Advanced modeling of low energy electrons responsible for surface charging

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Why are we interested in low energy electrons (< 200 keV) in the inner magnetosphere?

- Surface charging by electrons with < 100 keV can cause significant damage and spacecraft anomalies.

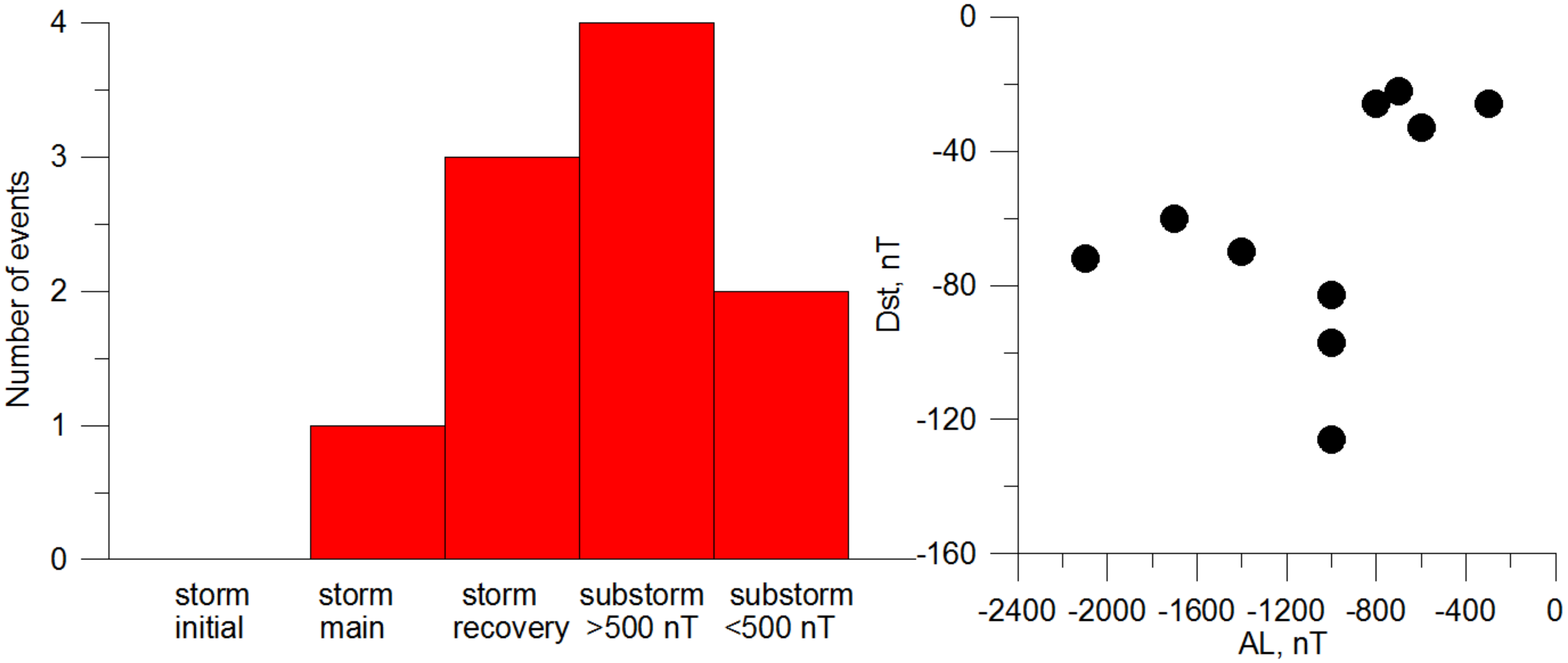
- The distribution of low energy electrons, the seed population (10 to few hundreds of keV), is critically important for radiation belt dynamics.

- Chorus emissions (intense whistler mode waves) excited in the low-density region outside the plasmapause are associated with the injection of keV plasma sheet electrons into the inner magnetosphere.

- The electron flux at the keV energies is largely determined by convective and substorm-associated electric fields and varies significantly with geomagnetic activity driven by the solar wind – variations on time scales of minutes!
  No averaging over an hour/day/orbit!

Surface charging events vs. geomagnetic conditions

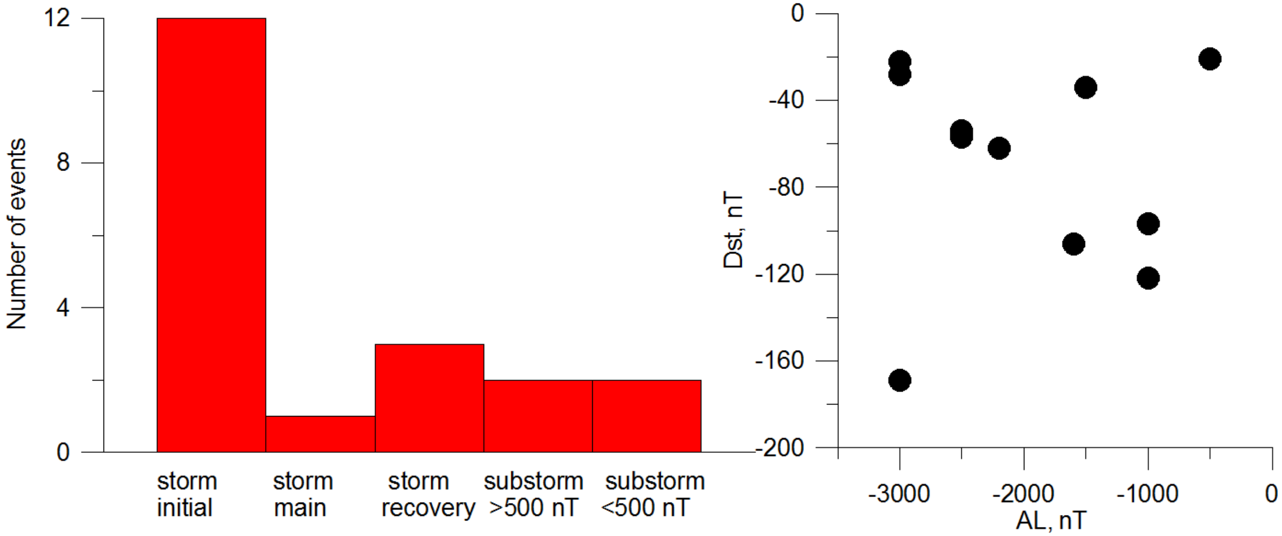
Events with consecutive absolute potentials **< -10000 V**



Data: LANL (1989-2005), 1989-046, 1990-095, 1991-080, 1994-084, LANL-97A, LANL-01A and LANL-02A, MPA (Magnetospheric Plasma Analyzer), SOPA (Synchronous Orbit Particle Analyzer) and EPD (Energetic Particle Detector), from 1 eV to several MeV

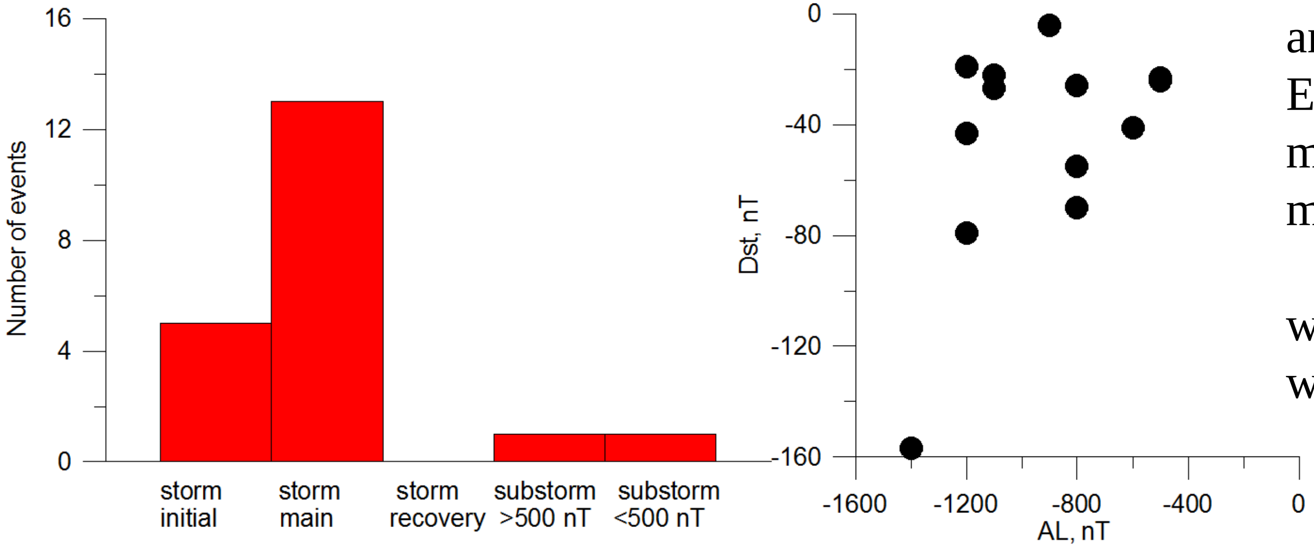
Matéo Vélez et al., Severe geostationary environments: from flight data to numerical estimation of spacecraft surface charging, *Journal of Spacecraft and Rockets, submitted, 2015*

Surface charging events vs. geomagnetic conditions



High Fluxes at All Energies (**HFAE**)

worst five minutes and
worst fifteen minutes



High Flux at Low Energy and Low Flux at High Energy (**LFHE**):
max flux for 10-50 keV and min flux above 200 keV

worst five minutes and
worst fifteen minutes

Matéo Vélez et al., Severe geostationary environments: from flight data to numerical estimation of spacecraft surface charging, *Journal of Spacecraft and Rockets, submitted, 2015*

It is challenging to model (nowcast) and forecast low energy electrons

• Following low energy electrons in large-scale **magnetic and electric fields:**
Correct models for these fields are extremely hard to develop

• Specification of a correct **initial conditions in the plasma sheet** is very nontrivial

• **Coefficients for radial diffusion** when electrons move from the plasma sheet (10 Re) to inner regions (<6 Re) are far from being exact.

• How to introduce low energy electrons' losses correctly? Electron lifetimes due to interactions with chorus and hiss, other waves, are they important?

• **Substorms** play a significant role in keV **electron transport and energy increase.**
How to include them properly?

Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM) for low energy electrons

(*Ganushkina et al., 2013, 2014, 2015*)

- traces **electrons** with arbitrary pitch angles from the plasma sheet to the inner L-shell regions with energies up to **300 keV** in time-dependent magnetic and electric fields

- traces a distribution of particles in the **drift approximation** under the conservation of the 1st and 2^{nd} adiabatic invariants. Liouville theorem is used to gain information of the entire distribution function

- for the obtained distribution function, we apply **radial diffusion** by solving the radial diffusion equation

- electron losses: convection outflow and pitch angle diffusion by the **electron lifetimes**

- advantage of IMPTAM: can utilize any magnetic or electric field model, including self-consistent magnetic field and substorm-associated electromagnetic fields.

Run online in real time: http://fp7-spacecast.eu and imptam.fmi.fi

Advances in IMPTAM for electrons

Magnetic field model: *Tsyganenko* T96 (Dst, Psw, IMF By and Bz)

Electric field model: *Boyle et al*. (1997) (Vsw, IMF B, By, Bz)

Boundary conditions at 10 Re: newly developed empirical model for electron number density and temperature in the plasma sheet based on THEMIS observations (instead of *Tsyganenko and Mukai* (2003) model for ions) (Vsw, IMF Bz,Nsw)

Radial diffusion with diffusion coefficients D_{LL} (*Brautigam and Albert*, 2000)

$$D_{LL} = 10^{0.056Kp - 9.325} L^{10}$$

Losses:

Parameterization of the electron lifetimes due to interactions with chorus waves [*Orlova and Shprits*, 2014] and **due to interactions with hiss waves** [*Orlova et al.*, 2014]: polynomial expressions with coefficients dependent on energy, radial distance, MLT sector and Kp.

Boundary conditions in the plasma sheet for modeling of keV electrons

Near-Earth plasma sheet is the source for keV electrons in the inner magnetosphere.
In the near-Earth plasma sheet, continuous measurements of plasma sheet electrons are not available, in contrast to geostationary orbit.

No solar wind driven empirical relations for electron fluxes or moments of electron distribution function which can be used easily for radiation belt modeling.

Our previous studies [*Ganushkina et al*., 2013, 2014]:
we set the model **boundary at 10 R_E** and use the **kappa electron distribution** function.
Parameters of the kappa distribution function: **number density *n* and temperature *T*** in the plasma sheet given by the empirical model derived from Geotail data by TM03 *Tsyganenko and Mukai* [2003]. The **electron *n* is assumed to be the same as that for ions** in the TM03 model, but **Te/Ti = 0.2** is taken into account (*Wang et al*., 2012).

Applying this model for boundary conditions has a number of **limitations**:

(1) Model was derived from **Geotail data for ions** (limited detector energy range <40keV).

(2) ratio **Te/Ti can vary** during disturbed conditions.

(3) at distances closer than 10 Re, the correlation between Ti and Te might not exist at all and no certain ratio can be determined (*Runov et al*., 2015).

Model for electron temperature at 6-11 R_e based on Cluster and THEMIS data: Empirical relations

Every point in the inner magnetosphere is defined by two normalized coordinates ϕ^* and R^*. The angle

$\phi^* = \frac{2}{\pi}\arctan\left(\frac{-Y_{GSM}}{X_{GSM}}\right)$ and R^* is the geocentric distance normalized by 10 R_E.

The number density in the plasma sheet (*Nps*) is given in cm^{-3} as follows:

$$N_{ps} = 0.2579 - 0.1148\phi^* - 0.1520\phi^{*2} + \left(0.3094 - 0.1486\phi^*\right)N_{SW}^* + \left(1.187 - 1.104R^*\right)B_S^{*0.715}$$

$$N_{SW}^*\left(t_0\right) = \frac{1}{10cm^{-3}5.75h}\int_{t_0-0.33h}^{t_0-6.08h} N_{SW}\left(t\right)dt,\ \ B_S^*\left(t_0\right) = \frac{1}{2nT5.25h}\int_{t_0-0.33h}^{t_0-6.08h} B_S\left(t\right)dt$$

Nsw is the solar wind density and Bs is the sourthward IMF Bz.

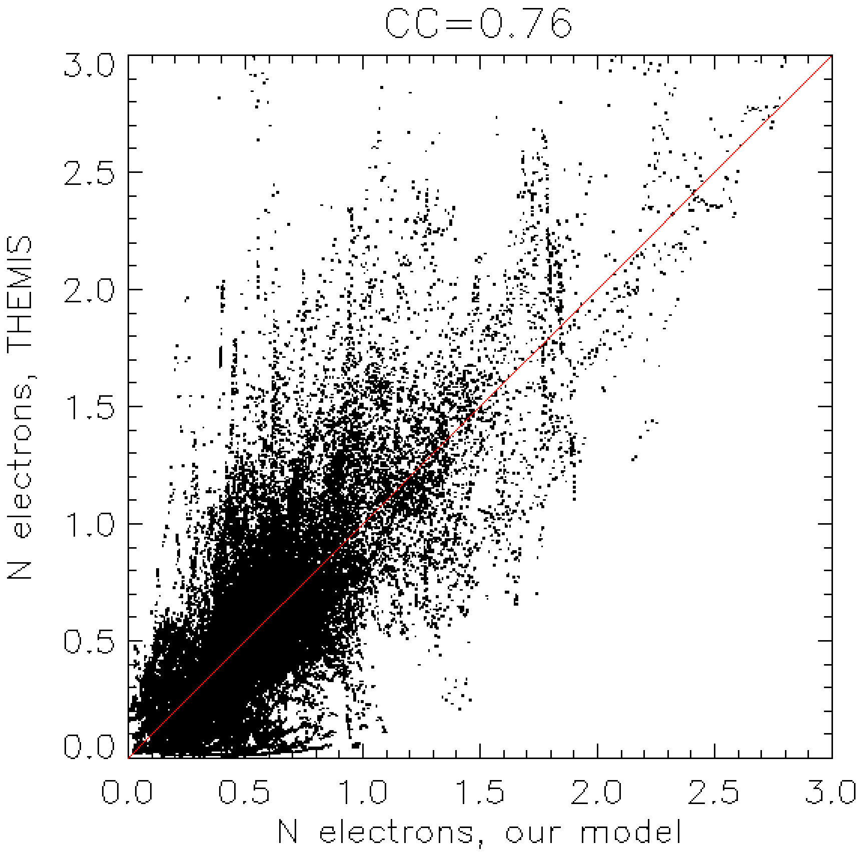
The temperature in the plasma sheet (*Tps*) is given in keV as follows:

$$T_{ps} = \left[\begin{matrix} 2.749 - 2.611R^* + 0.6191\phi^* - 0.6271\phi^* R^* + 0.5907\phi^{*2} R^* + \\ + \left(1.918R^* + 1.466\phi^{*2} - 2.224\phi^{*2}R^*\right)V_{SW}^* - 0.3587\phi^* B_S^{*0.513} - 0.6948R^* B_N^{*0.498} \end{matrix}\right]^2$$

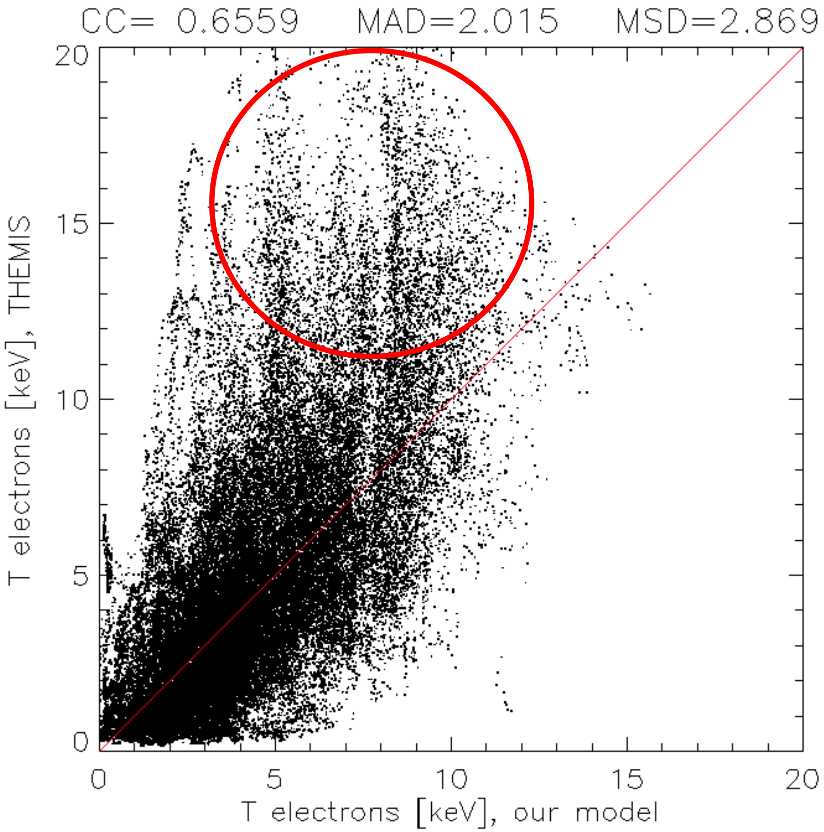
$$V_{SW}^*\left(t_0\right) = \frac{1}{400km/s}V_{SW}\left(t - 1.58h\right),\ \ B_S^*\left(t_0\right) = \frac{1}{2nT1.5h}\int_{t_{0-0.33h}}^{t_0-1.83h} B_S\left(t\right)dt,\ \ B_N^*\left(t_0\right) = \frac{1}{2nT3.25h}\int_{t_0-0.33h}^{t_0-3.58h} B_N\left(t\right)dt$$

Vsw, *Bs*, and *Bn* are solar wind density, southward and northward IMF Bz components

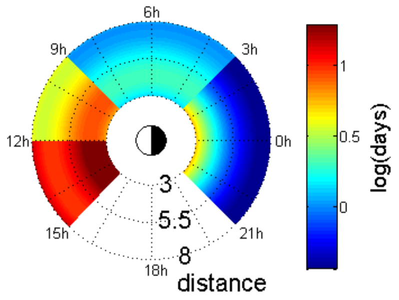
Empirical model for plasma sheet electrons at 6-11 R_e based on THEMIS data: Performance

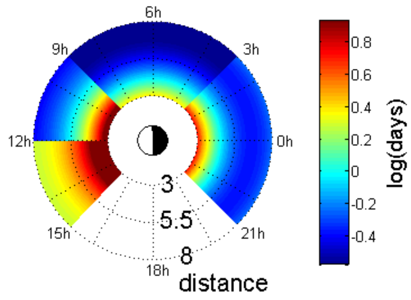


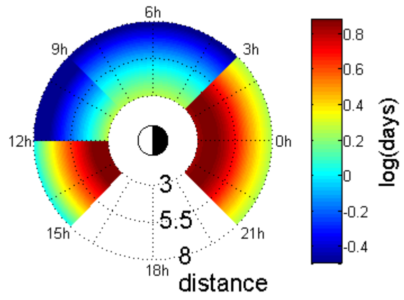
Hot plasma
carried by BBFs
(substorm injections)?

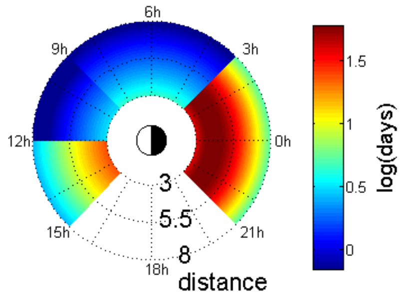


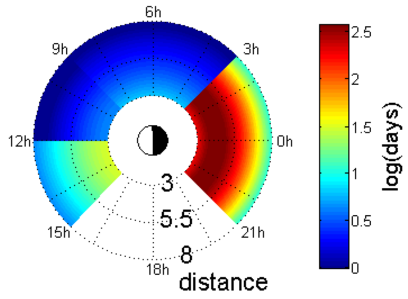
Losses for low energy electrons due to wave-particle interactions


electron lifetime E= 5 keV , Kp=3


electron lifetime E= 10 keV , Kp=3


electron lifetime E= 50 keV , Kp=3


electron lifetime E=100 keV , Kp=3

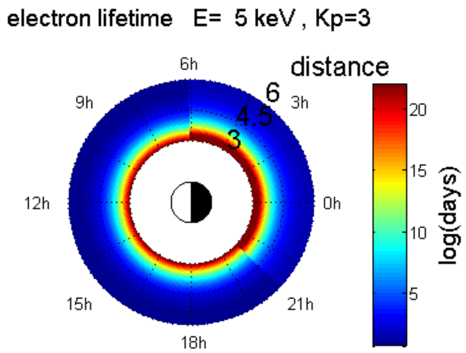

electron lifetime E=150 keV , Kp=3

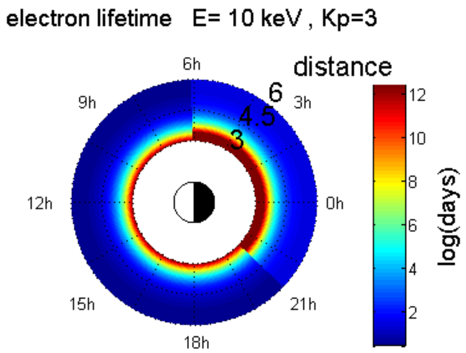
Parameterization of the electron lifetimes due to interactions with chorus waves [*Orlova and Shprits*, 2014]:

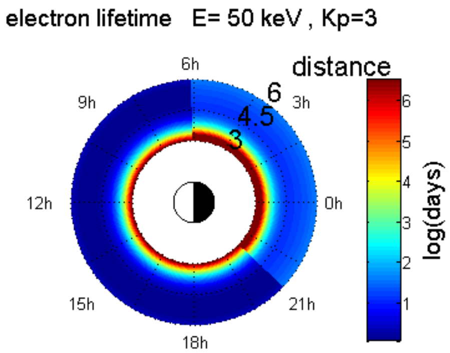
polynomial expressions with 33 coefficients dependent on energy, radial distance, MLT sector and Kp.

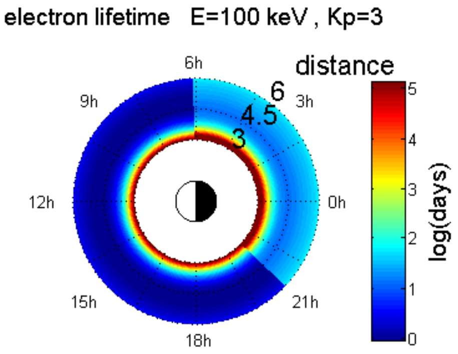
The model can be used for R=3-8 R_E, Kp= 0-6, and electron energies from 1 keV to 2 MeV. MLT sectors include the night (-3≤MLT≤3), dawn (3≤MLT≤9), prenoon (9≤MLT≤12), and postnoon (12≤MLT≤15) segments**.**

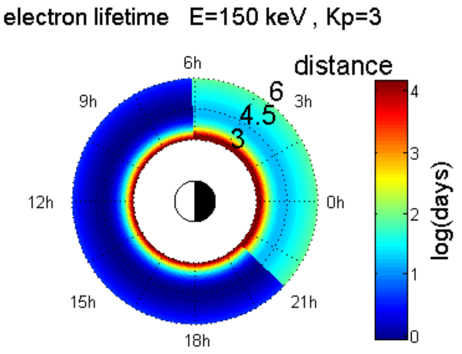
Losses for low energy electrons due to wave-particle interactions


electron lifetime E= 5 keV , Kp=3


electron lifetime E= 10 keV , Kp=3


electron lifetime E= 50 keV , Kp=3


electron lifetime E=100 keV , Kp=3

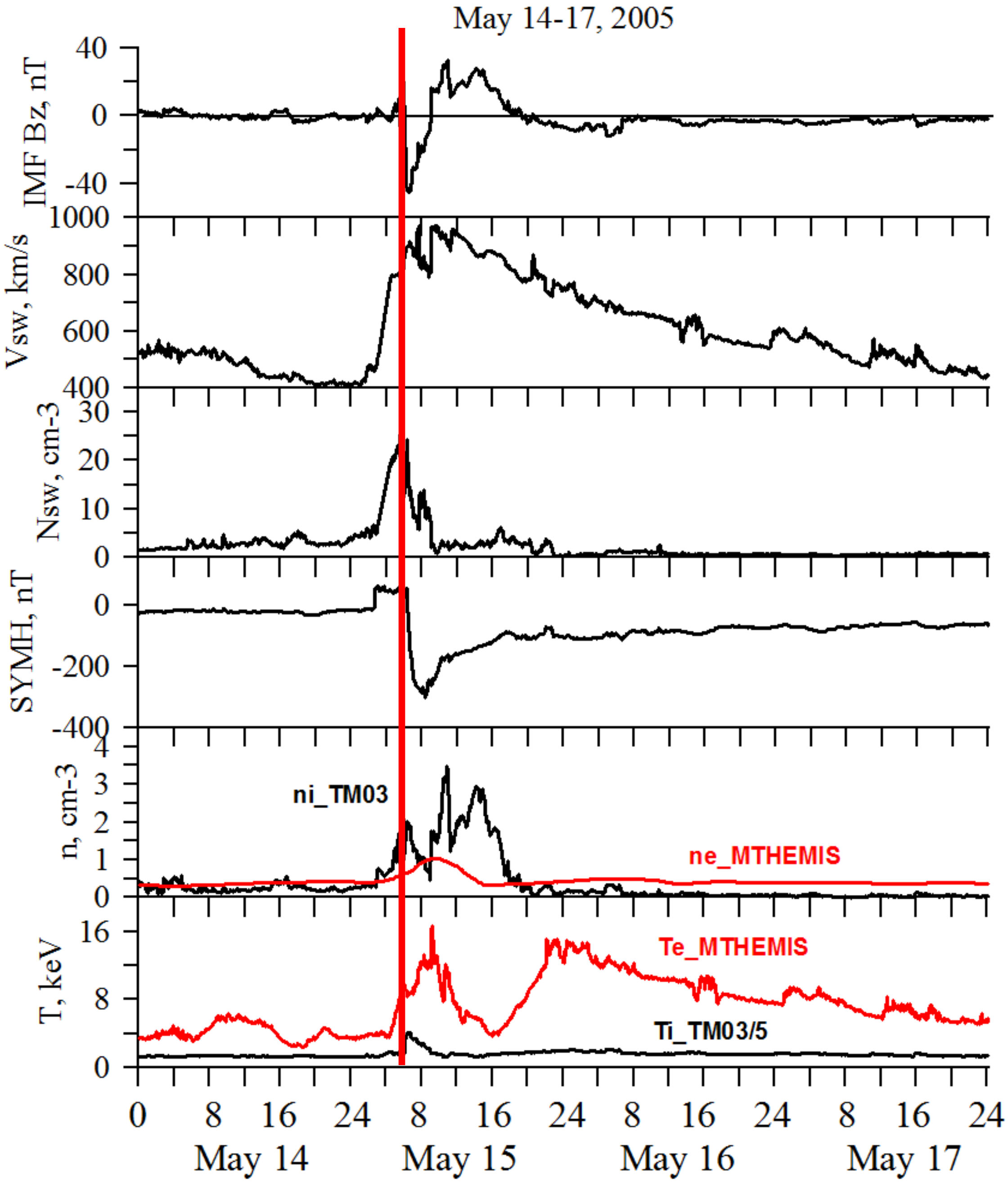

electron lifetime E=150 keV , Kp=3

Parameterization of the electron lifetimes due to interactions with hiss waves [*Orlova et al.*, 2014]:
two sectors, nightside at 21-06 MLT and dayside at 06-21 MLT,
with corresponding coefficients. The obtained parameterization is valid for distances from 3 to 6 Re, *Kp*-indices up to 6, and energies from 1 keV to 10 MeV.

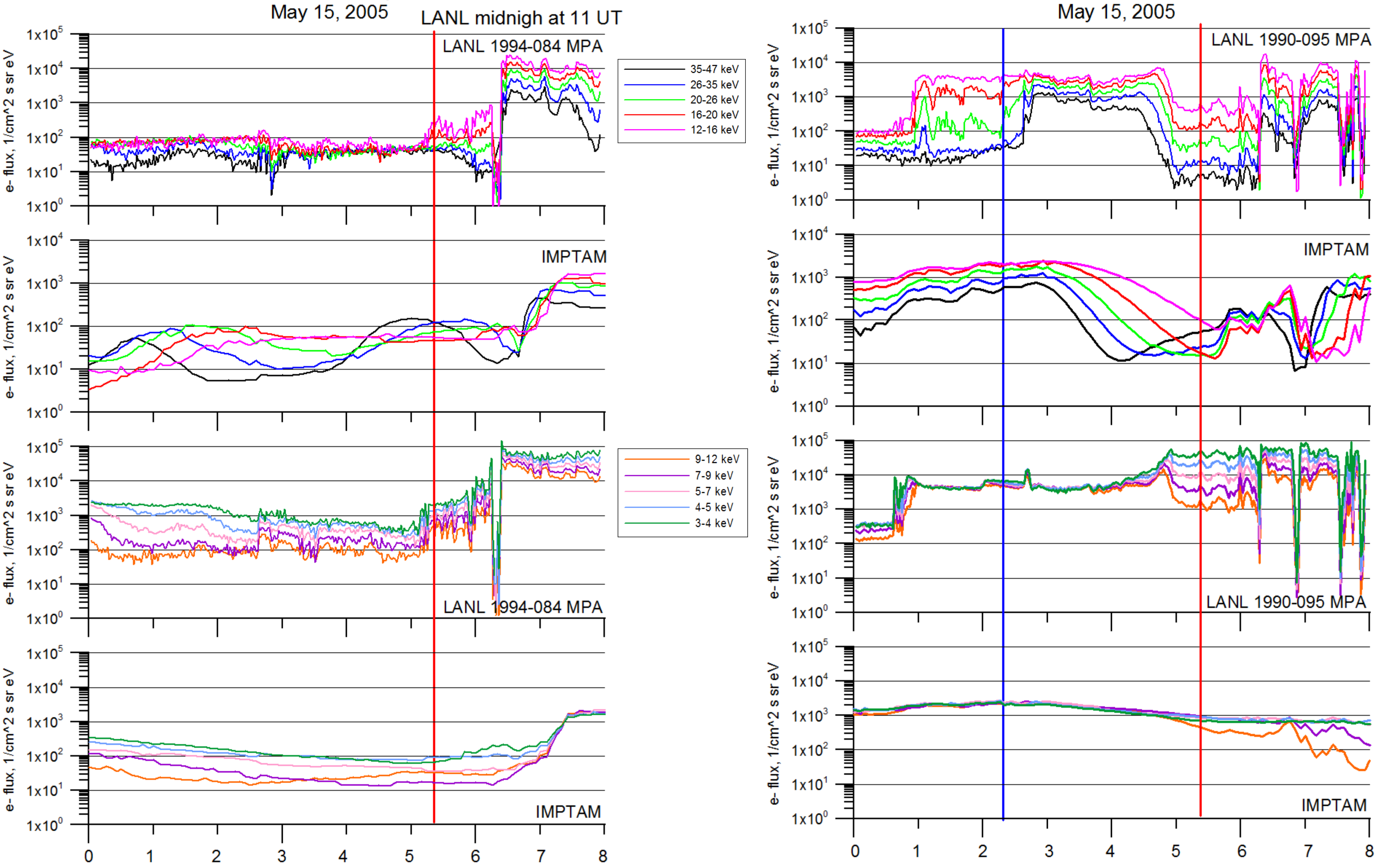
May 14 – 17, 2005 storm event

absolute potentials < -10000 V

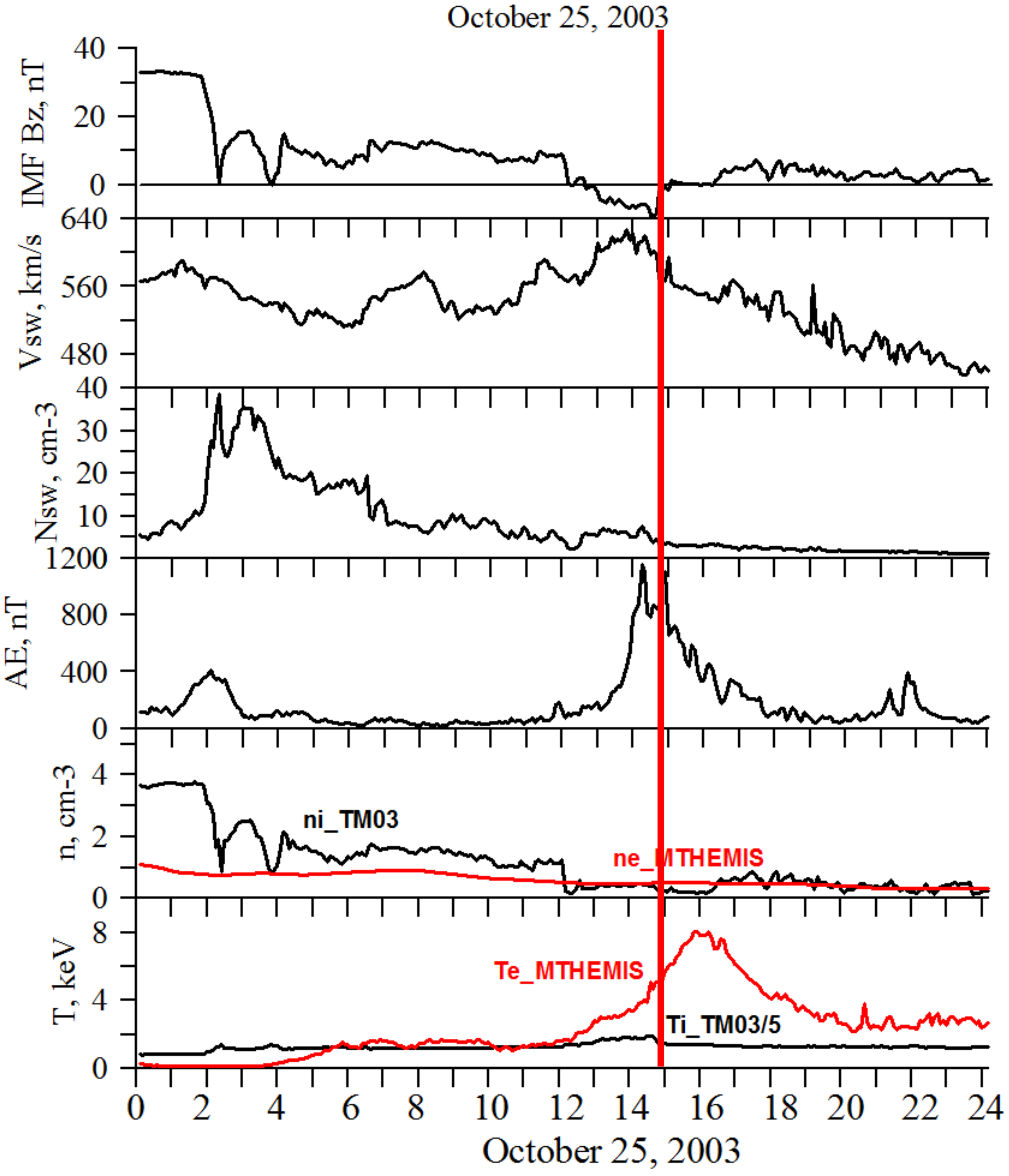
LANL 1990-095:
May 15, 2005, 0521 UT



May 14 – 17, 2005 storm event



Smaller-scale flux variations are missing but values of modeled fluxes are close to observed ones



October 25, 2003 substorm event

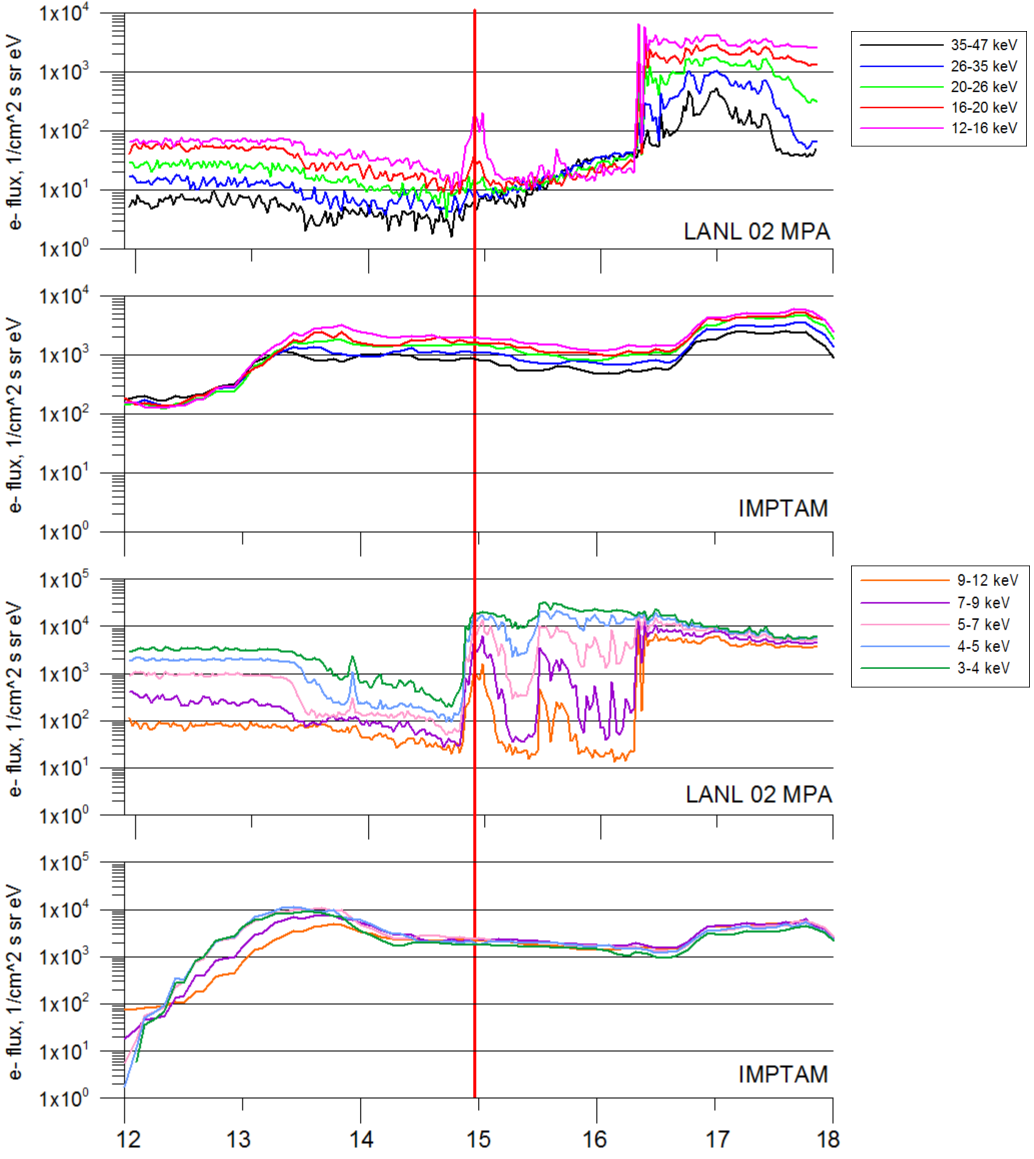
High Flux at Low Energy and Low Flux at High Energy (**LFHE**):
max flux for 10-50 keV and min flux above 200 keV

worst five minutes

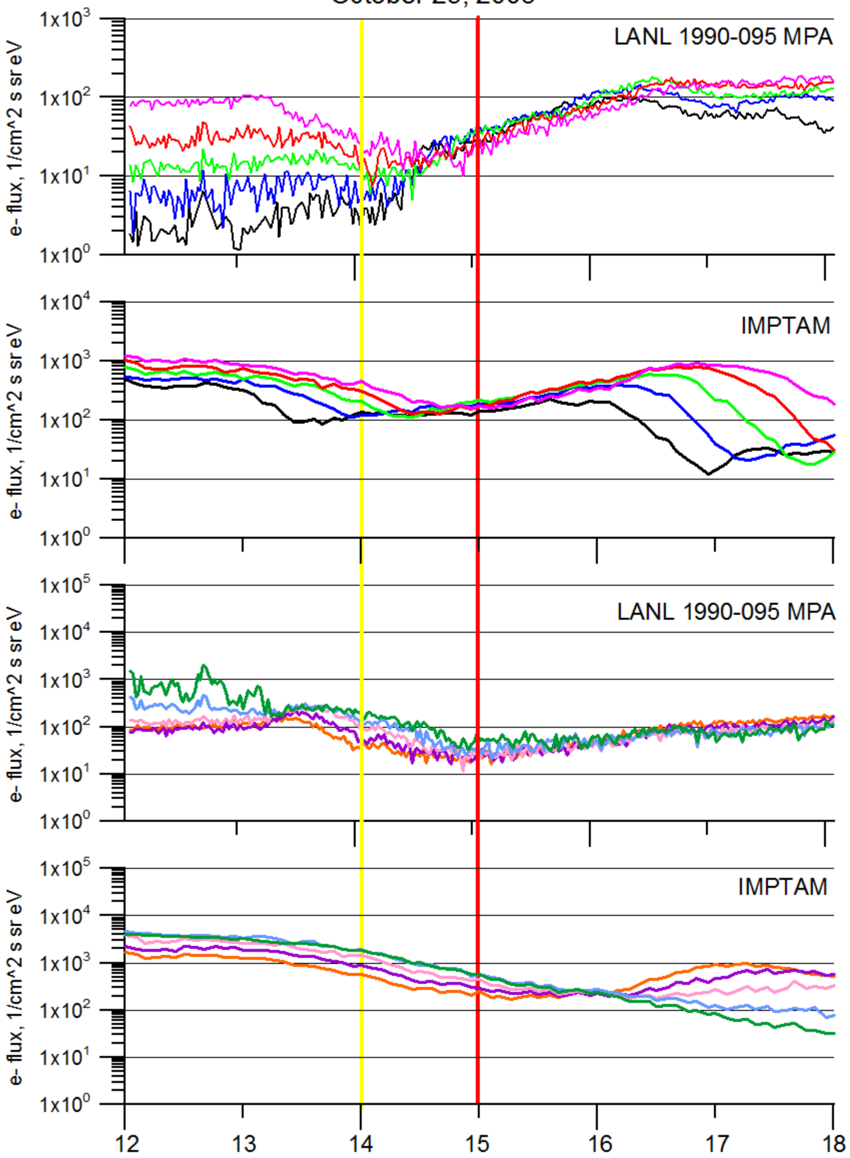
LANL 1994-084:
October 25, 2003, 1454 UT

October 25, 2003 substorm event

October 25, 2003 LANL midnight at 19 UT



October 25, 2003



Substorm flux variations are missing but values of modeled fluxes are close to observed ones

Summary

1. IMPTAM is very suitable for modeling of fluxes of low energy electrons (< 200 keV) responsible for surface charging

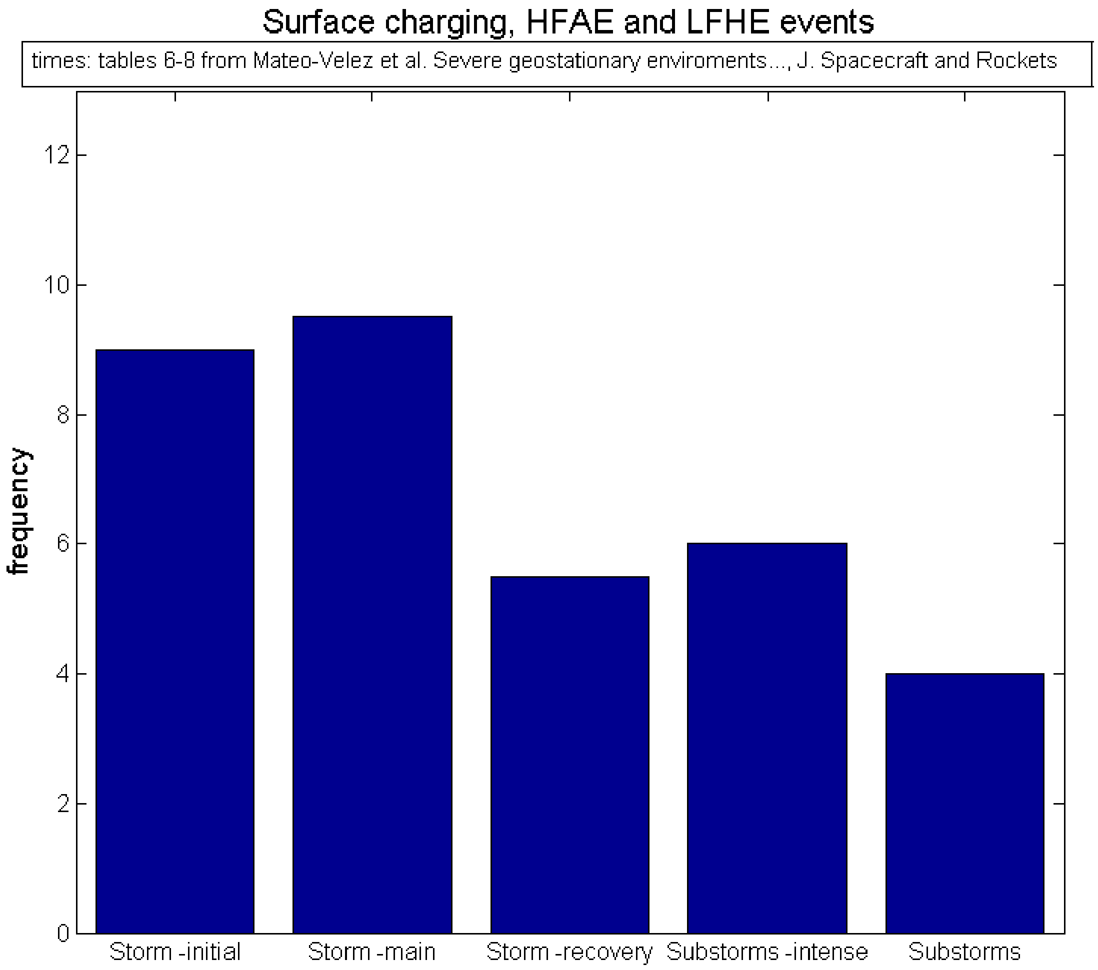
2. It is NOT necessary to have even a moderate storm for significant surface charging event to happen

3. It is a challenge to model low energy electrons with their important variations on 10 min scales. Advance made: A revision of the source model at 10 Re in the plasma sheet was done using the particle data from THEMIS ESA and SST instruments for years 2007-2013. Most advanced representation of loss processes for low energy electrons due to wave-particle interactions with chorus and hiss were incorporated using electron lifetimes following *Orlova and Shprits* [2014] and *Orlova et al*. [2014].

4. Modeling of 2 documented surface charging events detected at LANL: Smaller-scale flux variations are missing but values of modeled fluxes are close to observed ones

5. Still open issue: proper incorporation of substorm effects

Surface charging events vs. geomagnetic conditions



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