Losses for keV electrons as electron lifetimes in IMPTAM

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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!

It is challenging to nowcast and forecast low energy electrons

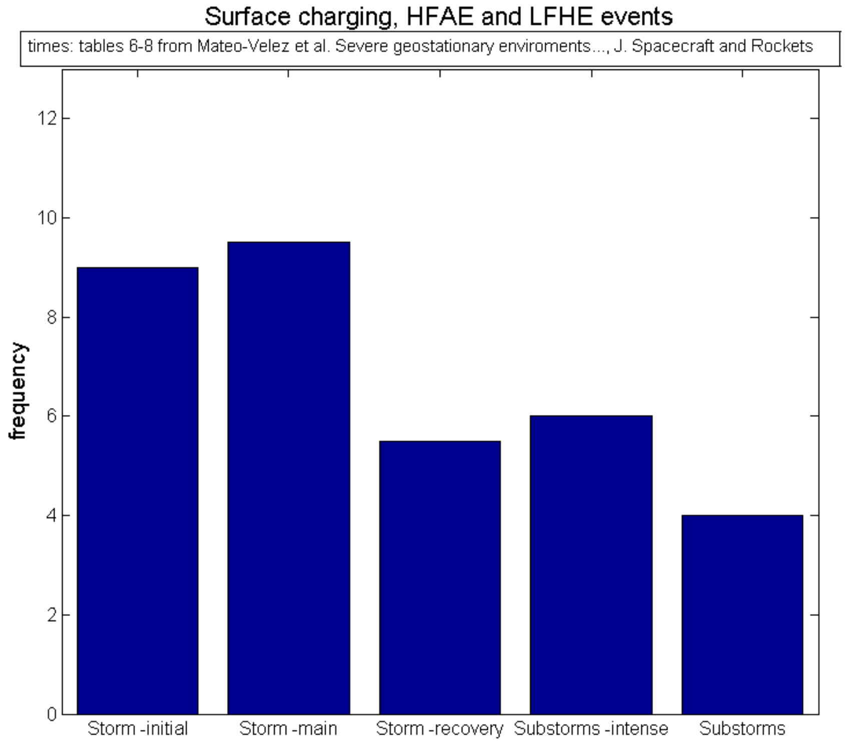
It is **NOT necessary tohave even a modera** **storm for significant surface charging** eve to happen

The keV electron flux is largely determined by convective and substorm-associated electric fields and varies significantly with geomagnetic activity – variations on time scales of minutes!

No averaging over an hour/day/orbit!

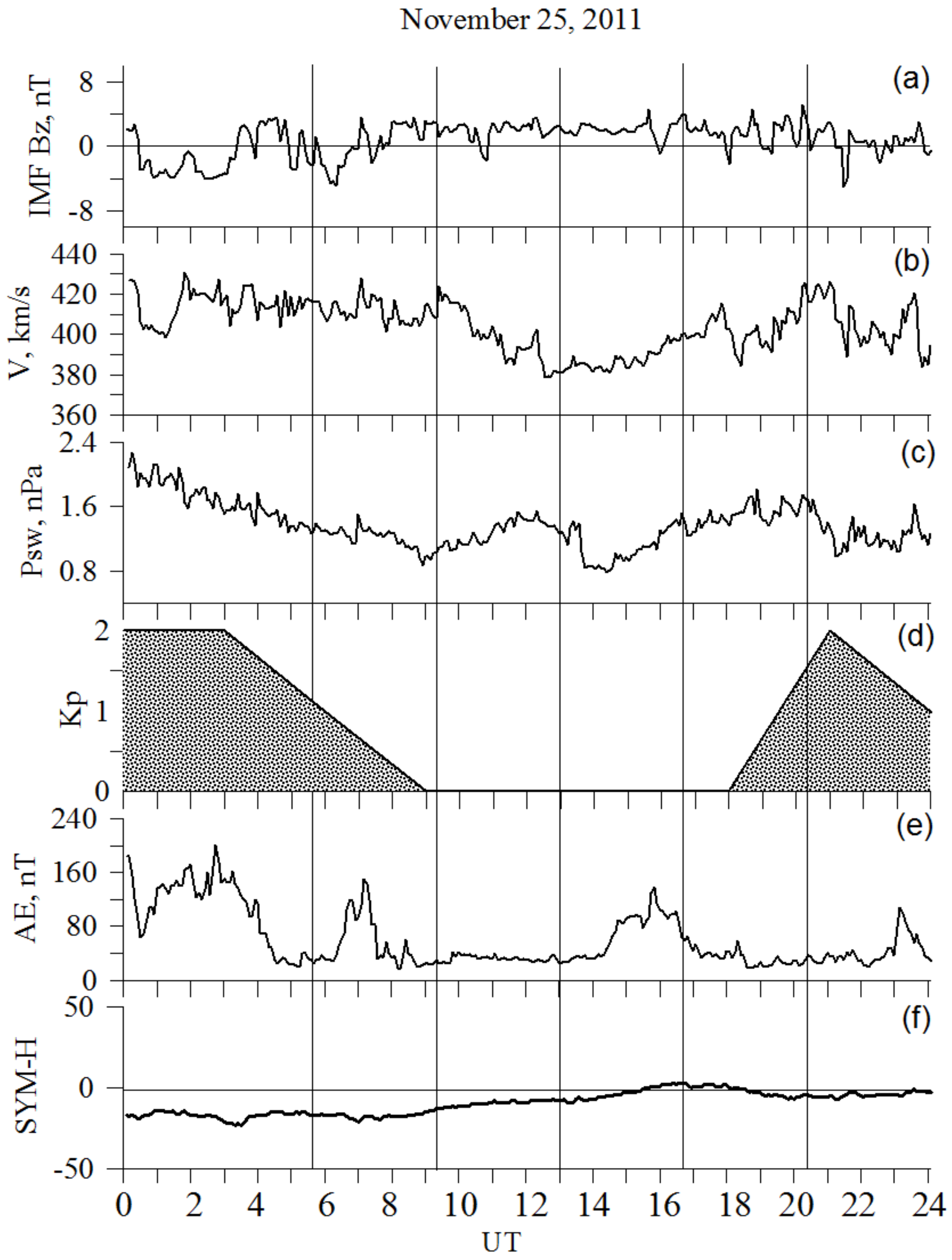
Correct models for electromagnetic fields, boundary conditions, losses are extremely hard to develop

Surface charging events vs. geomagnetic conditions



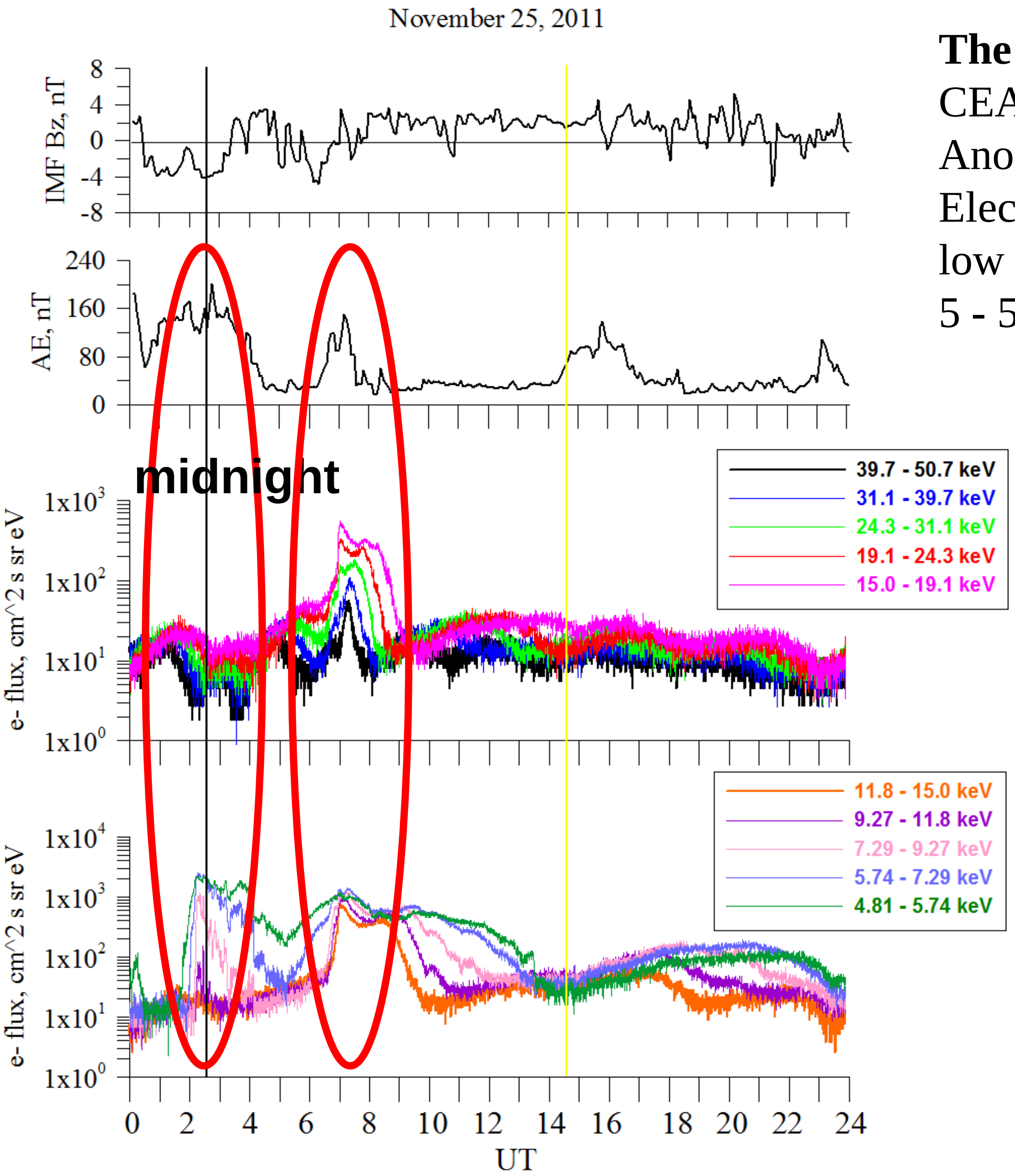
Matéo Vélez et al., Severe geostationary environments: from flight data to numerical estimation of spacecraft surface charging, *Journal of Spacecraft and Rockets, submitted, 2015*

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.

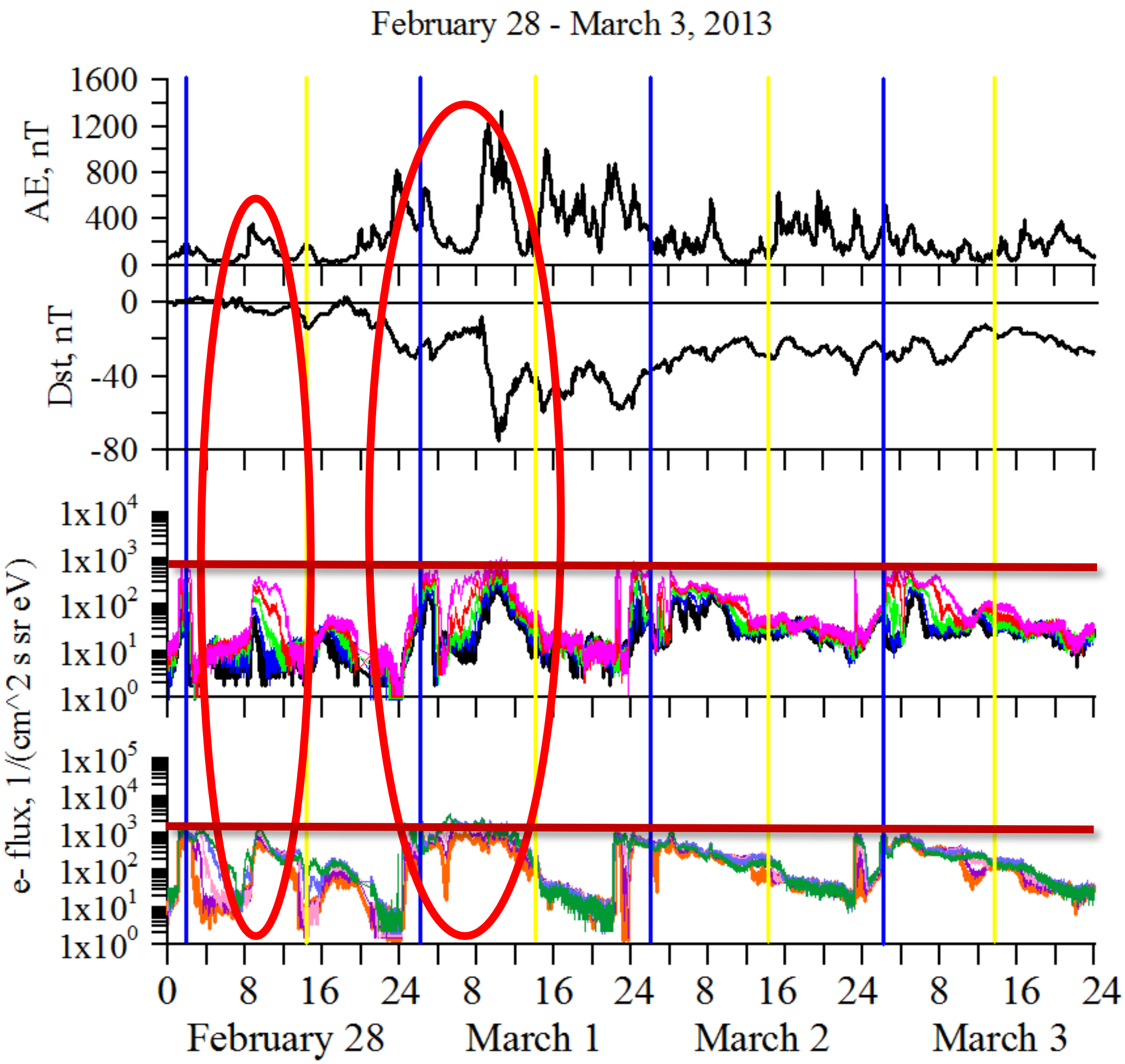
- **Flux increases** are related to **AE peaks** only (less than 200 nT, small, isolated substorms)

- 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

Similar increase in electron fluxes during AE = 400 nT and AE=1200 nT



Small, CIR-driven storm with
Dst of 75 nT,
IMF Bz of -5 -10 nT,
Vsw from 350 to 650 km/s,
Psw peak at 8 nPa,
AE peaks of 800-1200 nT

AMC12 electron data

- peaks in both 15-50 keV and 5-15 keV electron fluxes show correlation with AE

- 2 orders of magnitude increase

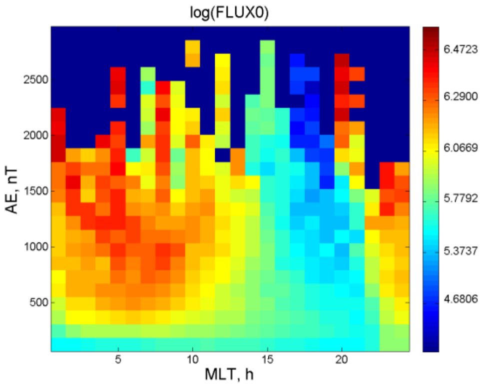
- all energies increase at midnight, when AE is only 200 nT

- same order of increase for AE = 800 nT and even for 1200 nT

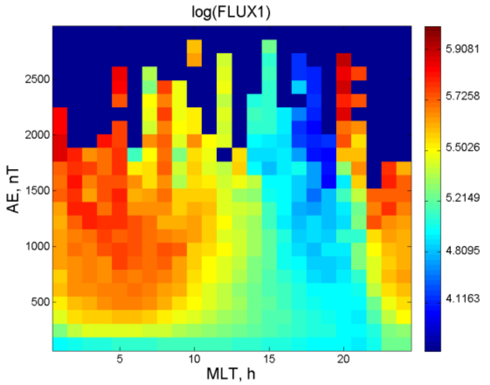
Log(flux)

Flux(MLT, AE)

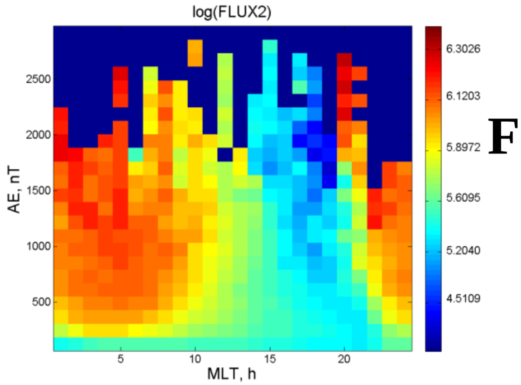
39.7-50.7 keV



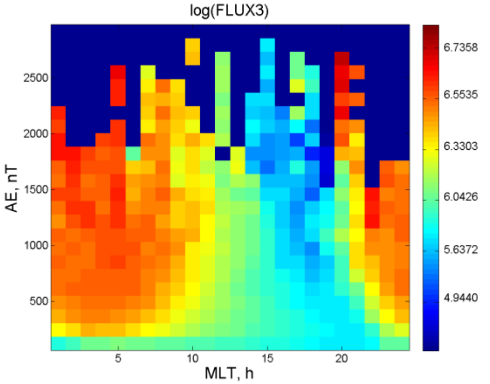
31.1-39.7 keV



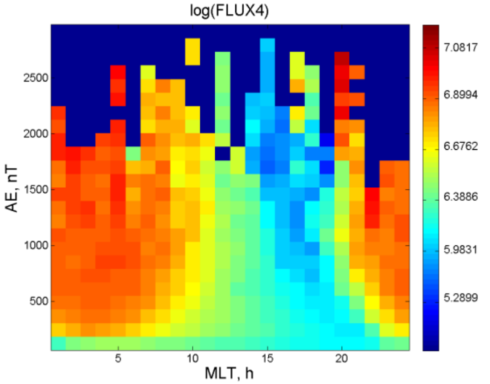
24.3-31.1 keV



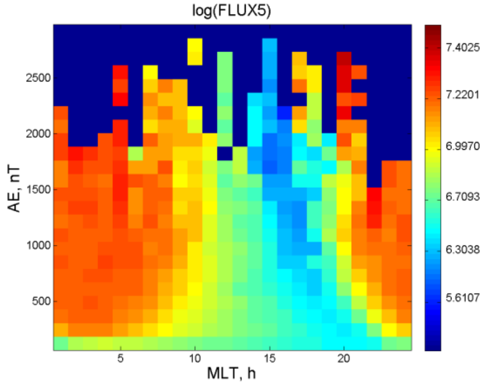
19.1-24.3 keV



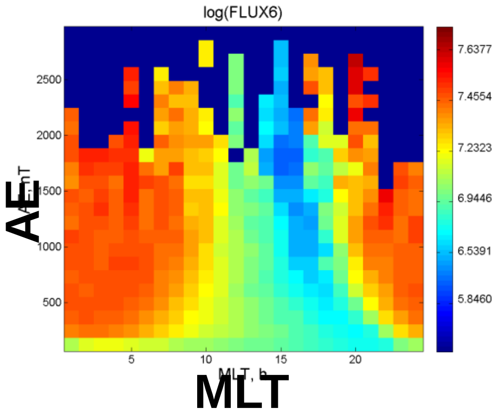
15.0-19.1 keV



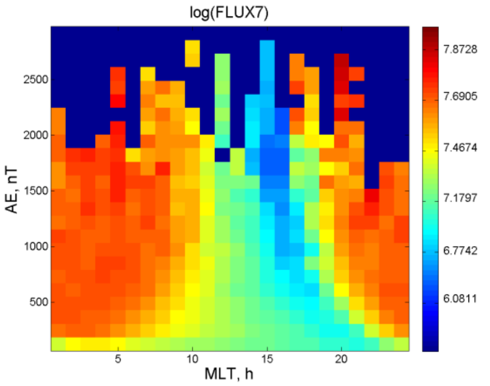
11.8-15.0 keV



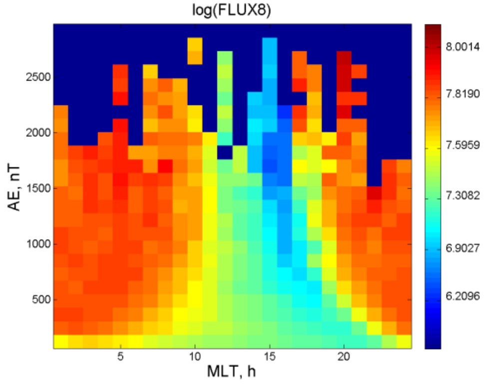
9.27-11.8 keV



7.29-9.27 keV



5.74-7.29 keV

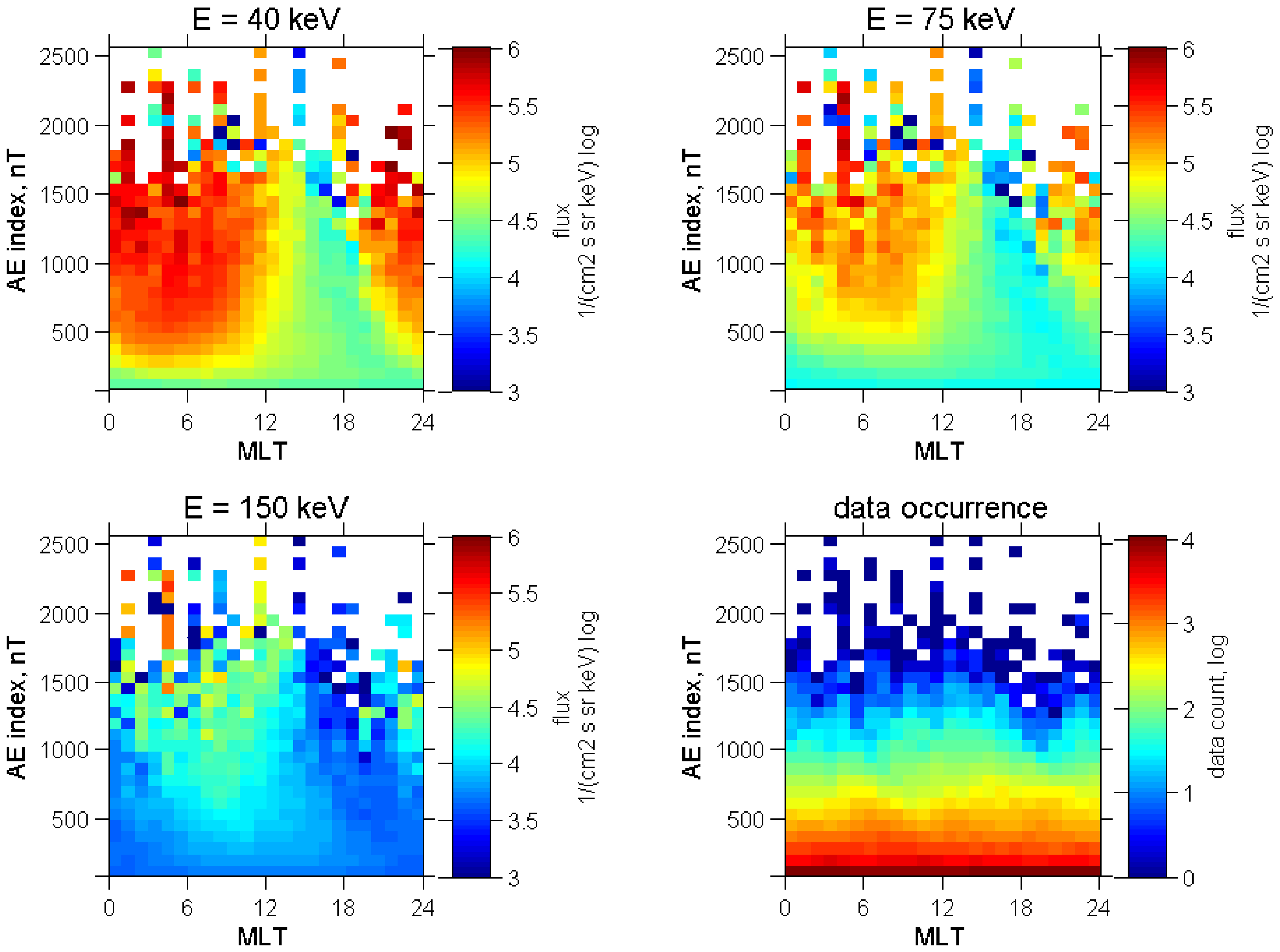


AMC 12 CEASE-II ESA data, 2010-2014

The higher the energy, the less distributed the flux peak

No distinct dependence on AE strength

GOES 13 MAGED electron fluxes (MLT, AE) 2011-2015



No distinct dependence of electron fluxes on AE strength

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, imptam.fmi.fi, http://csem.engin.umich.edu/tools/imptam/

Inner Magnetosphere Particle Transport and Acceleration Model: Diffusion

Next **Radial diffusion** is applied (*Schulz and Lanzerotti*, 1974)

$$\frac{df}{dt} = L^2 \frac{\partial}{\partial L}\left(\frac{1}{L^2} D_{LL} \frac{\partial f}{\partial L}\right) - \frac{f}{\tau}$$

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

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

And **Pitch- angle diffusion** by introducing electron lifetimes

- by *Chen et al*. (2005) for strong diffusion
- and *Shprits et al*. (2007) for weak diffusion

Inner Magnetosphere Particle Transport and Acceleration Model: Electrons' Lifetimes

Strong diffusion: $$\tau_{sd} = \left(\frac{\gamma m_0}{p}\right)\left[\frac{2\Psi B_h}{1-\eta}\right]$$

p is the particle momentum, γ is the ratio of relativistic mass to rest mass, Bh is the magnetic field at either foot point of field line, Ψ is the magnetic flux tube volume, η =0.25 backscatter coefficient (25% of electrons that will mirror at or below 0.02 Re are scattered back to flux tube instead of precipitating into atmosphere)

Weak diffusion: $$\tau_{wd} = 4.8\cdot 10^4 B_w^{-2} L^{-1} E^2, \quad B_w^2 = 2\cdot 10^{2.5+0.18Kp}$$

Bw is the local wave amplitude, E is kinetic energy in MeV

AMC 12 CEASE II ESA data

AMC 12 geostationary satellite, CEASE-II instrument contains an Electrostatic Analyzer (ESA) for measuring low energy electron fluxes in 10 channels, 5 - 50 keV.

Small, CIR-driven storm with **Dst of 75 nT**
IMF Bz of -5 -10 nT,
Vsw from 350 to 650 km/s,
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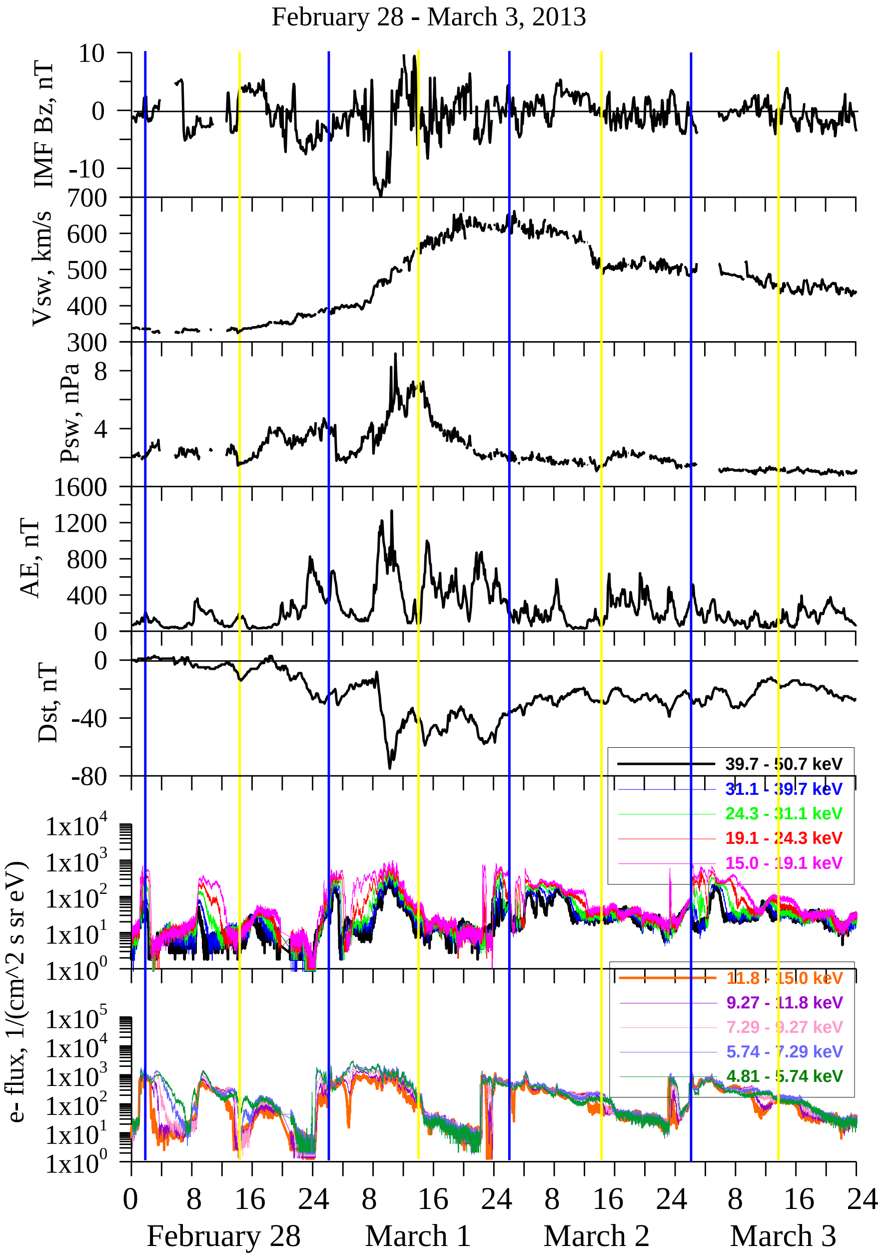
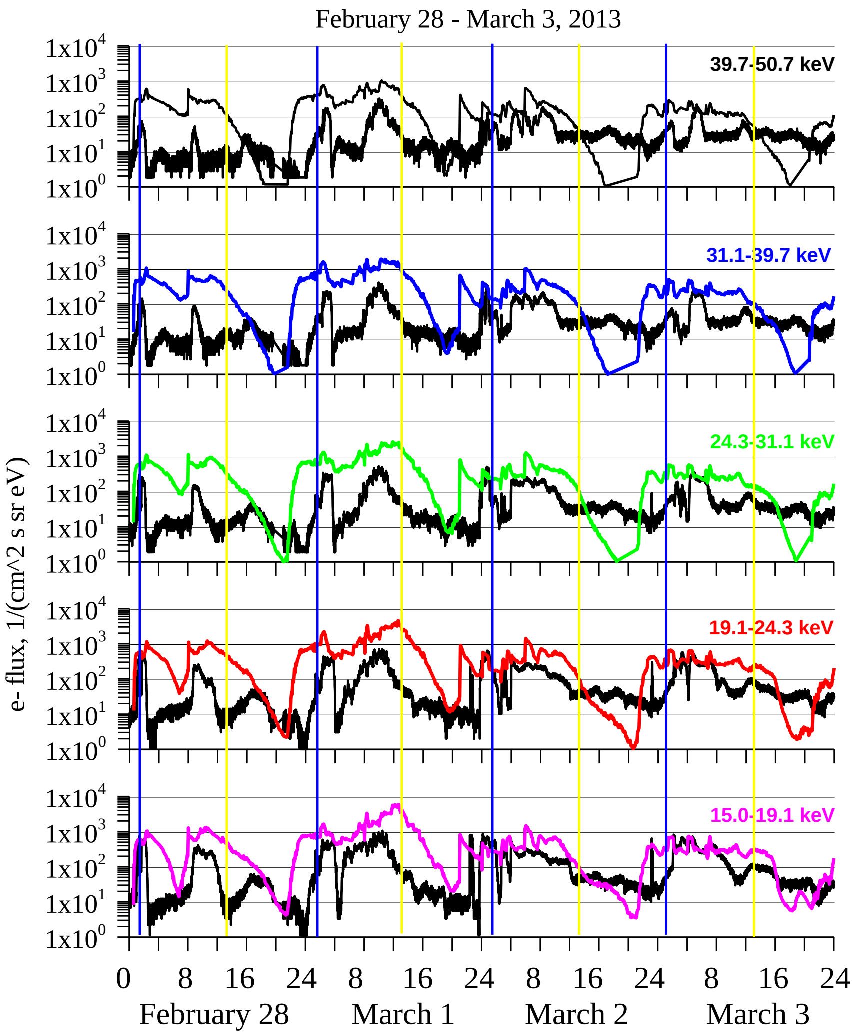
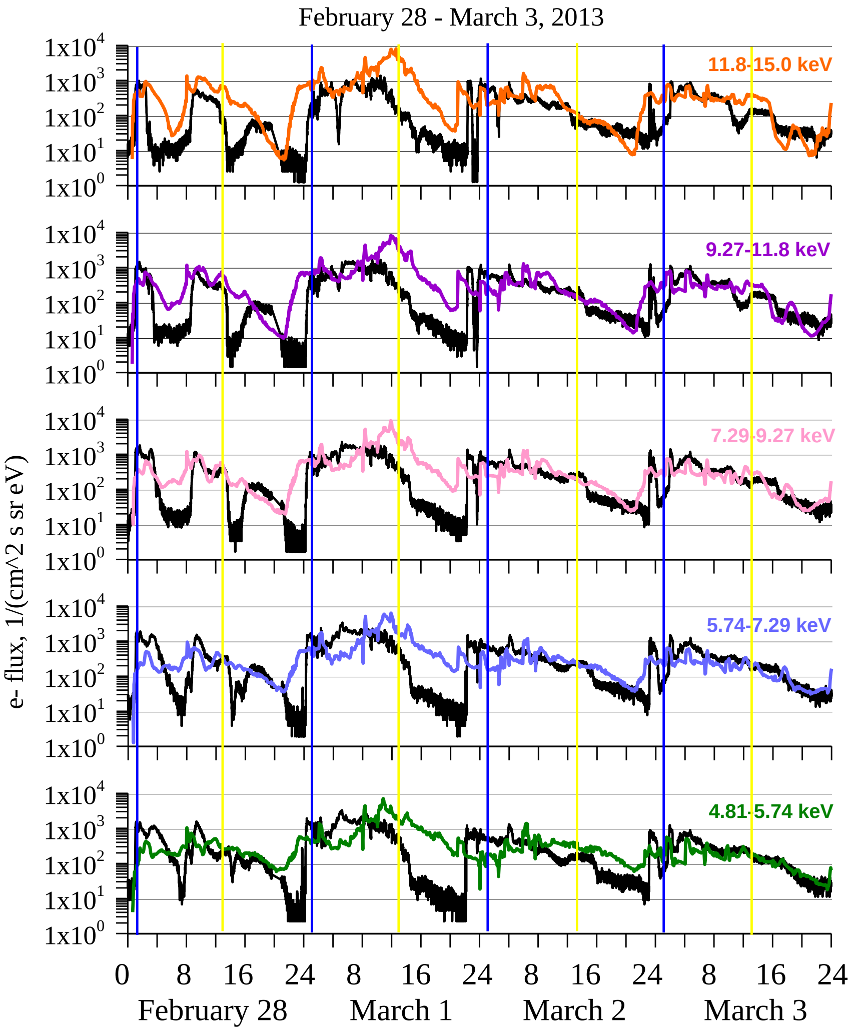


Electron fluxes observed by AMC 12 CEASE II ESA instrument for 15-50 keV energies and modeled

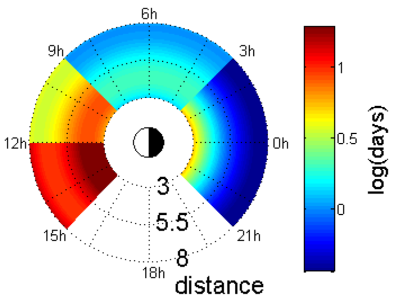
with ***Chen et al.* [2005]** electron lifetimes for strong and ***Shprits et al.* [2007]** for weak diffusion



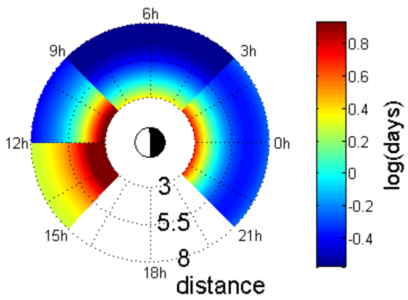


Losses for low energy electrons due to wave-particle interactions

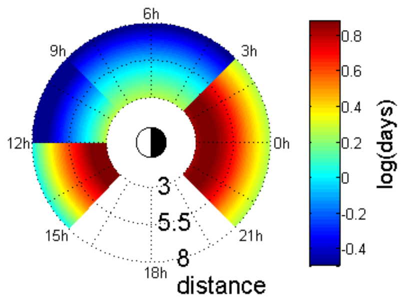
electron lifetime E= 5 keV , Kp=3



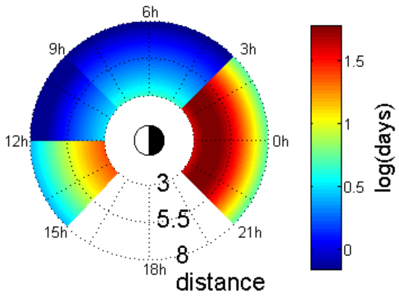
electron lifetime E= 10 keV , Kp=3



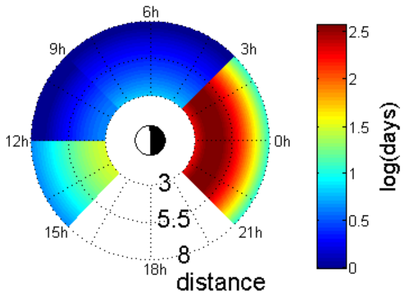
electron lifetime E= 50 keV , Kp=3



electron lifetime E=100 keV , Kp=3

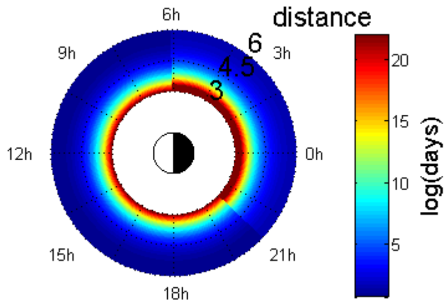


electron lifetime E=150 keV , Kp=3

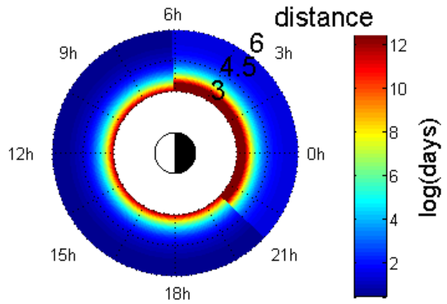


Parameterization of the electron lifetimes due to interactions with chorus waves [*Orlova and Shprits*, 2014]:
polynomial expressions with 33 coefficients dependent on energy, radial distance, MLT sector and Kp.
The model can be used for R=3-8 R_E, Kp= 0-6, and electron energies from 1 keV to 2 MeV.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

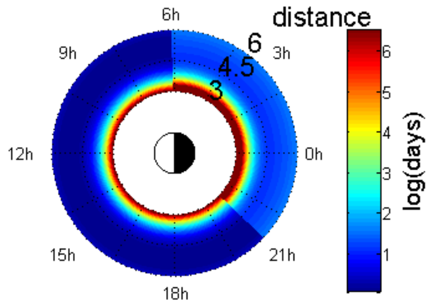
Losses for low energy electrons due to wave-particle interactions



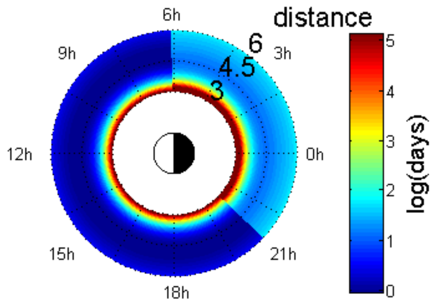
electron lifetime E= 5 keV , Kp=3



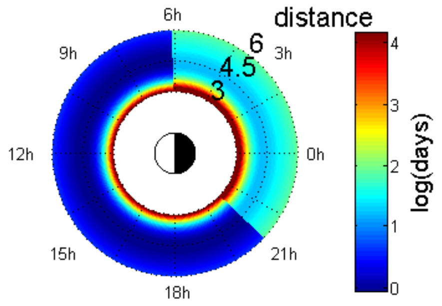
electron lifetime E= 10 keV , Kp=3



electron lifetime E= 50 keV , Kp=3



electron lifetime E=100 keV , Kp=3

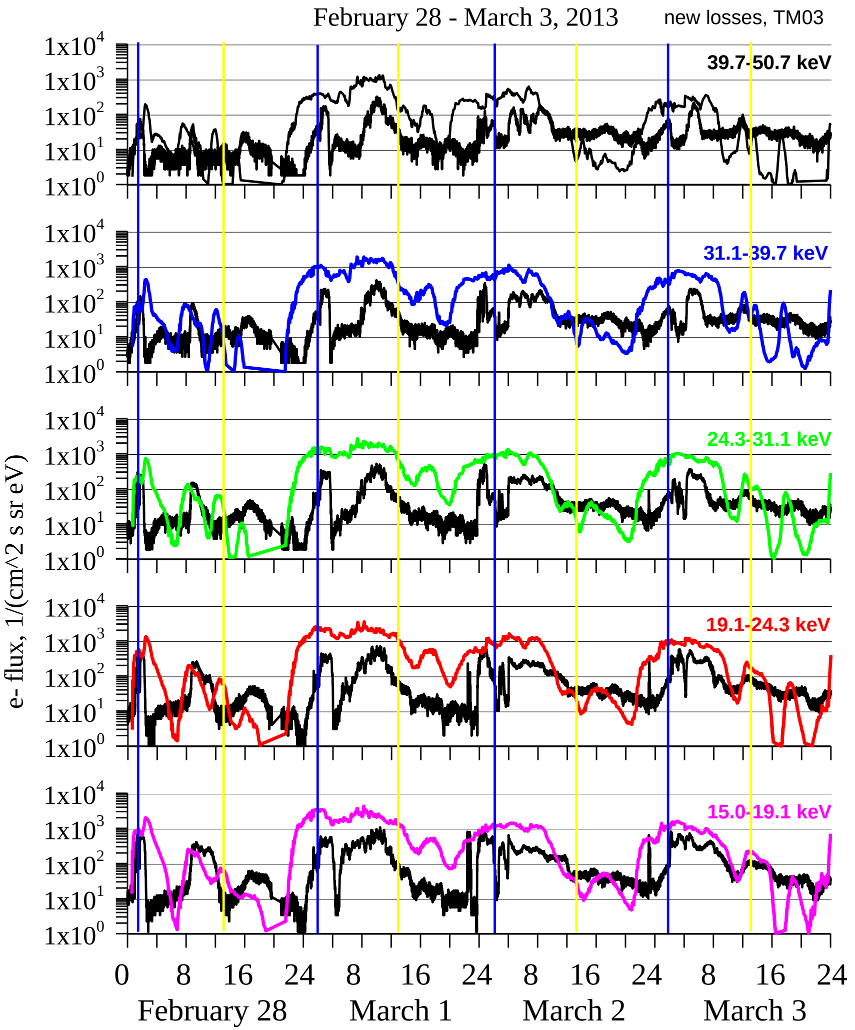


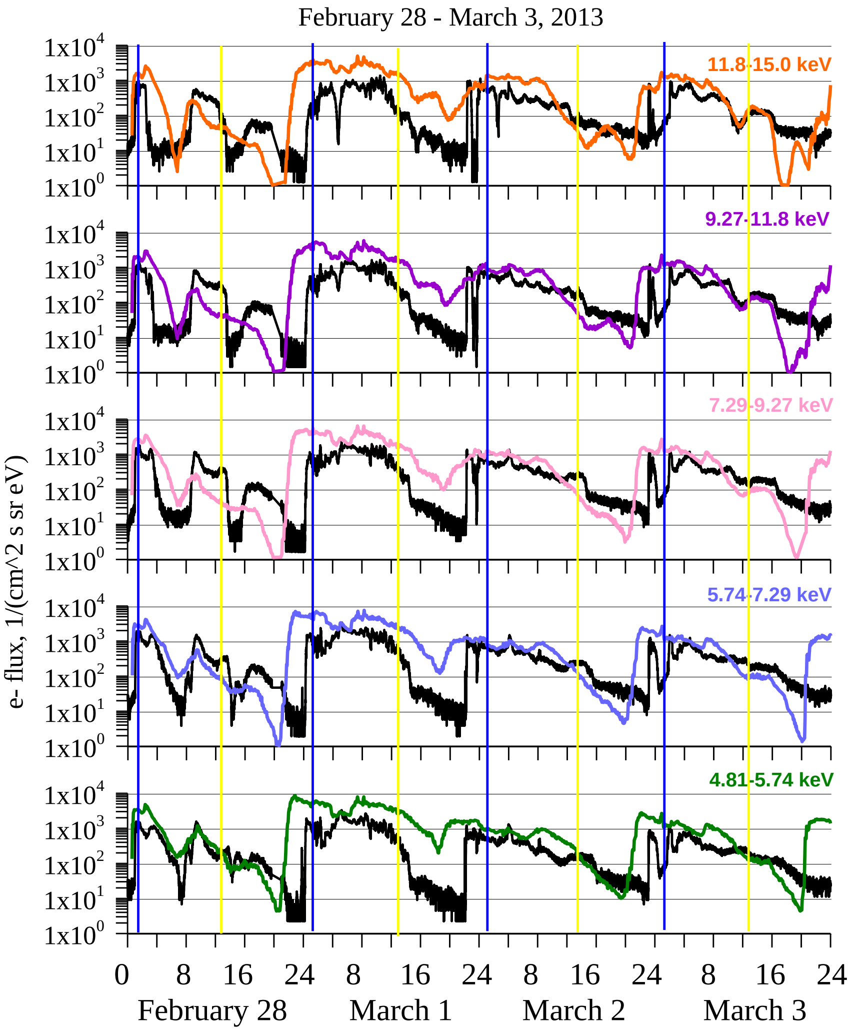
electron lifetime E=150 keV , Kp=3

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 5-15 keV energies and modeled

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





Pitch angle diffusion coefficients from the BAS chorus diffusion model

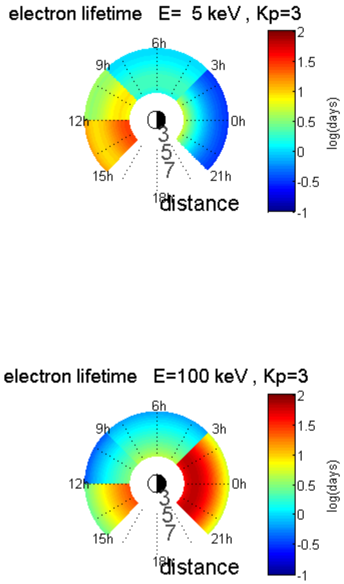
BAS chorus diffusion model [*Horne et al*., 2013; *Glauert et al*., 2014] provides pitch angle diffusion coefficients Dαα due to interactions with chorus waves
for Kp = 0, 1, 2, 3, and 4
at L-shells from 1.5 to 10 with 0.5 step and
in all MLT sectors binned by 3 hours
for pitch angles from 0 to 90 degrees with 1 degree step.

For low energy electrons, 10 energies are covered, namely, 1, 2, 3, 6, 10, 20, 30, 60, 100, and 200 keV.

Shprits et al. [2006] showed that when the pitch angle diffusion coefficient (as a function of the equatorial pitch angle) does not exhibit local minima below 1/10th of the scattering rate near the edge of the loss cone, the electron lifetimes can be estimated as the inverse value of the pitch-angle diffusion coefficient near the edge of the loss cone as

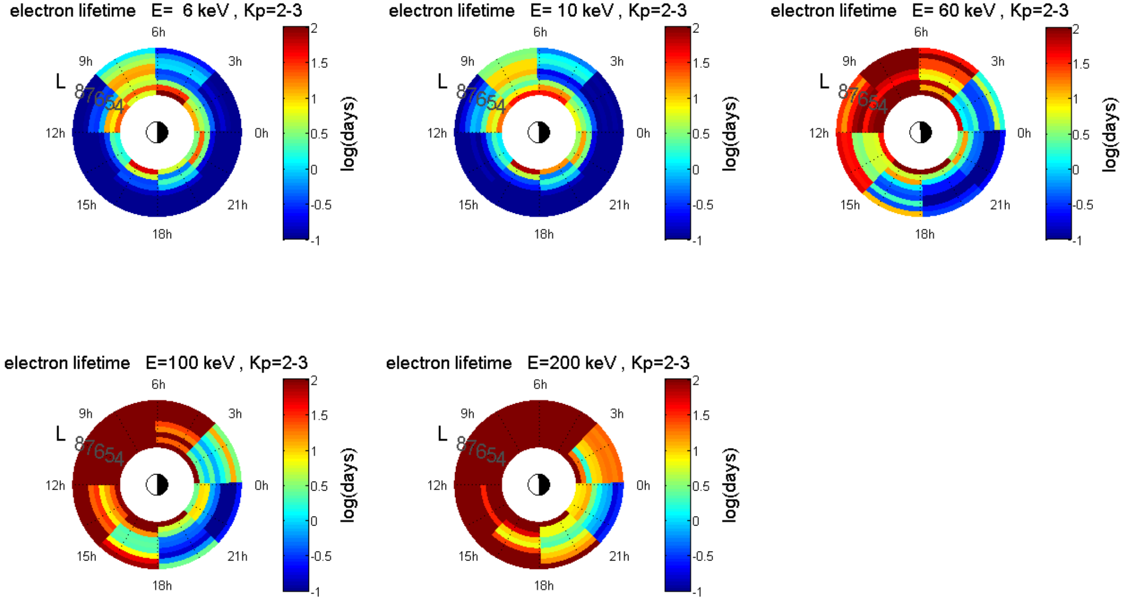
$$\tau = \frac{1}{D_{\alpha\alpha}\left(\alpha_{LC}\right)}$$

We determined the loss cone pitch angles αLC at each L-shell and find the corresponding Dαα at the edge of loss cones by interpolating the available Dαα at pitch angles around it.

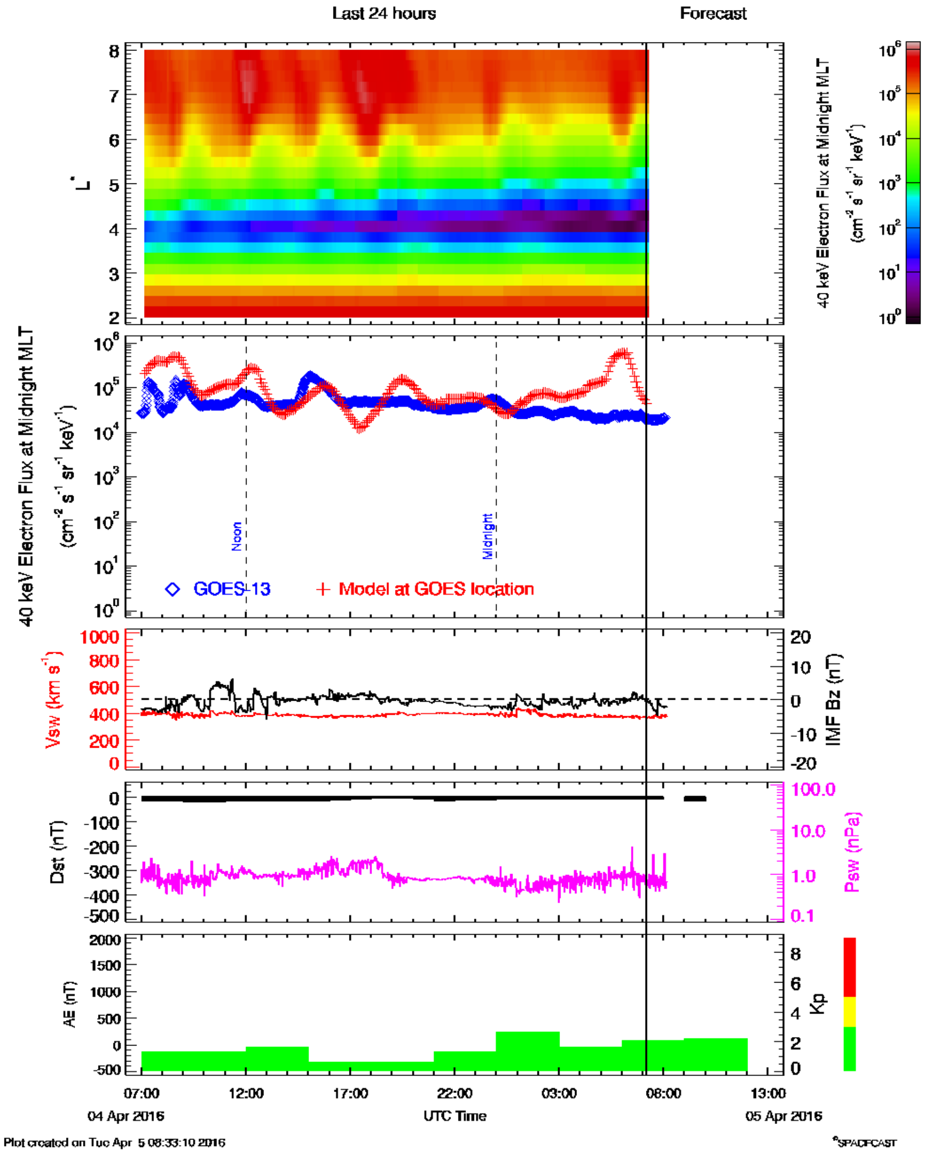


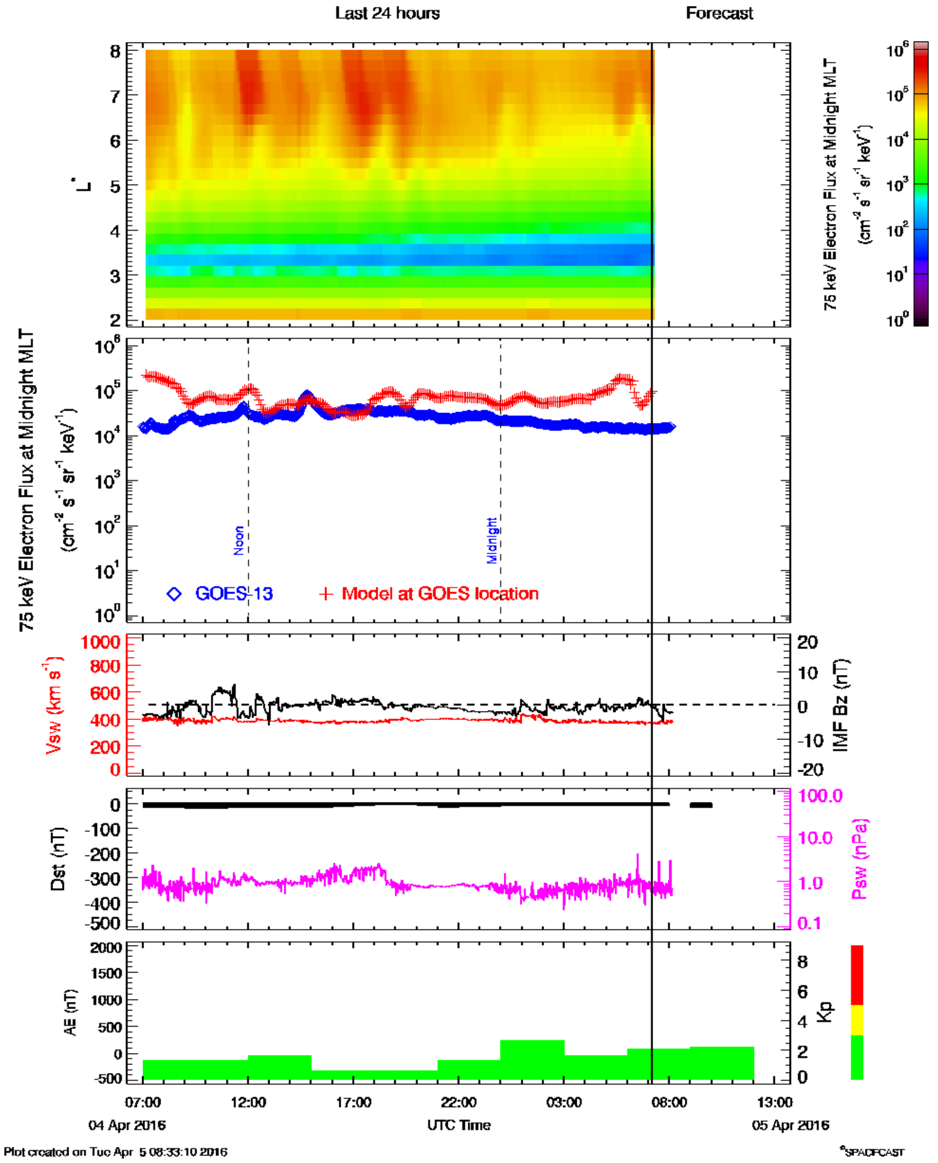
Lifetimes log10(τ)(chorus) in days as (L, MLT) maps, for electron energies of 6, 10, 60, 100, and 200 keV and Kp =3 computed from BAS chorus diffusion model

Lifetimes log10(τ)(chorus) in days as (L, MLT) maps, for electron energies of 5, 10, 50, 100, and 150 keV and Kp =3 following *Orlova and Shprits* [2014].



Current IMPTAM output compared to GOES MAGED 40 and 75 keV electron fluxes





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.

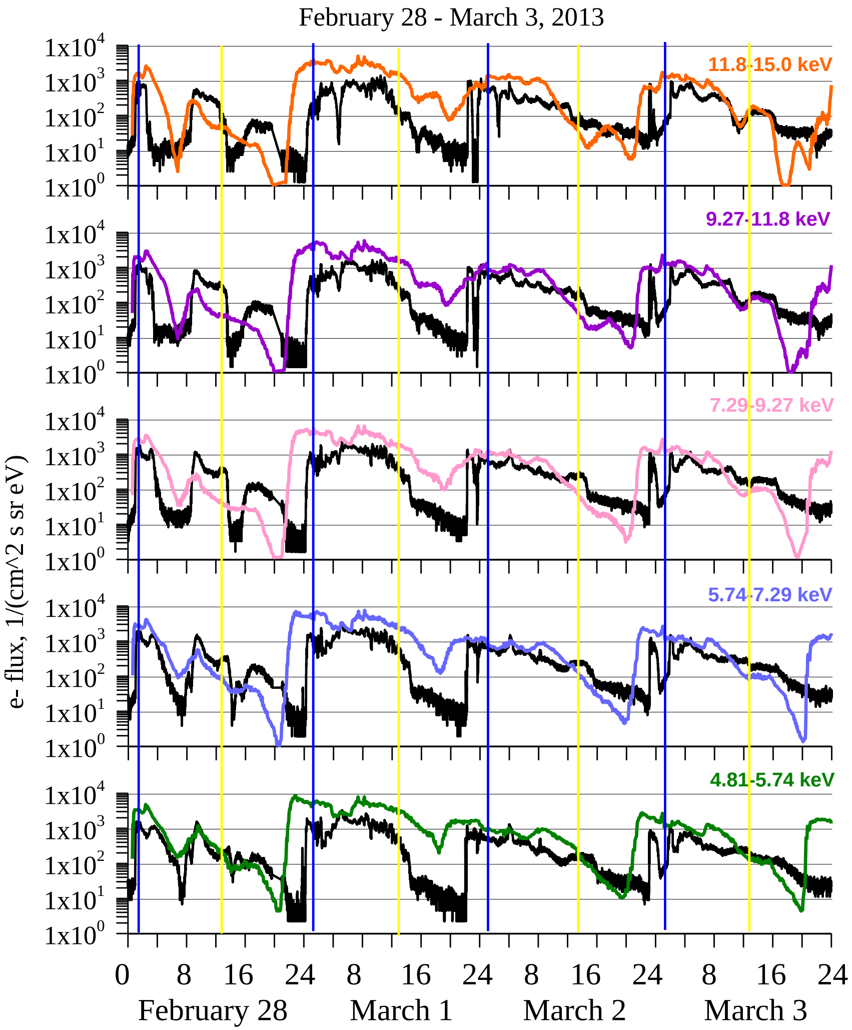
(2) magnetic and electric fields everywhere dependent on time;
The **magnetic field model is Tsyganenko T96 model** [*Tsyganenko*, 1995] with Dst index, solar wind pressure P_{SW}, and IMF B_Y and B_Z as input parameters. The **electric field** is determined using the solar wind speed V_{SW}, the IMF 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**.

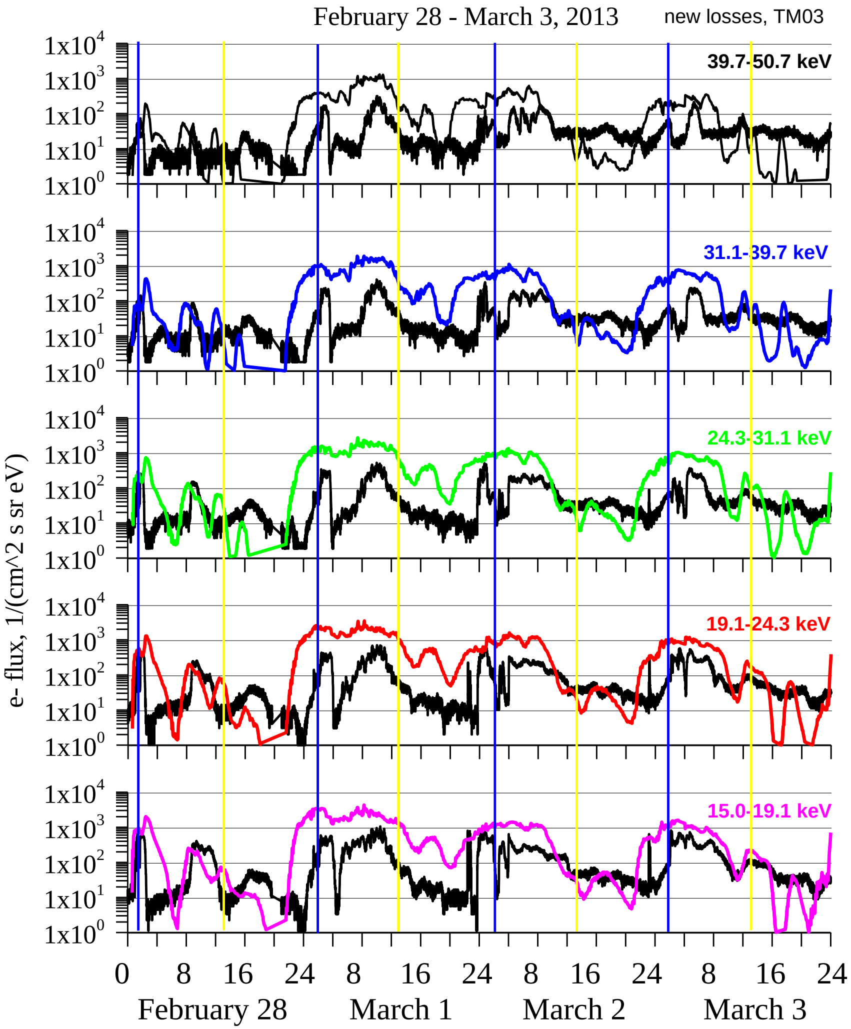
(3) drift velocities;

(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].

Electron fluxes observed by AMC 12 CEASE II ESA instrument for 15-50 keV energies and modeled

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





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 but low energy electrons (at geostationary) are not organized by AE index, for example.

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