How to estimate properties of auroral magnetospheric generators from ionospheric observations of discrete auroral arcs and models of the magnetosphere-ionosphere coupling: simulations and case study

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Outline of the talk

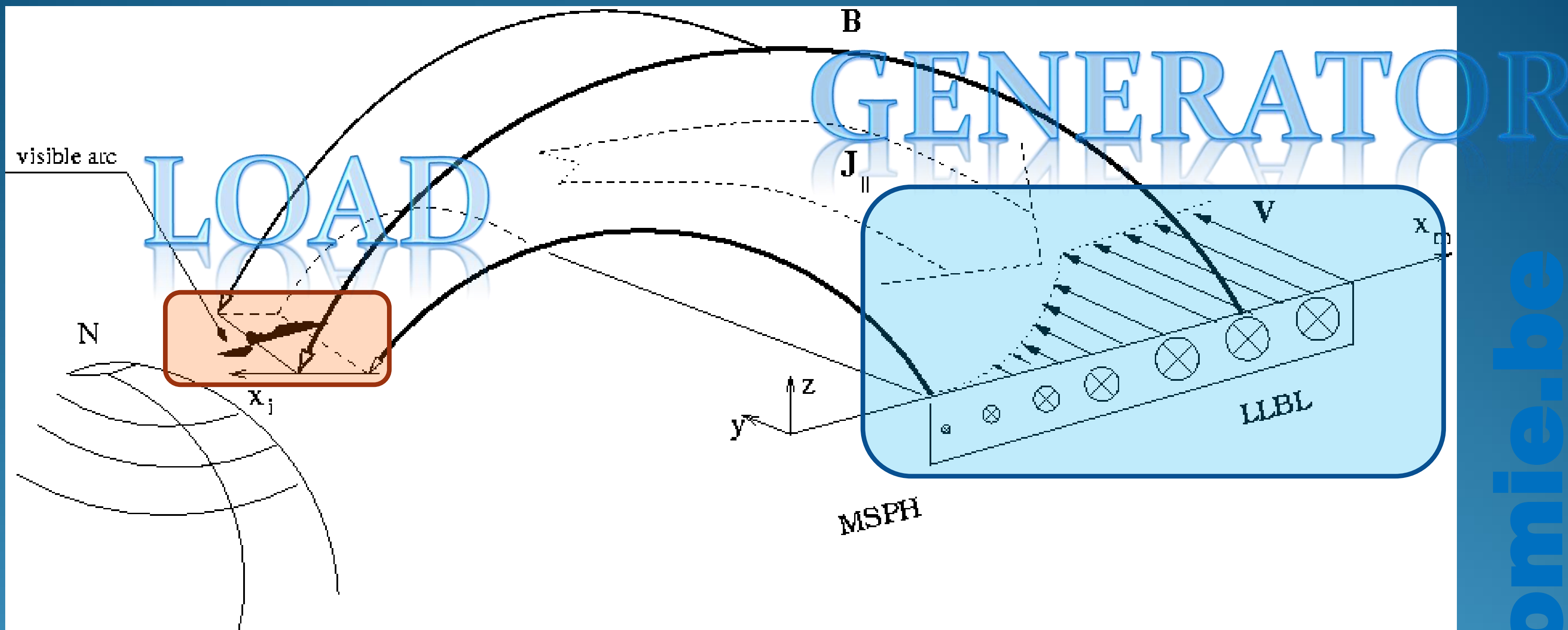
- **Quasistationary Magnetosphere – Ionosphere Coupling**
  - The magnetospheric generator
  - The current-voltage relationship
  - The ionospheric current continuity
  - Parametric studies on the auroral electrodynamics

- **MI coupling model validation**:
  - Cluster-DMSP conjunctions in the auroral oval dusk sector
  - Cluster-TIMED conjuctions + TRANSCAR modeling of auroral emission rates in the polar cap

- **A minimization procedure to estimate generator properties from remote or in-situ observations of auroral arcs** :
  - MI coupling and the constrained « inverse » problem: infering data on the generator from ground based observations

- **Summary, Conclusions**

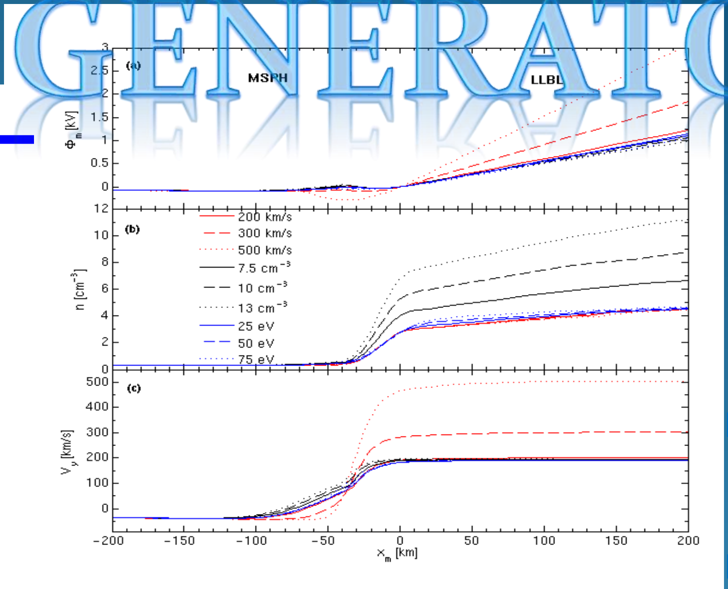
Modeling the global auroral circuit



- planar TD surface at the interface between plasmas with different macroscopic properties (*Sestero, 1966; Lemaire & Burlaga, 1976; Roth et al., 1996; Echim & Lemaire, 2005*)
  - **latitudinal dependence of electrodynamic parameters: $j_{||}, \varepsilon_{em}, E, \Sigma_P$**
  - **uniform ionospheric densities and temperatures: e^-, H^+, O^+, He^+**
- magnetospheric generators with convergent E-field: *Chiu and Cornwall, 1978; Lyons 1980, 1981*
  - **empirical model for Pedersen conductance**
- Models of auroral generators based on sharp interfaces: *Galperin et al, 1992; Roth et al. 1993; Lennartson , 2006; Johannsson et al., 2006; Echim, Roth, De Keyser, 2007,2008*
  - **B parallel to z-axis; $E = (E_x, 0, E_{||})$; $J = (J_x, 0, J_z)$**

Quasi-stationary magnetosphere-ionosphere coupling:
Numerical implementation of the model

GENERATOR



Numerical model

Input parameters: $\Phi_m(x_m)$, N_m, T_m, ΔV_m

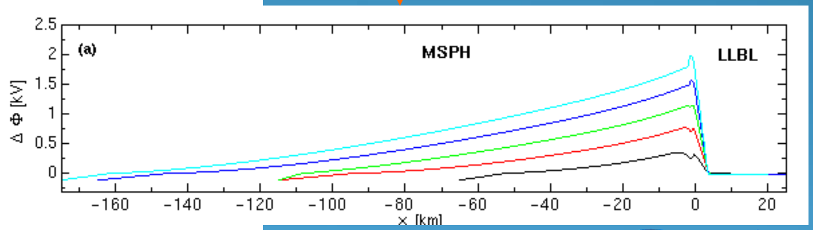
Current-voltage relationship, $j_{||}(V_{||})$

$$j_{||}(x_i) = -\frac{\partial}{\partial x_i} I_p = \frac{\partial}{\partial x_i}\left(\Sigma_p \frac{\partial \phi_i}{\partial x_i}\right)$$

Output: $\Phi_i(x_i)$, $V_{||}(x_i) = \Phi_i - \Phi_m$

Two-point boundary condition: $V_{||}(+/-x_{iL}) = 0$

Input parameters: N_i, T_i, Σ_P model, $\Delta x_i = 2x_{iL}$



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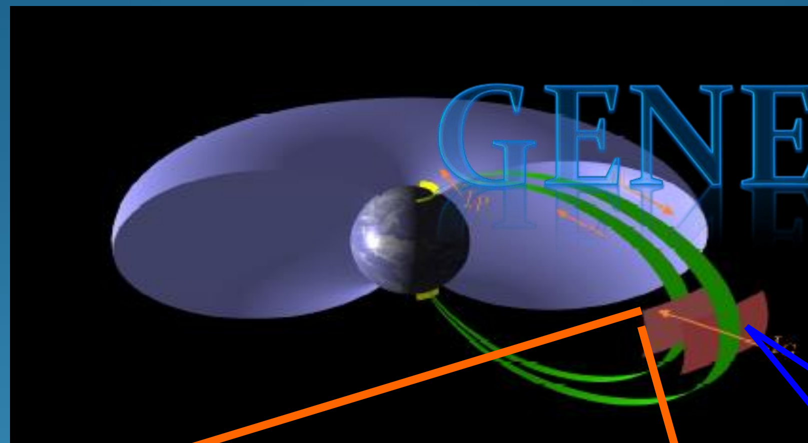
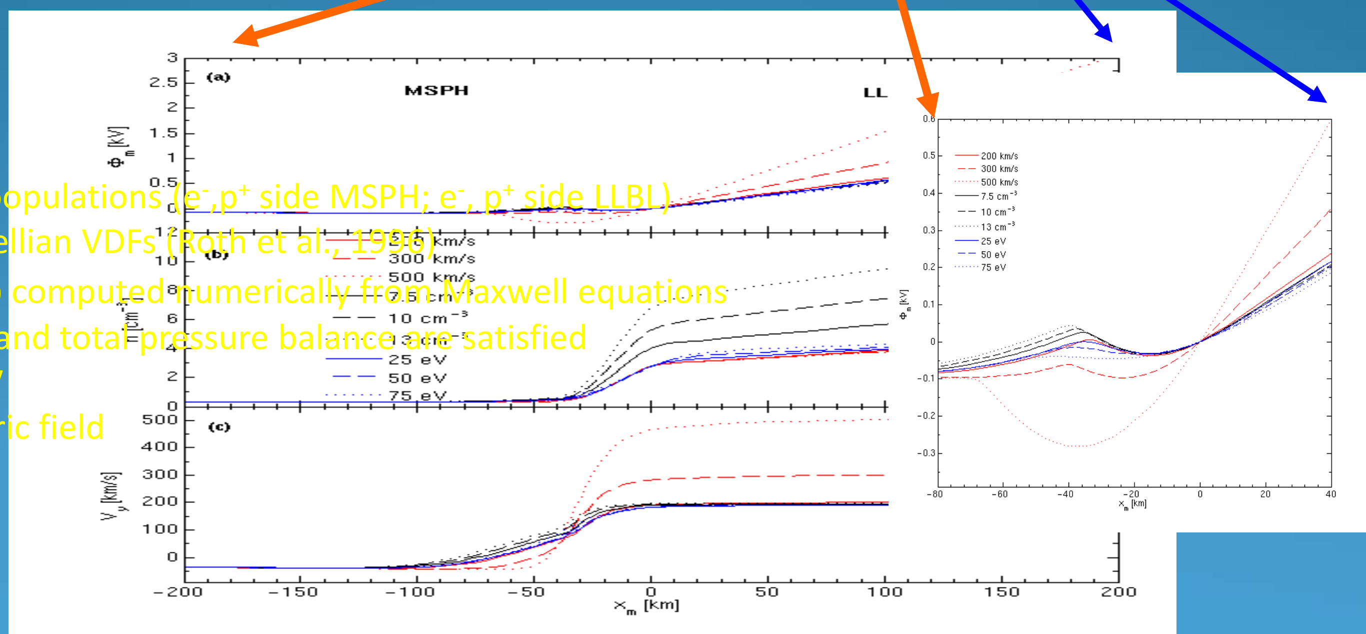
Tangential interfaces as auroral generators





- two asymptotic populations (e^-,p^+ side MSPH; e^-, p^+ side LLBL)
- piecewise Maxwellian VDFs (Roth et al., 1996)
- $\Phi_m(x_m)$ and $\mathbf{a}(x_m)$ computed numerically from Maxwell equations
- Quasi-neutrality and total pressure balance are satisfied
- shears of **B** and **V**
- convergent electric field

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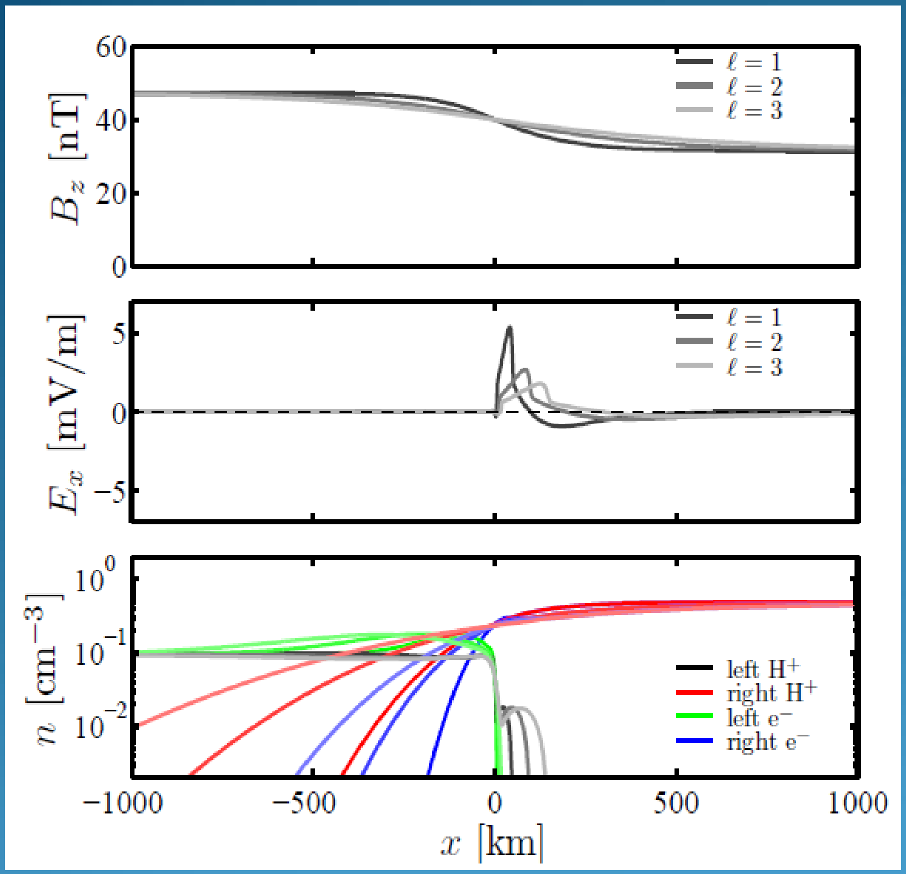
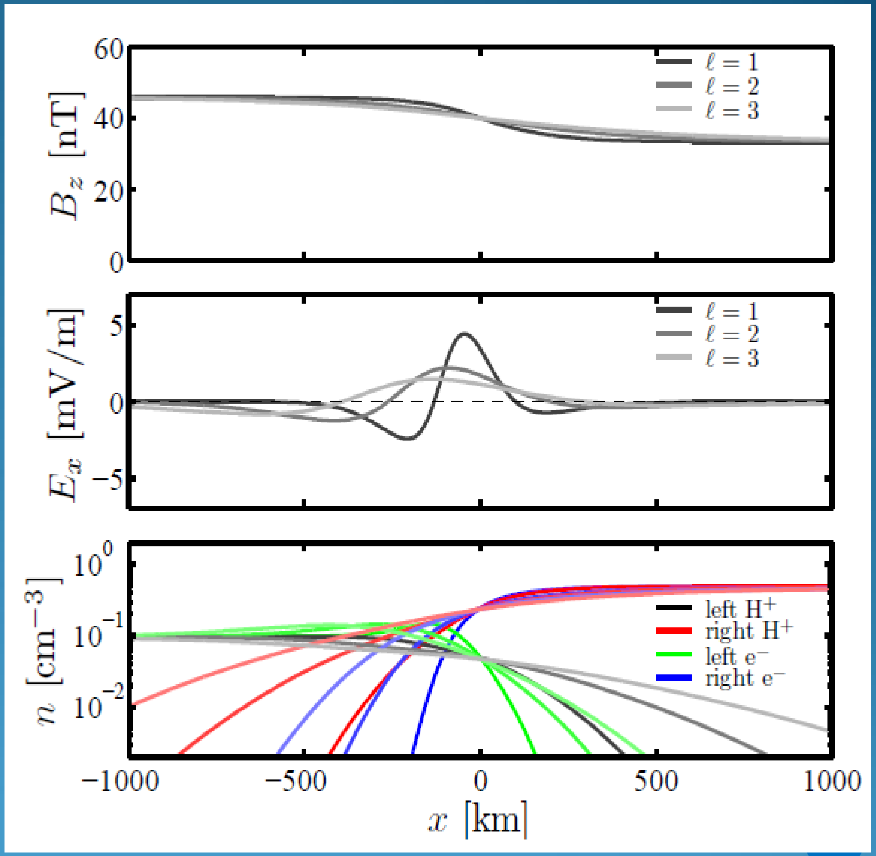
Quasi-stationary magnetosphere-ionosphere coupling:
Parametric studies of the generator (De Keyser & Echim, 2013)

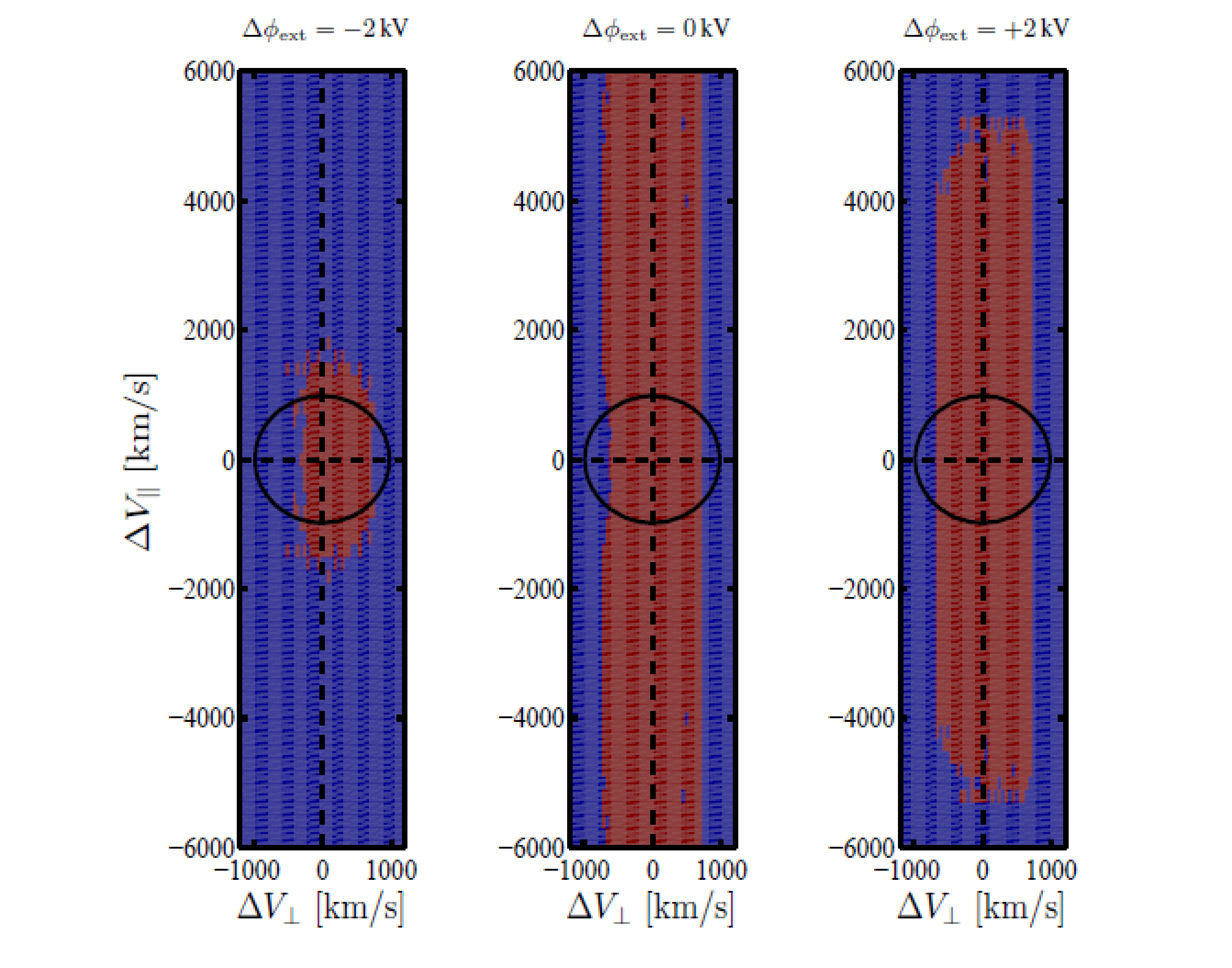


"Cold (~eV)-hot (~keV)" interface



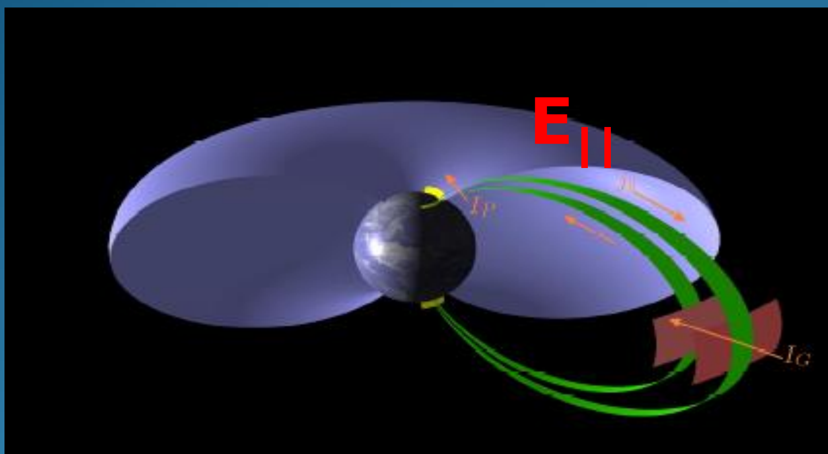
"Hot (~keV)-hot (~keV)" interface

Quasi-stationary magnetosphere-ionosphere coupling:
Existence of Vlasov equilibrium generators (De Keyser & Echim, 2013)



Existence domain (in red) of the "Cold-hot" interface

Ionospheric module: Kinetic treatment of particle dynamics in mirroring field with parallel E-field



Electrons (Knight, 1973; Lemaire&Scherer, 1973)

$$j_{\parallel e} = ebN_e^{msph}\sqrt{\frac{KT_e^{msph}}{2\pi m_e}}\left[1-\left(\frac{b-1}{b}\right)\exp\left\{-\frac{e\Delta\Phi}{kT_e^{msph}(b-1)}\right\}\right]-$$

$$ebN_e^{ionos}\sqrt{\frac{KT_e^{ionos}}{2\pi m_e}}e^{-\frac{e\Delta\Phi}{kT_e^{ionos}}}\left[1-\left(\frac{b-1}{b}\right)\exp\left\{-\frac{e\Delta\Phi}{kT_e^{ionos}(b-1)}\right\}\right]$$

Conservation of the magnetic moment

$$\mu = \frac{m_\alpha v_\perp^2}{2B(z)} = ct.$$

Ions (Lemaire & Scherer, 1971)

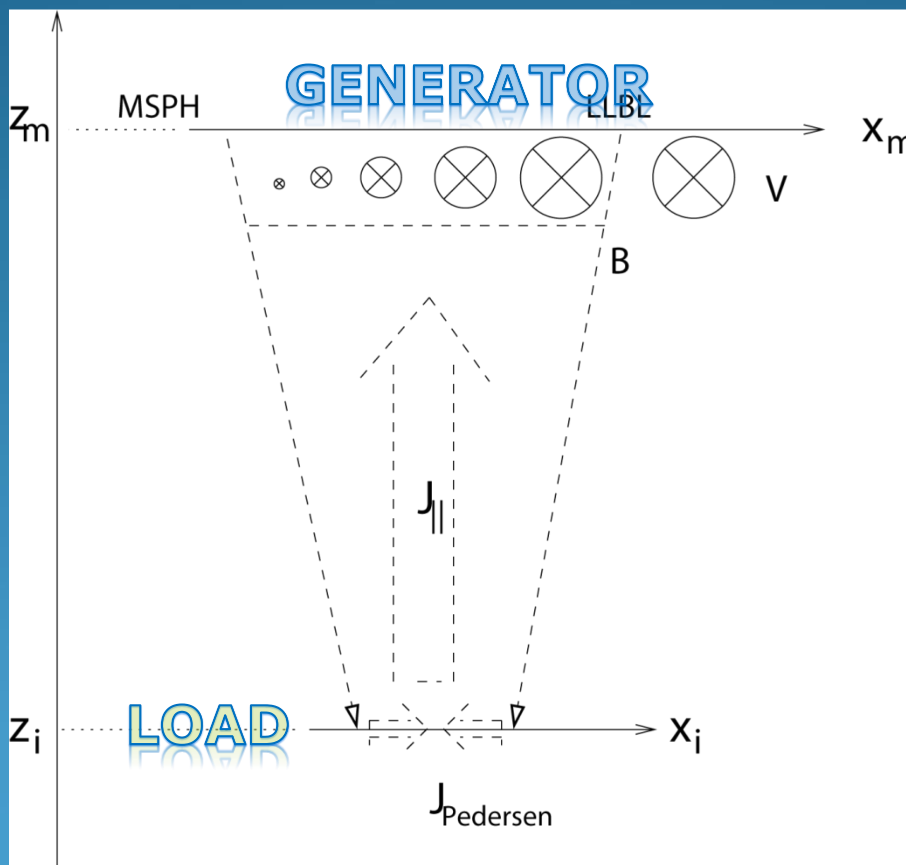
$$j_{\parallel\alpha}^{ionos} = q_\alpha N_\alpha^{ionos}\sqrt{\frac{KT_\alpha^{ionos}}{2\pi m_\alpha}}\frac{B_m}{B_i}$$

"upgoing"

Conservation of the total energy

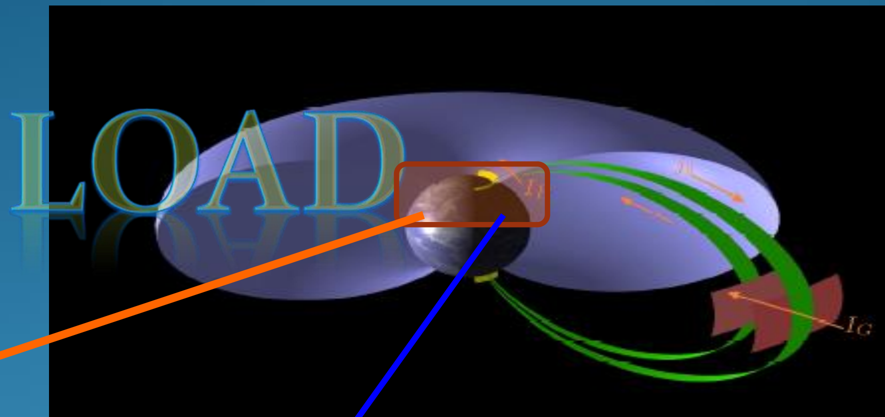
$$\frac{m_\alpha\left(v_\parallel^2 + v_\perp^2\right)}{2} + q_\alpha\Phi(z) = ct.$$

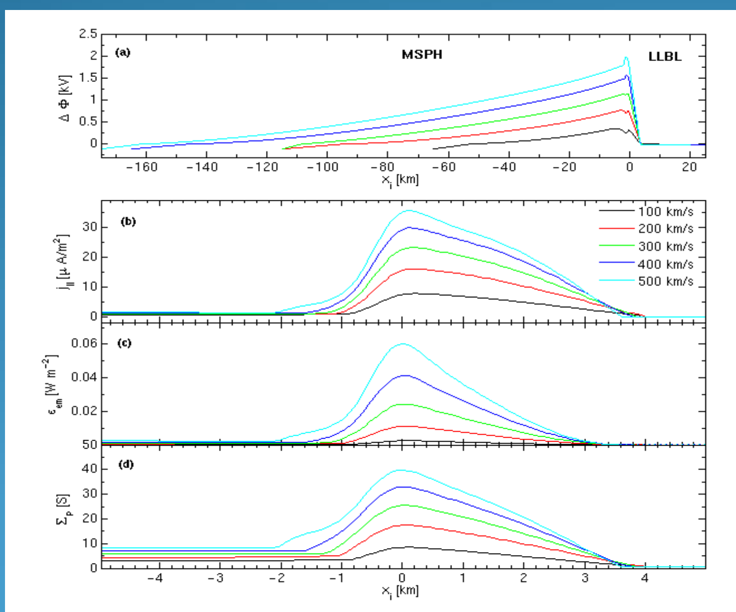
Ionospheric module: The conical geometry



$$x_i = x_m\sqrt{B_m/Bi}$$

Ionospheric module: Current continuity in the ionosphere





- Current continuity, topside ionosphere:

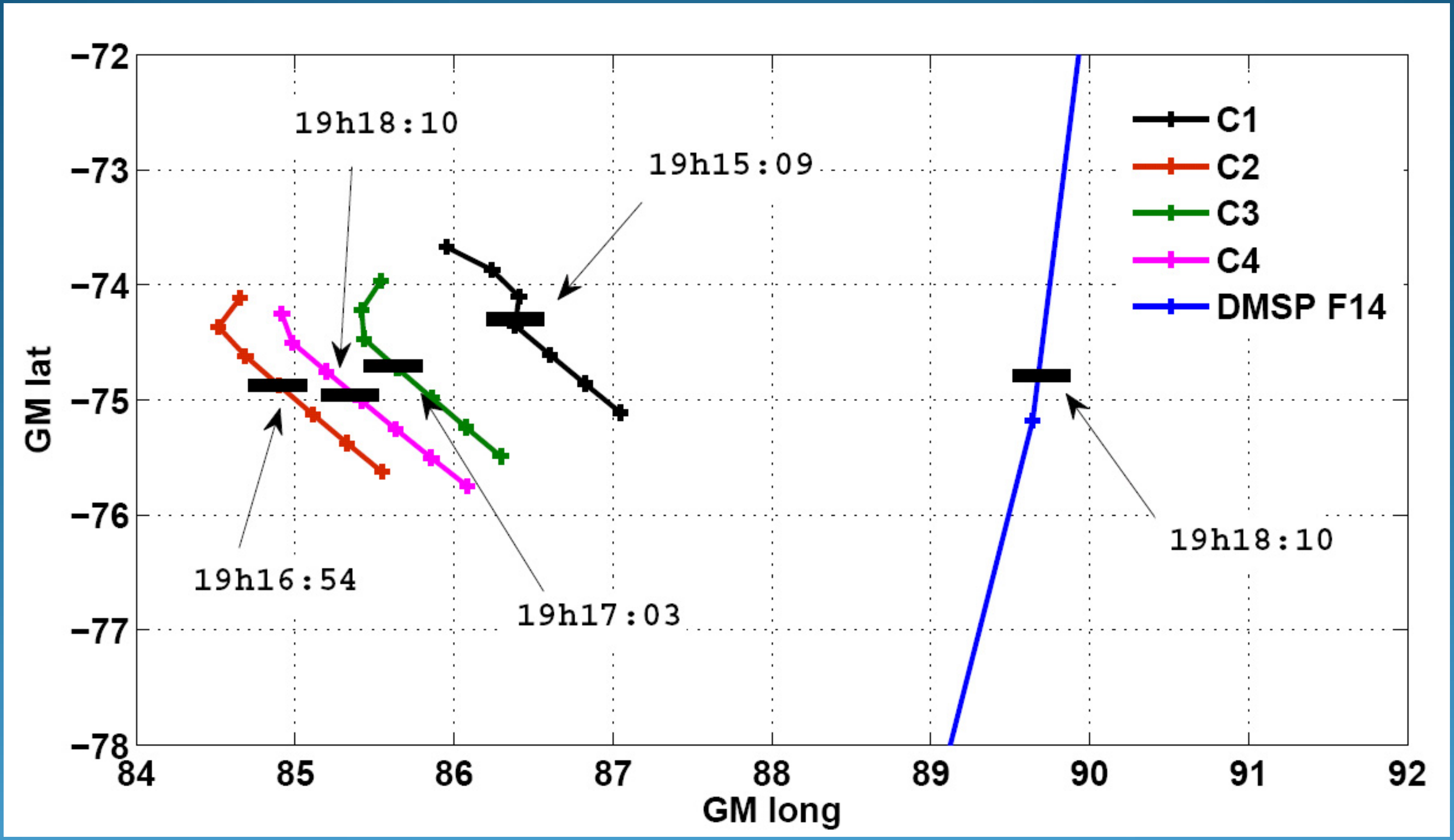
$$j_{II}(x_i, \Phi_i - \Phi_m) = -\frac{\partial}{\partial x_i} I_p = \frac{\partial}{\partial x_i}\left(\Sigma_p \frac{\partial \phi_i}{\partial x_i}\right)$$

- Ionospheric feedback – energy dependent conductance:

$$\Sigma_p = 0.5 + 160\sqrt{\varepsilon_\parallel}$$ (Harel et al., 1977)

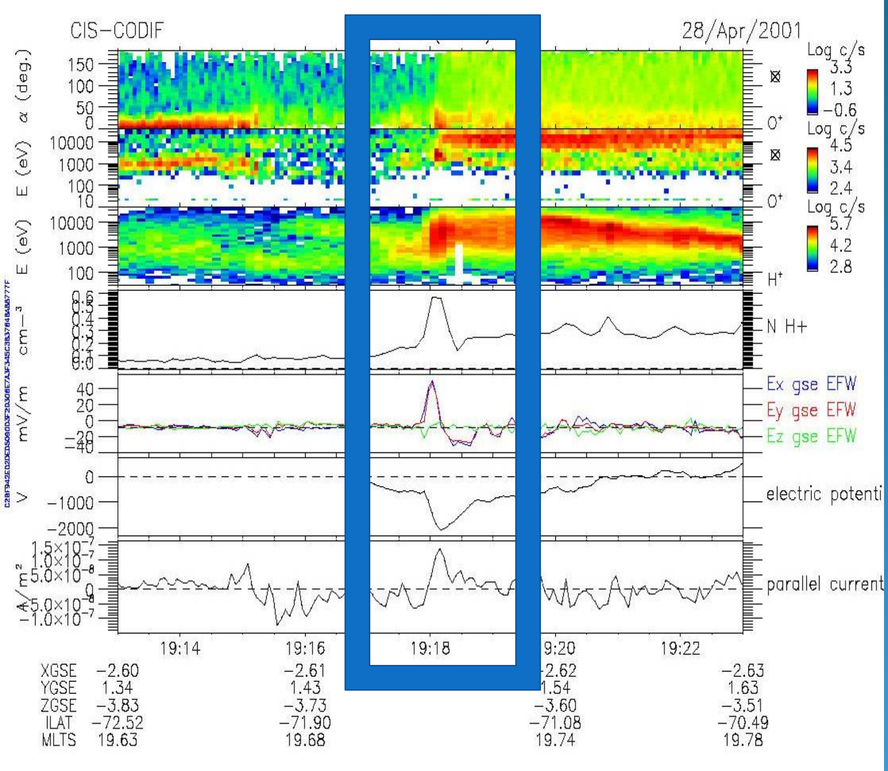
- Self-consistent Φ_m; ad-hoc models in previous studies (Chiu and Cornwall, 1980; Lyons, 1980, 1981)

Observations and validation: Cluster- DMSP conjunction 28/04/01



Observations and validation: Cluster- DMSP conjunction 28/04/01

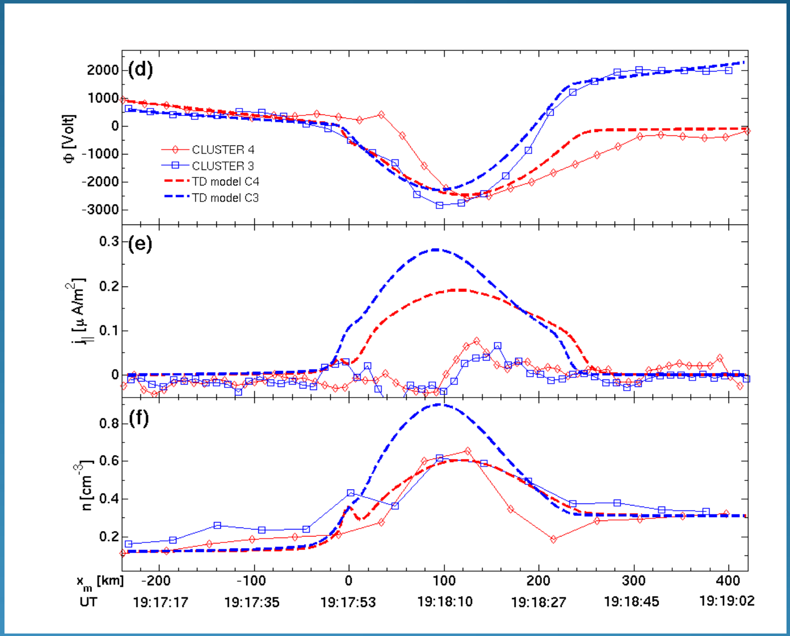
DATA



Vaivads et al., GRL, 2003

- Asymmetric potential well (**~2000V, ~120 km**)
- density peak (**0.85 cm^{-3}** (CIS), **~80 km**) coincides with minimum of potential
- pair of FA current, upward sheet peeks in centre of transition
- field lines maps towards the magnetopause

MODEL

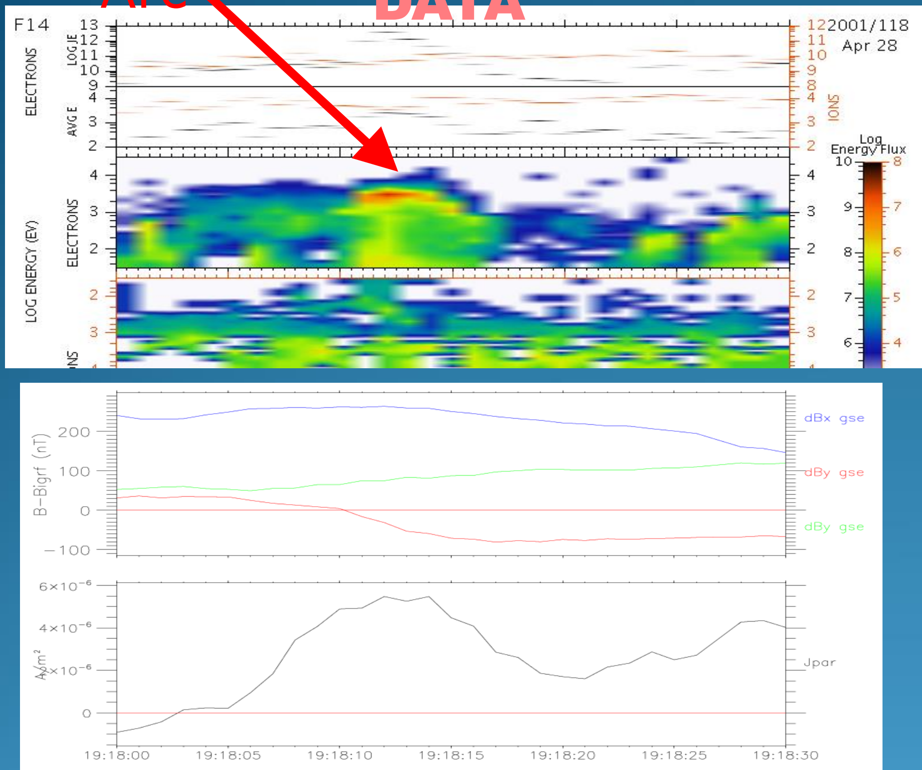


Echim et al., GRL, 2009:

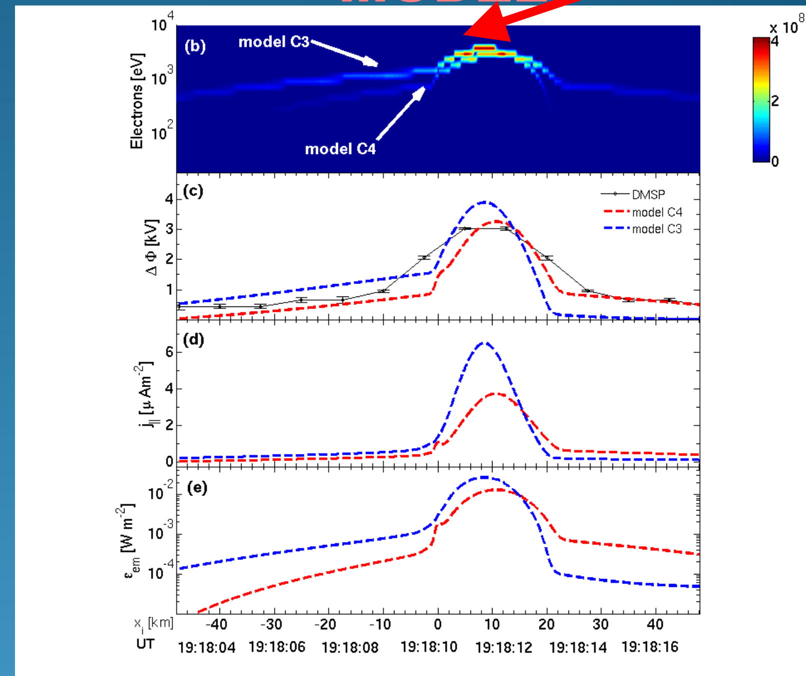
- Model TD transition obtained with asymptotic parameters scaled to observations
- asymmetric potential well (**~3000V**, **~200 km**)
- density peak coincides with minimum of potential
- FA current, upward sheet peeks in centre of transition

Observations and validation: Cluster- DMSP conjunction 28/04/01

Arc DATA



MODEL Arc



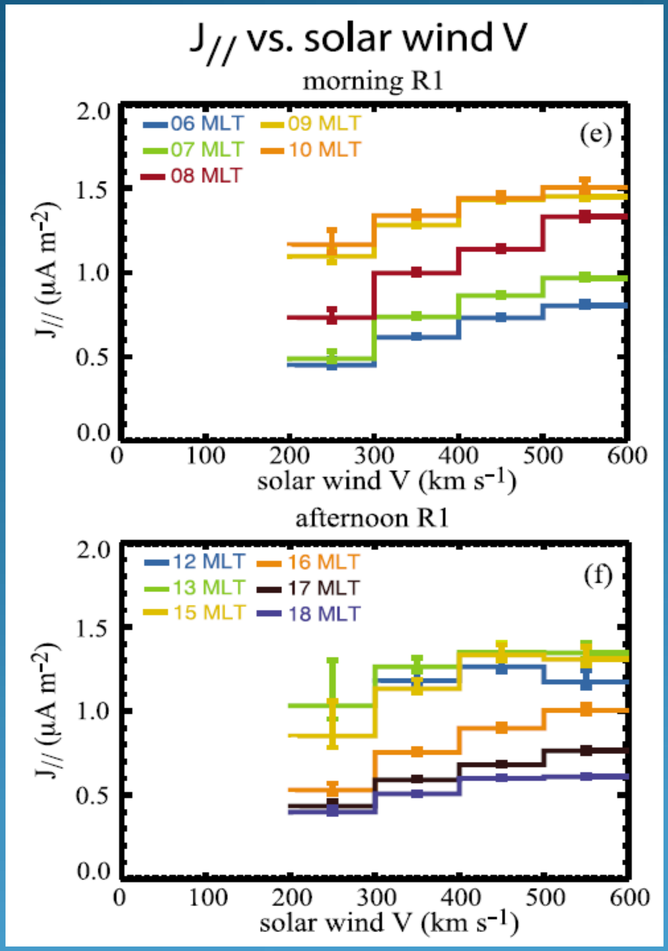
Vaivads et al., GRL, 2003:

- precipitating electrons with energy spectrum consistent with **$\Delta\Phi$~3.5 kV**
- arc width of about **15-25 km**
- peak electron energy flux **20 mW/m²**
- peak current density **~6μA/m²**

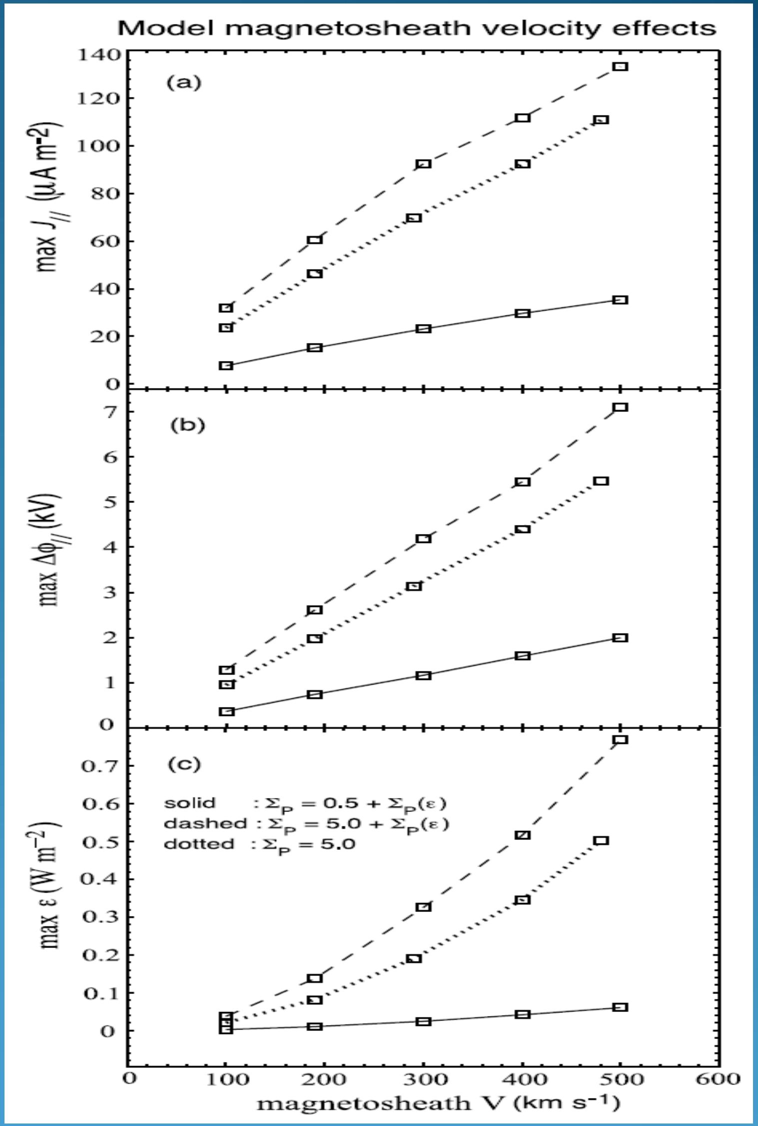
Echim et al., GRL, 2009:

- solution obtained at 800 km altitude
- FA potential-drop **$\Delta\Phi$ = 3.2 – 3.8 kV**
- arc width of about **25 km**
- peak electron energy flux **12-26 mW/m²**
- peak current density **~6μA/m²**

Observations and validation: dayside field-aligned current densities from DMSP and velocity shear effects

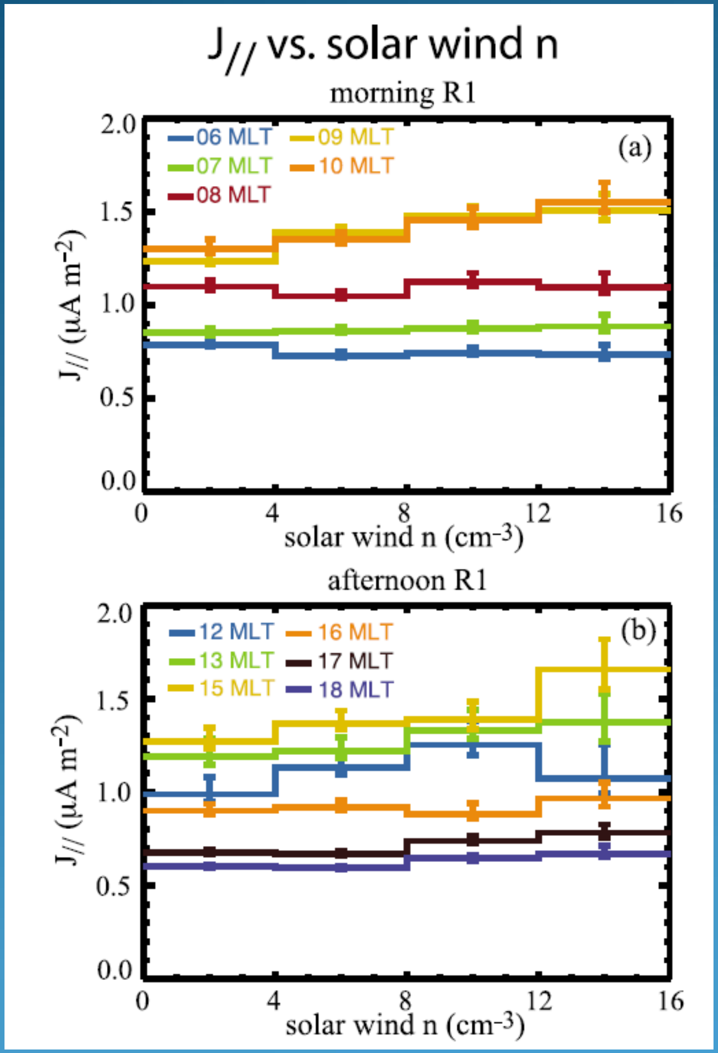


Velocity shear in the LLBL, effects derived from DMSP observations (Wing et al., 2011)

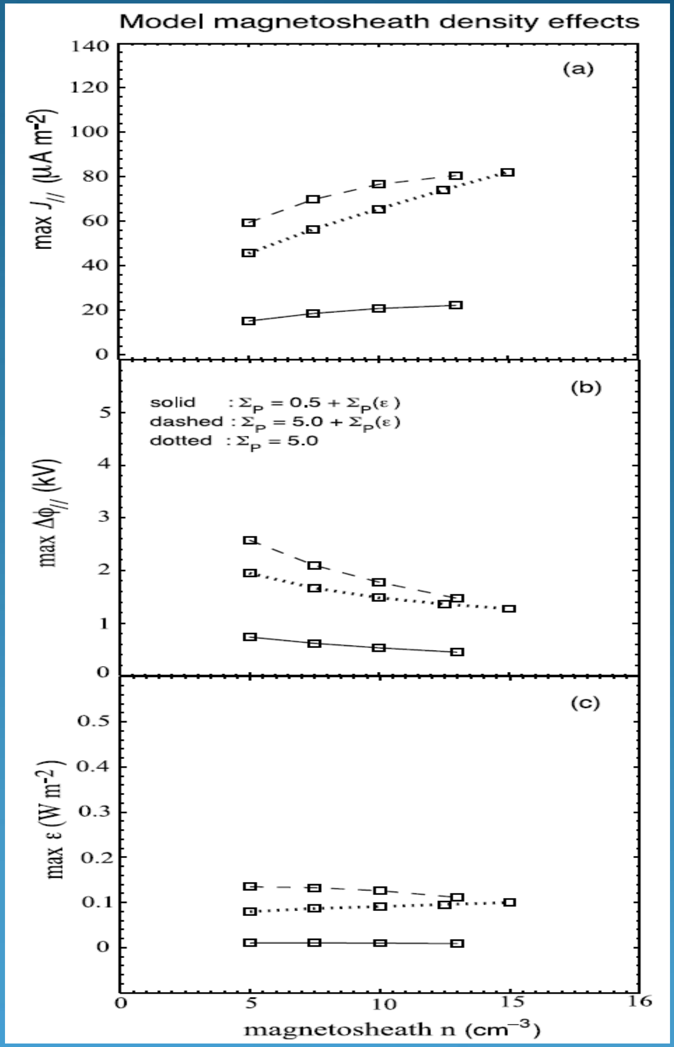


Shear effects from MI coupling model (Echim et al., 2008)

Observations and validation: dayside field-aligned current densities from DMSP and effects of the generator density generator

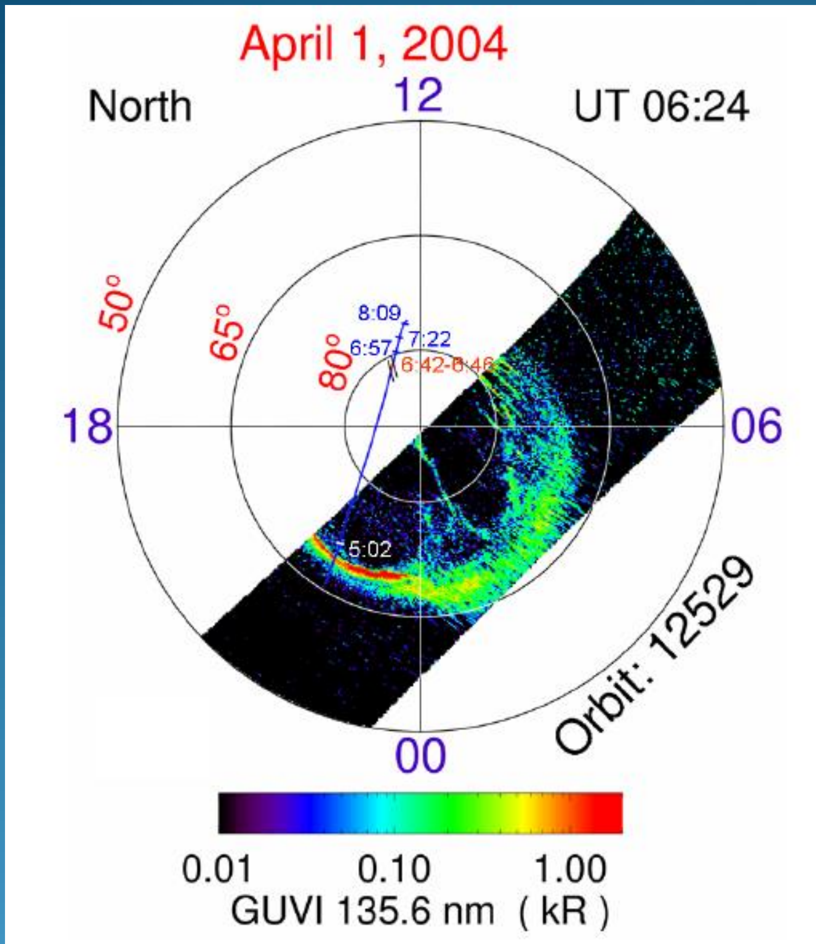


Density gradient in the LLBL, effects derived from DMSP observations (Wing et al., 2011)

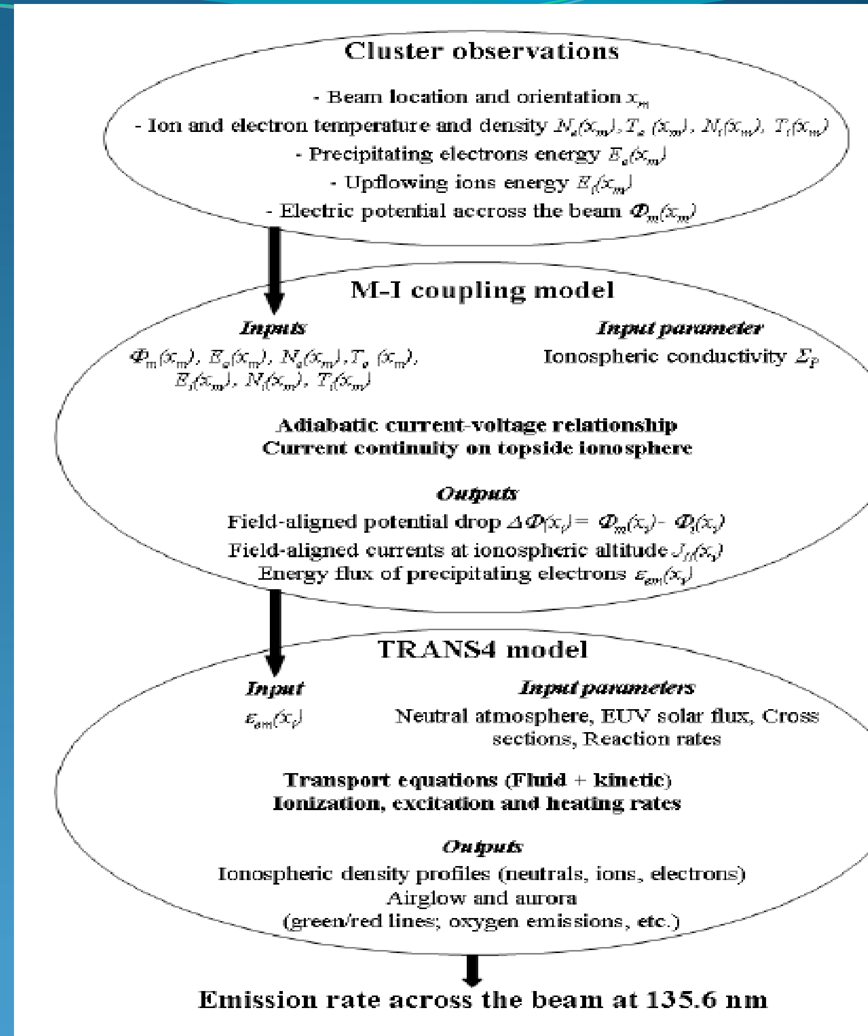


Density effects from MI coupling model (Echim et al., 2008)

Observations and validation: polar cap arc observed by Cluster and TIMED

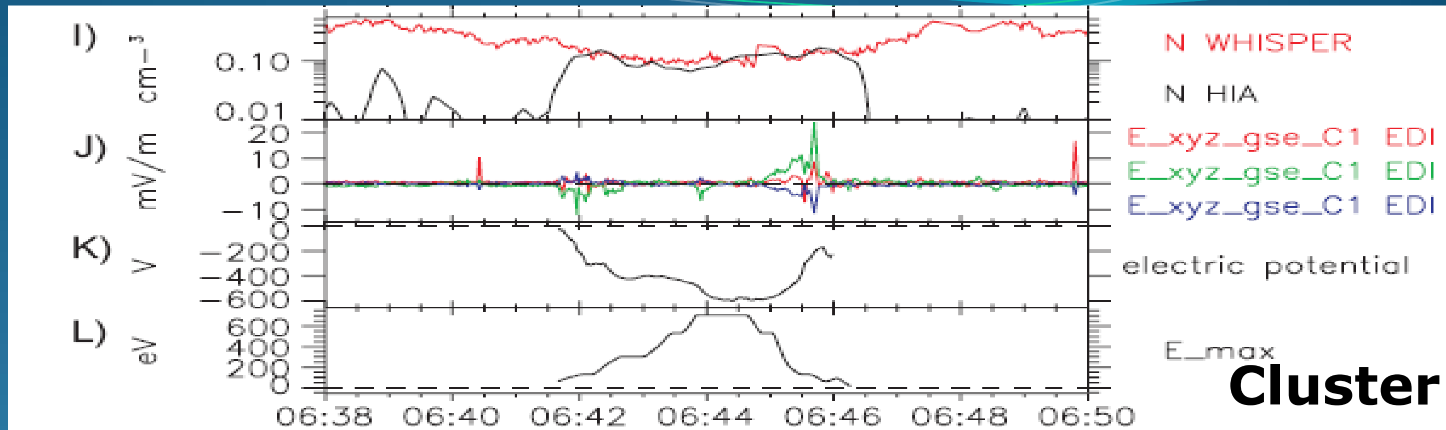


Joint observations by TIMED and Cluster of a polar cap arc and ion outflows (Maggiolo et al., 2012)

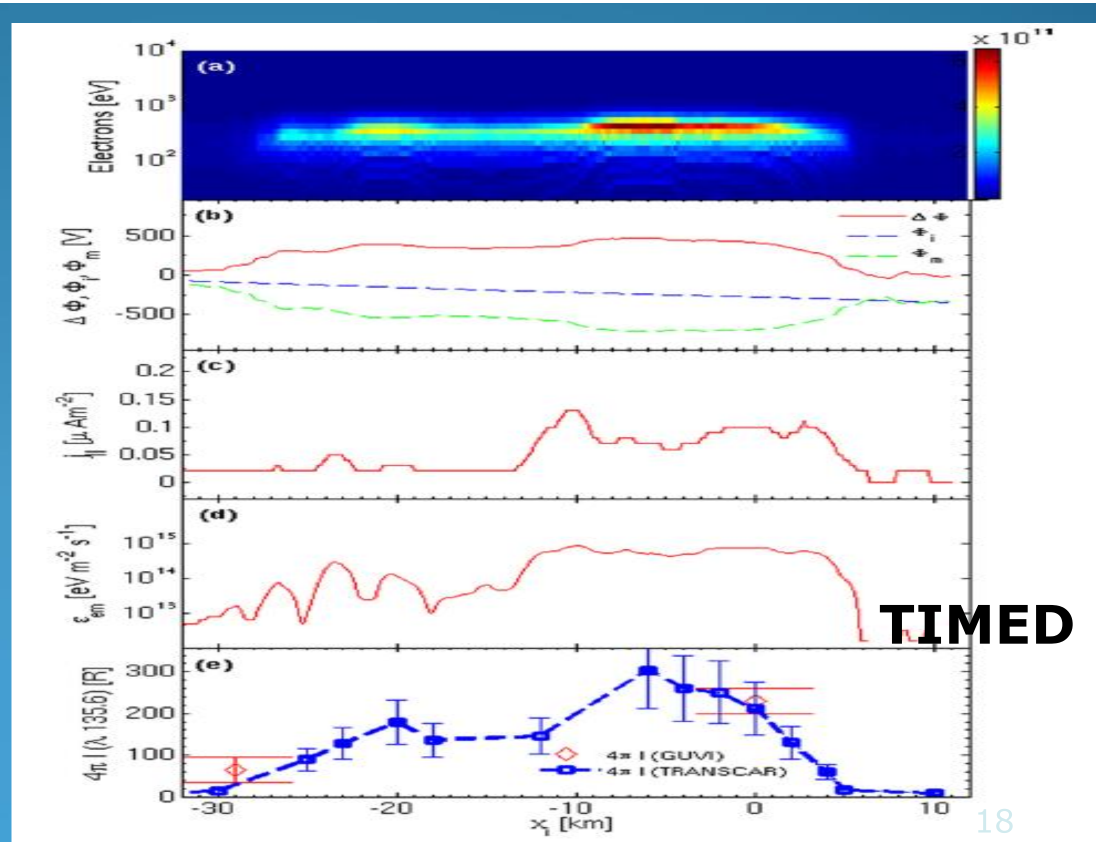


Modeling of auroral emission rates using observations and modeling (Maggiolo et al., 2012)

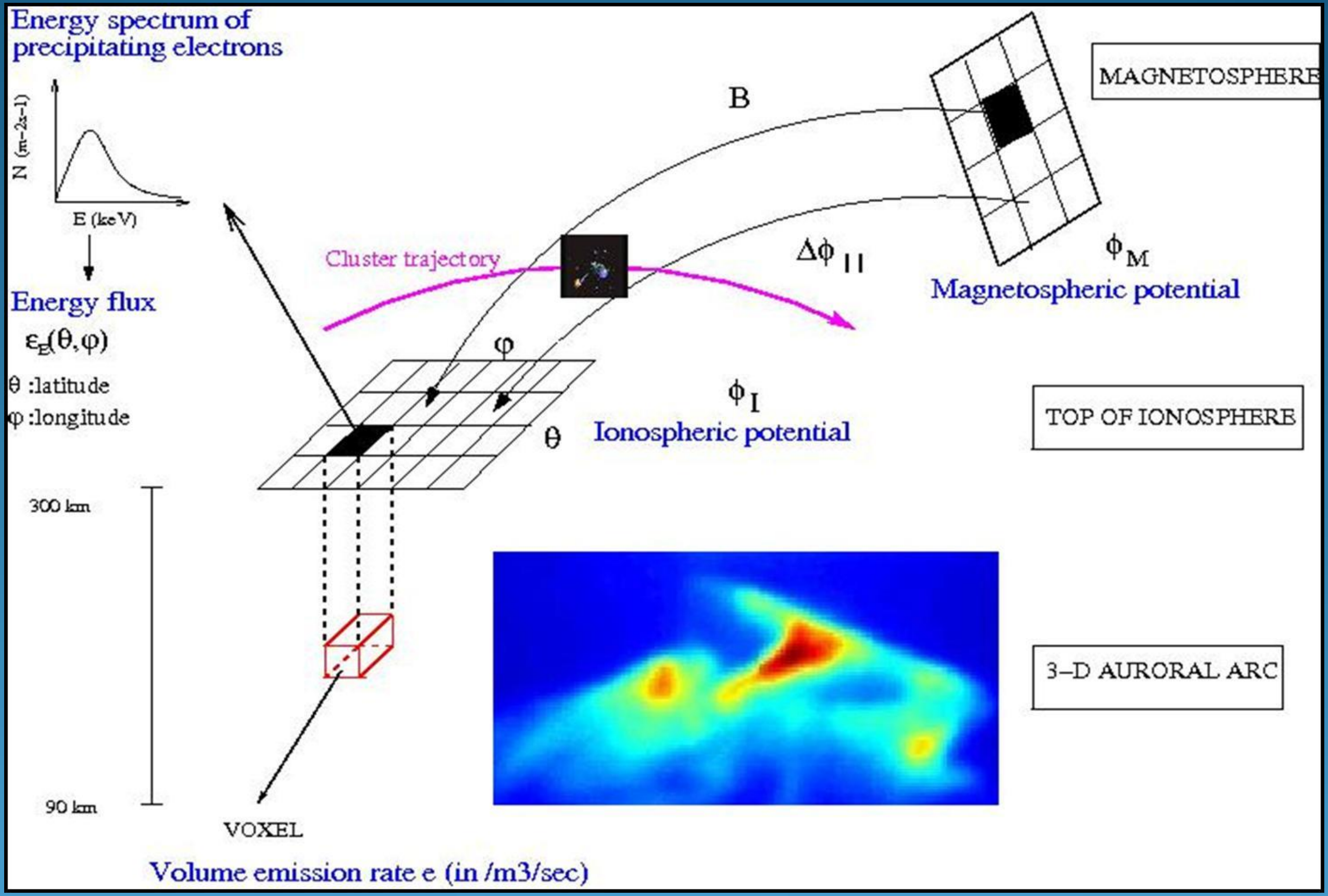
Observations and validation: polar cap arc observed by Cluster and TIMED



Modeling of polar cap arc electrodynamics and UV emission rates: electron energy spectrum from model, electric potential (Cluster observations and MI coupling model), field-aligned current density (model), precipitating energy flux (model), UV emission rates from GUVI and TRANS4 (Maggiolo et al., 2012)



New perspectives : the “inverse” problem



Based on ALIS optical observations and tomography one can derive the energy spectrum of precipitating electrons. Using a minimization procedure one can derive the generator configuration that fits best the auroral observations.

How to estimate properties of auroral magnetospheric generators from ionospheric observations of discrete auroral arcs

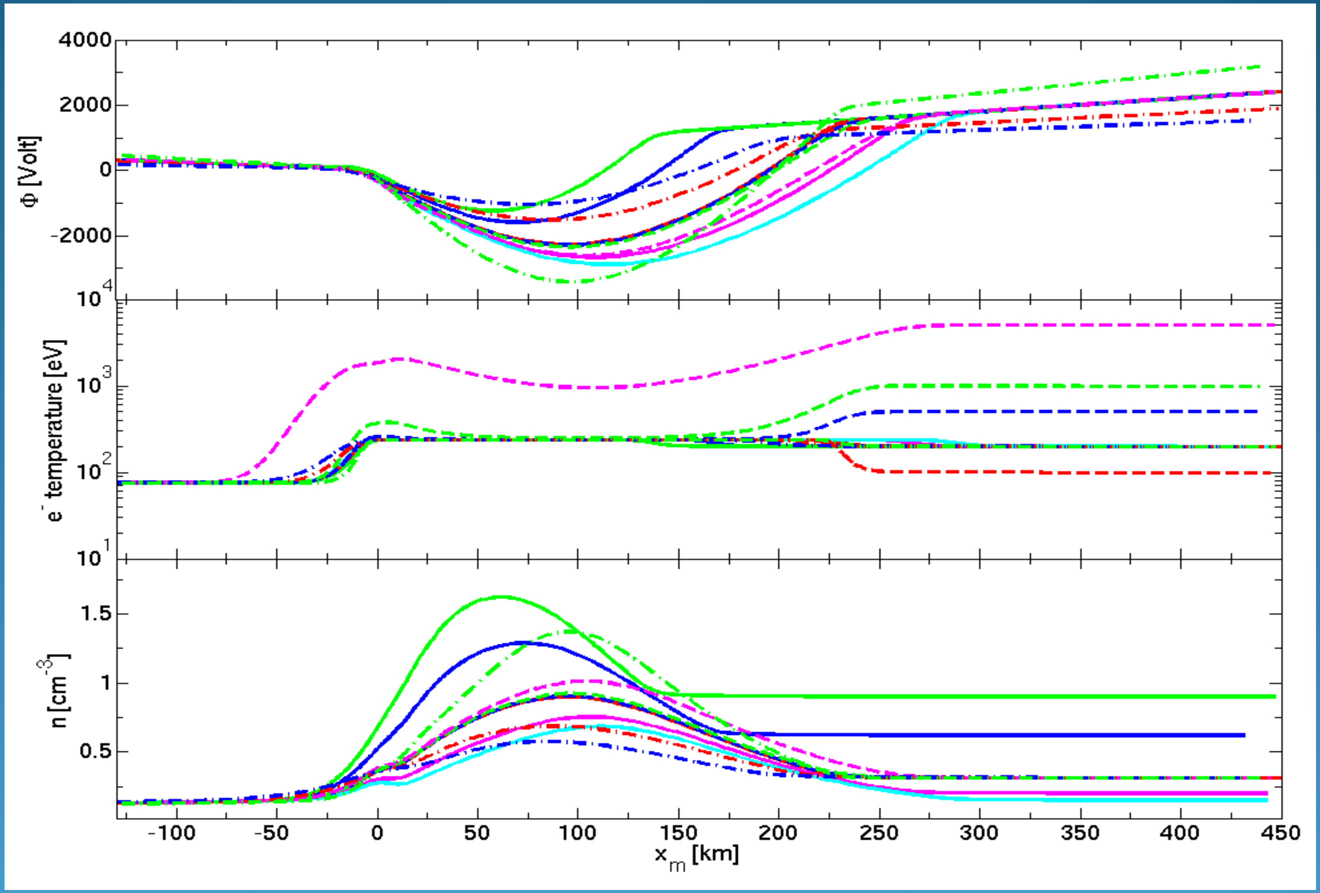
STEP 1: Generate a family of magnetospheric interface generator (MIG) solutions with some a-priori insight on its possible location

STEP 2: Generate a statistical ensemble of solutions for the electrodynamic properties of the auroral arc by solving the current continuity for all electric field profiles provided by the MIG solutions

STEP 3: apply a minimization procedure in the least-squares sense to estimate the best simulation fit for a set of observational data (e.g., field-aligned potential drop, energy flux of precipitating electrons)

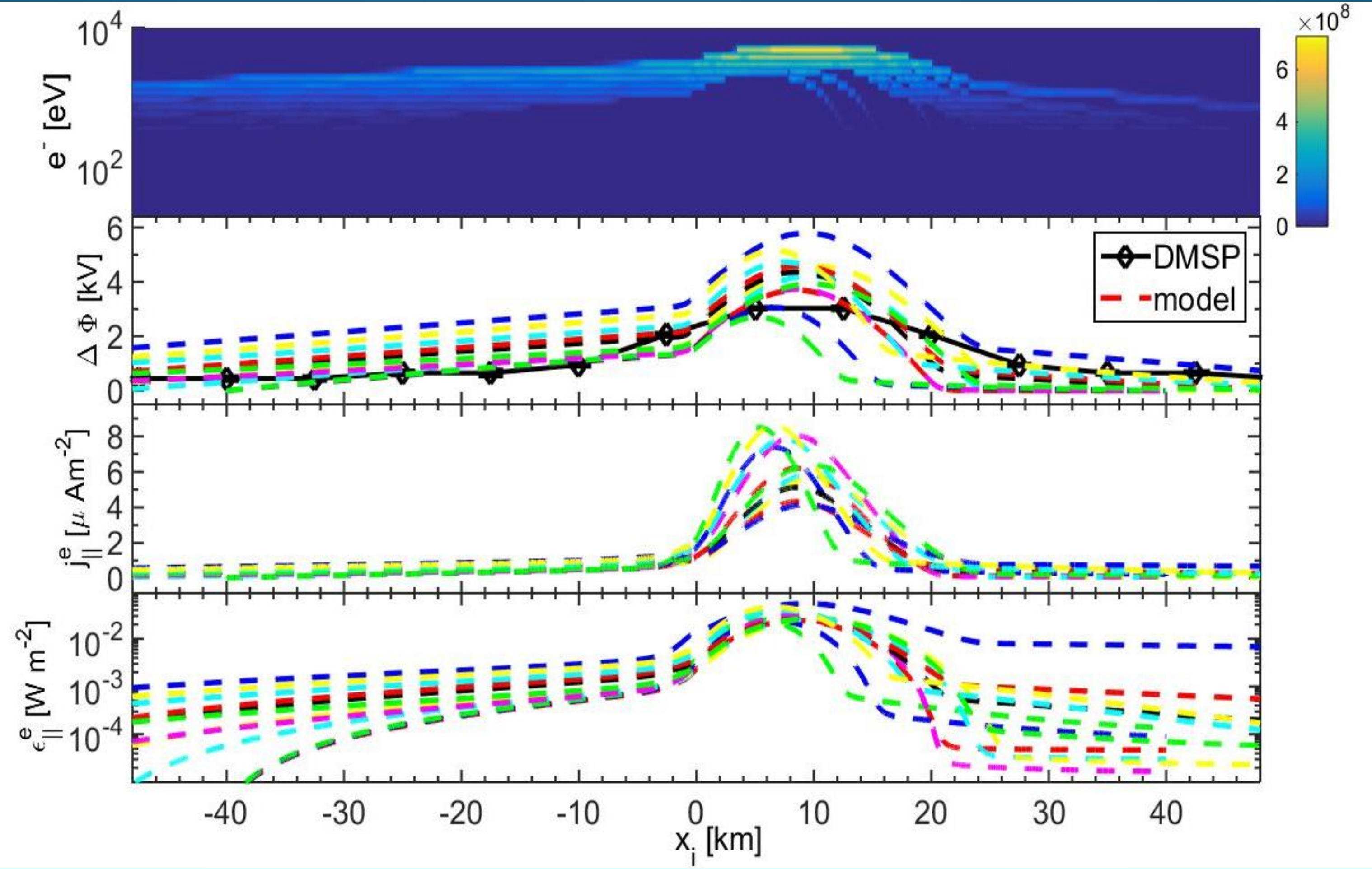
STEP 4: Select the best fit of auroral parameters and the corresponding MIG solution; the latter provides an estimation of the generator properties

STEP 1 : An ensemble of MIG solutions



Ensemble of generator solutions computed for a PSBL-like interface and a range of parameters including various density and temperature gradients, magnetic compression ratios. The panels show the electric potential, the electron temperature, the plasma density.

STEP 2 : An ensemble of auroral arcs generated by the MIG solutions computed at STEP 1



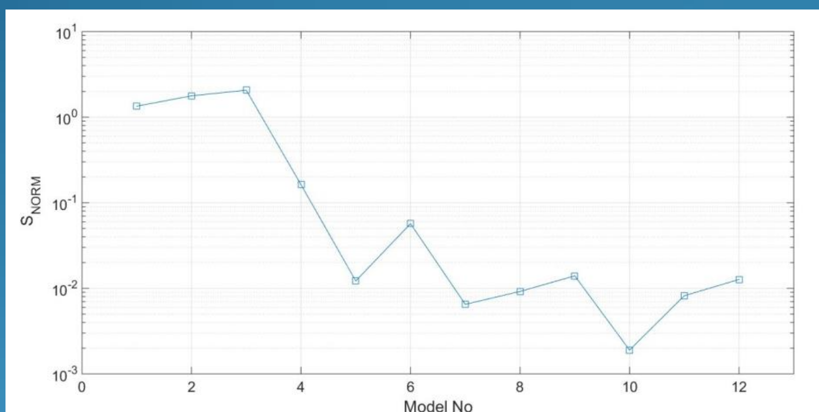
Ensemble of auroral electrodynamics solutions for the generators simulated at STEP 1. The panels show: synthetic electron energy spectrum, field-aligned potential difference, field-aligned current density, flux of precipitating energy. In black and diamond symbols are traced DMSP observations on 28/04/2001.

STEP 3 : Minimization procedure to select the best fit to experimental observations

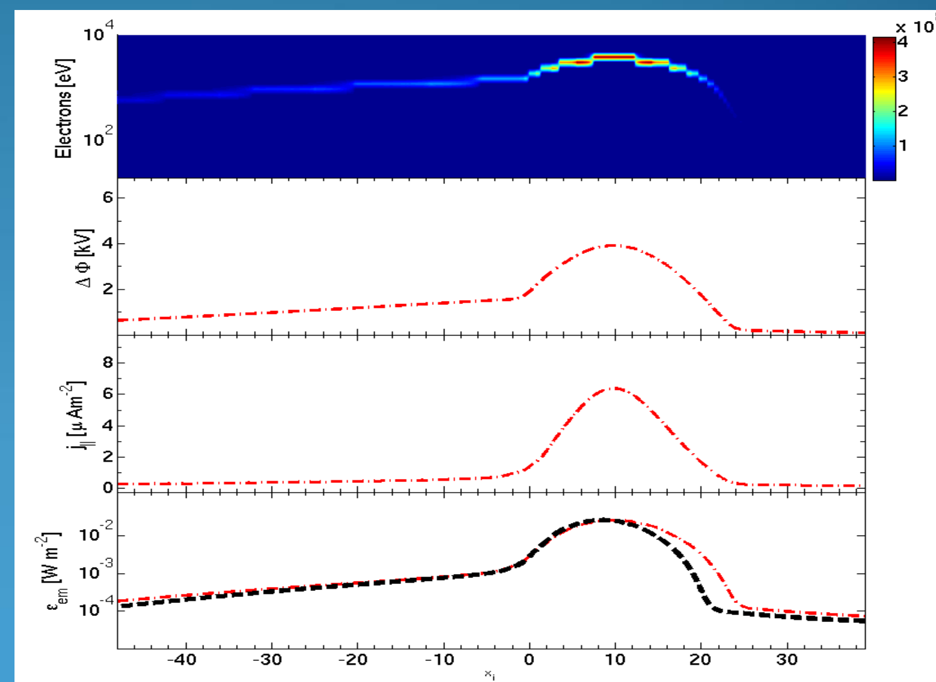
- the quantity to be minimized is defined as a norm defect with respect to the observational data:

$$S_{NORM} = \sum_{i=1}^{N} \frac{\sqrt{\left|V_i^{model}\right|^2 - \left|V_i^{obs}\right|^2}}{\left|V_i^{obs}\right|}$$

V_i^{obs} is the field-aligned potential drop $\Delta\Phi_{II}$ estimated from DMSP measurements.

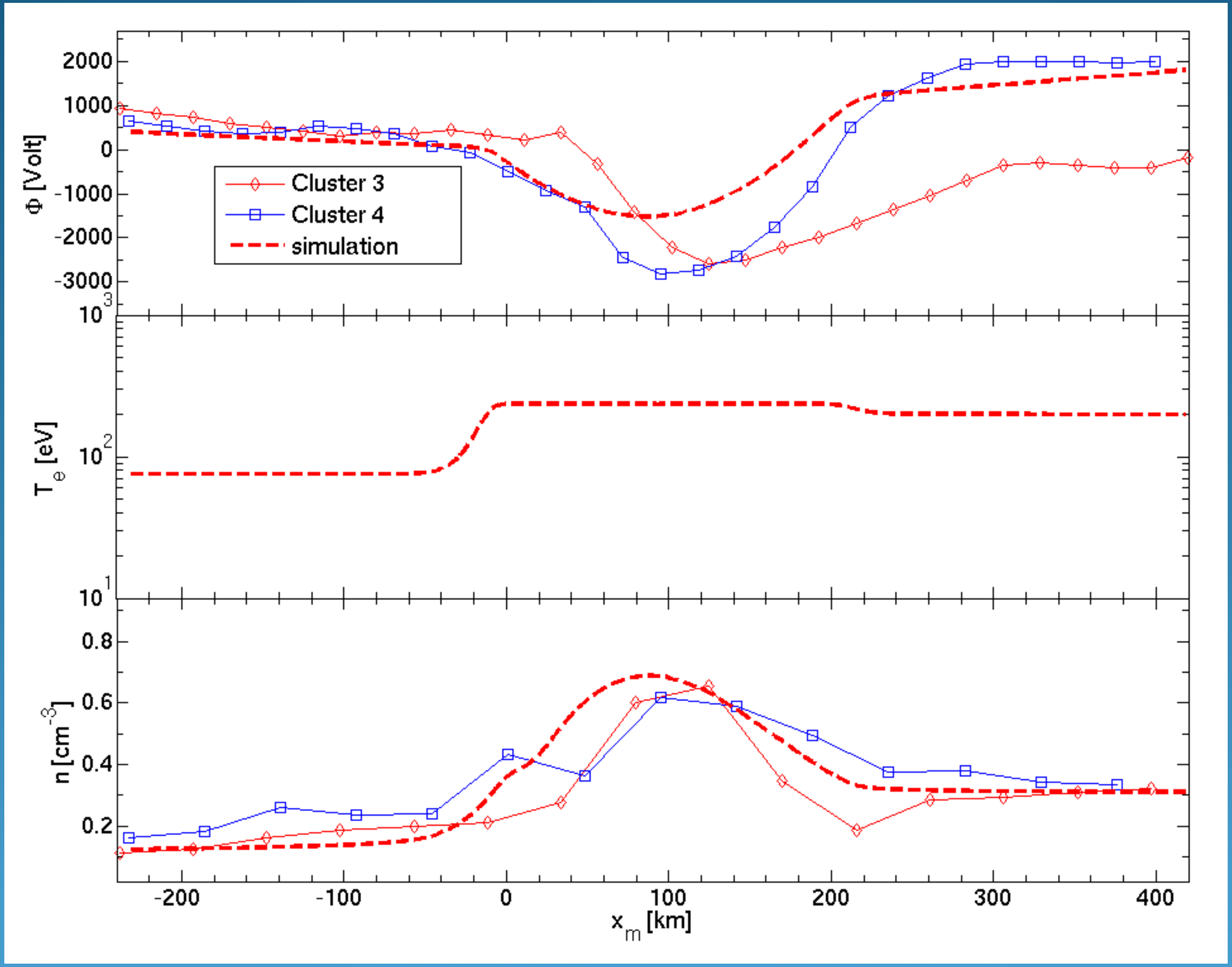


The norm defect for 12 different auroral arc solutions compared to DMSP observations.



Selected auroral solution based on S_{NORM}.

STEP 4 : Select the best fit of auroral parameters and the corresponding MIG solution



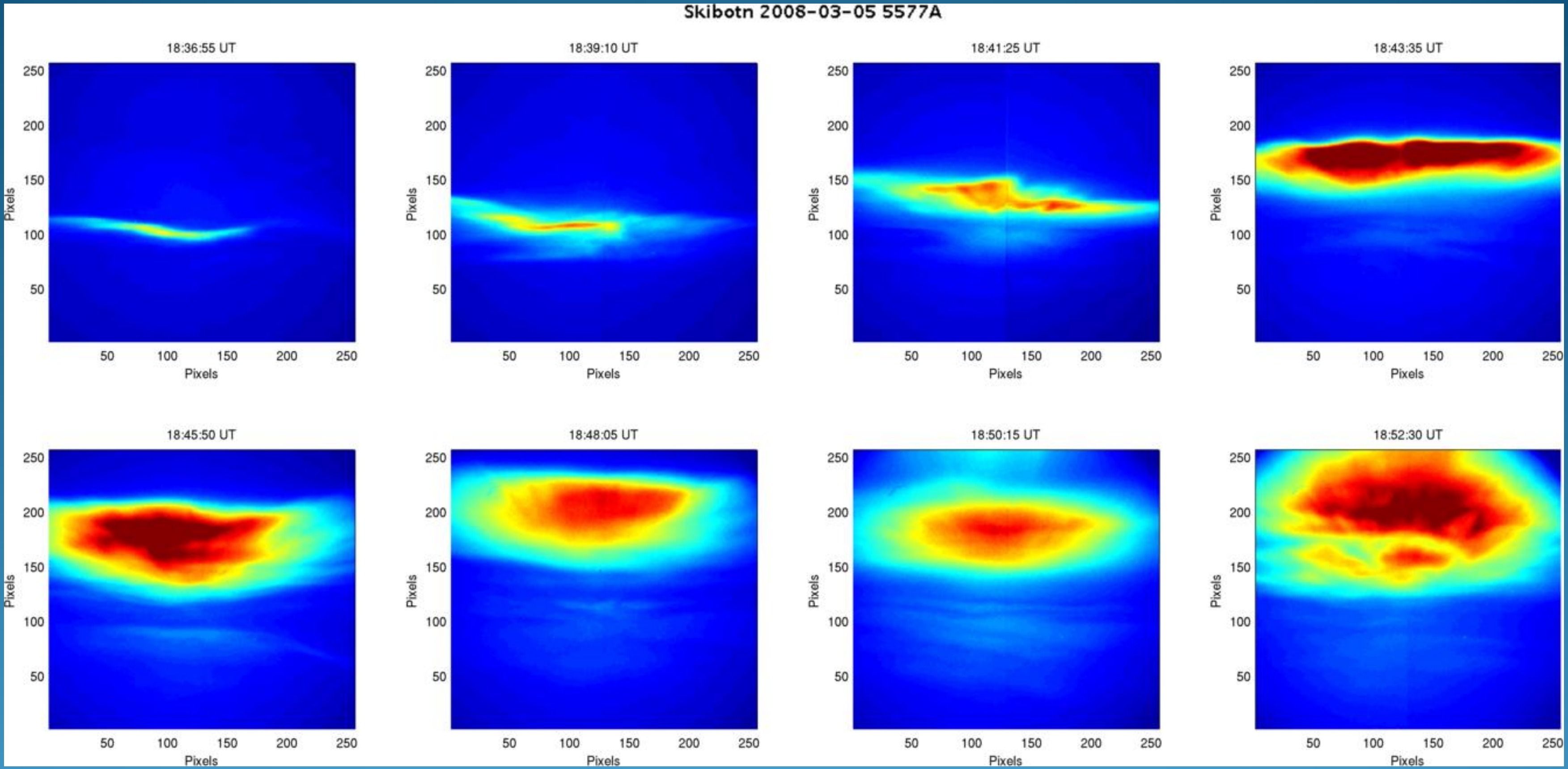
Selected magnetospheric generator solution based on S_{NORM}. superimposed are Cluster observations at the PSBL (Echim et al., 2009)

STEP 4 : Select the best fit of auroral parameters and the corresponding MIG solution

	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11
N_{e2} [cm^{-3}]	0.31	0.2	0.62	0.9	0.15	0.31	0.31	0.31	0.31	0.31	0.31
T_{e2} [eV]	200	200	200	200	200	500	1000	5000	200	200	200
B [nT]	480	480	480	480	480	480	480	480	345	256	697

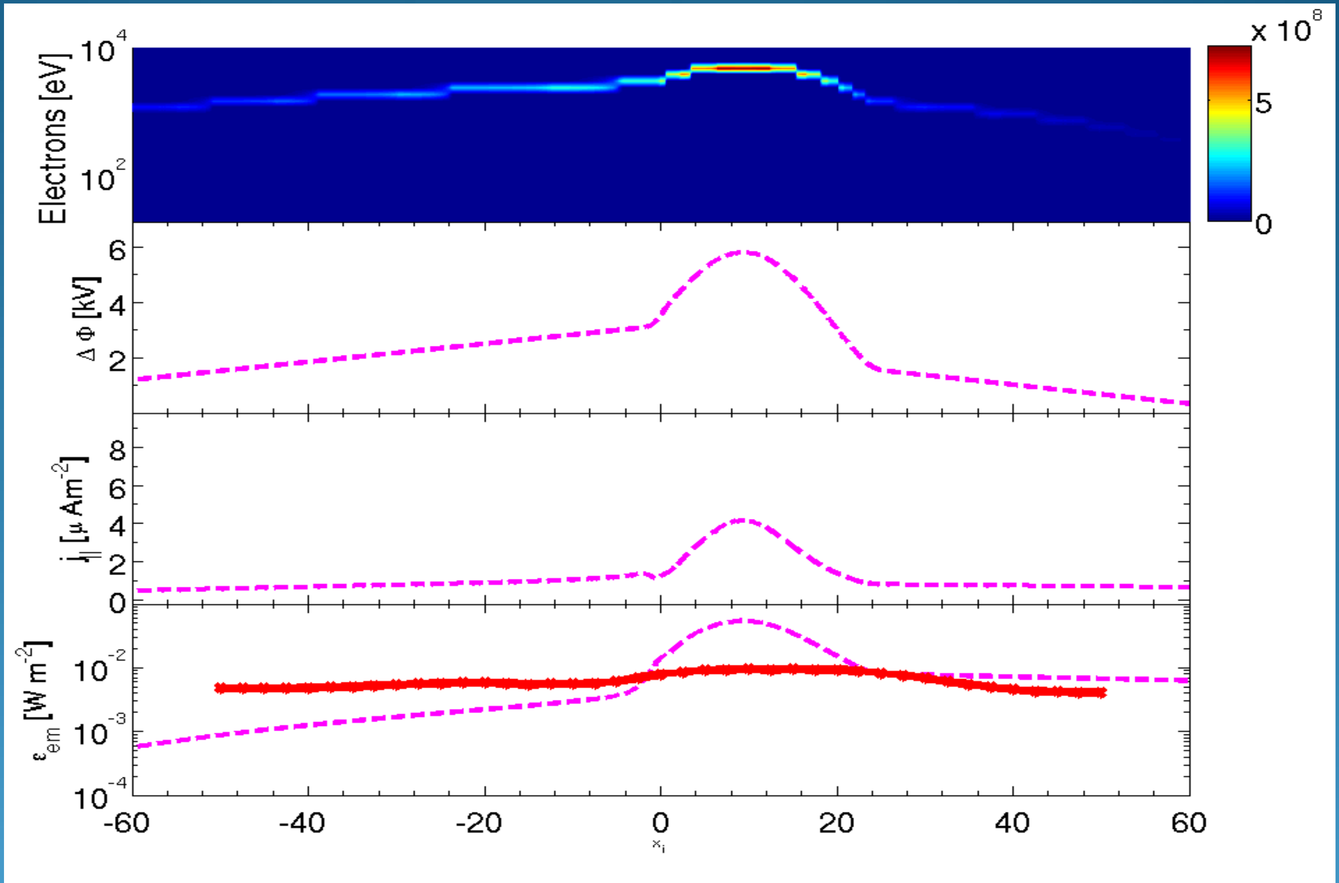
Parametric description of the right side (PSBL-like) of the MIG solution; the eleven sets (denoted from M1 to M11) are considered as boundary conditions for solutions of the Vlasov-Maxwell set of equations. The plasma bulk velocity is fixed and equal to 8.5 km/s. The asymptotic state at left is compatible with lobe plasma, has fixed values for the electron and ion density (0.12 cm-3), the electron and ion temperature , Ne1=75 eV and Np1=250 eV, the plasma bulk velocity, Vey1=Vpy1=0.5 km/s.

Some tests with ALIS data



Auroral observations from Skibotn station of the ALIS auroral network on 05/03/2008. The tomography analysis and the inversion technique provide the electron energy spectrum and the fluc of precipitating energy that is an input for the minimization procedure that fits the auroral electrodynamic parameters to observations.

Some tests with ALIS data



Auroral electrodynamics solutions derived from the inverse problem for auroral observations of a 100 km wide auroral arc in the dusk sector of the oval prior to a substorm onset. It is shown the solution selected by the minimisation procedure and the energy spectrum (in red) derived from tomography of ALIS data.

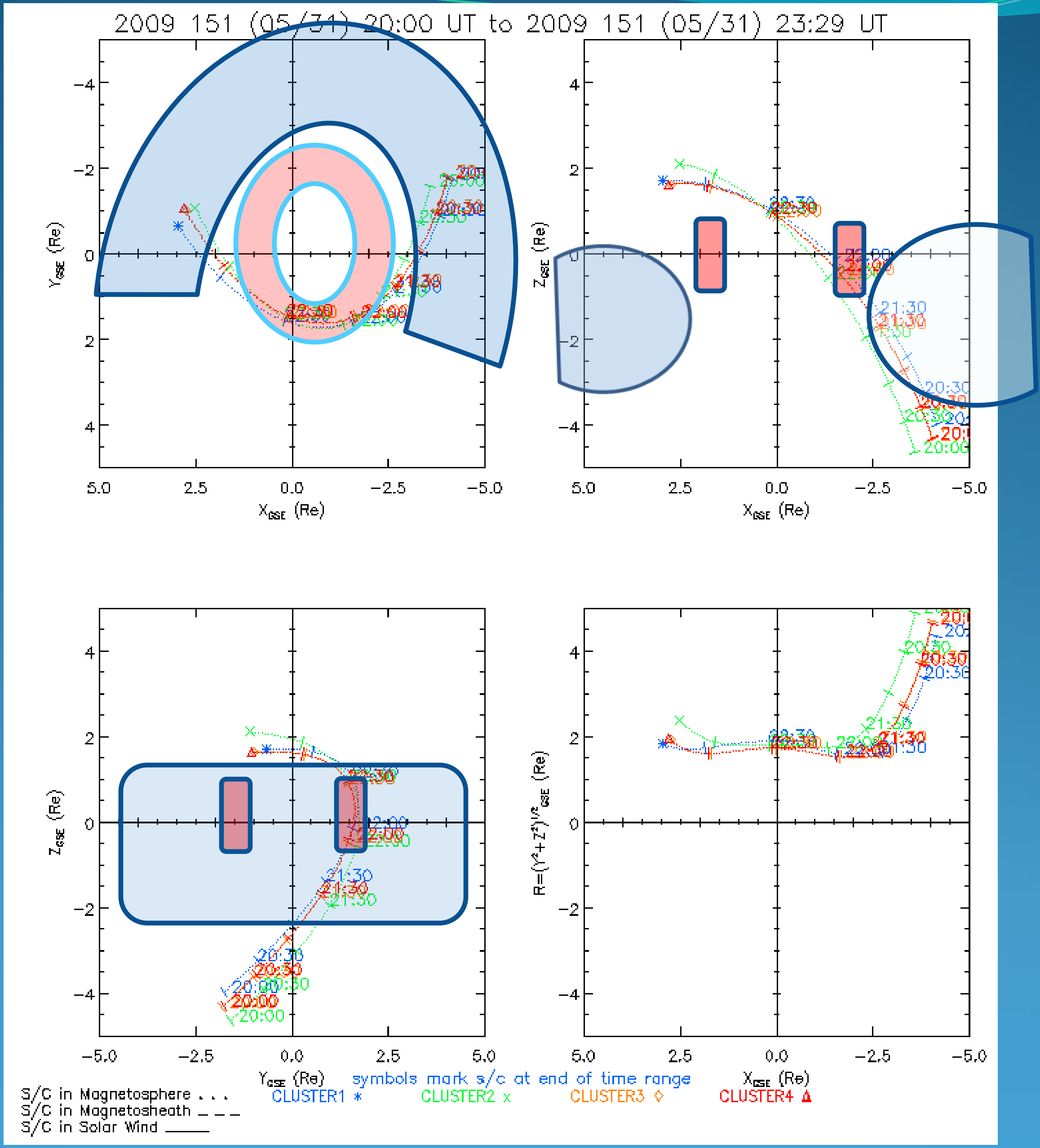
Summary, Conclusions

- A magnetosphere-ionosphere coupling model based on a self-consistent description of the generator, a kinetic current-voltage relationship and a description of the ionosphere helps to understand the effects of the magnetospheric variability on the auroral electrodynamics.

- The model shows how velocity shears in the LLBL may drive increased dayside field-aligned current densities.

- The model describes also the coupling between the PSBL and discrete auroral arcs.

- The MI coupling model has the potential to help describing the state of the magnetospheric generator when the electrodynamics of the aurora is known from ground based observations , like, e.g., tomography.



2009 151 (05/31) 20:00 UT to 2009 151 (05/31) 23:29 UT
X_GSE (Re)
Y_GSE (Re)
Z_GSE (Re)
R=(Y²+Z²)^1/2_GSE (Re)
symbols mark s/c at end of time range
S/C in Magnetosphere . . .
S/C in Magnetosheath _ _ _
S/C in Solar Wind ____
CLUSTER1 *
CLUSTER2 x
CLUSTER3 ◊
CLUSTER4 Δ