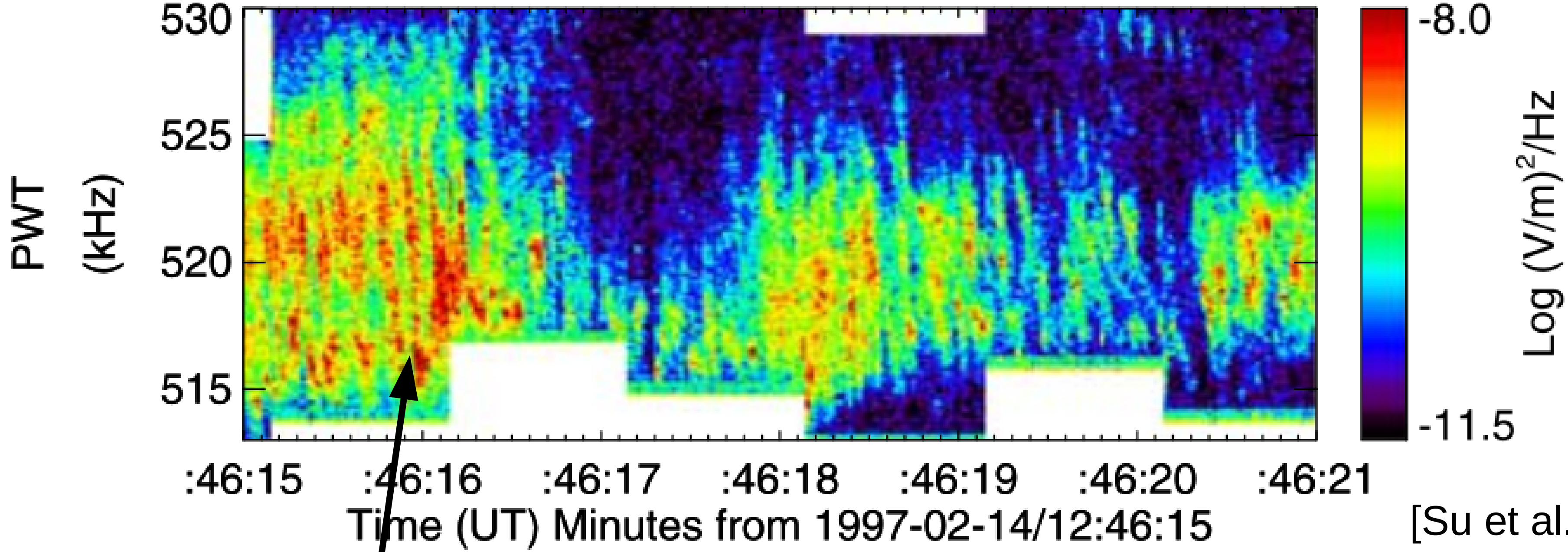
Proposed by Ergun et al., 2004, verified by simulations
[Su et al,2006 ;Hess et al., 2007]



A mostly unknown territory

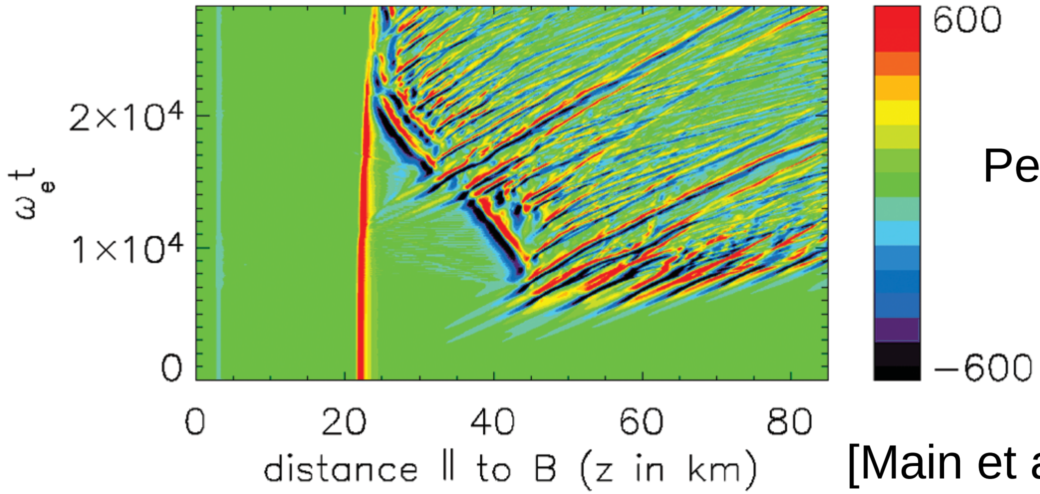


Region of Alfvén wave activity : Electron distributions show AW acceleration



[Su et al., 2008]

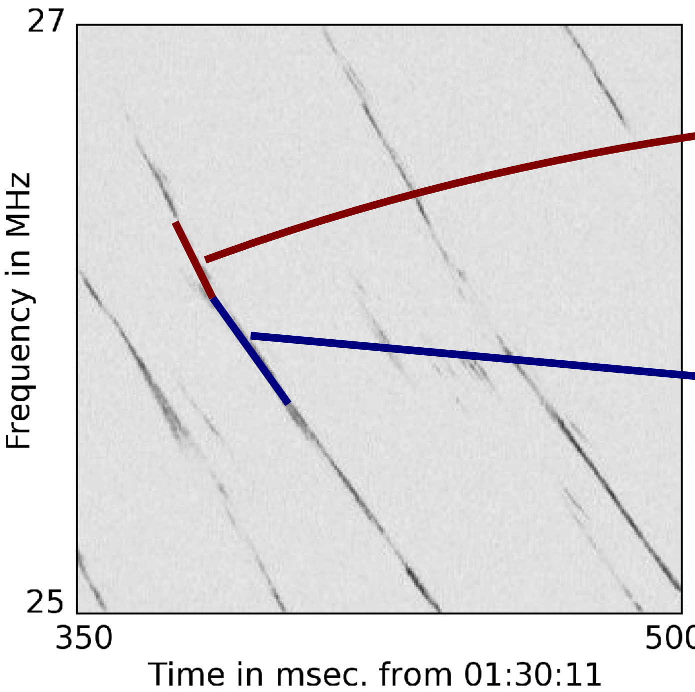
Drifting ion holes



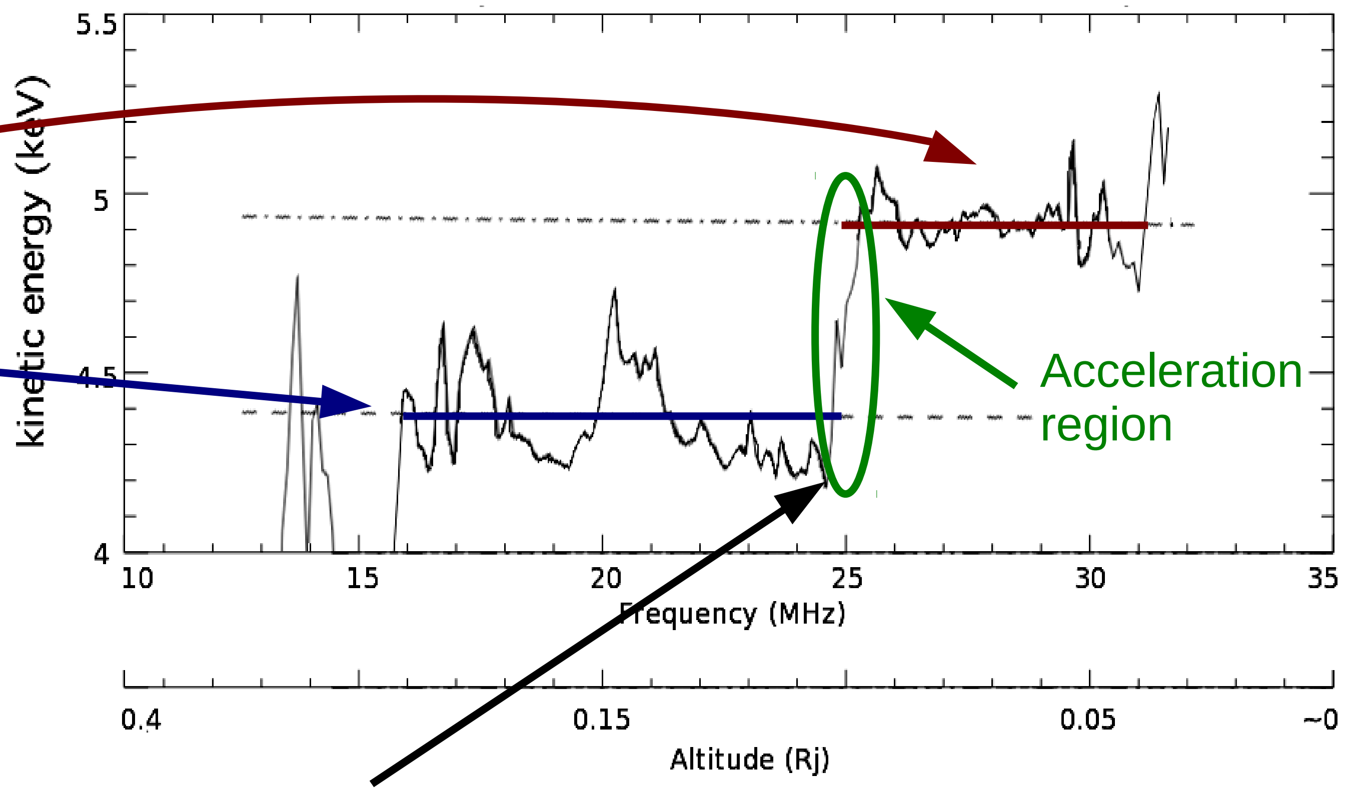
Period depends on Alfvén wave frequency !?

[Main et al., 2006]

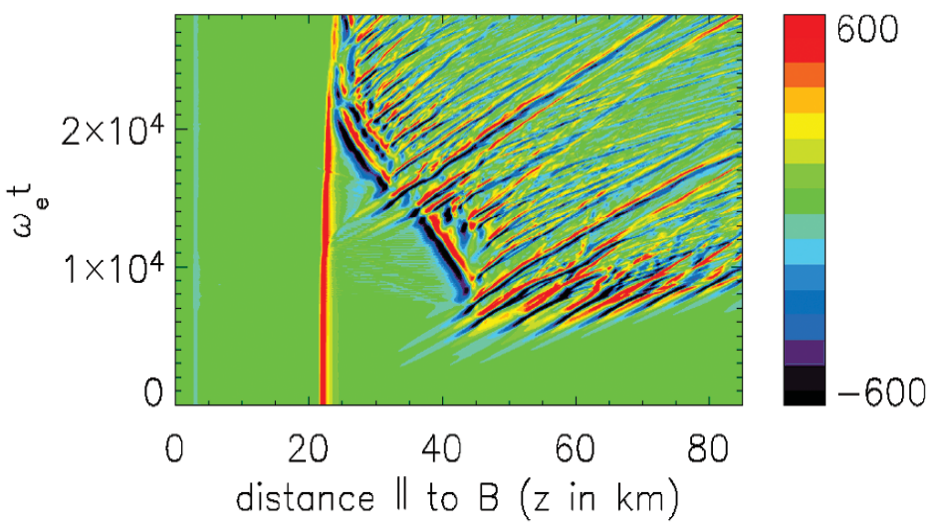
Region of Alfvén wave activity : Electron distribution shows AW acceleration



[Hess et al., 2007, 2009]



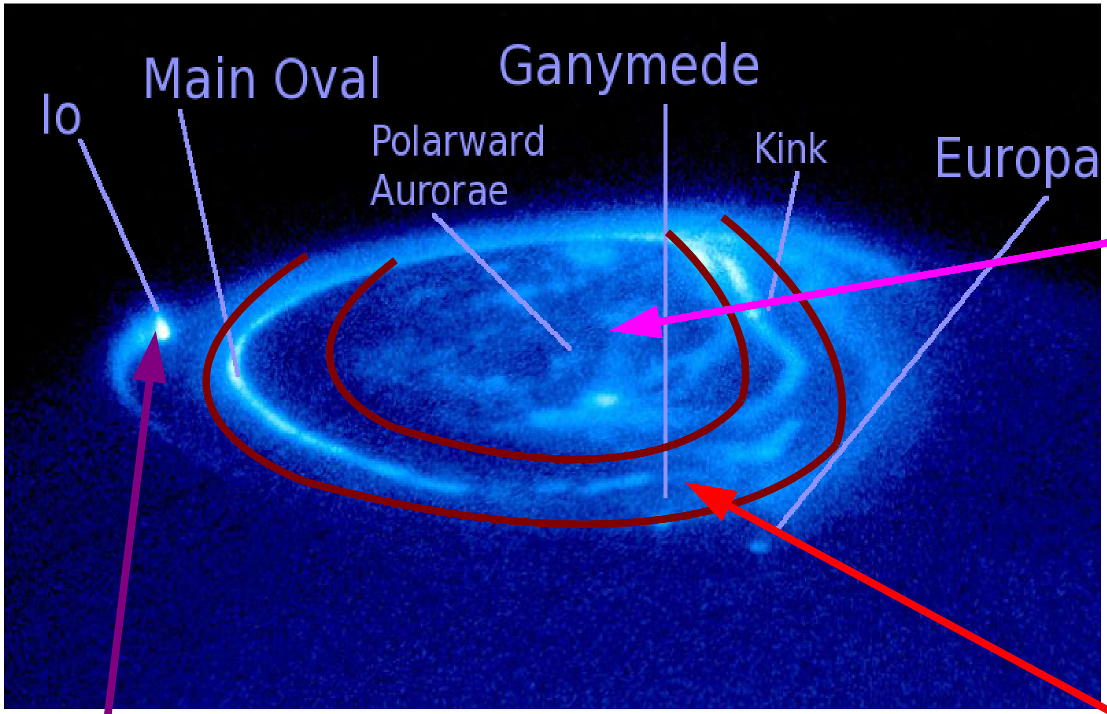
Drifting electrostatic structures @ ion acoustic velocity



Unexplained 200 sec. period.
Related to Alfvén waves ?

[Main et al., 2006]

Which ones at Jupiter?



Maps far from Jupiter.
Alfvén travel time of several hours.

To the point where the mapping of the structure using instantaneous field line is totally irrelevant.

Transient currents
(AW acceleration or reconnection)

Slow and continuous outward transport of the plasma.

Steadiest-state current system.

Still, fast perturbations at small scales [Kivelson et al. 2005].
Probable minor contribution of transient currents [see Hess et al. poster].

Transient interactions
Electron acceleration by Alfven waves