Atelier magnétosphères planétaires,
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L'estimation de fortes températures et faibles densités électroniques par la sonde de Langmuir de Cassini autour de Saturne

A man's noise is another man's signal

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(et les équipes Cassini-RPWS/CAPS)

Conclusion : the Langmuir probes are not only detectors for cold and dense ionospheric plasma, but can also provide information about hot magnetospheric plasma

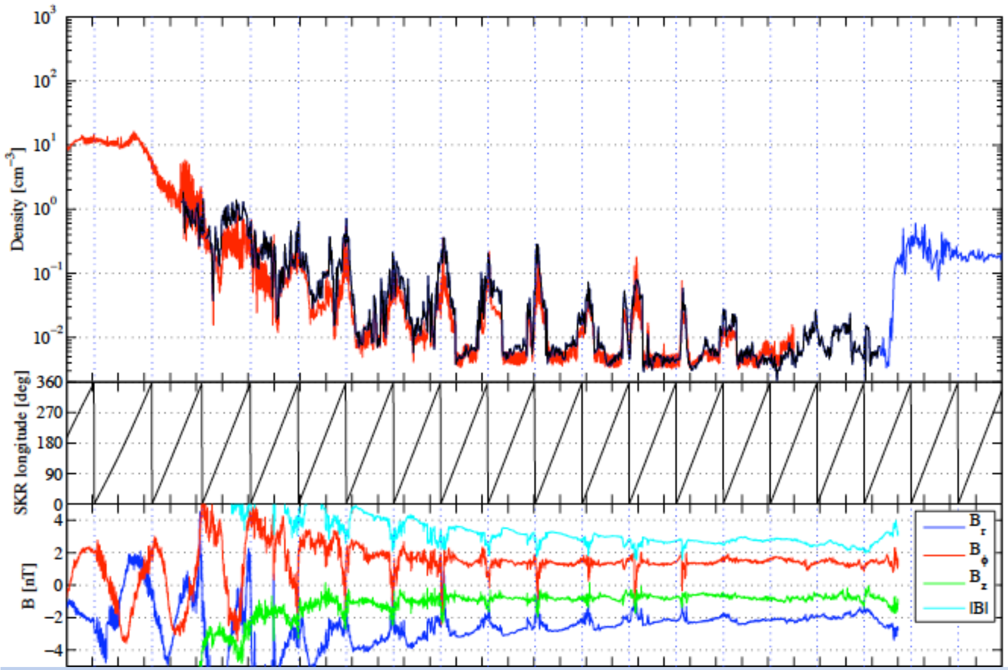
Introduction : what is a Langmuir probe ?

- ✓ Classically used in laboratory experiments, often onboard planetary missions (Astrid2 / Demeter / Rosetta / MAVEN / Cassini / JUICE …)
- ✓ A Langmuir probe (LP) is a conducting sphere mounted on a boom. Its potential (Ubias) is artificially varied to collect ions or electrons depending on the sign of the potential.
- ✓ The fitting of the curve Current = f(Ubias) allows to extract many plasma characteristics : electron (ne) and ion density (ni), electron temperature (Te), spacecraft potential (Usc)

Problem : limited to **low temperatures** (< few eV) and **high densities** (> several part/cm3)

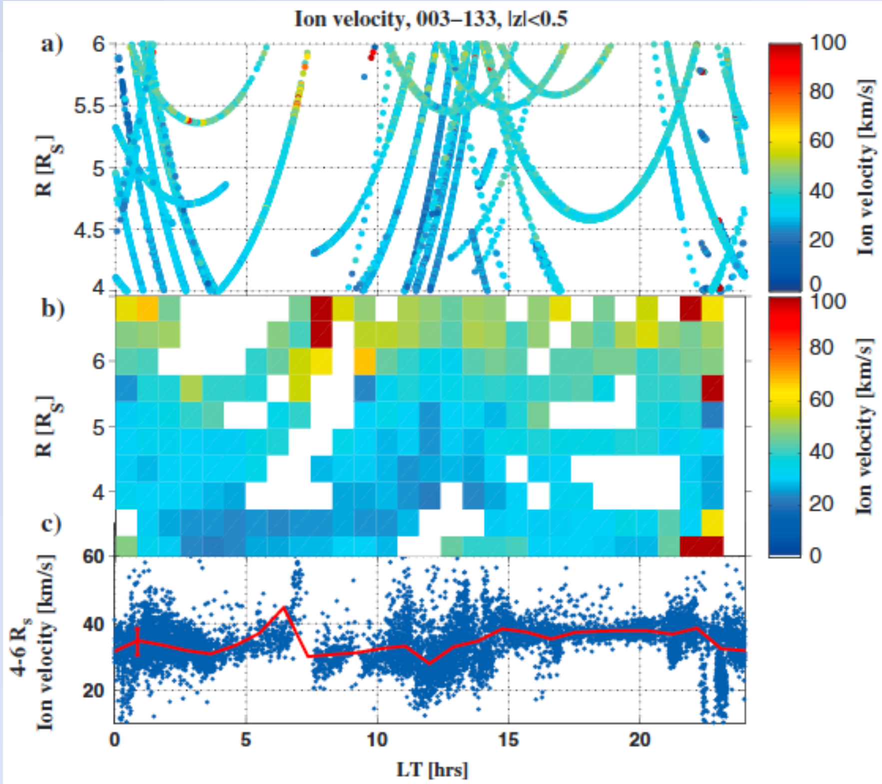
→ mostly used for ionospheric plasma

Examples of LP magnetospheric studies



Mapping of equatorial cold electron density in the outer magnetosphere (L>10) by Morooka et al. (2009)

Low densities measured from a proxy based on the floating potential of the Langmuir probe



Mapping of equatorial cold ion density and velocity in the inner magnetosphere (L<7) by Holmberg et al. (2014)

A day-night asymmetry for both ion density and velocity, potentially induced by the radiation pressure force on E ring dust grains (≈ additional electric field of 0.1–2 mV/m)

Can we also derive information about hot plasma from the LP observations ?

Which currents are measured ?

Theory

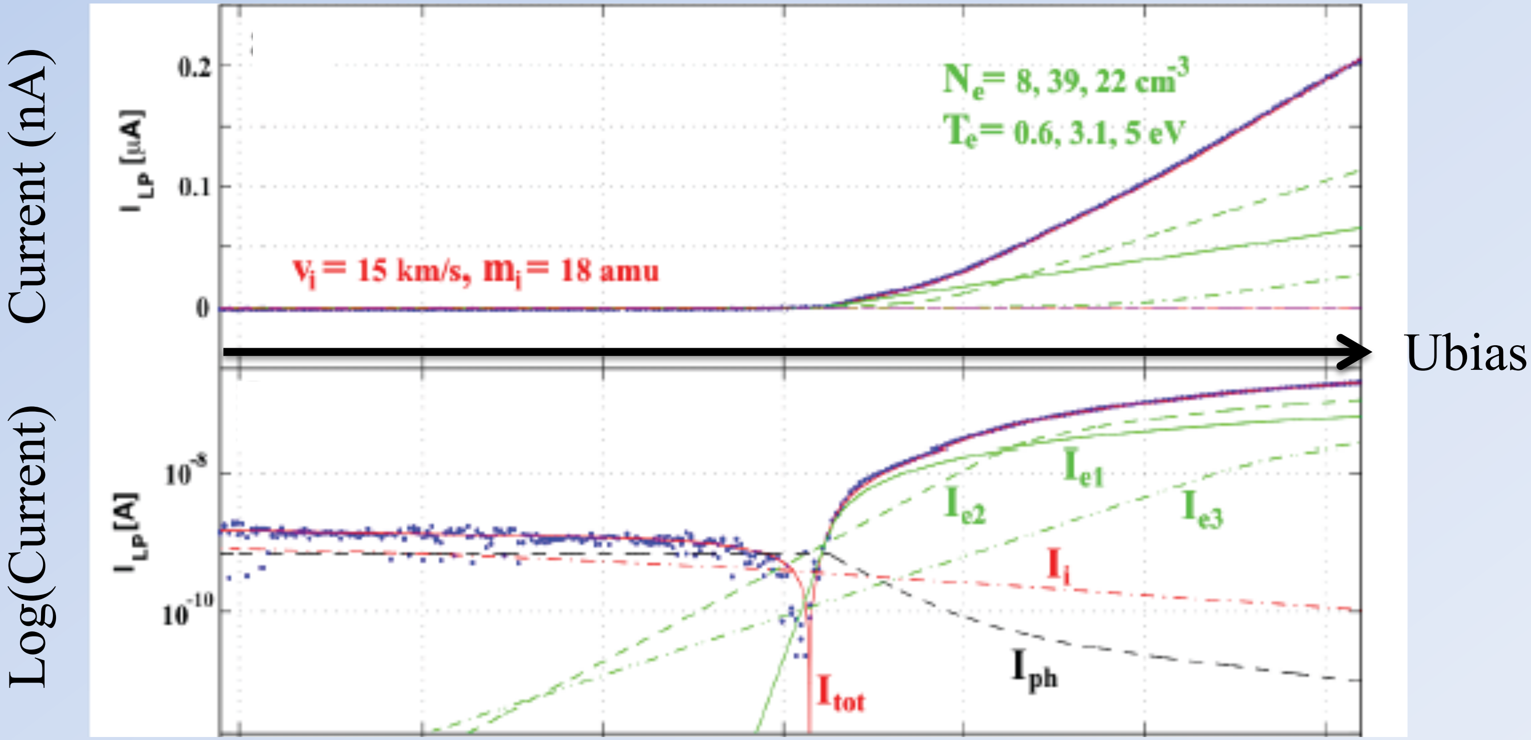
$$I = I_i + I_e + I_{ph,Ly-\alpha}(+I_{e*,i*} + I_{dust}) =$$

Ions

Electrons

Photo-electrons

eventually secondary electrons



Which currents are measured ?

Theory

Data analysis

$$I = I_i + I_e + I_{ph,Ly-\alpha}\,(+I_{e*,i*} + I_{dust}) = m - bU_b$$

Ions

Electrons

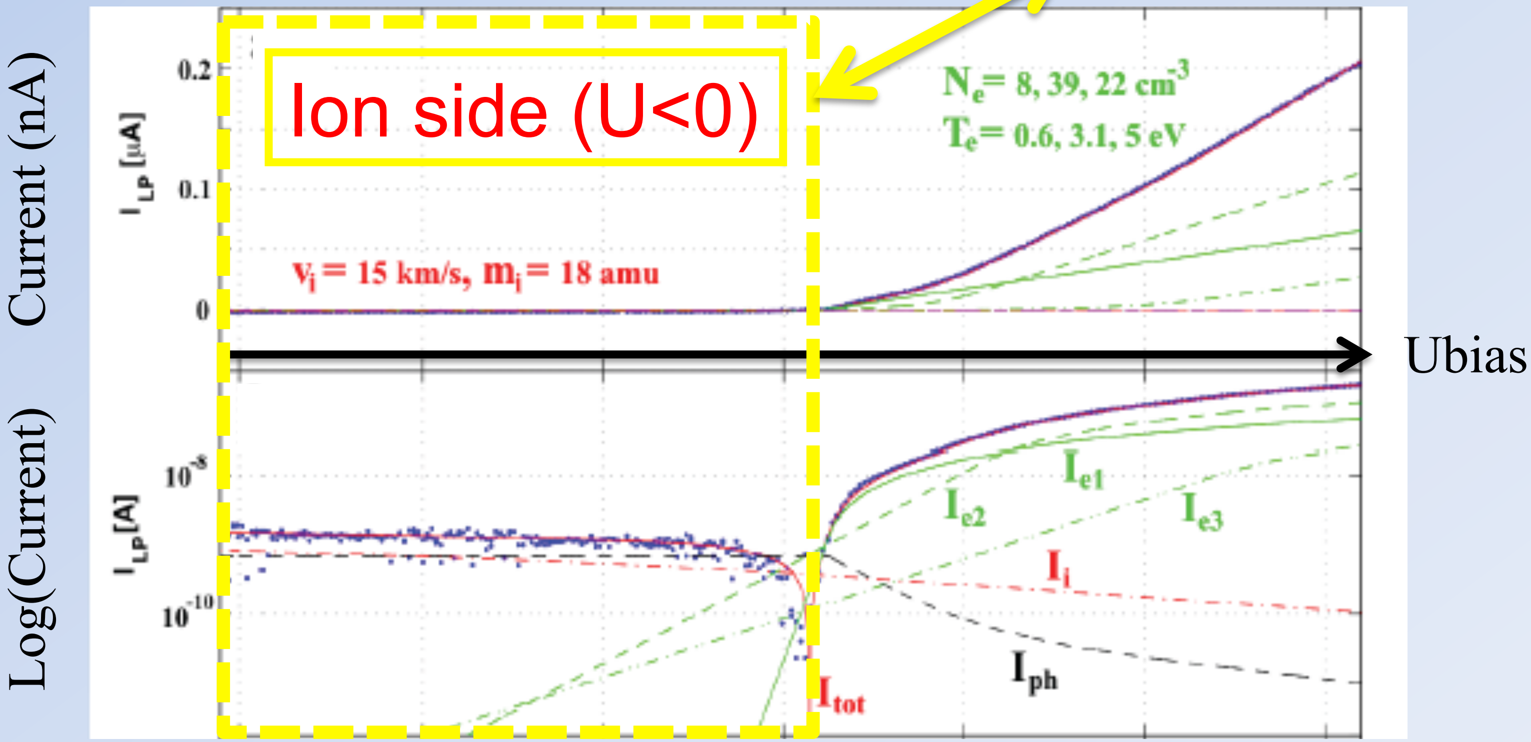
Photo-electrons

eventually secondary electrons

DC level

Slope

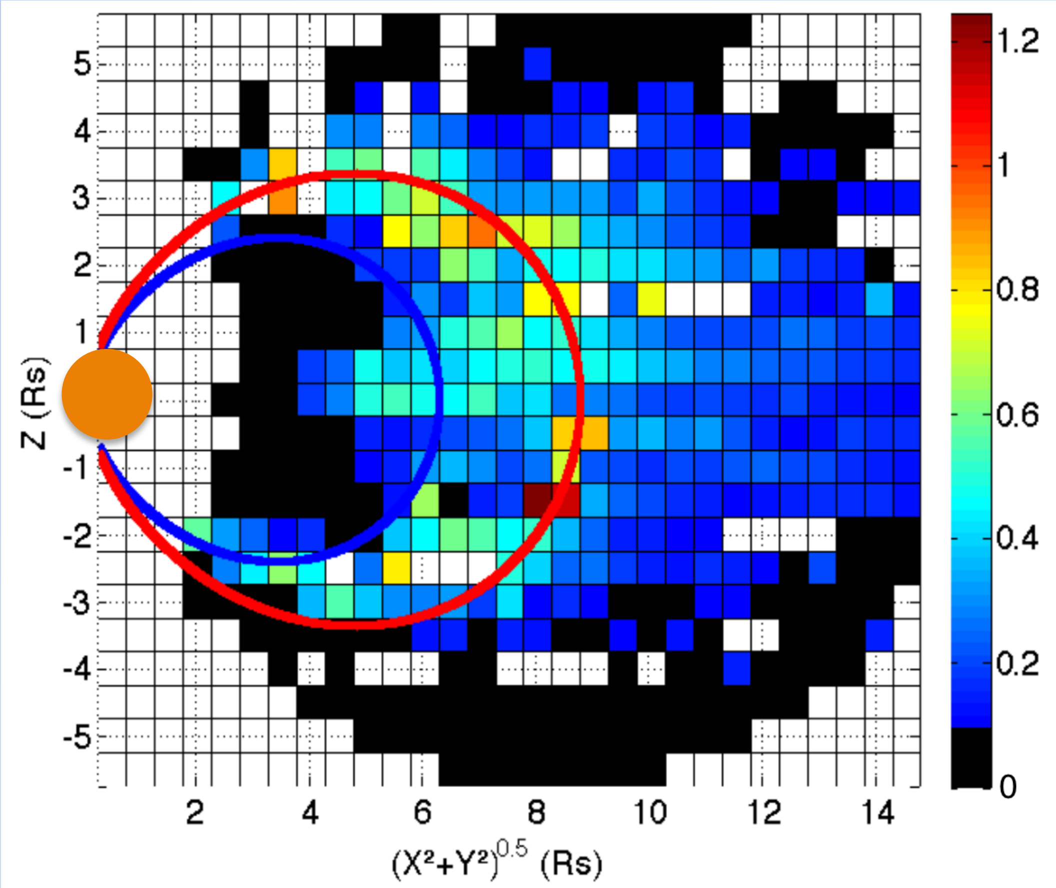
Bias potential



Start of the study : a current belt

Ion side current
(U<0) in nA

Dione
Rhea
Saturne



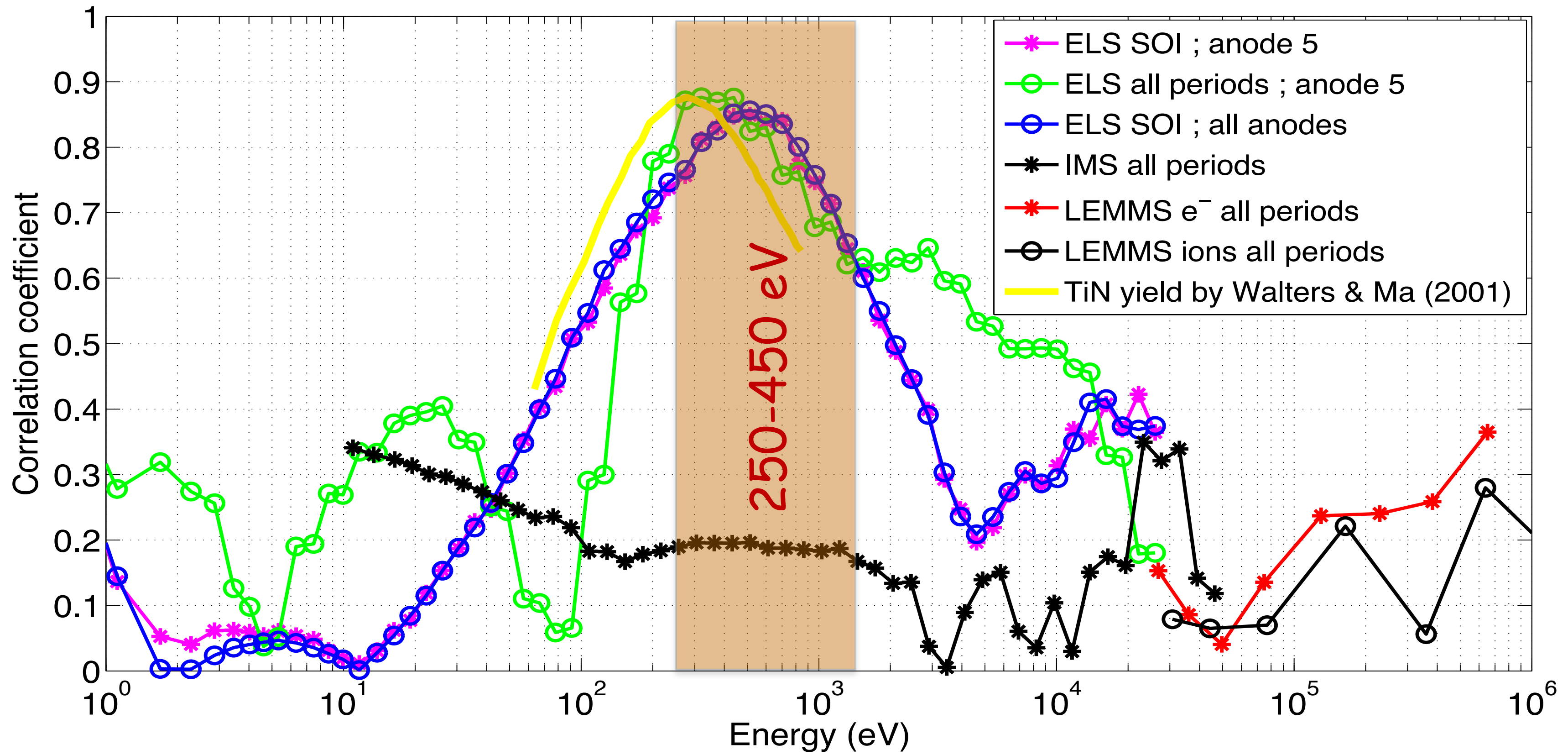
All data during 2005-2008

Garnier et al. 2012

Surprise : do we observe Saturn's radiation belts with the Langmuir probe ??

Origin of the observed "belt"

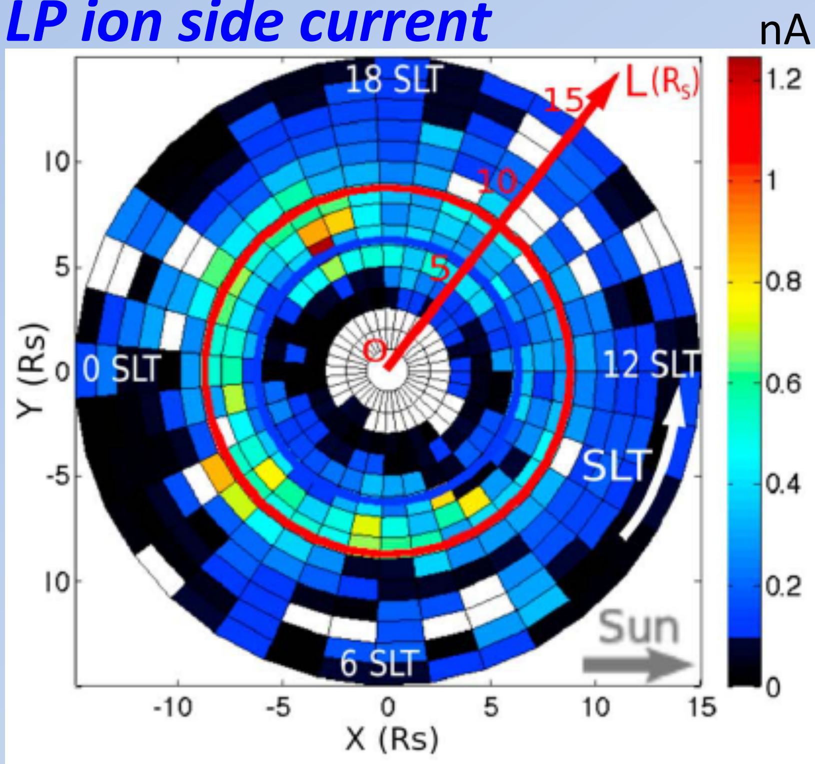
Only the current I_{e*} of energetic electrons (and their induced secondaries) can explain the observations.



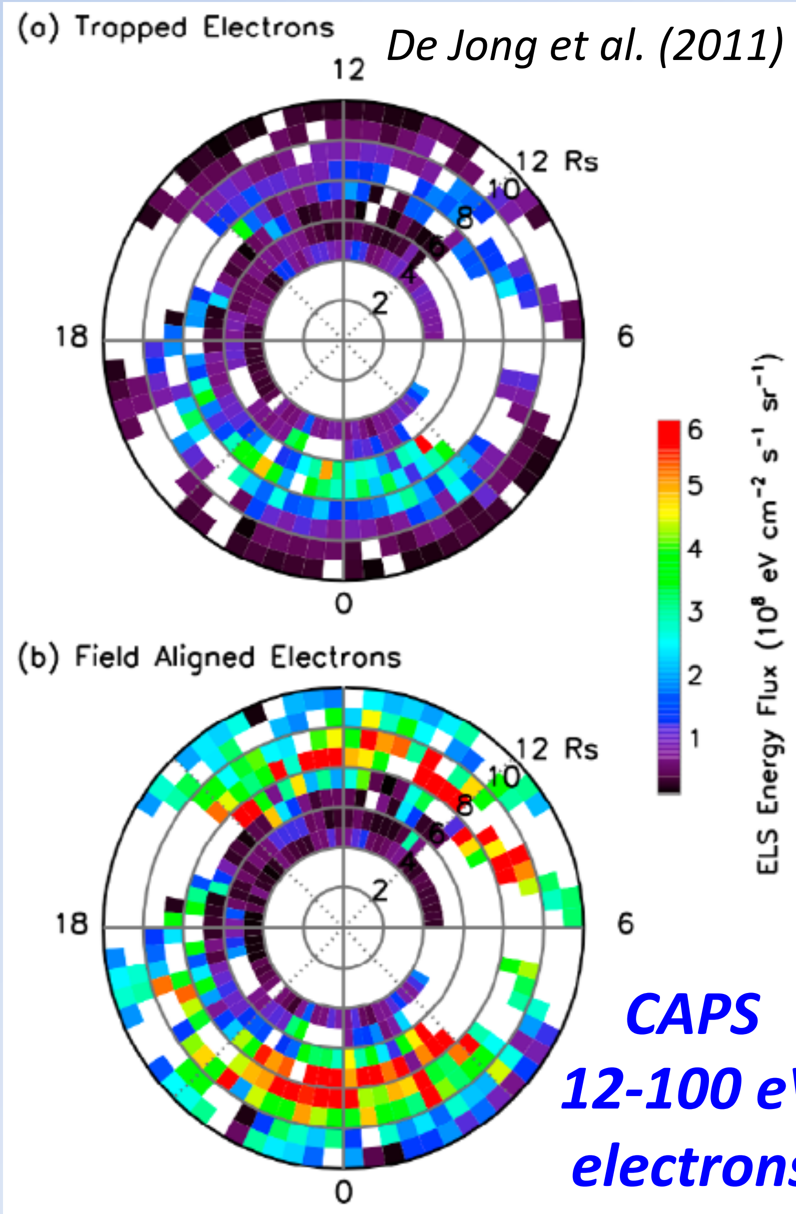
Confirmation by a correlation analysis between the LP current and other instruments : strong correlation with impacting 250-450 eV electrons

Origin of the observed "belt"

LP ion side current



Garnier et al. 2012



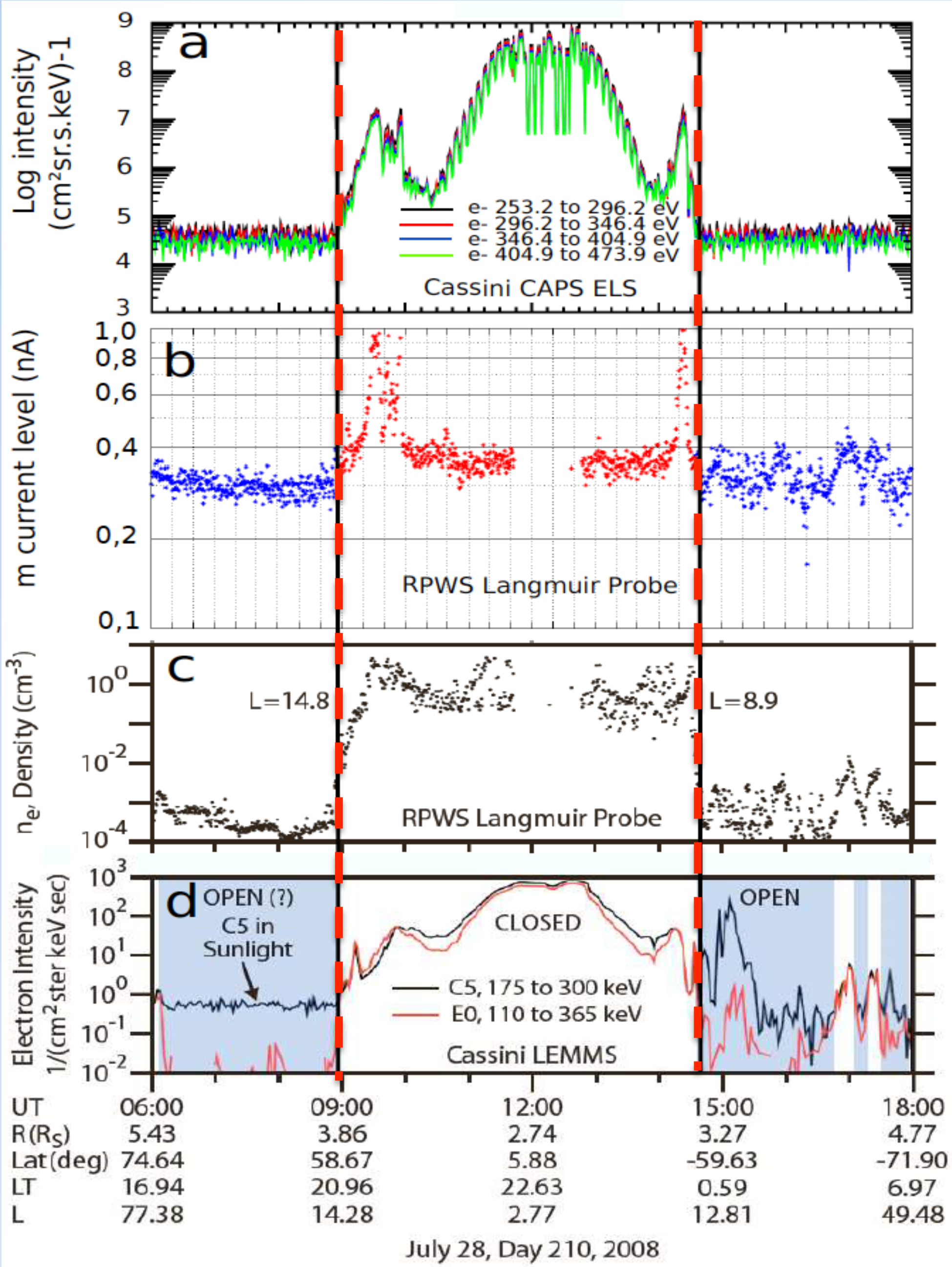
CAPS 12-100 eV electrons

Mapping the ion side current (and thus I_{e*}) of the LP reveals the radial profile as well as the day-night asymmetry of hot electrons, with similar results to CAPS measurements (Schippers 2008 ; De Jong et al. 2010, 2011)

The plasmapause-like boundary at Saturn

Mapping the ion side current of the LP reveals the electron density gradients inside L=6-10 and may thus help to locate the plasmapause-like boundary identified by Gurnett et al. (2010).

This boundary may also be coincident with the separation between closed and open field lines regions



Modeling the energetic current of the LP

- The current due to incident/secondary/backscattered electrons is :

$$I_{energet} = \frac{2\pi e}{m_e^2} A_{LP} \int_0^\infty E \boxed{f_{ie}(E)}(1 - \boxed{\delta_e(E)} - \boxed{\eta_e(E)}) dE * \boxed{e^{\frac{eU}{k_B T_e}}}$$

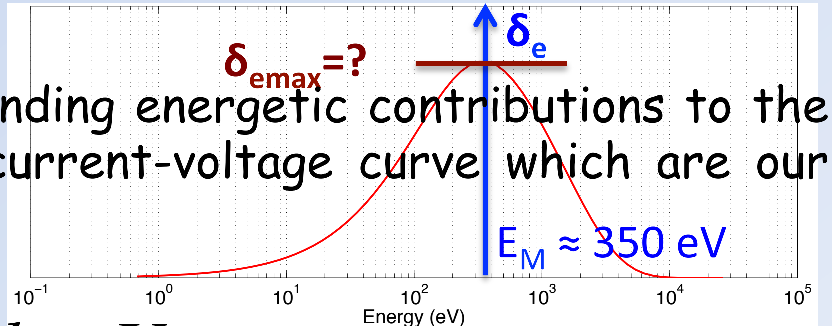
Incident electron distribution function (given by CAPS anode5)

Secondary electron yield

Backscattering coefficient

Boltzmann term

The secondary electron yield depends highly on $\delta_{e_{max}}$ (maximum value), which is a poorly known characteristic of the LP surface



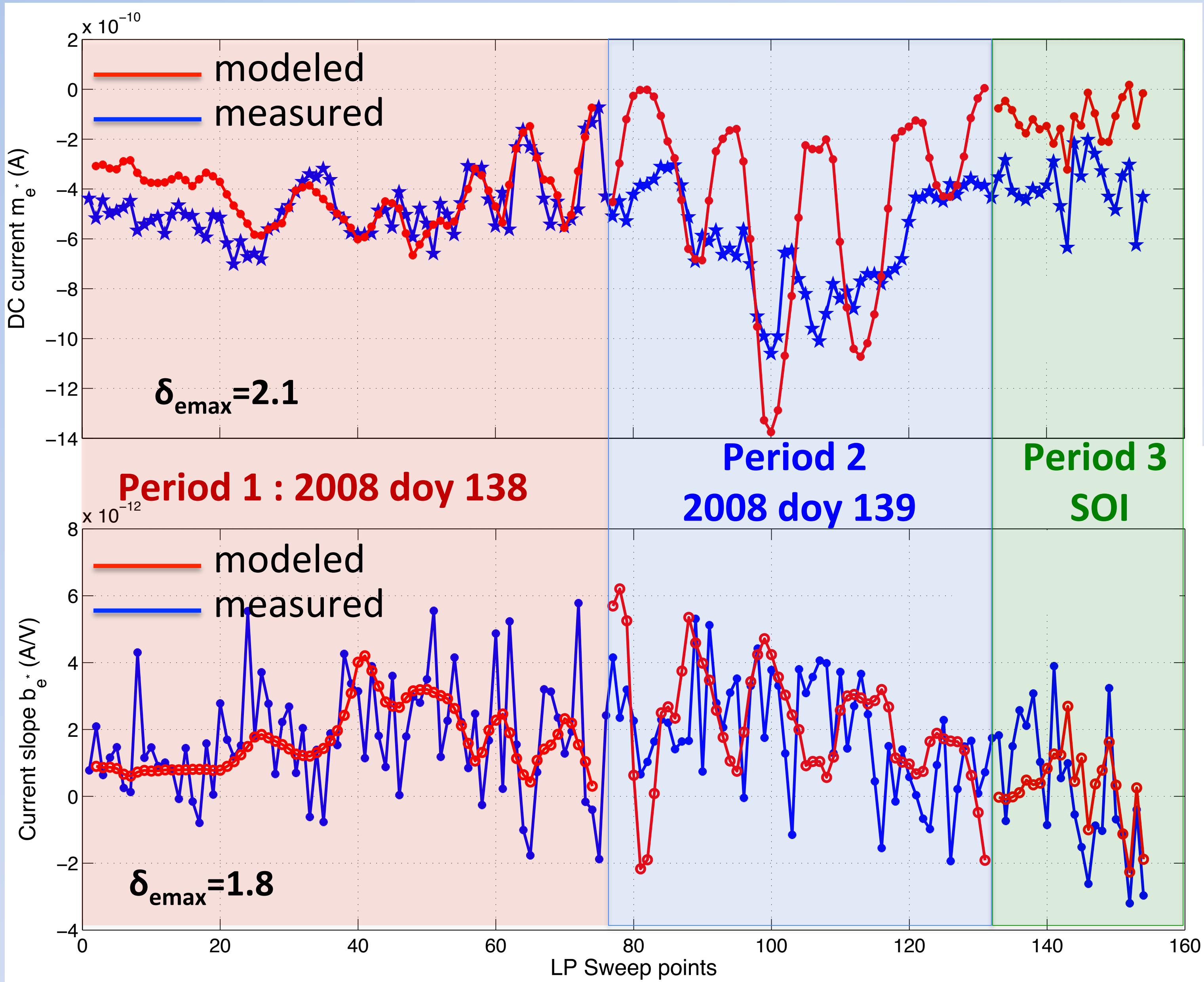
- One then needs to calculate the corresponding energetic contributions to the DC level (I_{ener}) and slope (b_{ener}) of the current-voltage curve which are our observable characteristics :

$$I_{energet} = I_{ener} - b_{ener} U_b$$

Modeling the energetic current : results

I_{ener}

b_{ener}



Estimating the hot electrons characteristics

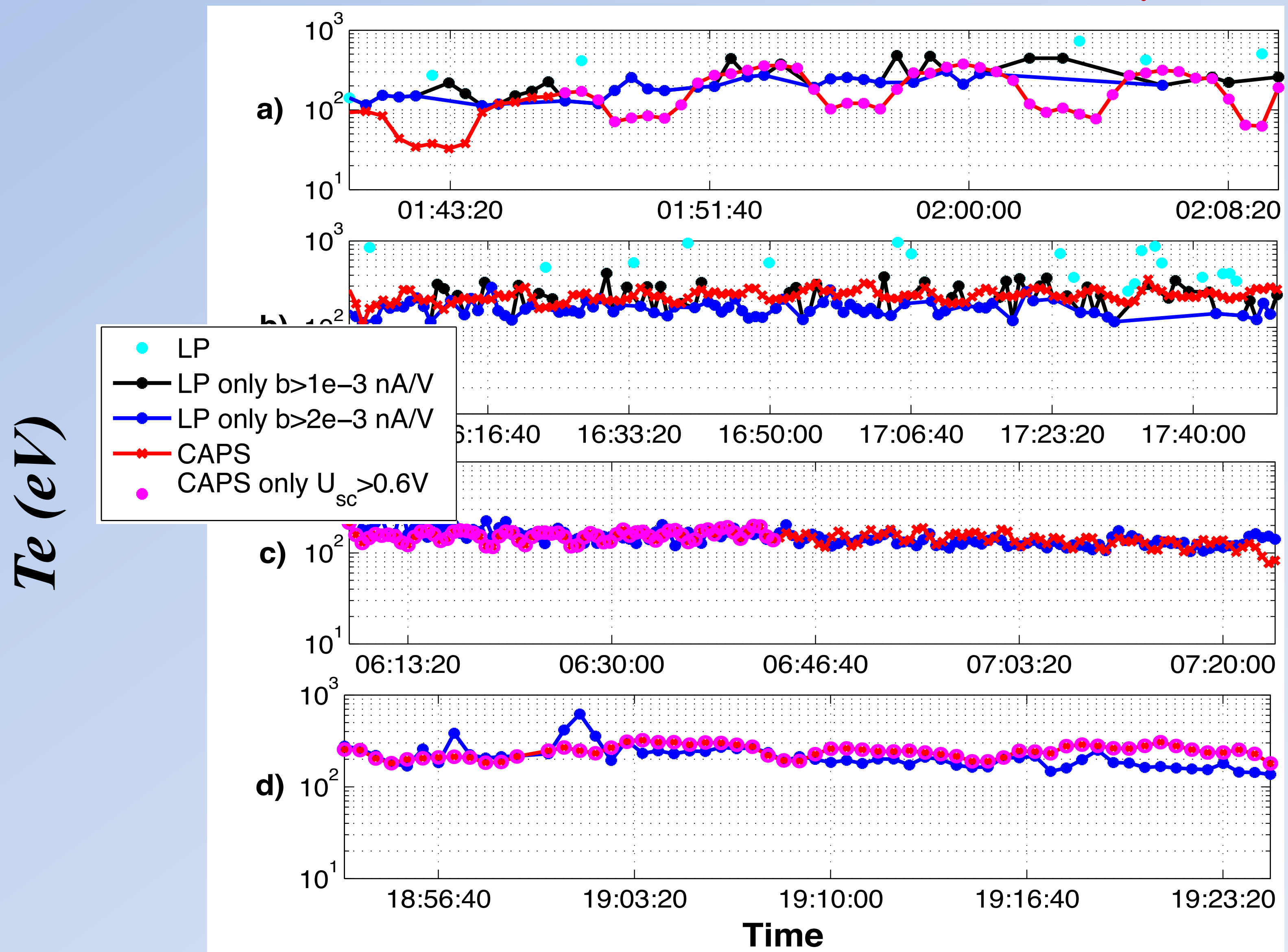
- For a maxwellian electron distribution function, the equations for the DC level and slope of the I-V curve lead to :

$$T_{e_{eV}} = \frac{I_{ener}}{b_{ener}} + 37/2 \qquad n_{e_{est}} = \frac{27 I_{ener_{moments}}}{KLA(k_B T_e/e - 37/2)}$$

➡ As long as the hot electrons (and secondaries) drive the measured current (i.e. off the cold and dense equatorial plasmadisk), we can estimate the ne/Te characteristics of these electrons.

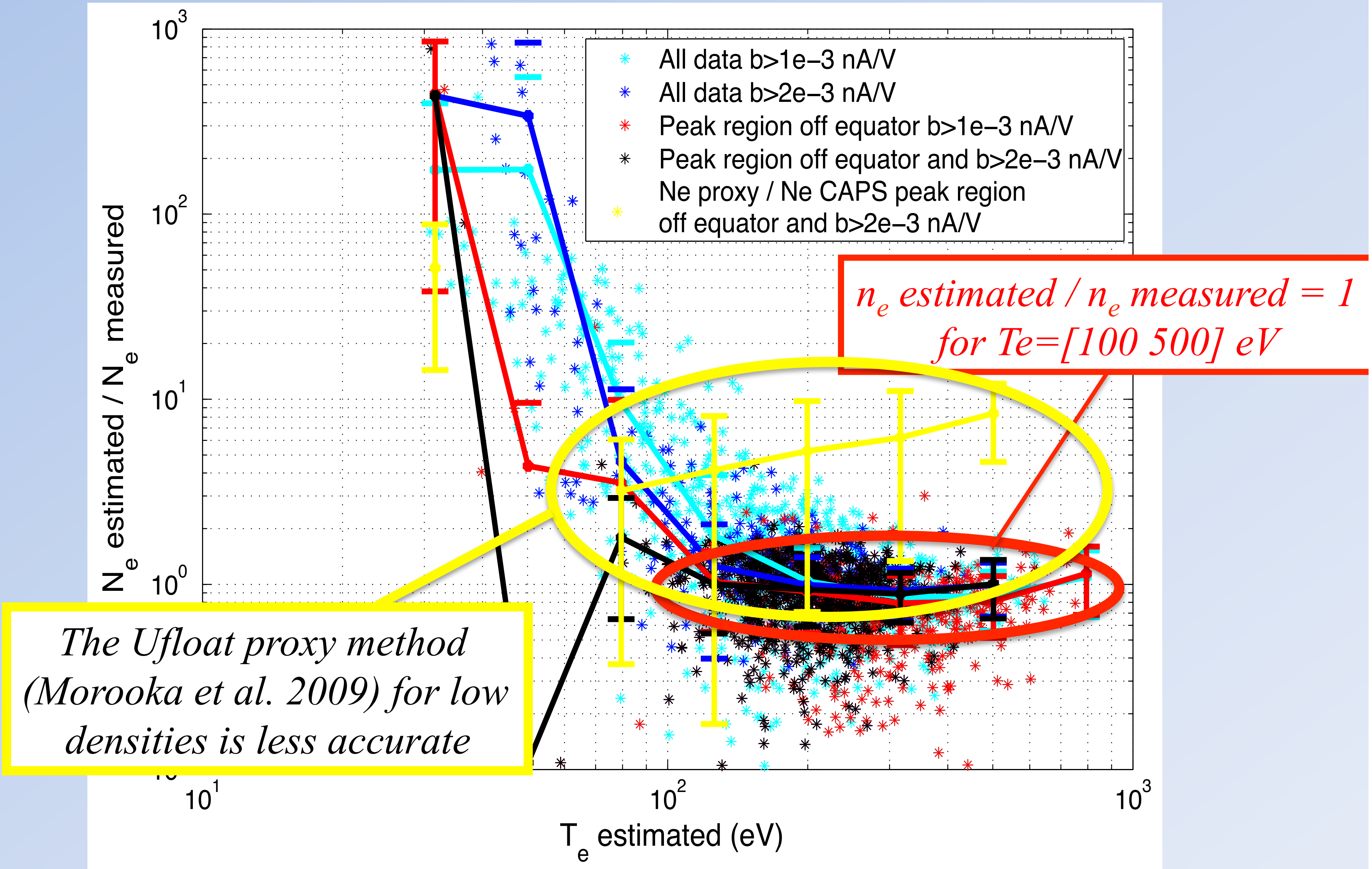
Potentially interesting since CAPS was shut down.

Estimation of the hot electrons temperature



Comparison between the estimated (by the LP) and measured (by CAPS) electron temperatures

Estimation of the hot electrons density



Ratio [n_e estimated/ n_e measured] during 5 years of data

Information about the pitch angle distribution

Question : can we get information about the pitch angle distribution (PAD) of the incident hot electrons ?

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Idea : the energetic current modeling includes the maximum secondary electron yield δ_{emax} (constant for a material), as well as the incident electron distribution function f_{ie} (often provided with a narrow PAD coverage by CAPS)

→ *one calculates the δ_{emax} needed to reproduce the observations at each time ; if this needed δ_{emax} is variable, then the partial distribution f_{ie} given by CAPS is not representative of the global distribution seen by the spherical LP*

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Method used

1. We add a weighting function to the CAPS incident electron distribution to account for the PAD anisotropies *(assuming max at an angle α_0)* :

$$J_{e,weighted}(t,E_i) = \frac{J_{e,anode5}(t,E_i)}{\left|\cos(\alpha(t)-\alpha_0)\right|}$$

α : pitch angle of anode 5

α_0 : peak angle of PAD

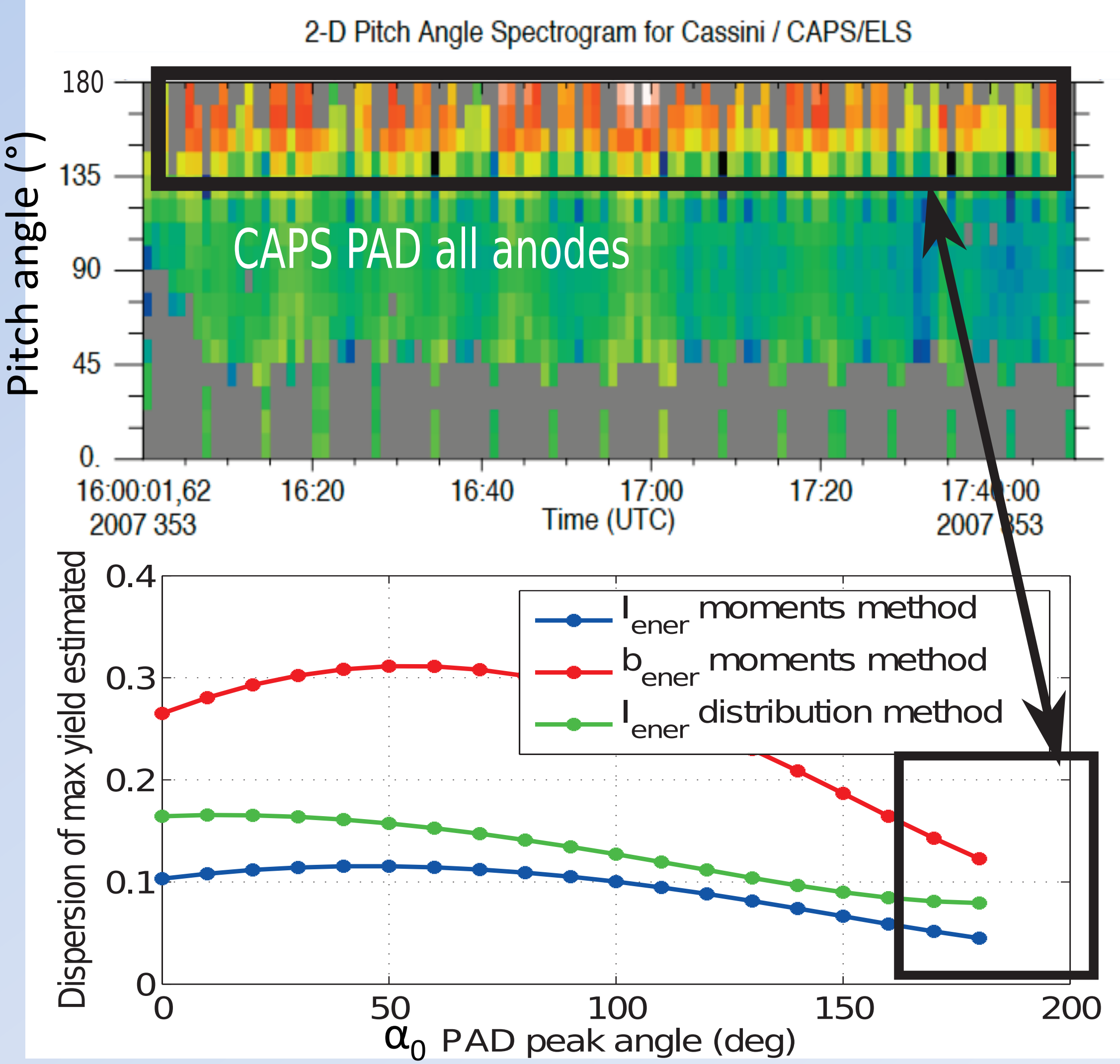
2. We make the peak PAD angle α_0 vary from 0 to π, and we search for the angle leading to the most stable value of δ_{emax}

Informations sur la distribution en angle d'attaque

Case study when CAPS has a broad pich angle coverage with a clear PAD peak for incident electrons at 180°

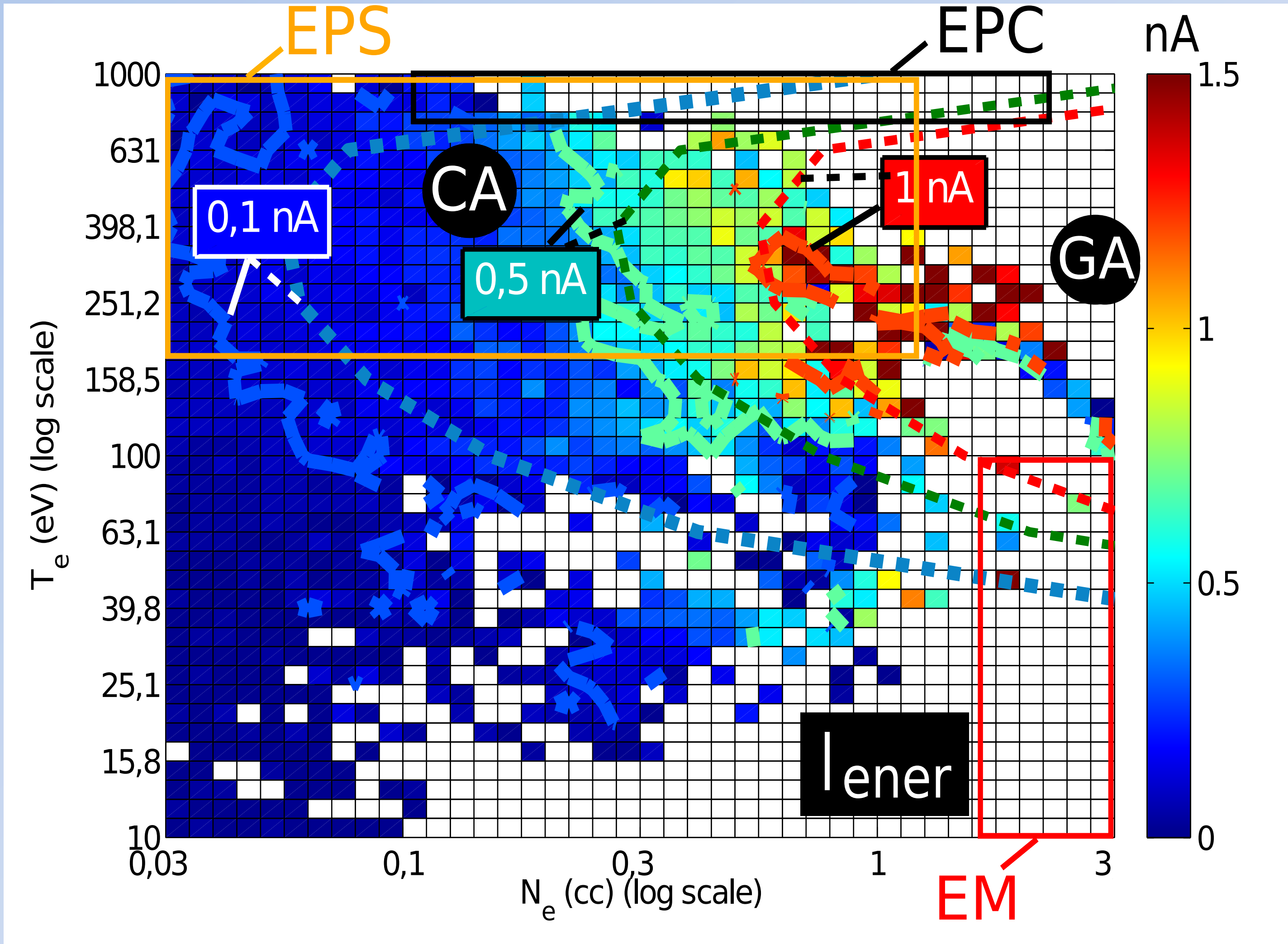
The dispersion for the δ_{emax} values is minimum for a simulated PAD peak at the value that is measured (about 180°).

We thus find the real peak angle of the PAD



Interesting skill of the LP when CAPS has a narrow angular coverage

Which influence of hot electrons in other environments ?



EPC : Earth Plasma Cavities

EM : Earth Magnetosheath

EPS : Earth Plasmasheet

SAT : Saturn (L=6-10 Z>2Rs)

GA : Ganymede

CA : Callisto

EU : Europa

I_{ener} values (energetic DC level) as a function of n_e/T_e measured at Saturn, with isocontours corresponding to observations (solid lines) and modeling (dashed)

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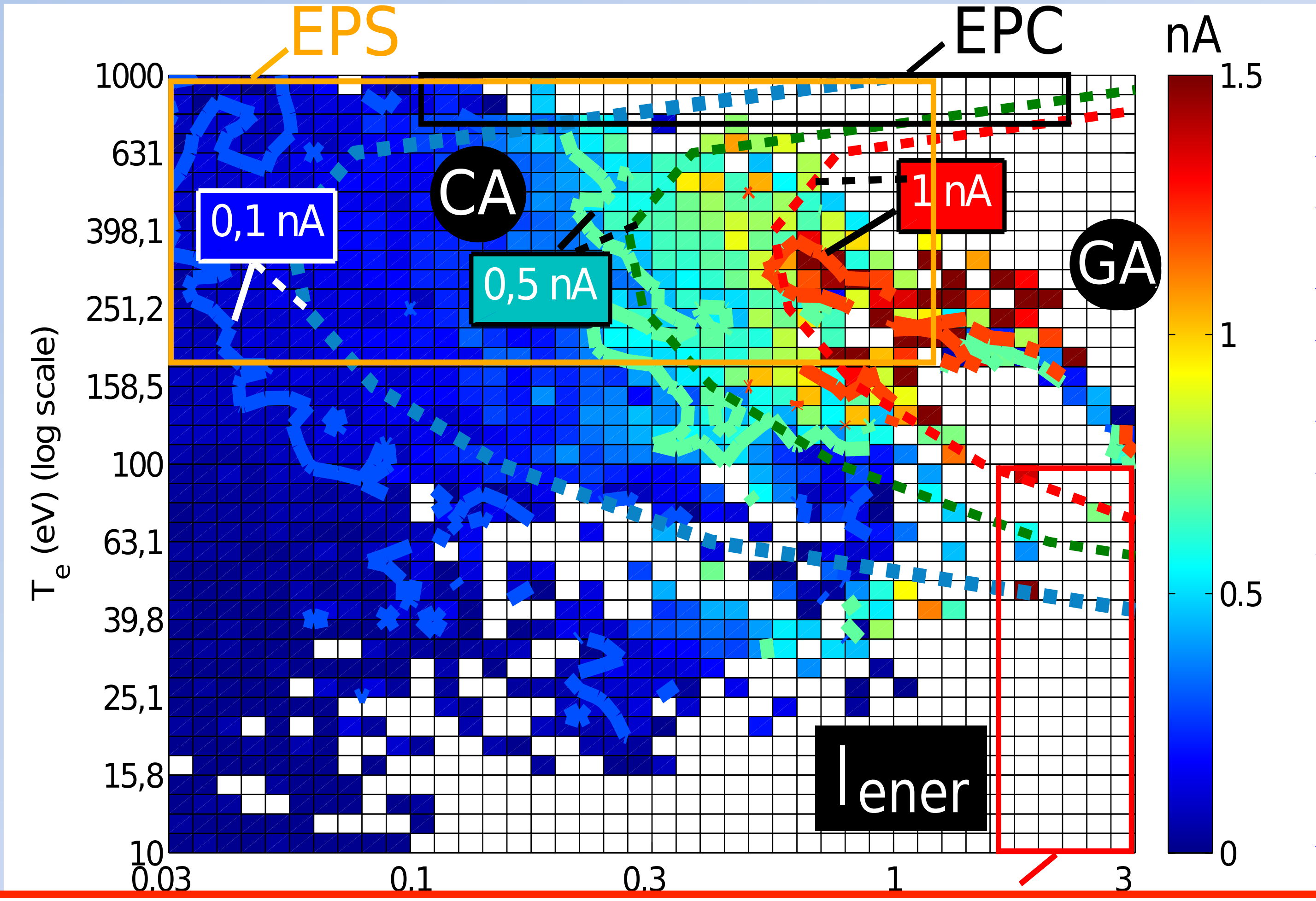

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We can, based on the known average plasma conditions, predict the energetic currents to be measured in any environment : significant influence expected at Earth, jovian satellites etc.

Conclusions

The Langmuir probe onboard Cassini is not only sensitive to cold and dense plasma, but also to hot electrons (100-500 eV) and to their secondaries.

- These electrons influence both the DC level and slope of the current-potential curve of the LP at negative potentials (ion collection side), in particular inside a "belt" at L=6-10 Rs.
- The analysis of the energetic current induced by hot electrons helps to identify and locate a plasmapause-like boundary at Saturn. It also allows to determine the critical and anticritical temperatures of the LP (important concepts for spacecraft charging).
- Modeling the energetic current allows to extract information about the incident 100-500 eV electrons : pitch angle anisotropies, temperature and density
- These results **enlarge the capabilities** of the Langmuir probes, with estimates of **magnetospheric hot and thin plasma** characteristics. Other environments may be of interest : Earth, jovian satellites…

MORE

How to extract I_{e*} ?

<u>Ion side</u> (negative potential $U_{LP/plasma} = U_{bias} + V_{float}$)

$$I(U<0) = m - bU_{bias}$$

$$\boxed{I_e{}^*} = m + bV_{float} - I_{ph} - I_{dust} - I_i$$

Given by Langmuir probe analysis

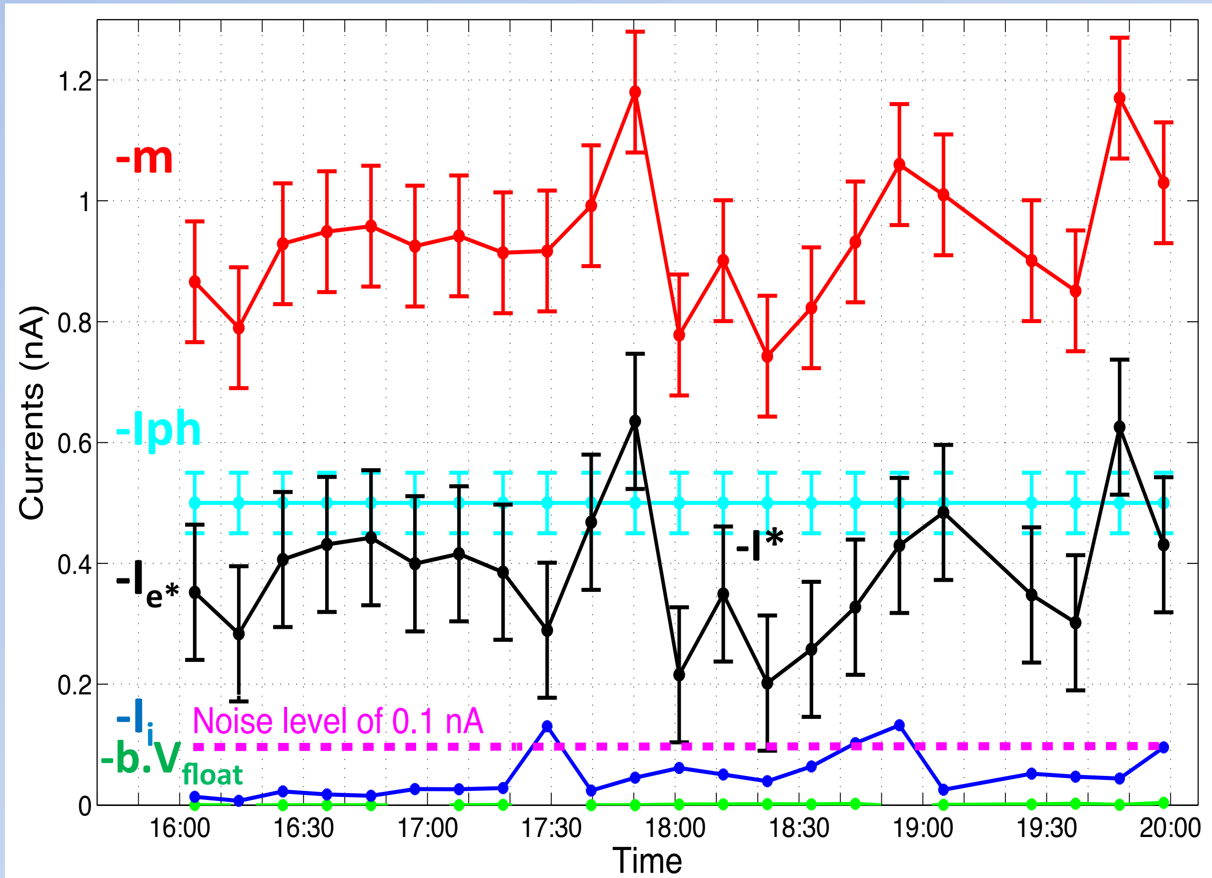
To be estimated independantly

- m (nA) : ion side DC level
- b (nA/V) : ion side slope
- Vfloat (V) : floating potential

- I_{ph} : estimated from solar index
- I_{dust} : absent off the equator
- I_i : ion current (cold and hot) : estimation from CAPS ion moments

⇒ I_{e*} may be extracted off the equator (no dust, few ions)

Extraction of I_{e*} during SOI



The energetic current I_{e*} is of the same order as the photoelectrons current in the « belt » region.

The current contributions from ambient ions and b*Vfloat are small/ negligible

The SOI period (2004, doy 182) was chosen as a case study to extract I_{e*} since :

- the « belt » region was encountered…

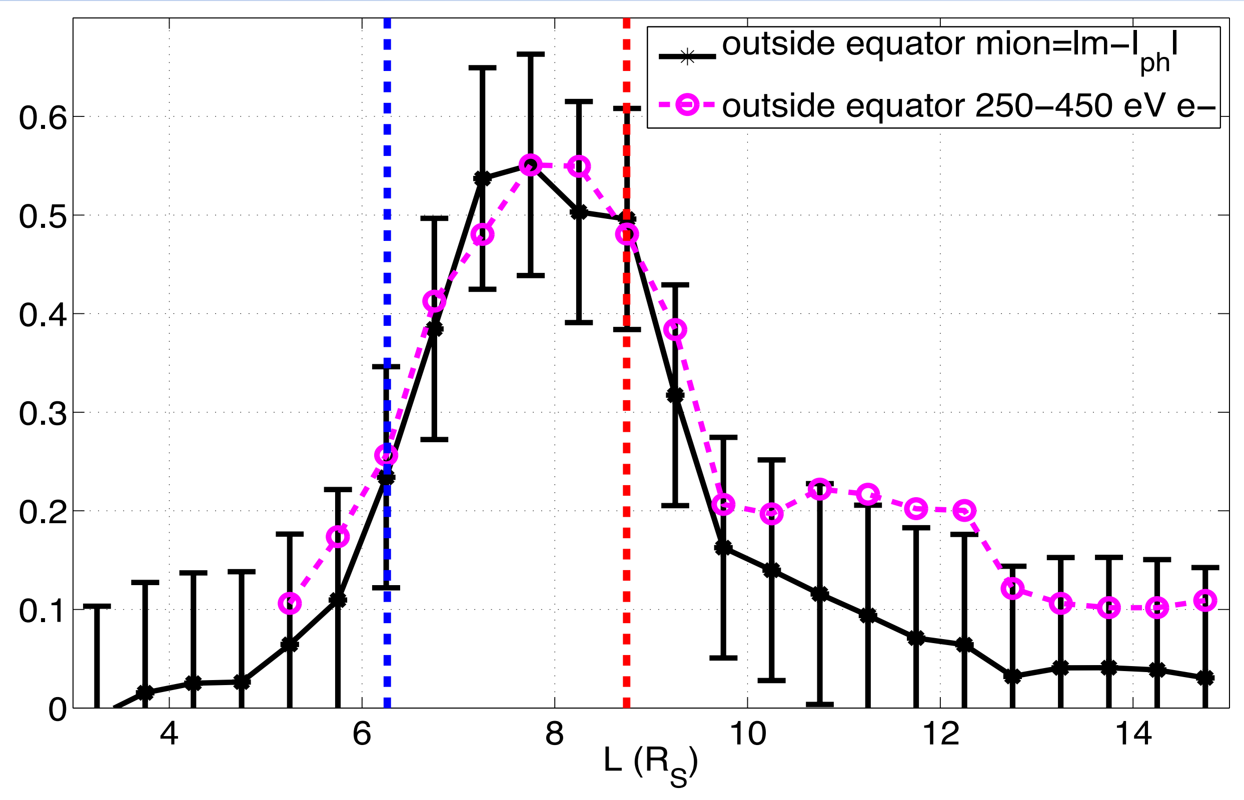
- … at locations where Idust can be neglected (off the equator, |Z|>1.2 Rs)

- ion moments are available from Sittler et al. (2006) to estimate I_i

Why a belt ?

Mapping I_{e*} (which can be approximated by Im-Iphl off the equator) reveals the same radial profile as the 250-450 eV electrons

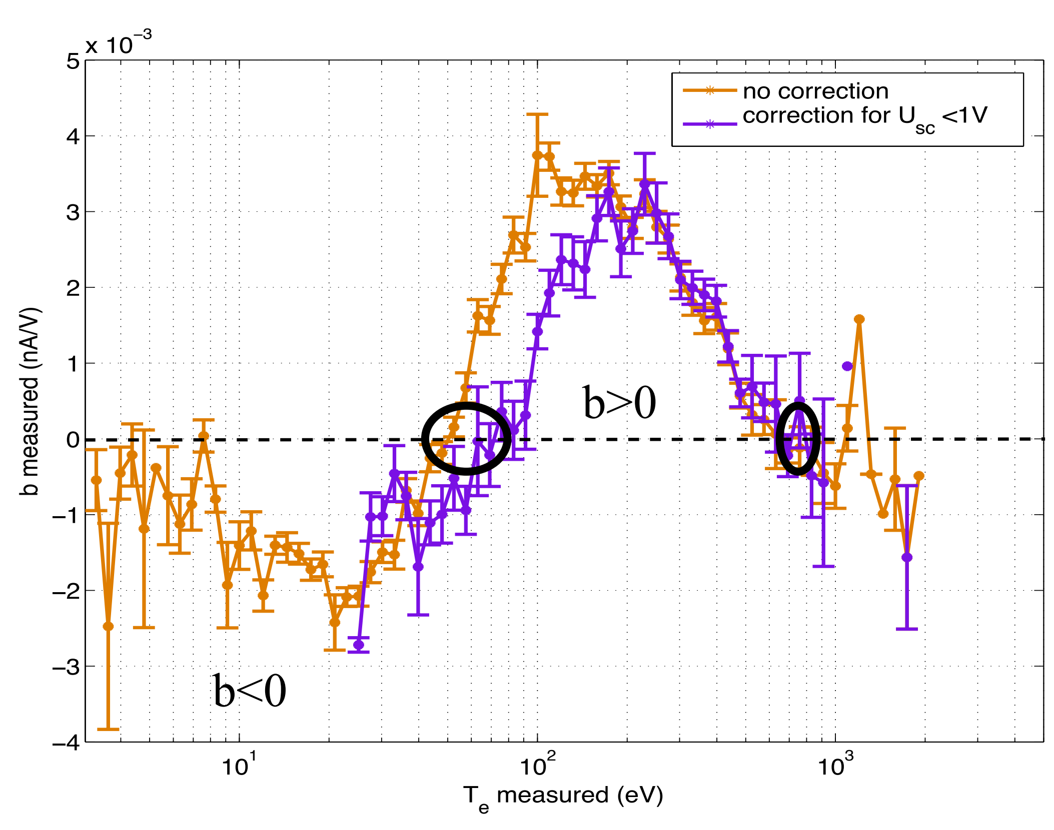
(see Schippers 2008, Rymer 2007, DeJong 2010)



A key boundary region connected to the ionosphere through field-aligned currents with an associated UV auroral oval

Identification of critical / anticritical charging temperatures

- Strong spacecraft (negative) charging events may be observed (e.g. in the Earth plasmasheet) when the incident electrons have a temperature above a critical value T* (Laframboise et al., 1982)
- Two specific temperatures - anticritical T_A and critical T* (see Lai and Tautz, 2008) separate temperature domains where the incident electrons dominate over or are dominated by secondaries
- We show that these temperatures are observed when the b_{ener} is null



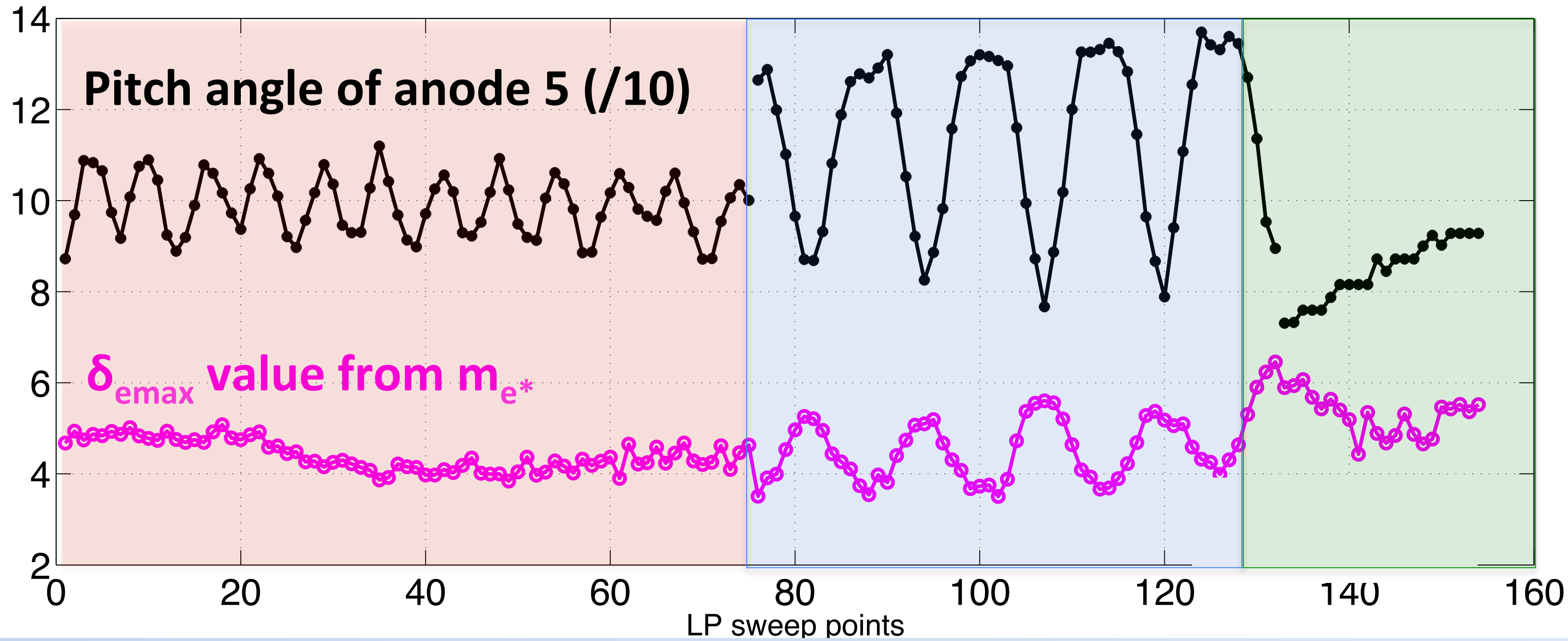
b_{ener} slope of the LP I-V curve as a function of T_e, with or without correction for small spacecraft potentials

➡ T_A = 50-60 eV and T* = 600-800 eV

First observational evidence for the existence of T_A

Estimation of the peak yield δ_{emax}

Calculation of the fictive δ_{emax} value needed to fit observations of m or b



Period 1 : 2008 doy 138

Period 2
2008 doy 139

Period 3
SOI

- ❑ δ_{emax} roughly stable around 4-5 from both be* and me* (should be constant !)
- ❑ But a strong influence of the orientation of the CAPS anode 5 (period 2)

➡ **Influence of an anisotropic pitch angle distribution of energetic electrons ?**