



Losses for keV electrons as electron lifetimes in IMPTAM

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Second meeting of ISSI International Team "Analysis of Cluster Inner Magnetosphere Campaign data, in application the dynamics of waves and wave-particle interaction within the outer radiation belt", May 9-13, 2016, International Space Science Institute, Bern, Switzerland.

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

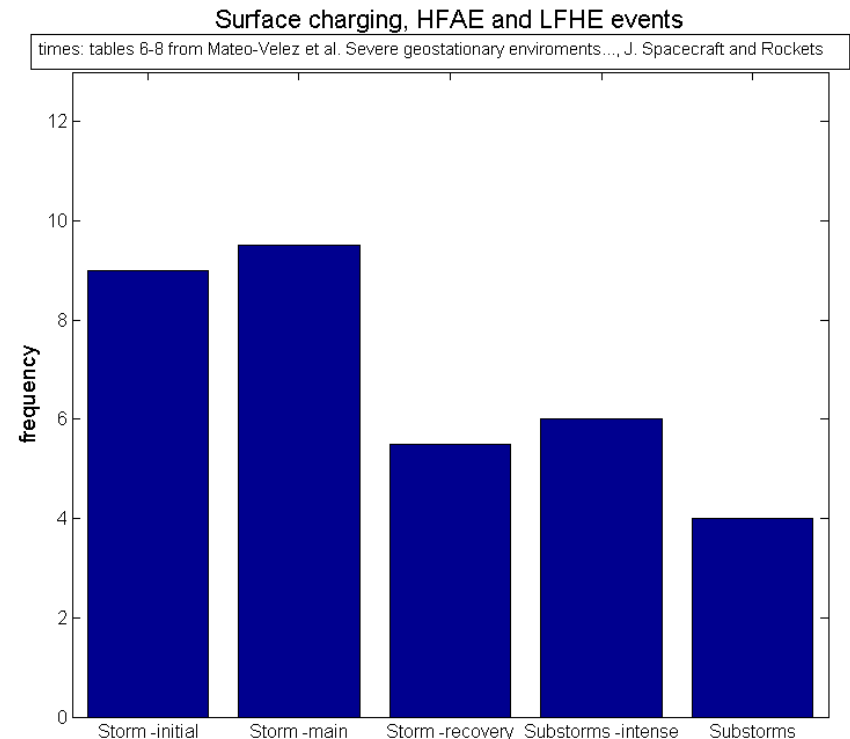
Surface charging events vs. geomagnetic conditions

It is **NOT** necessary to have even a moderate storm for significant surface charging events 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!

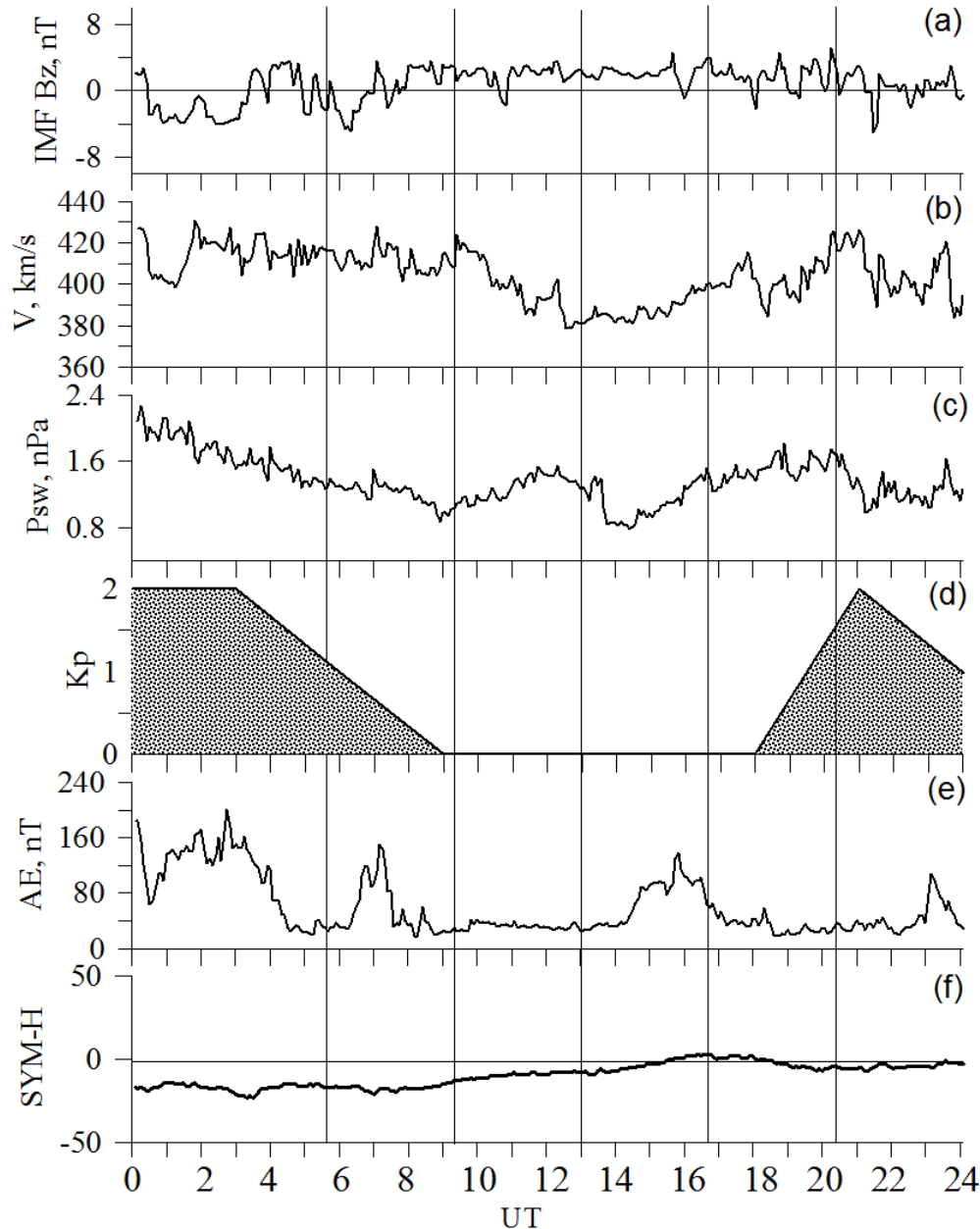
No averaging over an hour/day/orbit!

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



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

November 25, 2011

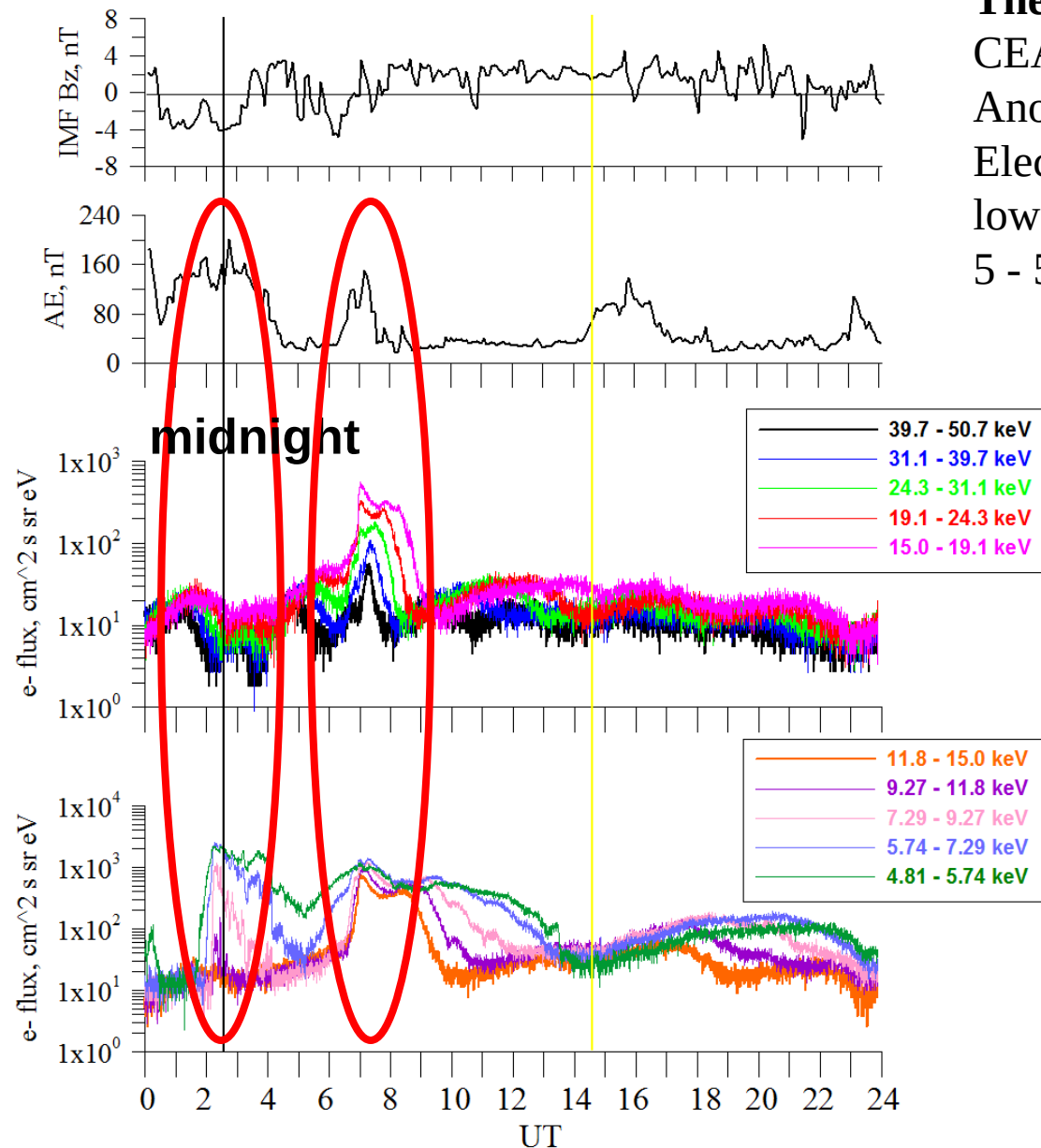


**No storm is needed
for 2-3 orders of
magnitude increase
of low energy electron
fluxes at
geostationary orbit**

Rather quiet event

5-50 keV electrons during quiet event

November 25, 2011



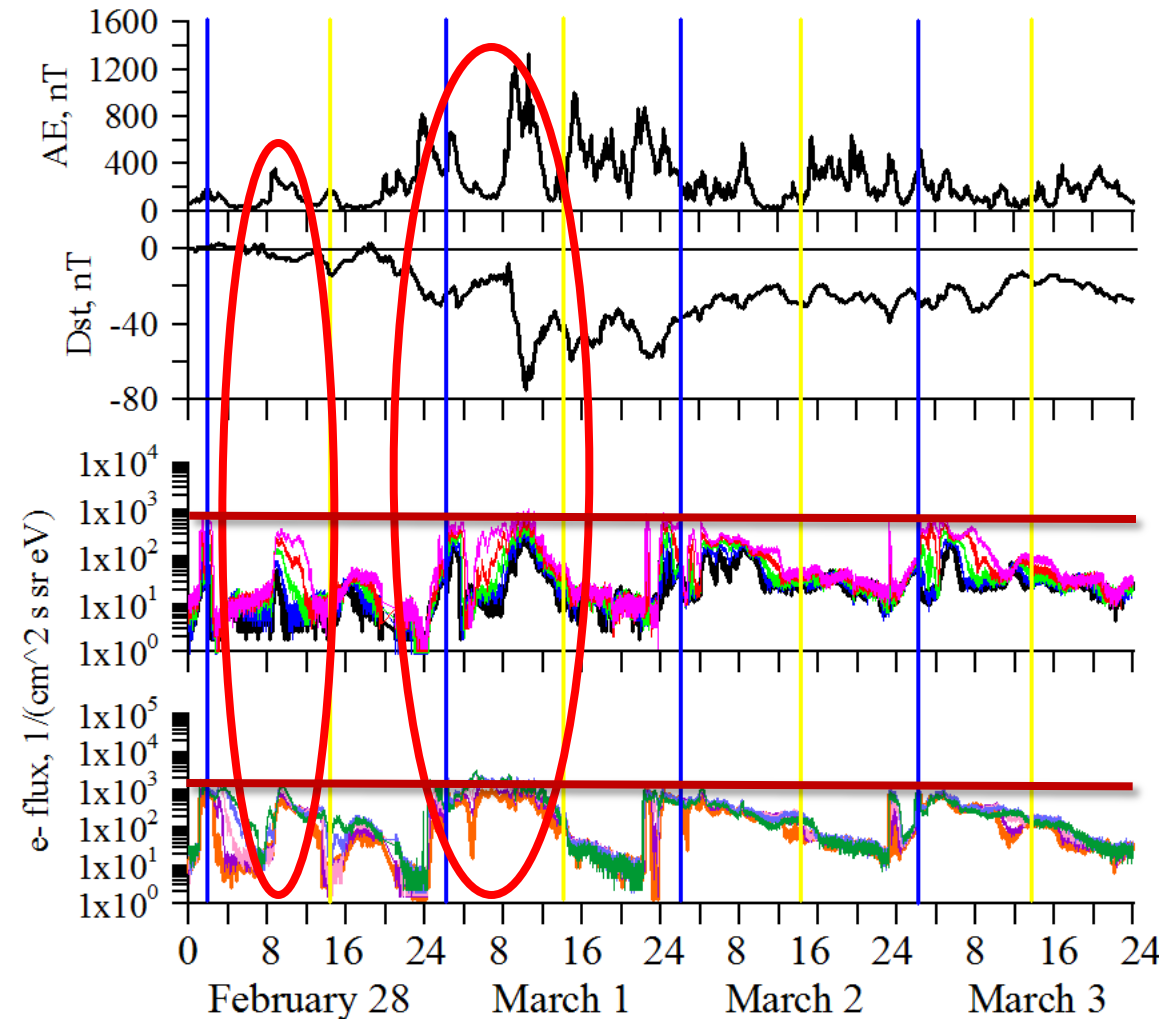
The data: AMC 12 geostationary satellite, CEASE-II (Compact Environmental Anomaly Sensor) instrument with Electrostatic Analyzer (ESA) for measuring low energy electron fluxes in 10 channels, 5 - 50 keV.

- **Flux increases** are related to **AE peaks** only (less than 200 nT, small, isolated substorms)
- The lower the energy, the larger the flux
- Electrons of different channels behave 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

February 28 - March 3, 2013



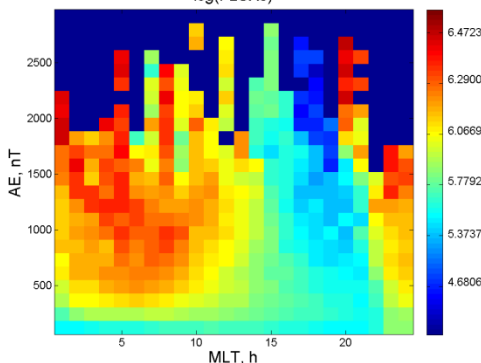
Small, CIR-driven storm with
Dst of 75 nT,
IMF Bz of -5 -10 nT,
Vsw from 350 to 650 km/s,
Psw peak at 8 nPa,
AE peaks of 800-1200 nT

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

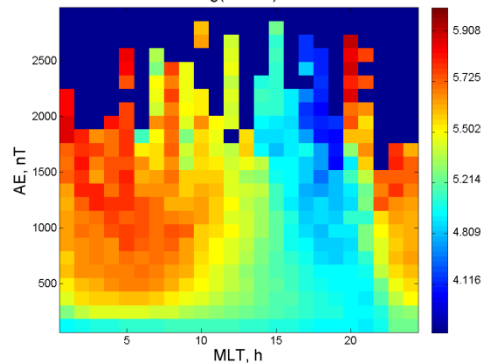
39.7-50.7 keV

log(FLUX0)



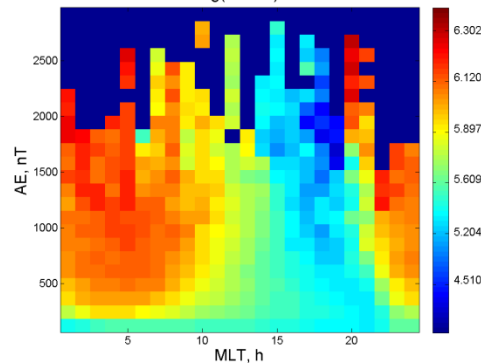
31.1-39.7 keV

log(FLUX1)



24.3-31.1 keV

log(FLUX2)



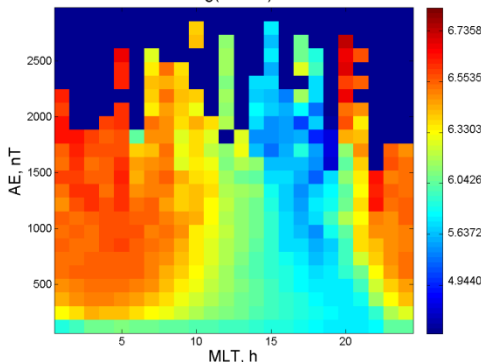
Log(flux)

Flux(MLT, AE)

**AMC 12
CEASE-II
ESA data,
2010-2014**

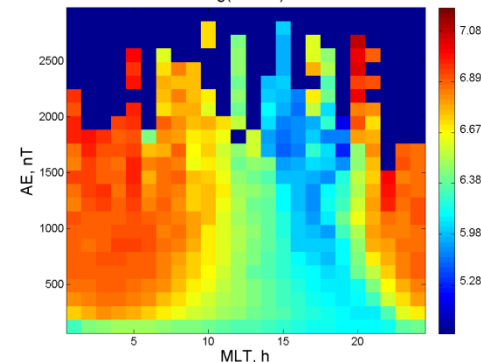
19.1-24.3 keV

log(FLUX3)



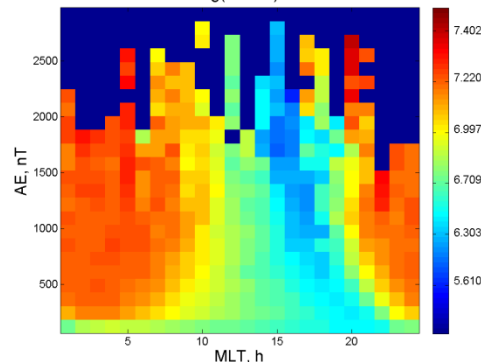
15.0-19.1 keV

log(FLUX4)



11.8-15.0 keV

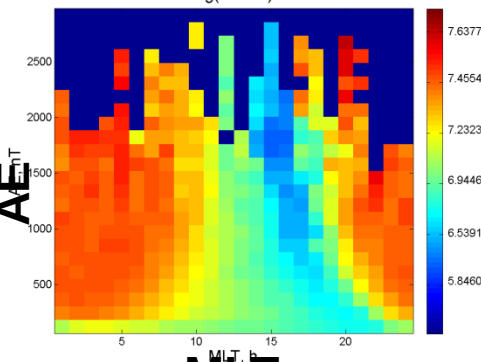
log(FLUX5)



The higher
the energy,
the less
distributed
the flux peak

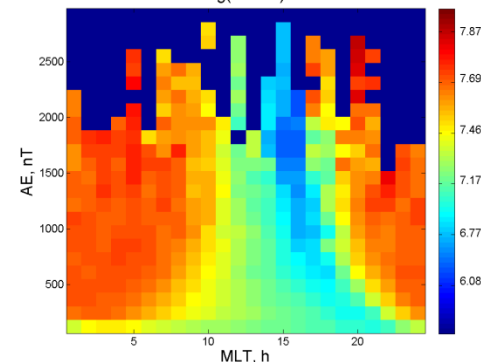
9.27-11.8 keV

log(FLUX6)



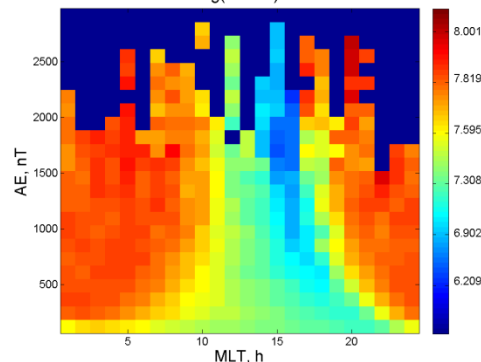
7.29-9.27 keV

log(FLUX7)



5.74-7.29 keV

log(FLUX8)

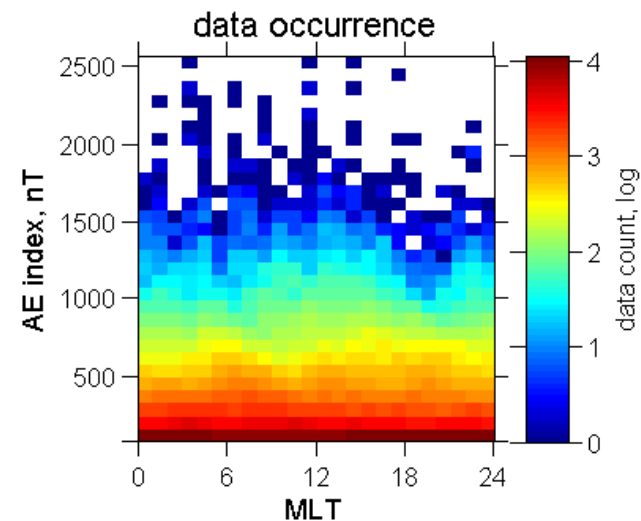
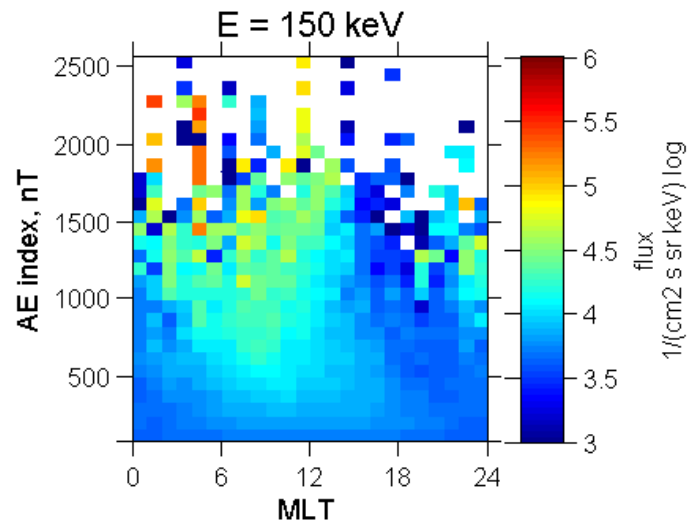
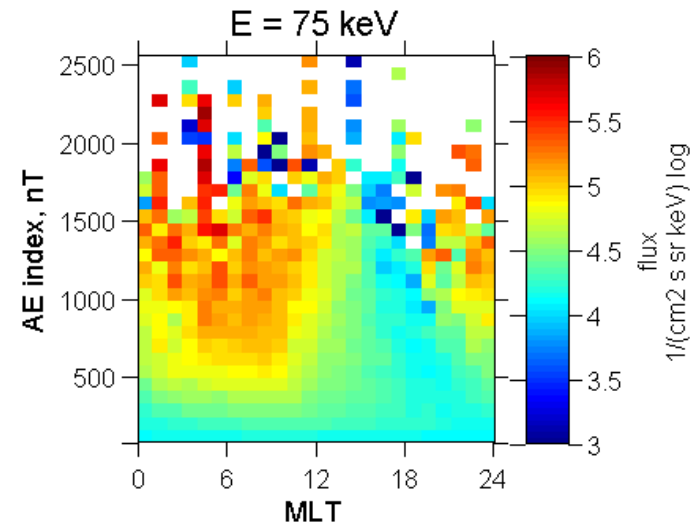
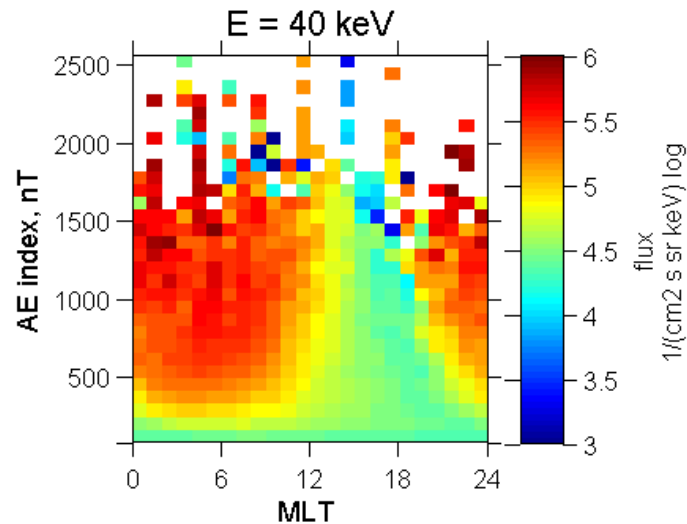


**No distinct
dependence
on AE
strength**

MLT

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 2nd 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, B_h is the magnetic field at either foot point of field line, Ψ is the magnetic flux tube volume, $\eta=0.25$ 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)

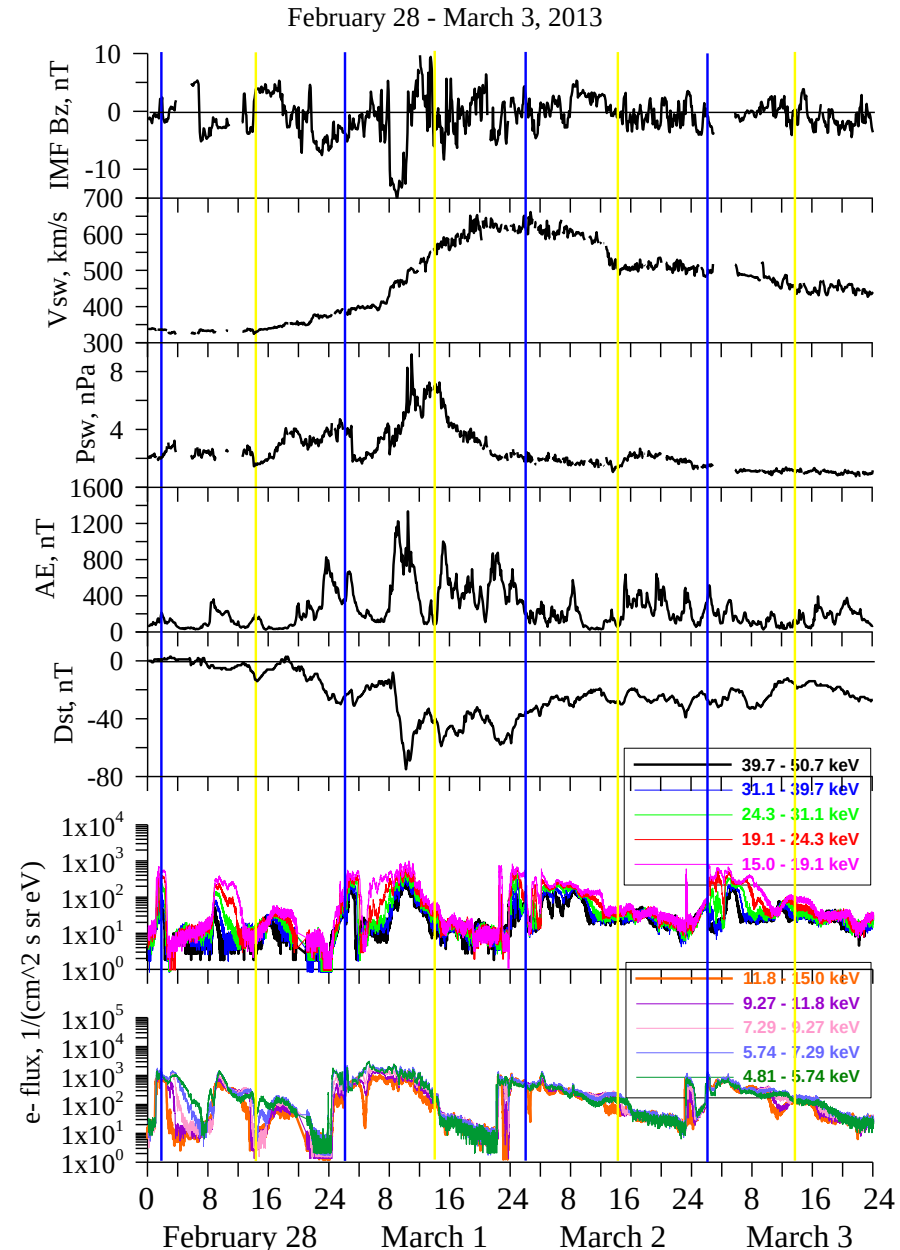
Weak diffusion:
$$\tau_{wd} = 4.8 \cdot 10^4 B_w^{-2} L^{-1} E^2, \quad B_w^2 = 2 \cdot 10^{2.5+0.18Kp}$$

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

AMC 12 CEASE II ESA data

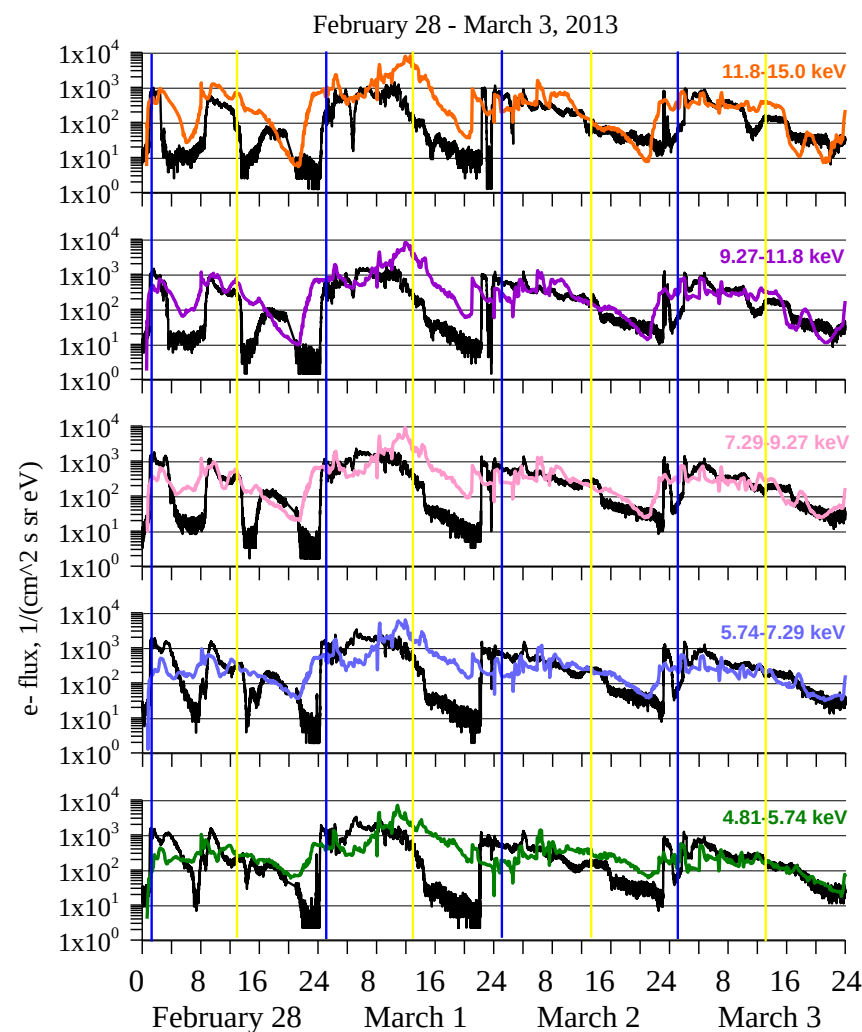
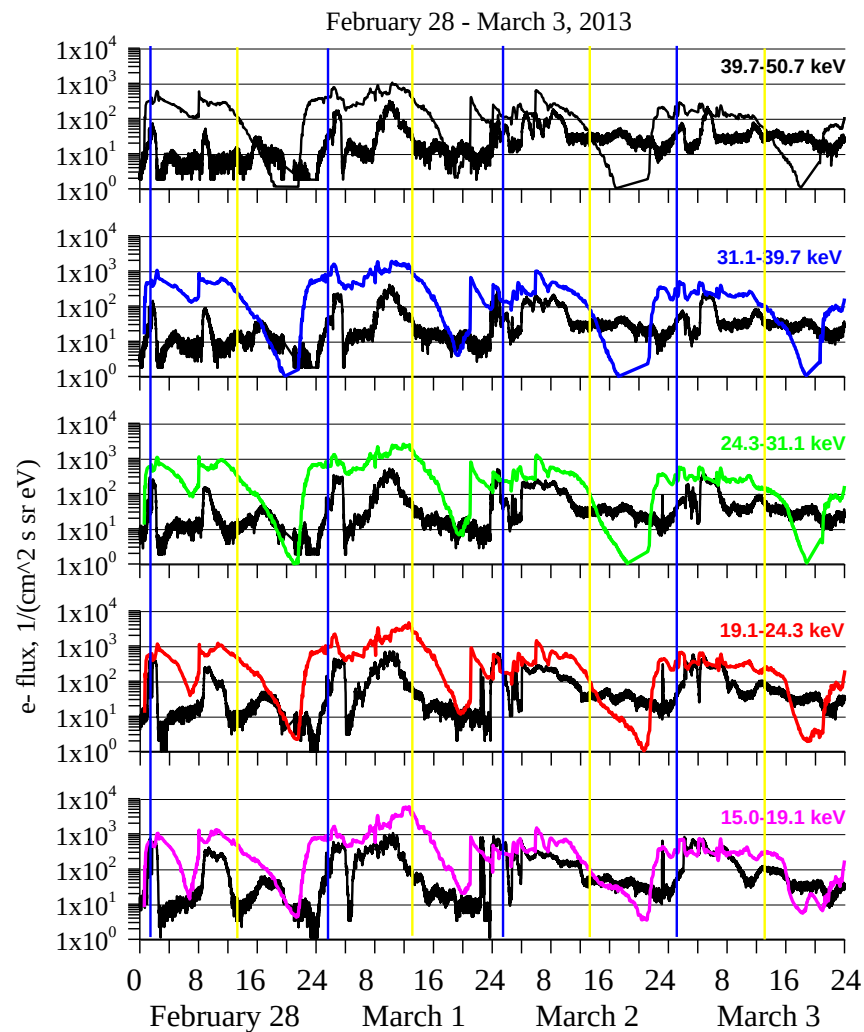
AMC 12 geostationary satellite, CEASE-II instrument contains an Electrostatic Analyzer (ESA) for measuring low energy electron fluxes in 10 channels, 5 - 50 keV.

Small, CIR-driven storm with **Dst** of 75 nT
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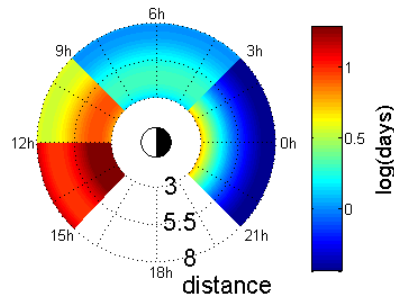
Electron fluxes observed by AMC 12 CEASE II ESA instrument for 15-50 keV energies and modeled

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

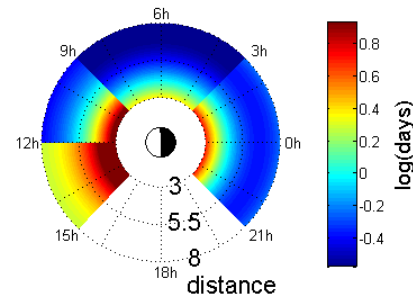


Losses for low energy electrons due to wave-particle interactions

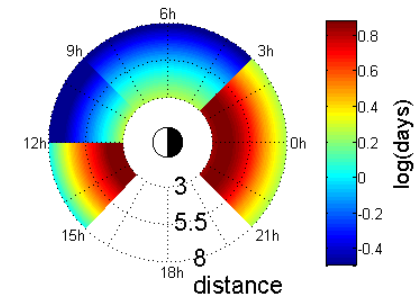
electron lifetime $E = 5 \text{ keV}$, $Kp=3$



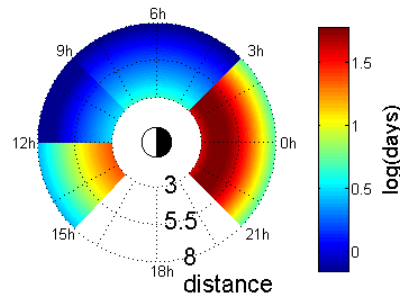
electron lifetime $E = 10 \text{ keV}$, $Kp=3$



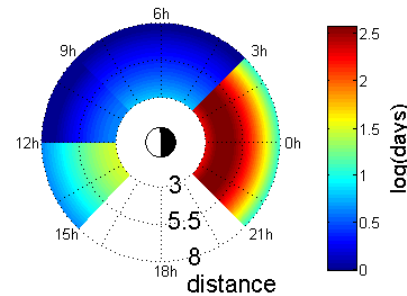
electron lifetime $E = 50 \text{ keV}$, $Kp=3$



electron lifetime $E = 100 \text{ keV}$, $Kp=3$



electron lifetime $E = 150 \text{ keV}$, $Kp=3$



Parameterization of the electron lifetimes due to interactions with chorus waves

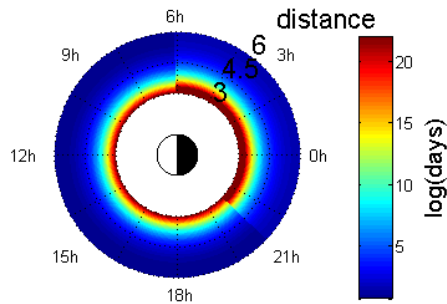
[Orlova and Shprits, 2014]:

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

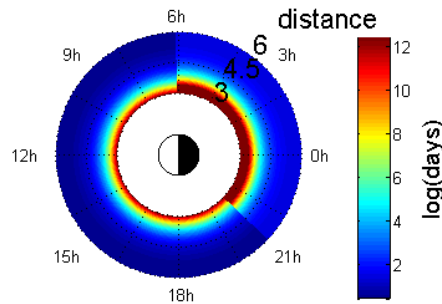
The model can be used for $R=3-8 R_E$, $Kp=0-6$, and electron energies from 1 keV to 2 MeV. MLT sectors include the night ($-3 \leq \text{MLT} \leq 3$), dawn ($3 \leq \text{MLT} \leq 9$), prenoon ($9 \leq \text{MLT} \leq 12$), and postnoon ($12 \leq \text{MLT} \leq 15$) segments.

Losses for low energy electrons due to wave-particle interactions

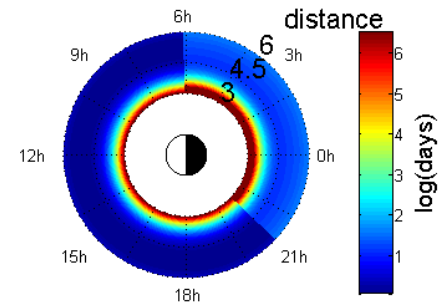
electron lifetime $E = 5 \text{ keV}$, $Kp=3$



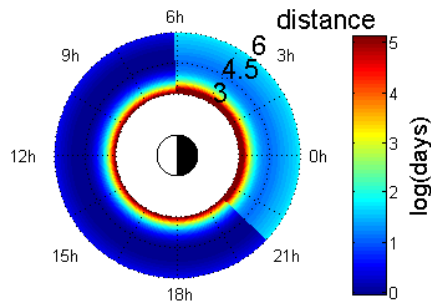
electron lifetime $E = 10 \text{ keV}$, $Kp=3$



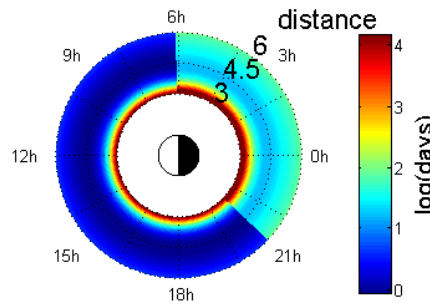
electron lifetime $E = 50 \text{ keV}$, $Kp=3$



electron lifetime $E = 100 \text{ keV}$, $Kp=3$



electron lifetime $E = 150 \text{ keV}$, $Kp=3$



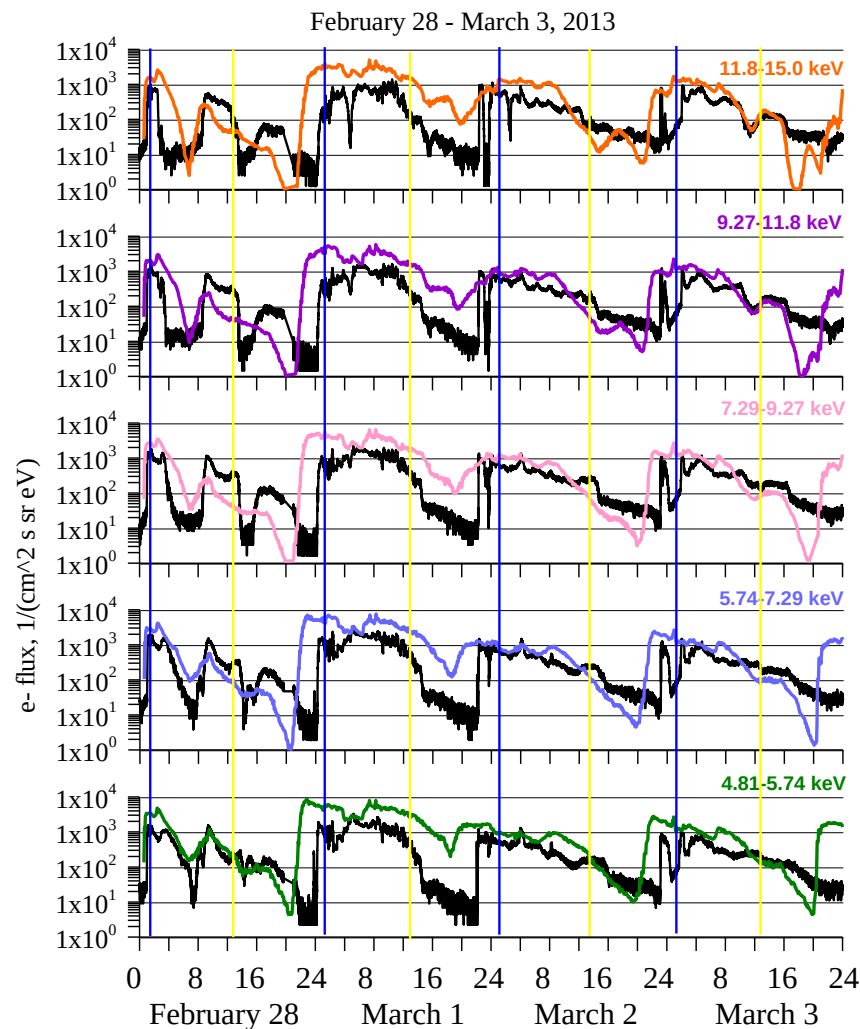
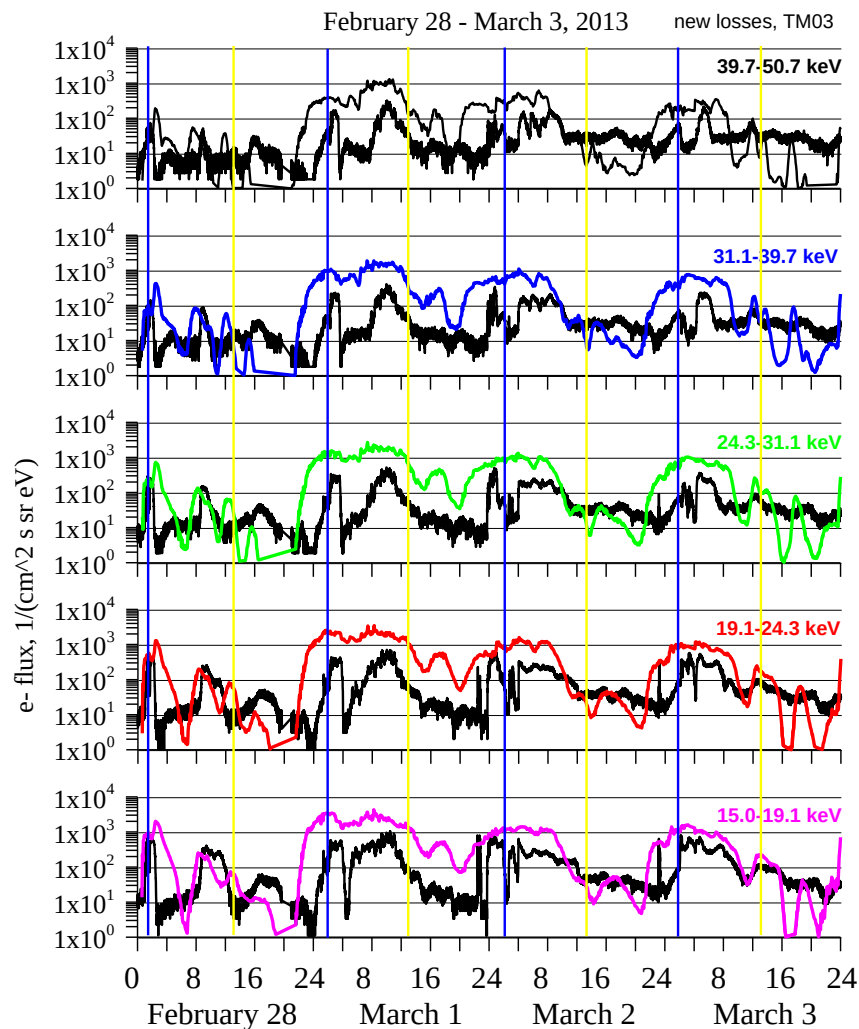
Parameterization of the electron lifetimes due to interactions with hiss waves

[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

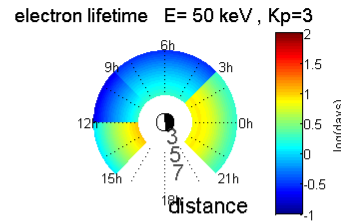
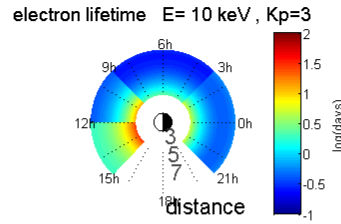
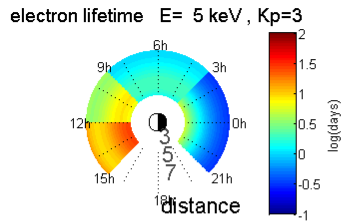
BAS chorus diffusion model [*Horne et al.*, 2013; *Glauert et al.*, 2014] provides pitch angle diffusion coefficients $D_{\alpha\alpha}$ due to interactions with chorus waves for $K_p = 0, 1, 2, 3$, and 4 at L-shells from 1.5 to 10 with 0.5 step and in all MLT sectors binned by 3 hours for pitch angles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

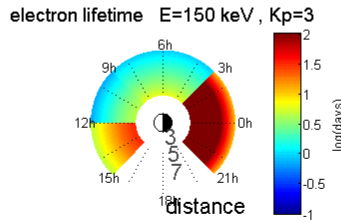
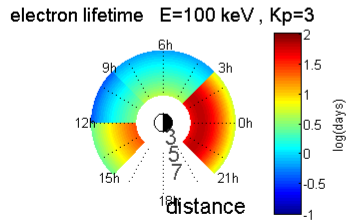
Shprits et al. [2006] showed that when the pitch angle diffusion coefficient (as a function of the equatorial pitch angle) does not exhibit local minima below 1/10th of the scattering rate near the edge of the loss cone, the electron lifetimes can be estimated as the inverse value of

the pitch-angle diffusion coefficient near the edge of the loss cone as
$$\tau = \frac{1}{D_{\alpha\alpha}(\alpha_{LC})}$$

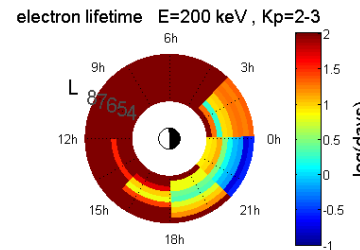
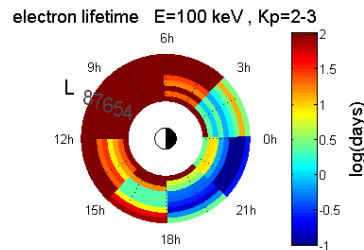
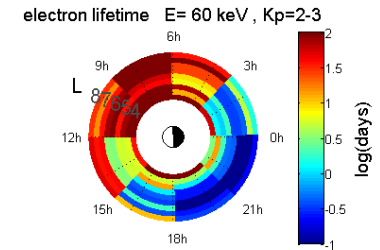
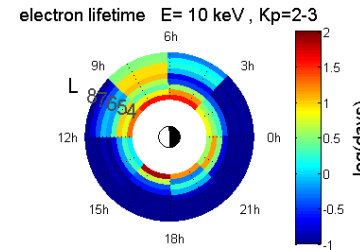
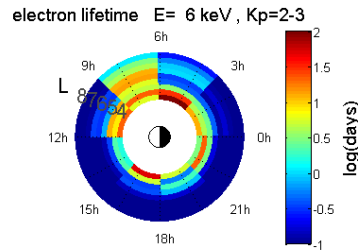
We determined the loss cone pitch angles α_{LC} at each L-shell and find the corresponding $D_{\alpha\alpha}$ at the edge of loss cones by interpolating the available $D_{\alpha\alpha}$ at pitch angles around it.



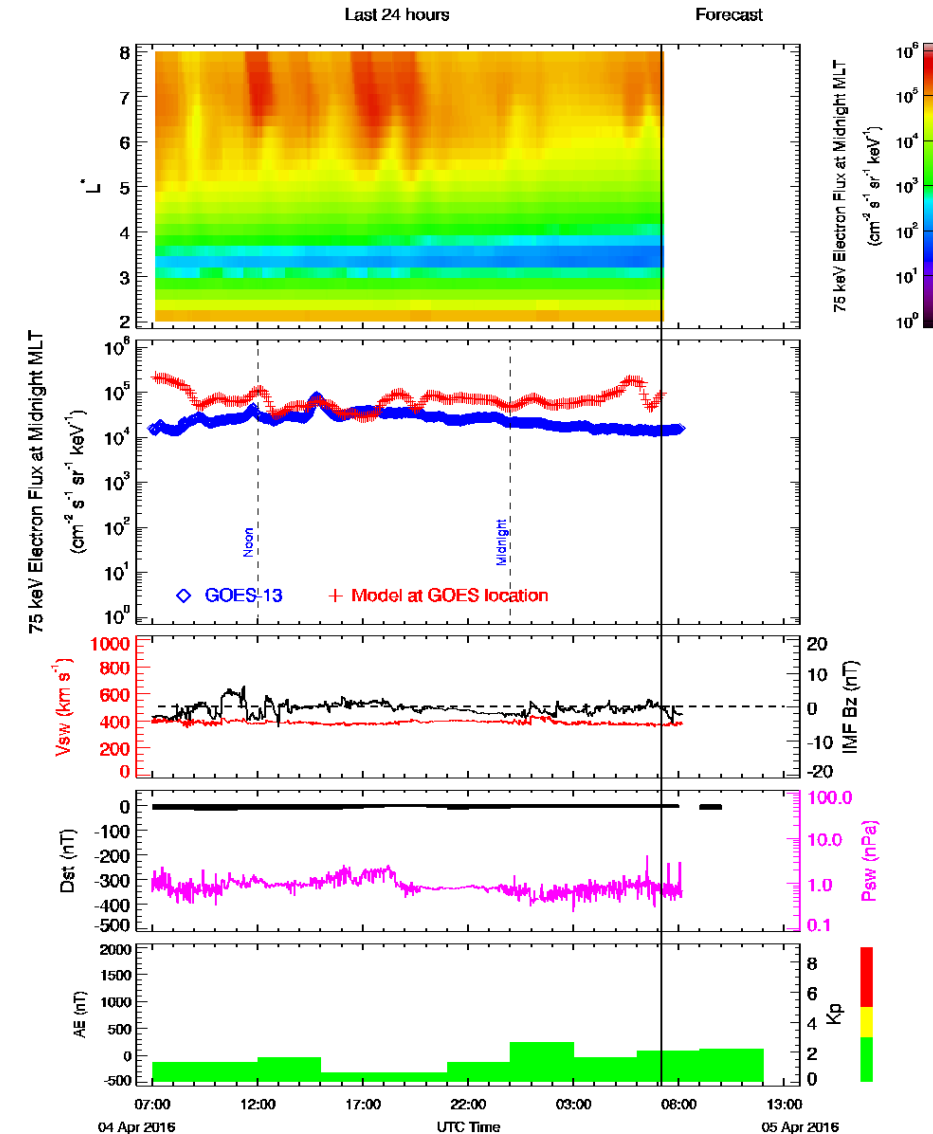
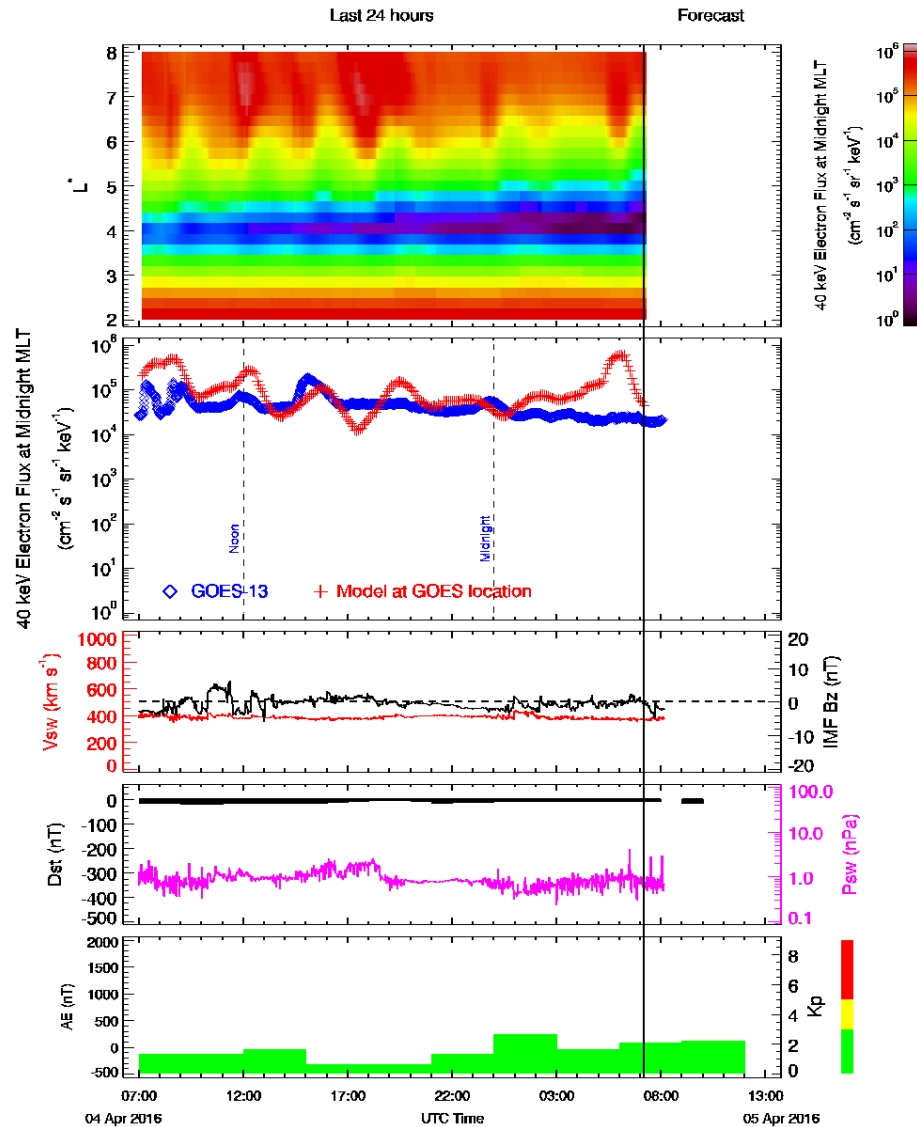
Lifetimes $\log_{10}(\tau)$ (chorus) in days as (L, MLT) maps, for electron energies of 6, 10, 60, 100, and 200 keV and Kp =3 computed from BAS chorus diffusion model



Lifetimes $\log_{10}(\tau)$ (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 angle**, 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**.

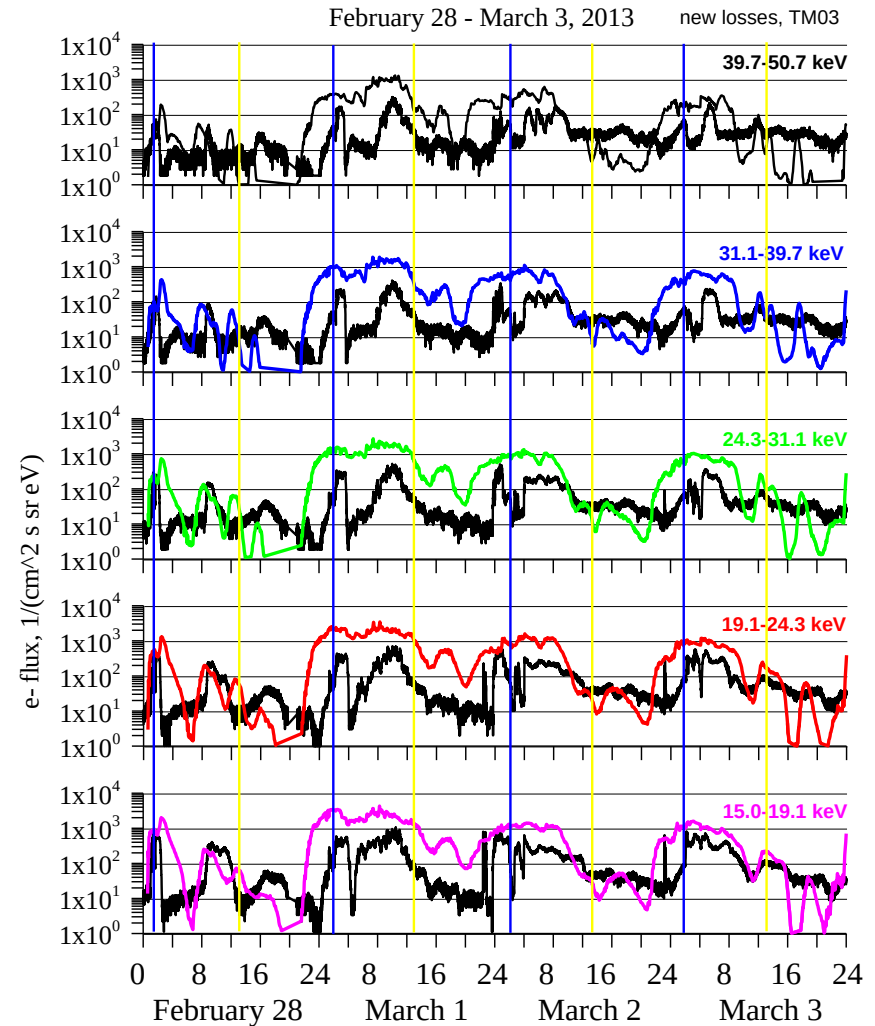
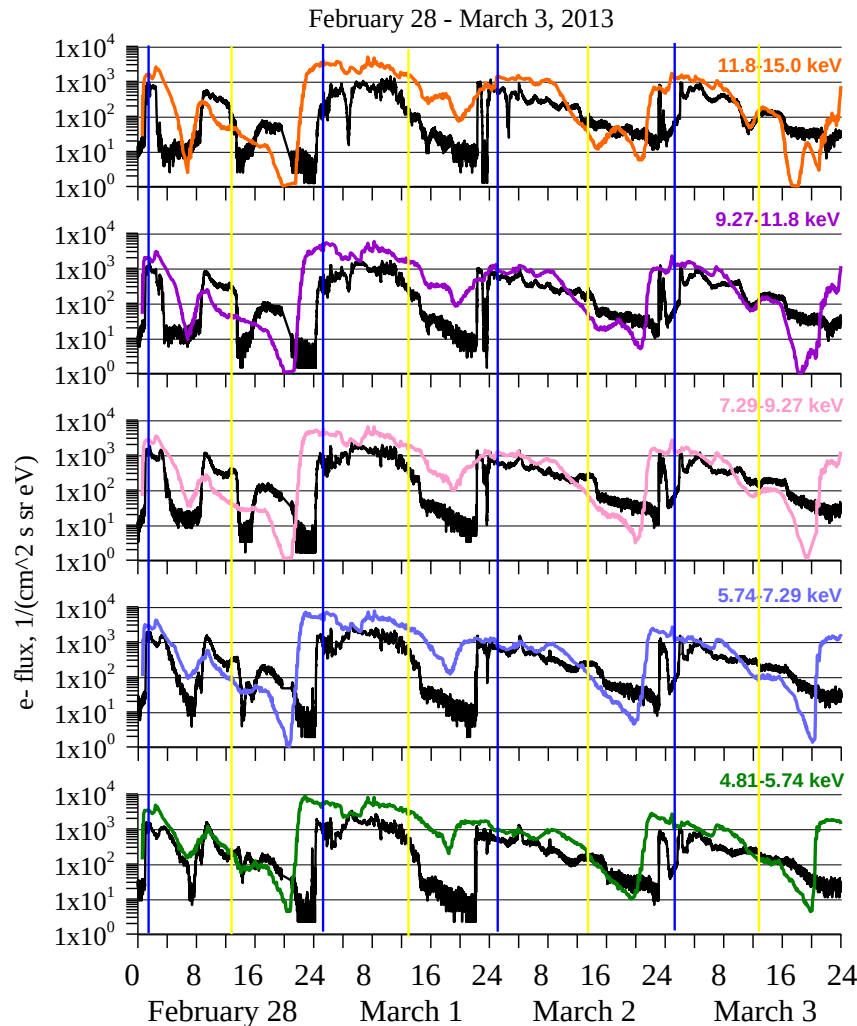
(3) drift velocities;

(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