From studying electron motion in the electromagnetic fields in the inner magnetosphere to the operational nowcast model for low energy (< 200 keV) electron fluxes 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 (*Whipple*, 1981; *Garrett*, 1981; *Purvis et al*., 1984; *Frezet et al*., 1988; *Koons et al*., 1999; *Hoeber et al*., 1998; *Davis et al*., 2008).

- The distribution of low energy electrons, the seed population (10 to few hundreds of keV), is critically important for radiation belt dynamics (*Horne et al*., 2005; *Chen et al*., 2007)

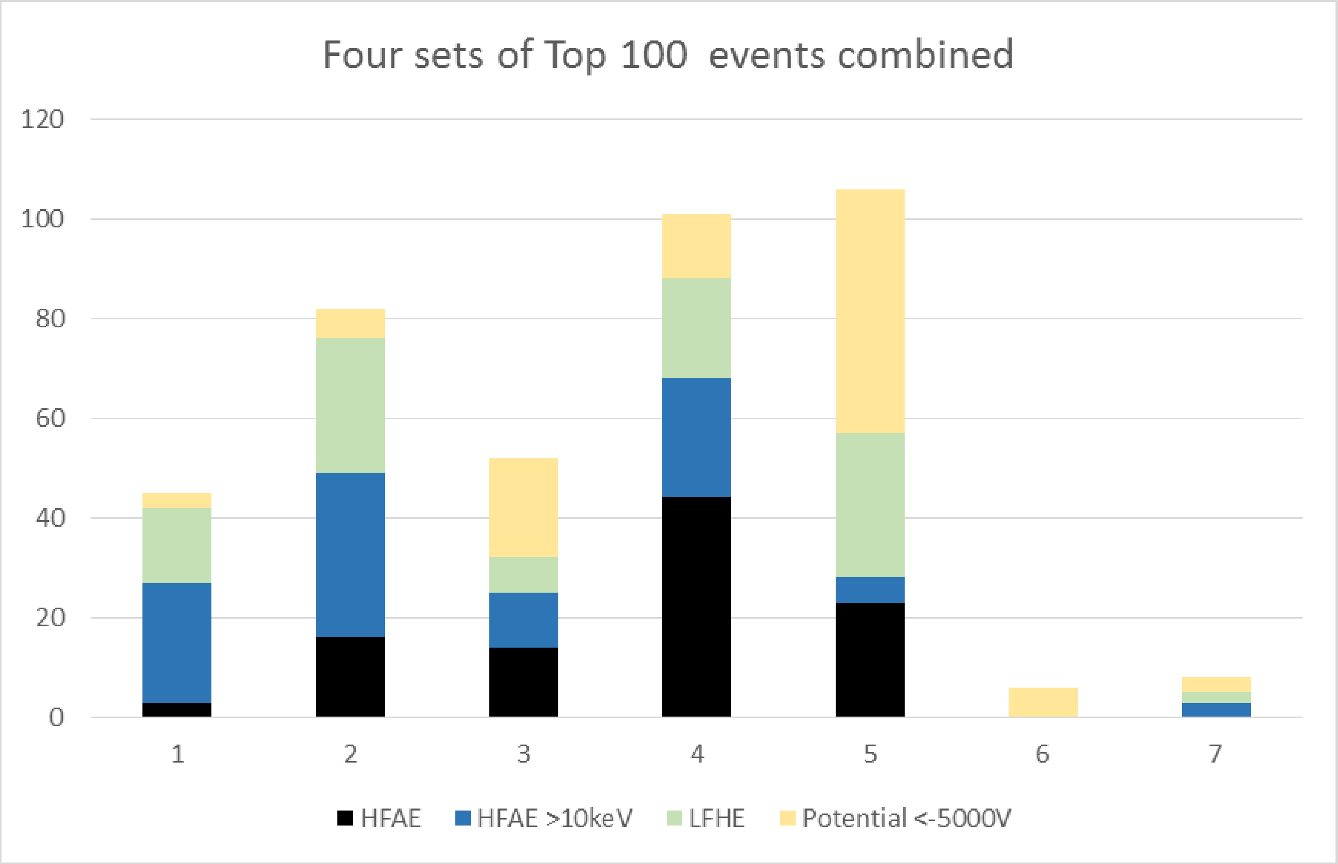
- Chorus emissions (intense whistler mode waves) excited in the low-density region outside the plasmapause are associated with the injection of keV plasma sheet electrons into the inner magnetosphere. (*Kennel and Petschek*, 1966; *Kennel and Thorne*, 1967; *Tsurutani and Smith*, 1974 *; Li et al*., 2008, 2012; *Meredith et al*., 2001).

The electron flux at the keV energies is largely determined by convective (*Korth et al*., 1999; *Friedel et al*., 2001; *Thomsen et al*., 2002; *Elkington et al*., 2004; *Miyoshi et al*., 2006; *Kurita et al*., 2011) and **substorm-associated** (*Vakulin et al*., 1988; *Grafodatskiy et al*., 1987; *Degtyarev et al*., 1990; *Fok et al*., 2001; *Khazanov et al*., 2004; *Kozelova et al*., 2006; *Ganushkina et al*., 2013) 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!

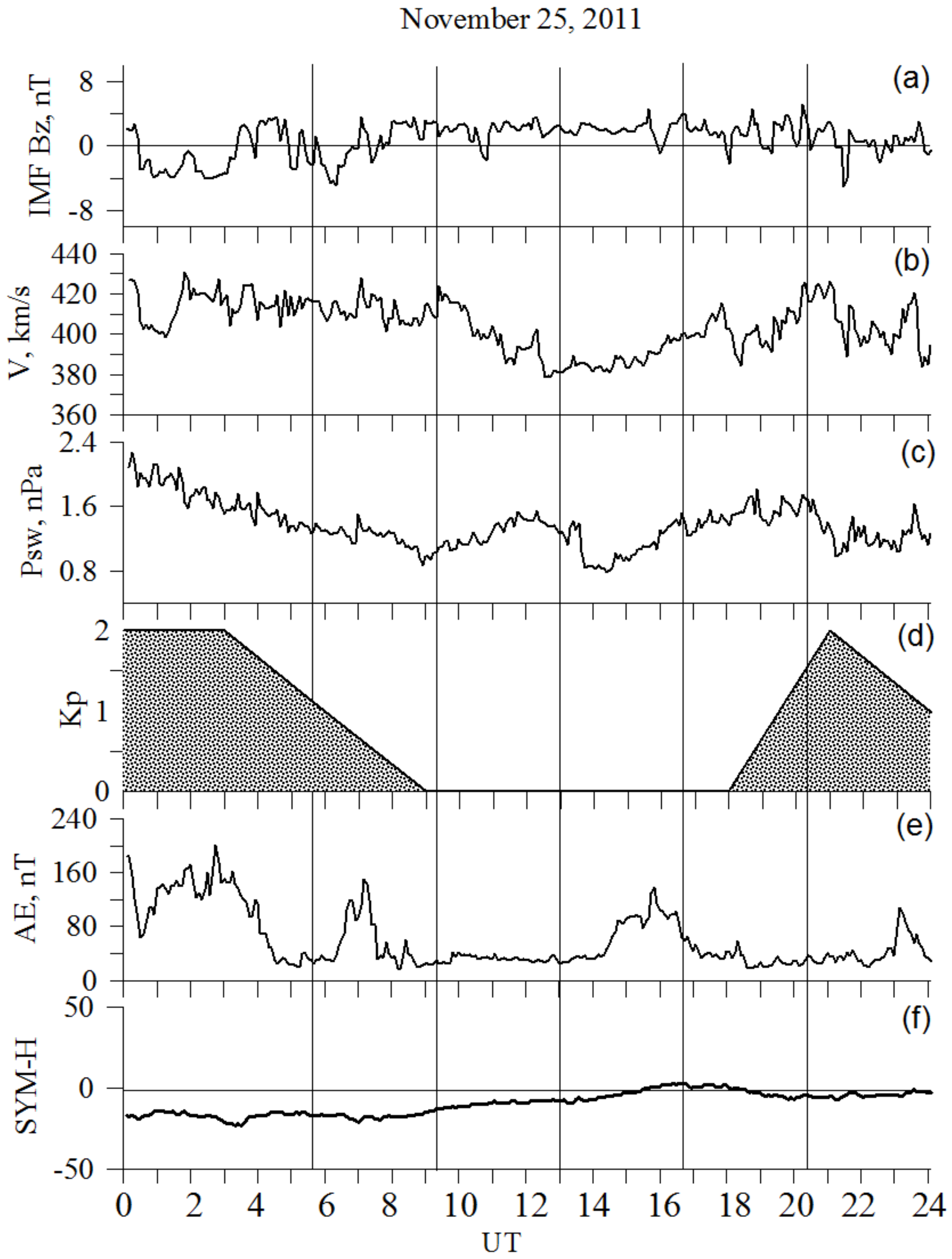
Space weather is more than storms (Louis Lanzerotti)

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

Surface charging events detected at LANL vs. geomagnetic conditions



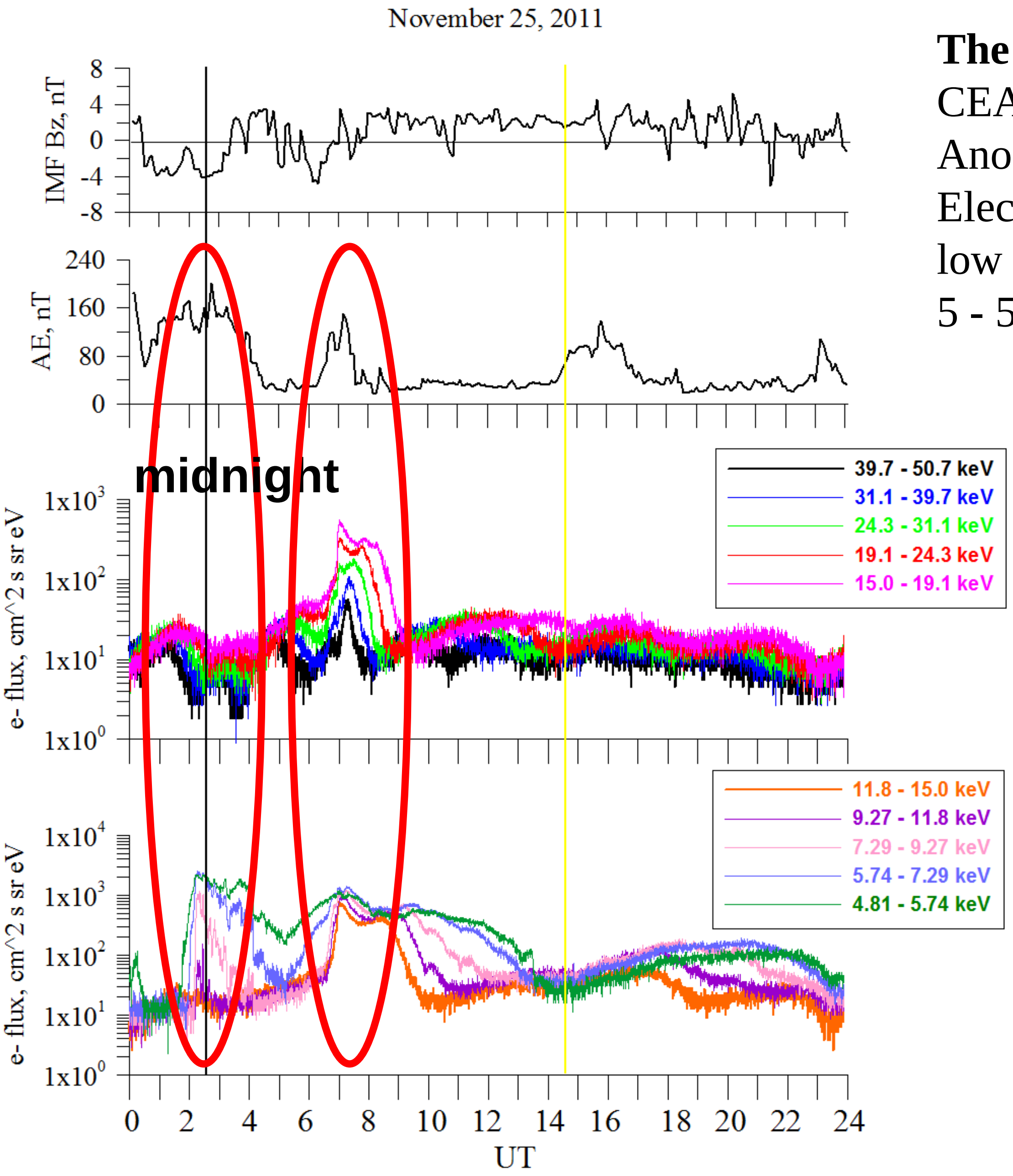
1. storm initial phase; 2. storm main phase; 3.storm recovery phase; 4. intense substorms (AE>=800 nT); 5. isolated substorms; 6.quiet; 7. unclear



No storm is needed for 2-3 orders of magnitude increase of low energy electron fluxes at geostationary orbit

Rather quiet event

5-50 keV electrons during quiet event



The data: AMC 12 geostationary satellite, CEASE-II (Compact Environmental Anomaly Sensor) instrument with Electrostatic Analyzer (ESA) for measuring low energy electron fluxes in 10 channels, 5 - 50 keV.

- **Flux increases** are related to **AE peaks** only (less than 200 nT, small, isolated substorms)

- The lower the energy, the large the flux

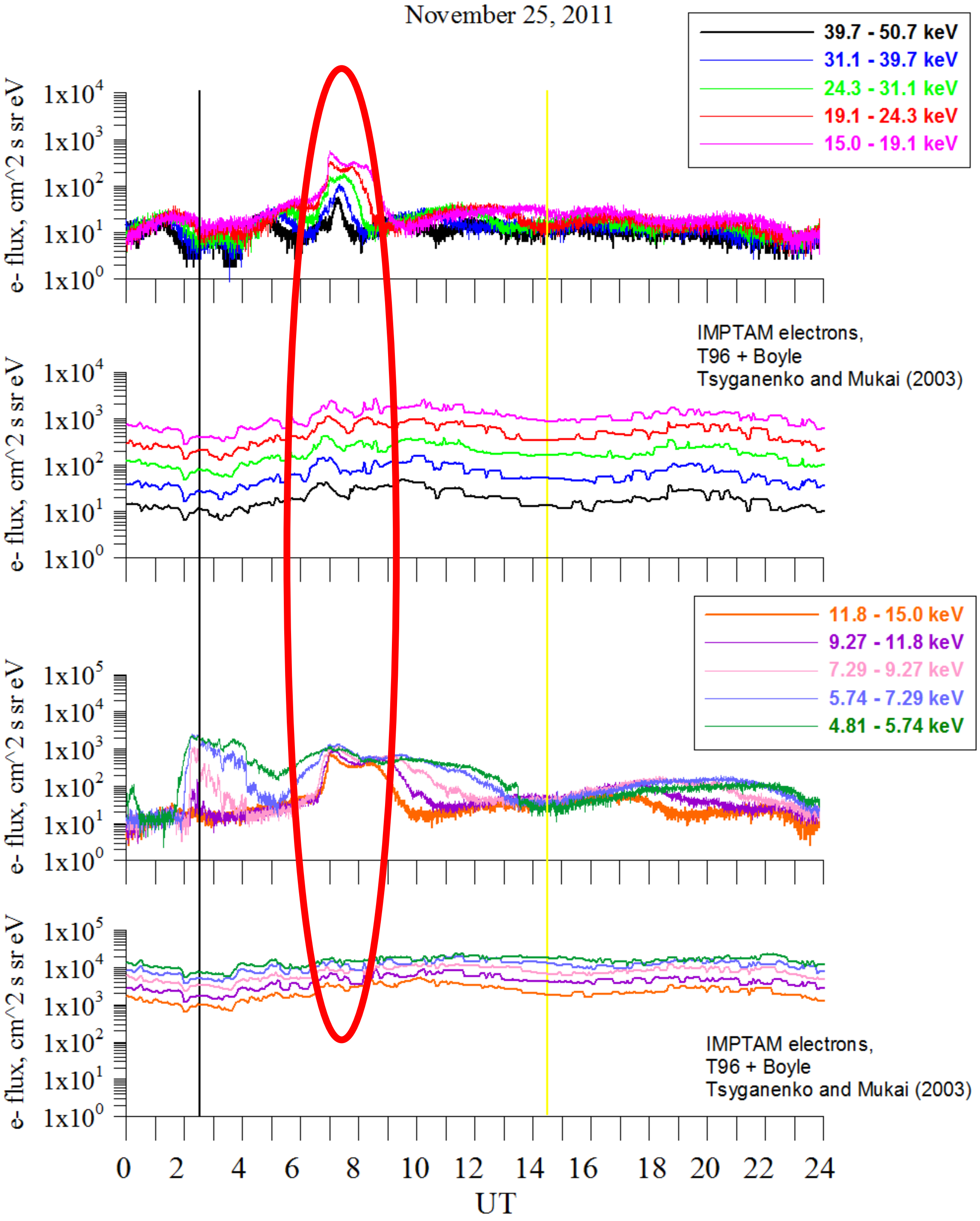
- Electrons of different channels behaves differently:
- 1st peak (AE=200 nT) at midnight seen for energies < 11 keV
- 2nd peak (AE=120 nT) at dawn, increase in all energies

Not a unique case

Inner Magnetosphere Particle Transport and Acceleration Model

The inner magnetosphere particle transport and acceleration model:
- follows distributions of ions and electrons with arbitrary pitch angles
- from the plasma sheet to the inner L-shell regions
- with energies reaching up to hundreds of keVs
- in time-dependent magnetic and electric fields.
- distribution of particles is traced in the guiding center, or drift, approximation

In order to follow the evolution of the particle **distribution function** f and particle **fluxes** in the inner magnetosphere dependent on the **position, time, energy, and pitch angl**e , it is necessary to specify:
(1) particle distribution at initial time at the model boundary;
(2) magnetic and electric fields everywhere dependent on time;
(3) drift velocities;
(3) all sources and losses of particles.
Magnetic field model: T96 (Dst, Psw, IMF By and Bz)
Electric field model: Boyle (Vsw, IMF B, By, Bz)
Boundary conditions: Tsyganenko and Mukai (Vsw, IMF Bz,Nsw)
Losses given as electron lifetimes: Kp, magnetic field



No significant variations in models' parameters –

no changes in modeled electron fluxes

It is not easy to model 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?

- **MAIN FACTOR: SUBSTORMS**.

Substorms play a significant role in keV **electron transport and energy increase.**

How to include them properly?

- Like electromagnetic pulse? [*Li et al*., 1998; *Zaharia et al*., 2000; *Sarris et al*., 2002; *Ganushkina et al*., 2005, 2013; *Gabrielse et al*., 2012, 2014] What are the parameters? Most probably, not the amplitude. Location? MLT-width?
- Do we need different representations for different types of substorms (isolated substorms, storm-time substorms?
- Low energy electrons (at geostationary) are not organized by AE, KP-organization misses dynamics, IMF BZ and Vsw are main parameters.

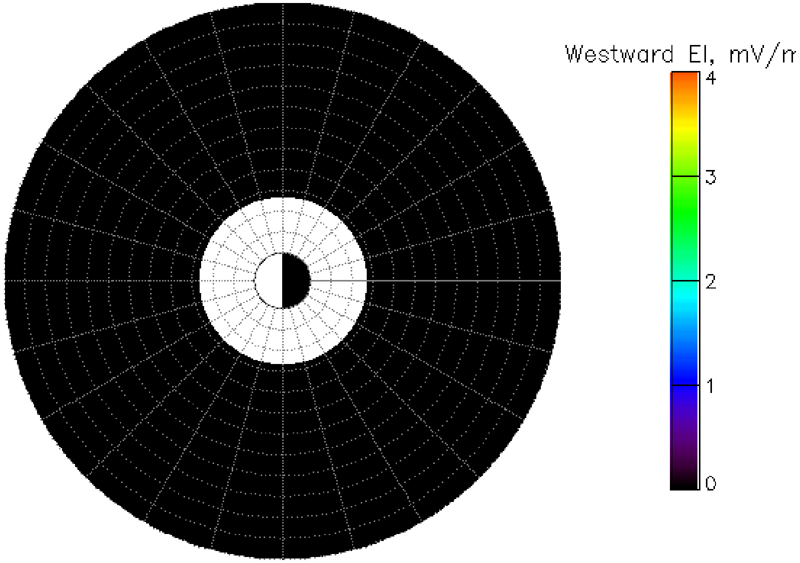
Present IMF and SW dependent models fail to represent the observed peaks associated with substorm activity

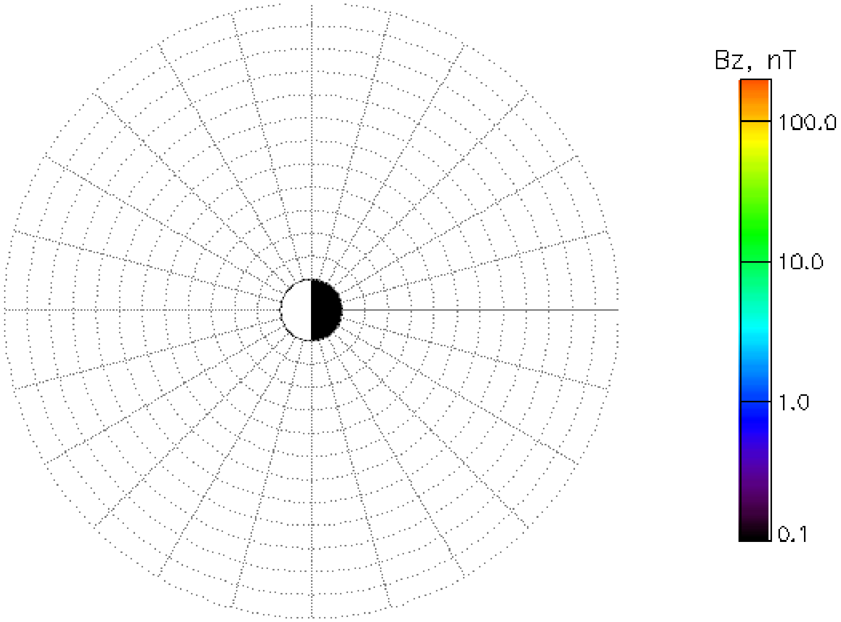
Electric field pulse model

Time varying fields associated with dipolarization in magnetotail, modeled as an electromagnetic pulse (*Li et al., 1998; Sarris et al., 2002*):

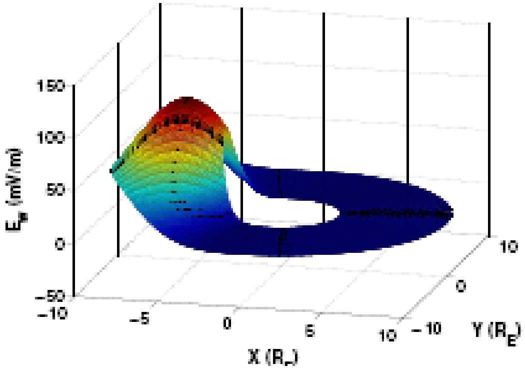
- Perturbed fields propagate from tail toward the Earth;
- Time-dependent Gaussian pulse with azimuthal E;
- E propagates radially inward at a decreasing velocity;
- decreases away from midnight.

Time-dependent B from the pulse is calculated by Faraday's law.

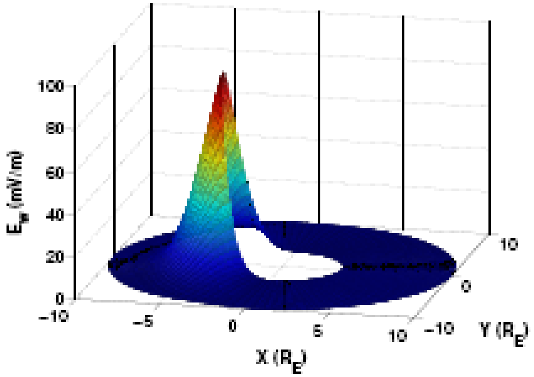




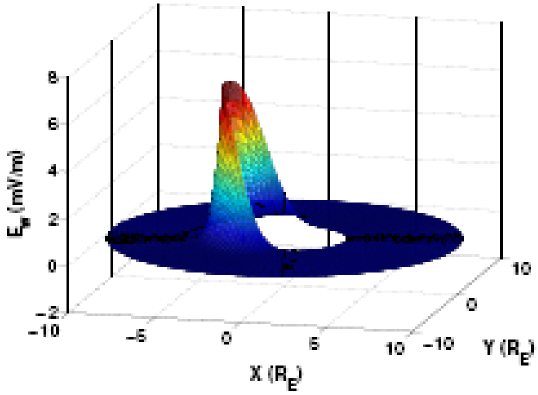
Launching electromagnetic pulses on substorm onsets



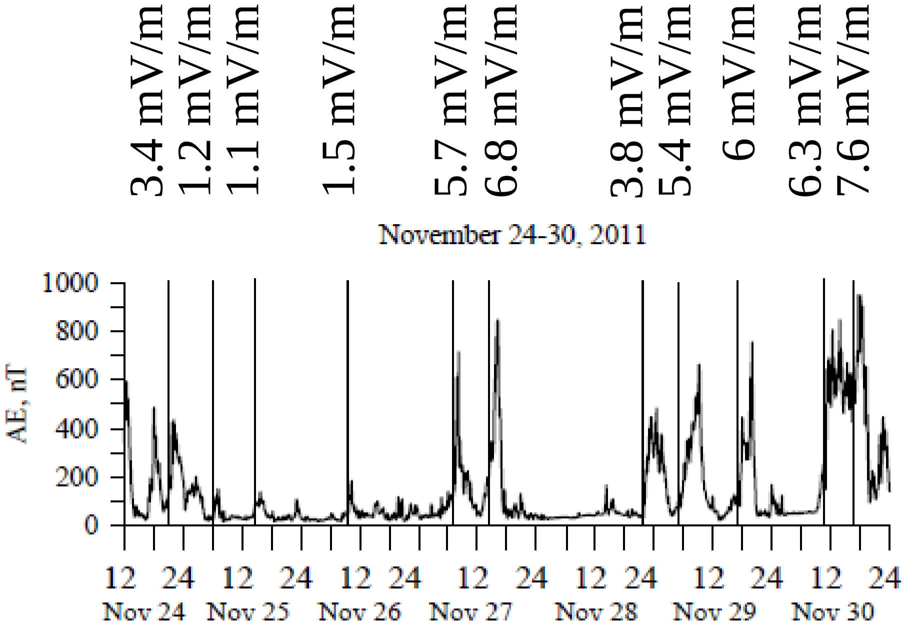
at 10 Re

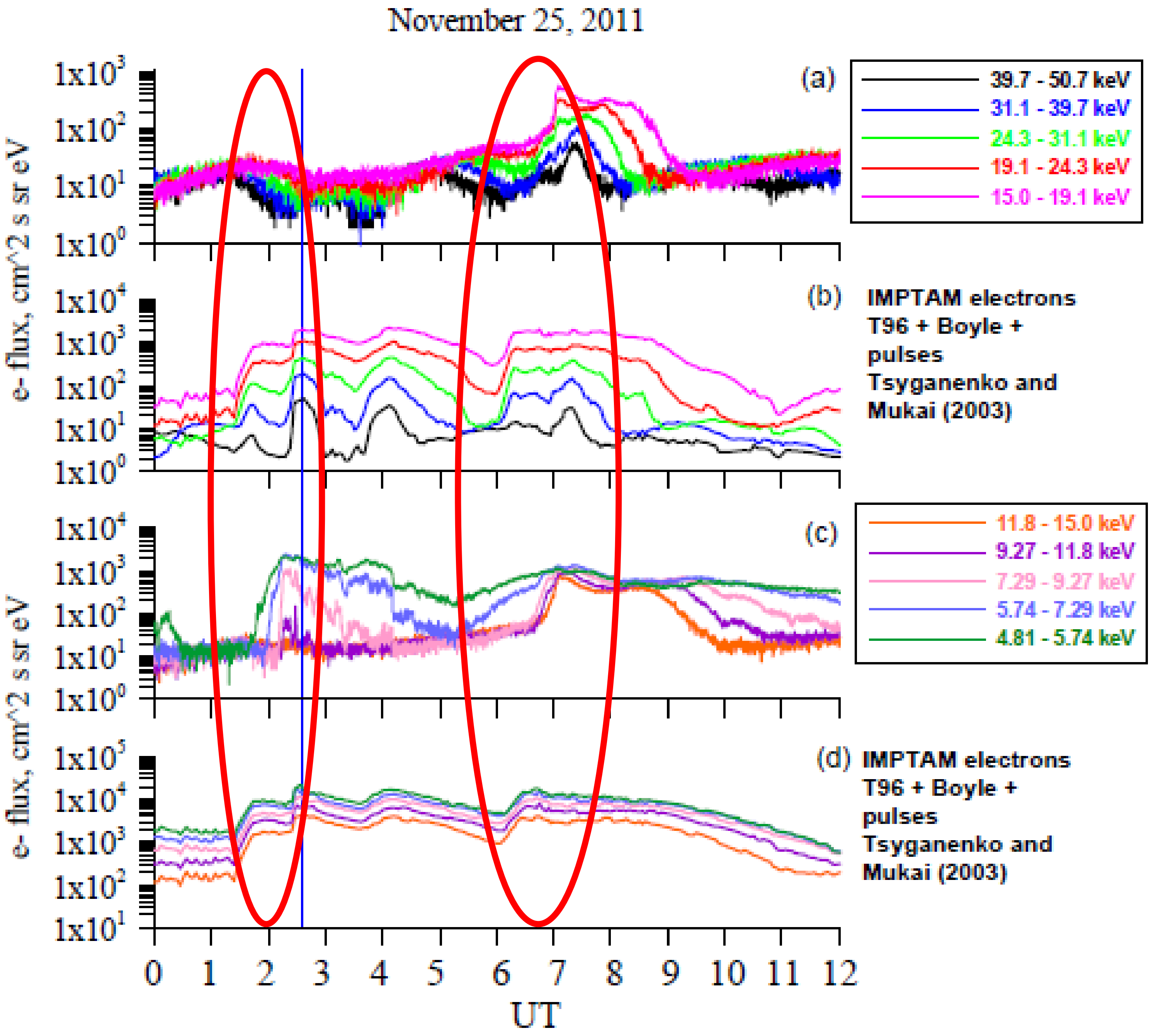


at 7 Re



at 3.5 Re




November 25, 2011
(a)
39.7 - 50.7 keV
31.1 - 39.7 keV
24.3 - 31.1 keV
19.1 - 24.3 keV
15.0 - 19.1 keV
(b)
IMPTAM electrons
T96 + Boyle +
pulses
Tsyganenko and
Mukai (2003)
(c)
11.8 - 15.0 keV
9.27 - 11.8 keV
7.29 - 9.27 keV
5.74 - 7.29 keV
4.81 - 5.74 keV
(d)
IMPTAM electrons
T96 + Boyle +
pulses
Tsyganenko and
Mukai (2003)
e- flux, cm^2 s sr eV
e- flux, cm^2 s sr eV
1x10^0
1x10^1
1x10^2
1x10^3
1x10^4
1x10^5
0 1 2 3 4 5 6 7 8 9 10 11 12
UT

Recent advances in IMPTAM for electrons

In order to follow the evolution of the particle **distribution function** f and particle **fluxes** in the inner magnetosphere dependent on the **position, time, energy, and pitch angl**e , it is necessary to specify:

(1) **particle distribution** at initial time **at the model boundary**;

Model boundary at 10 *Re* with kappa electron distribution function. Parameters are the number density *n* and temperature *T* in the plasma sheet given by **the new empirical model** at L=6-11 dependent on solar wind and IMF parameters **constructed using THEMIS** ESA (eV-30 keV) and SST (25 keV – 10 MeV) data during 2007-2013 (*Dubyagin et al*., 2016).

(2) magnetic and electric fields everywhere dependent on time;

The **magnetic field model is Tsyganenko T96 model** [*Tsyganenko*, 1995] with Dst index, solar wind pressure P_{SW}, and IMF B_Y and B_Z as input parameters. The **electric field** is determined using the solar wind speed V_{SW}, the IMF strength B_{IMF} and its components B_Y and B_Z (via IMF clock angle θ_{IMF}) being the ***Boyle et al*. [1997] ionospheric potential**.

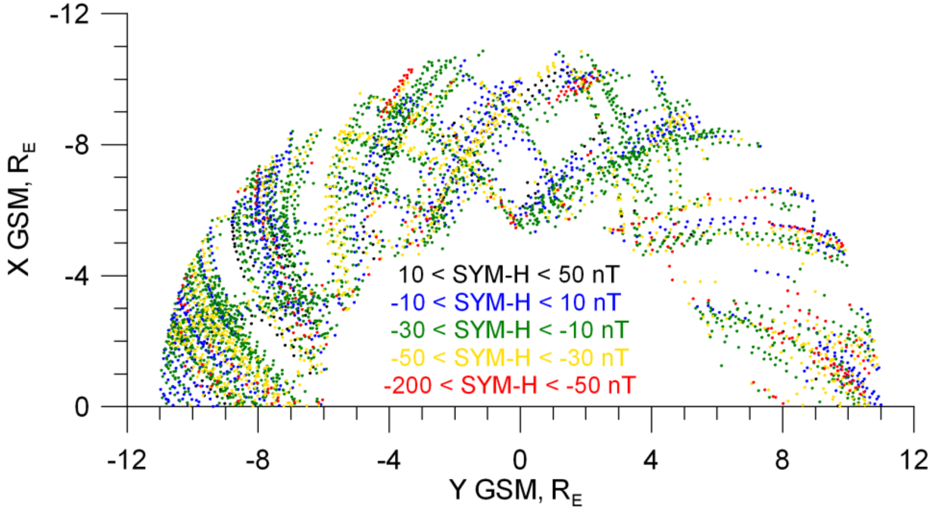
(3) drift velocities;

(4) all sources and **losses of particles**.

Most recent and advanced parameterization of the **electron lifetimes** due to interactions with chorus and hiss waves obtained by *Orlova and Shprits* [2014] and *Orlova et al.* [2014].

New empirical plasma sheet model

Dubyagin et al., JGR, 2016



Electron density model: 7 coefficients

$$N_e = 1.23 - 1.01\cdot r + 0.874\cdot r\phi^2 - 0.82\cdot\phi^2$$

positive → $\boxed{+0.392}\cdot N_{SW}$

positive → $\boxed{+\left(0.521 - 0.474\cdot r\right)}\cdot B_S$

Electron temperature model: 9 coefficients

$$T_e = [-0.0215 - 0.426\cdot\phi$$

positive → $\boxed{+0.874}\cdot V_{SW}$

positive → $\boxed{+\left(0.587 - 0.538\cdot r\phi^2\right)}\cdot B_S^{0.32}$

negative → $\boxed{-0.489\cdot r}\cdot B_N^{0.36}]^{2.31}$

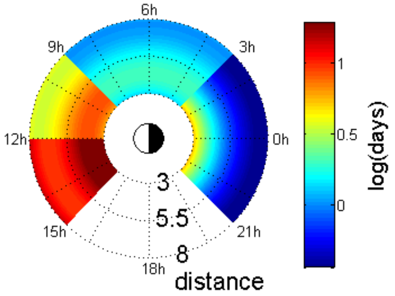
Analysed THEMIS data 6–11 Re
Data: THEMIS A, D, E probes;
ESA electrons: 30eV - 30 keV;
SST electrons ~25 keV - 300 keV

Density model: 2 input parameters
(1) Solar wind proton density
(2) IMF southward component
Temperature model: 3 input parameters
(1) Solar wind velocity
(2) IMF southward component
(3) IMF northward component

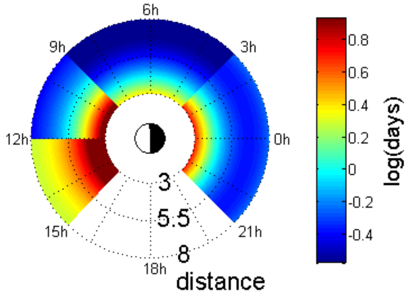
Both models show very good performance
Density: C.C.=0.82; RMS = 0.23 cm-3
Temperature: C.C.=0.75; RMS = 2.6 keV

Losses for low energy electrons due to wave-particle interactions

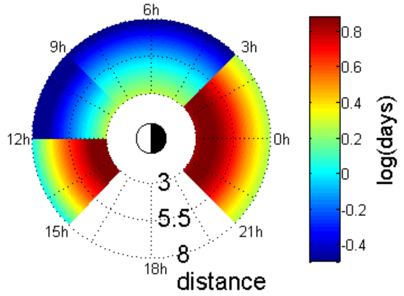
electron lifetime E= 5 keV , Kp=3



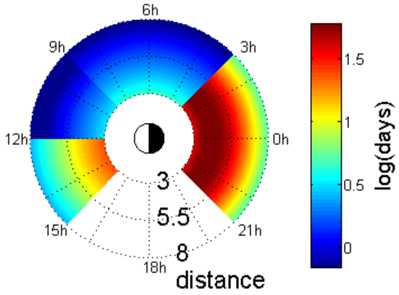
electron lifetime E= 10 keV , Kp=3



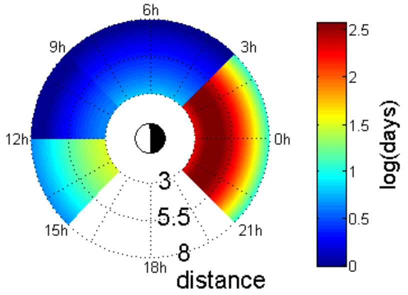
electron lifetime E= 50 keV , Kp=3



electron lifetime E=100 keV , Kp=3

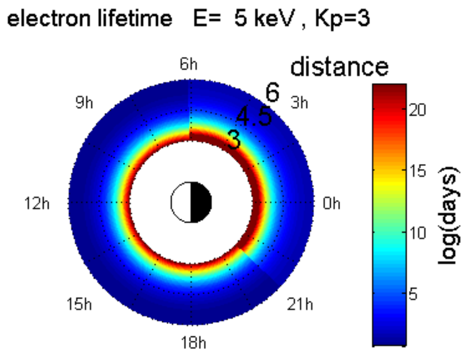


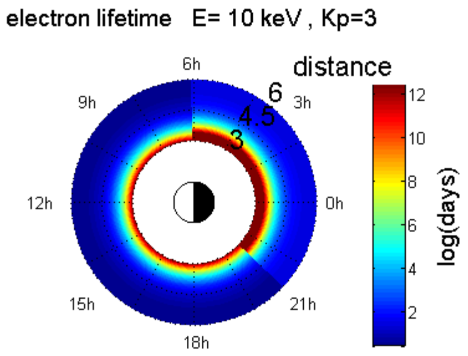
electron lifetime E=150 keV , Kp=3

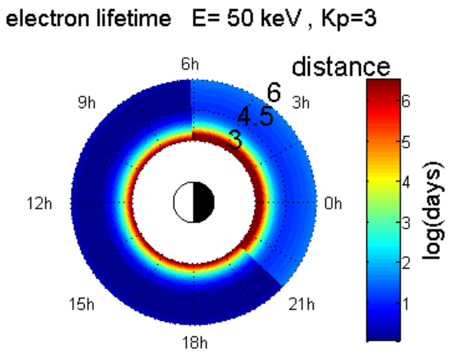


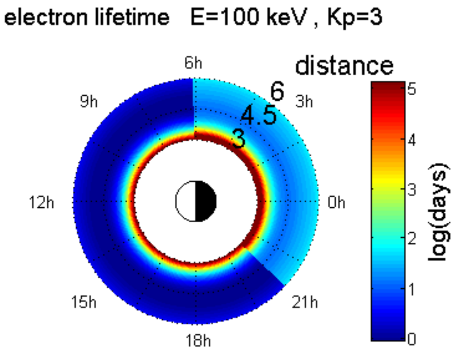
Parameterization of the electron lifetimes due to interactions with chorus waves [*Orlova and Shprits*, 2014]:
polynomial expressions with 33 coefficients dependent on energy, radial distance, MLT sector and Kp.
The model can be used for R=3-8 R_E, Kp= 0-6, and electron energies from 1 keV to 2 MeV. MLT sectors include the night (-3≤MLT≤3), dawn (3≤MLT≤9), prenoon (9≤MLT≤12), and postnoon (12≤MLT≤15) segments**.**

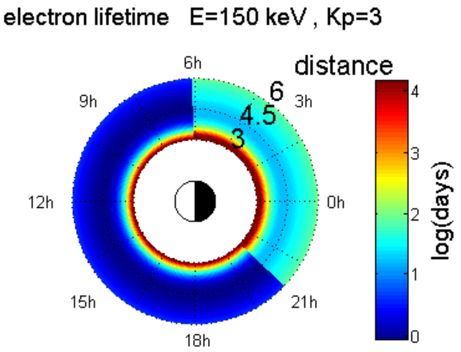
Losses for low energy electrons due to wave-particle interactions


electron lifetime E= 5 keV , Kp=3


electron lifetime E= 10 keV , Kp=3


electron lifetime E= 50 keV , Kp=3

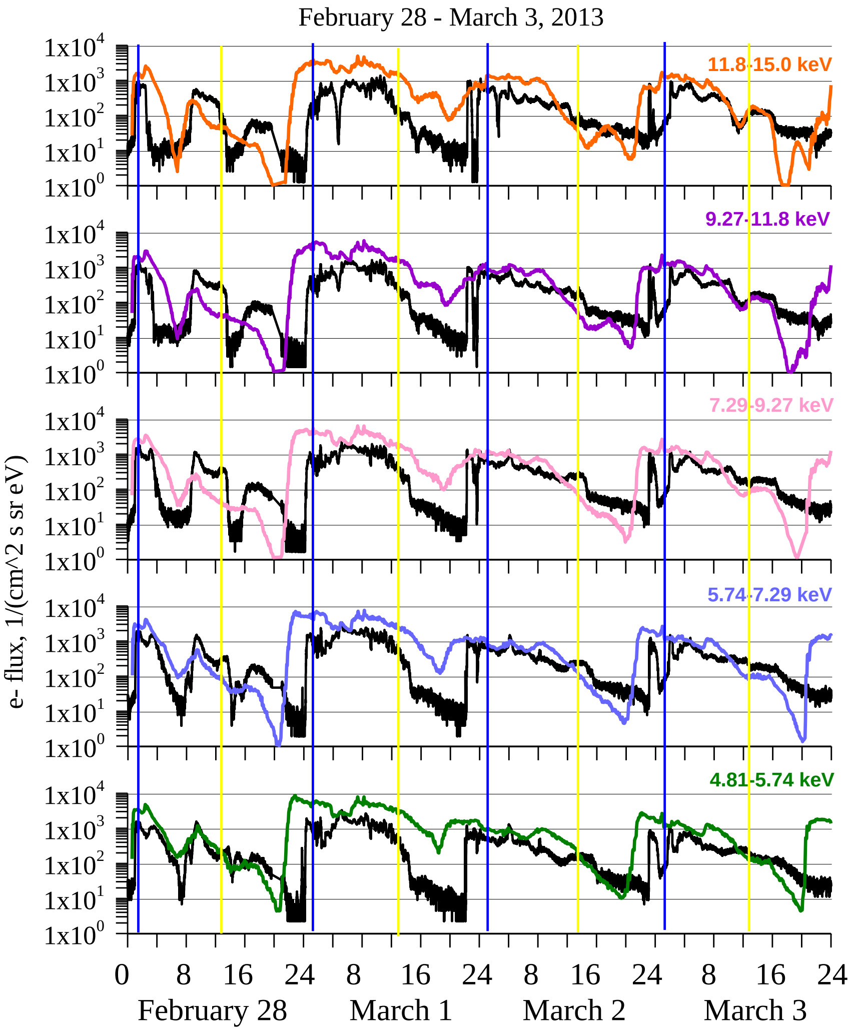

electron lifetime E=100 keV , Kp=3

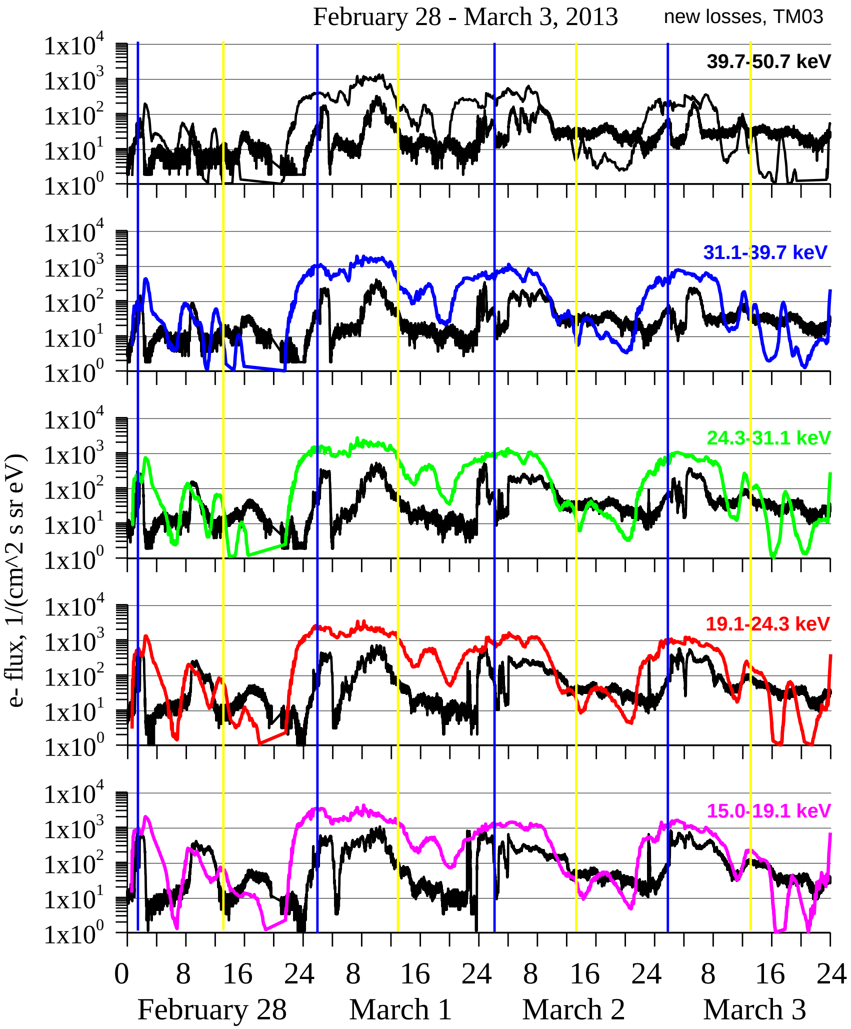

electron lifetime E=150 keV , Kp=3

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.

Electron fluxes observed by AMC 12 CEASE II ESA instrument for 5-50 keV energies and modeled

With **THEMIS** model ***Dubyagin et al.*, [2016]** and ***Orlova and Shprits* [2014] and *Orlova et al.* [2014]** electron lifetimes



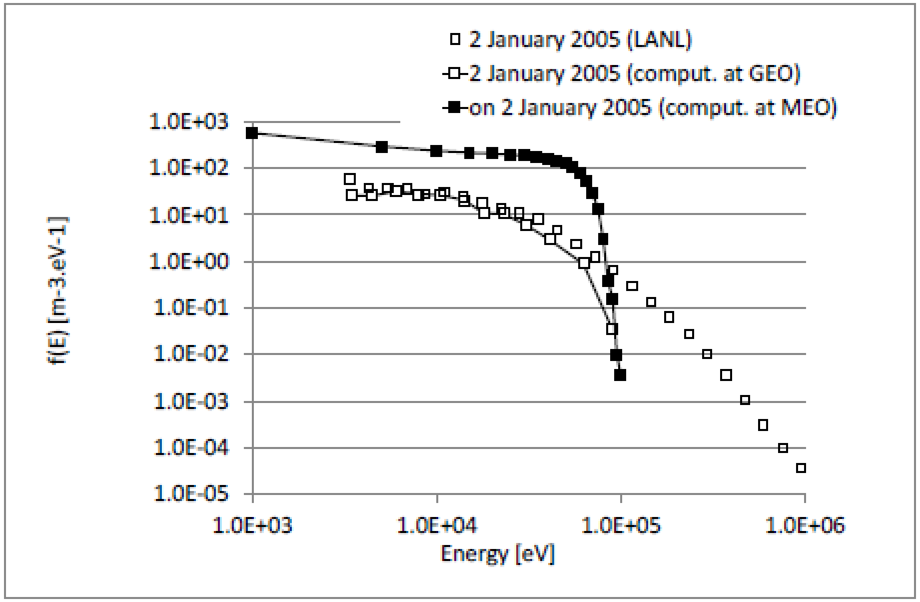


Selected GEO environments #1

LANL_1994_084 2005/01/02 15h46min12s MLT 04 47

3. IMPTAM computations

Surface event detected at LANL



GEO

Very good agreement with LANL< 50keV
Flux > 10 * LANL @ 100 keV

MEO L = 4.6

Flux *5-10 at low energy
Flux > 10-50 times the flux at GEO

IMPTAM e- flux at MEO as input to SPIS, the Spacecraft Plasma Interaction System
Software toolkit for spacecraft-plasma interactions and spacecraft charging modelling.
http://dev.spis.org/projects/spine/home/spis

From presentation at **SCTC 2016, April 4-8, Noordwijk, The Netherlands:** “From GEO/LEO environment data to the numerical estimation of spacecraft surface charging at MEO” by J.C. Mateo-Velez

Near-real time IMPTAM for low energy electrons

What do we present?
IMPTAM (Inner Magnetosphere Particle Transport and Acceleration model): nowcast model for low energy (< 200 keV) electrons in the near-Earth geospace, operating online at

http://fp7-spacecast.eu, imptam.fmi.fi,
http://csem.engin.umich.edu/tools/imptam/

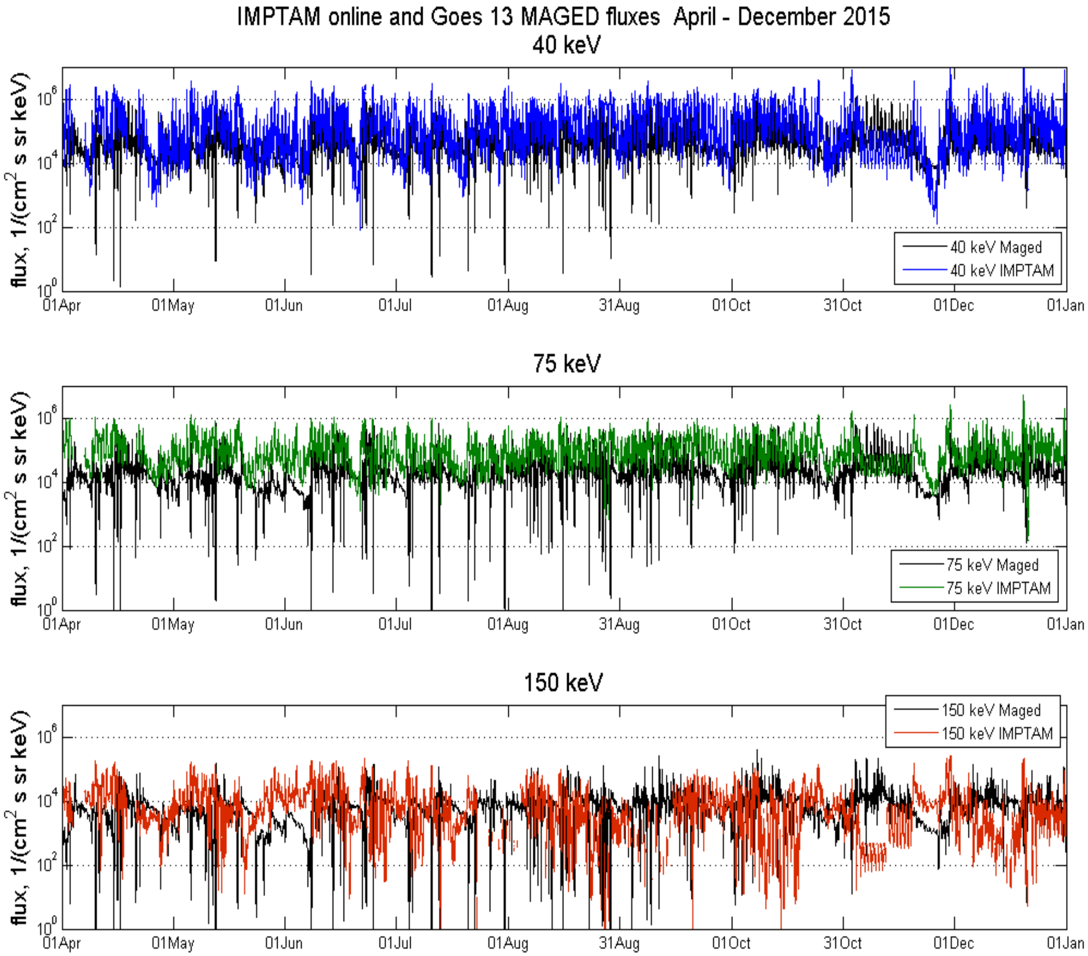
Why this model is important?
Low energy electron fluxes are very important to specify when hazardous satellite **surface charging** phenomena are considered.
They constitute the low energy part of the seed population for the high energy MeV particles in the **radiation belts**

What does the model provide?
The presented model provides the low energy electron flux at all locations and at all satellite orbits, when necessary, in the near-Earth space.

What are the drivers of the model?
The model is driven by the real time solar wind and Interplanetary Magnetic Field parameters with 1 hour time shift for propagation to the Earth's magnetopause, and by the real time geomagnetic activity index Dst.

IMPTAM performance: Long-term variations of low energy electron fluxes: IMPTAM vs GOES 13

IMPTAM long-term output of omni-directional electron fluxes compared statistically to GEOS-13 MAGED fluxes for energies of 40, 75 and 150 keV, the only available data in real time.



IMPTAM online and Goes 13 MAGED fluxes April - December 2015

40 keV

75 keV

150 keV

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. Substorms are important.

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 documented surface charging events detected at LANL with further propagation to MEO: good agreement at GEO, reasonable values at MEO?

5. Still open issue: proper incorporation of substorm effects