Forecasting the keV-electrons in the inner Earth's magnetosphere 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!

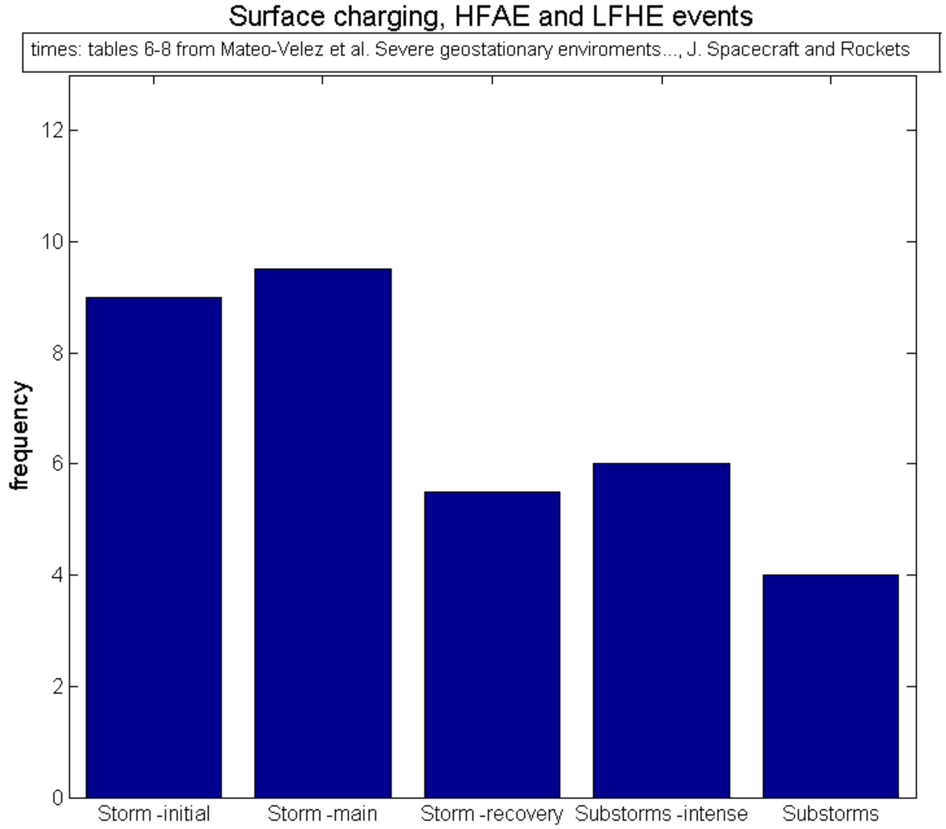
Space weather is more than storms (Louis Lanzerotti)

Surface charging events vs. geomagnetic conditions

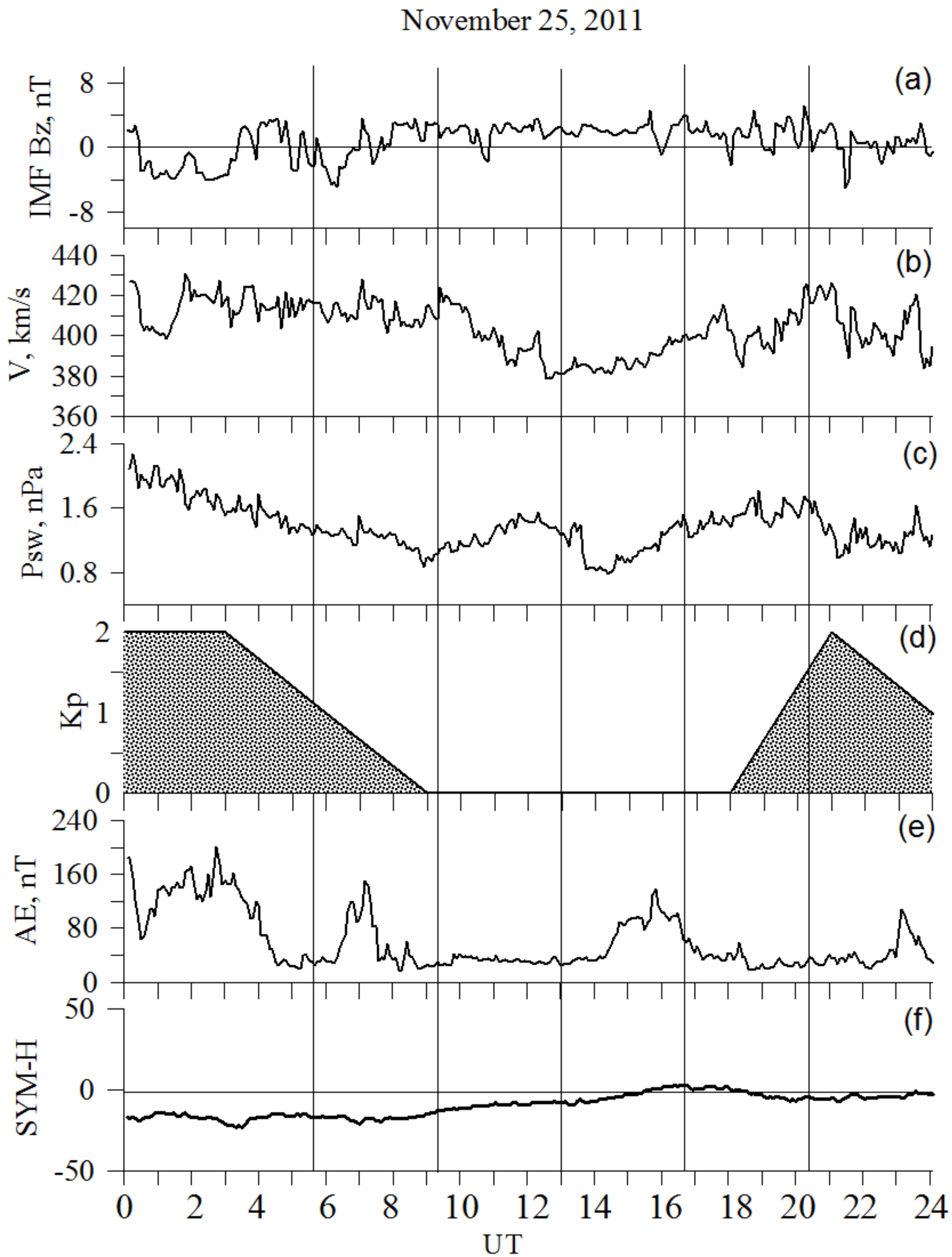
It is **NOT necessary to have even a moderate storm for significant surface charging** event to happen

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



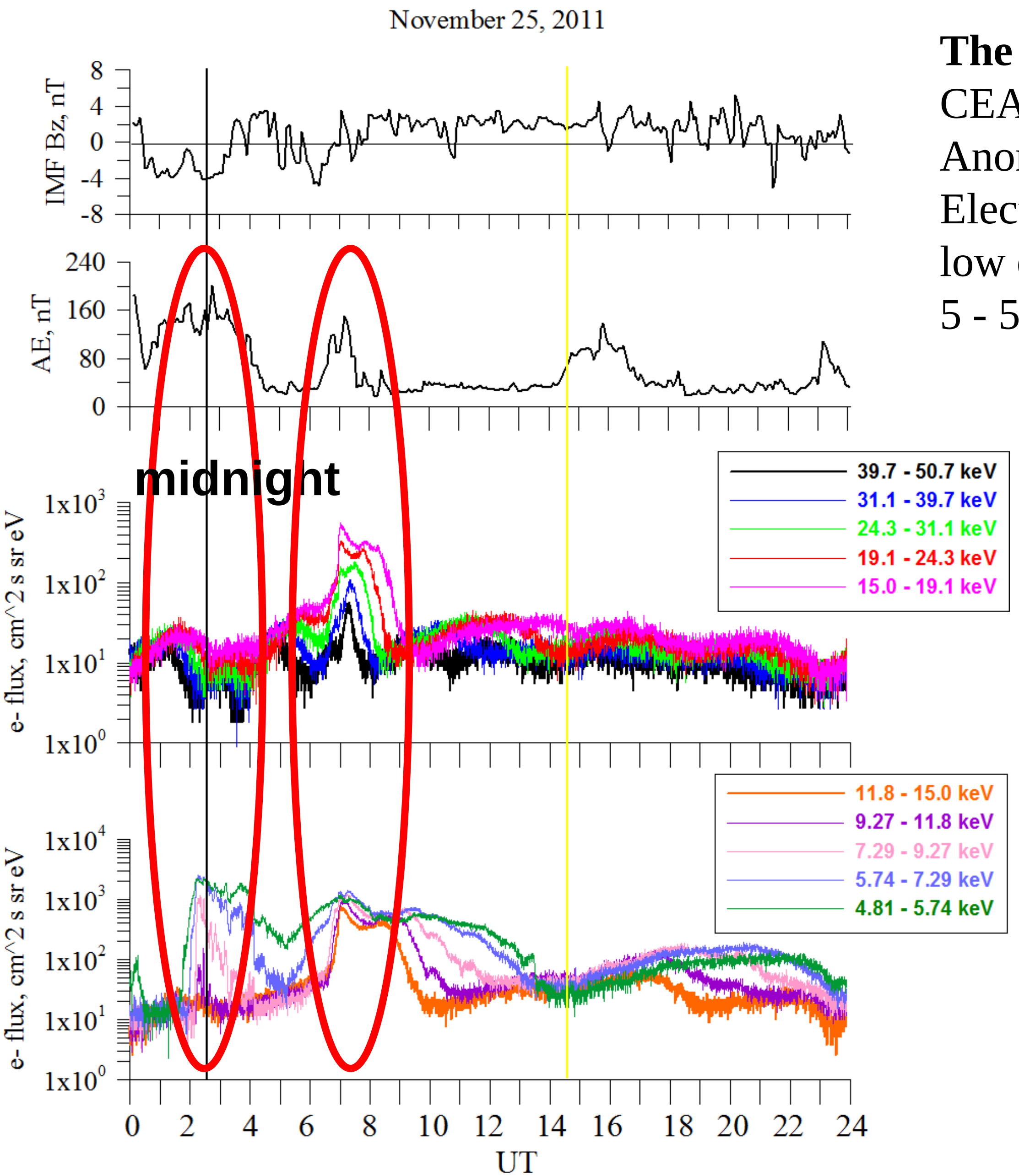
Matéo Vélez et al., Severe geostationary environments: from flight data to numerical estimation of spacecraft surface charging, *Journal of Spacecraft and Rockets, 2016.*



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.

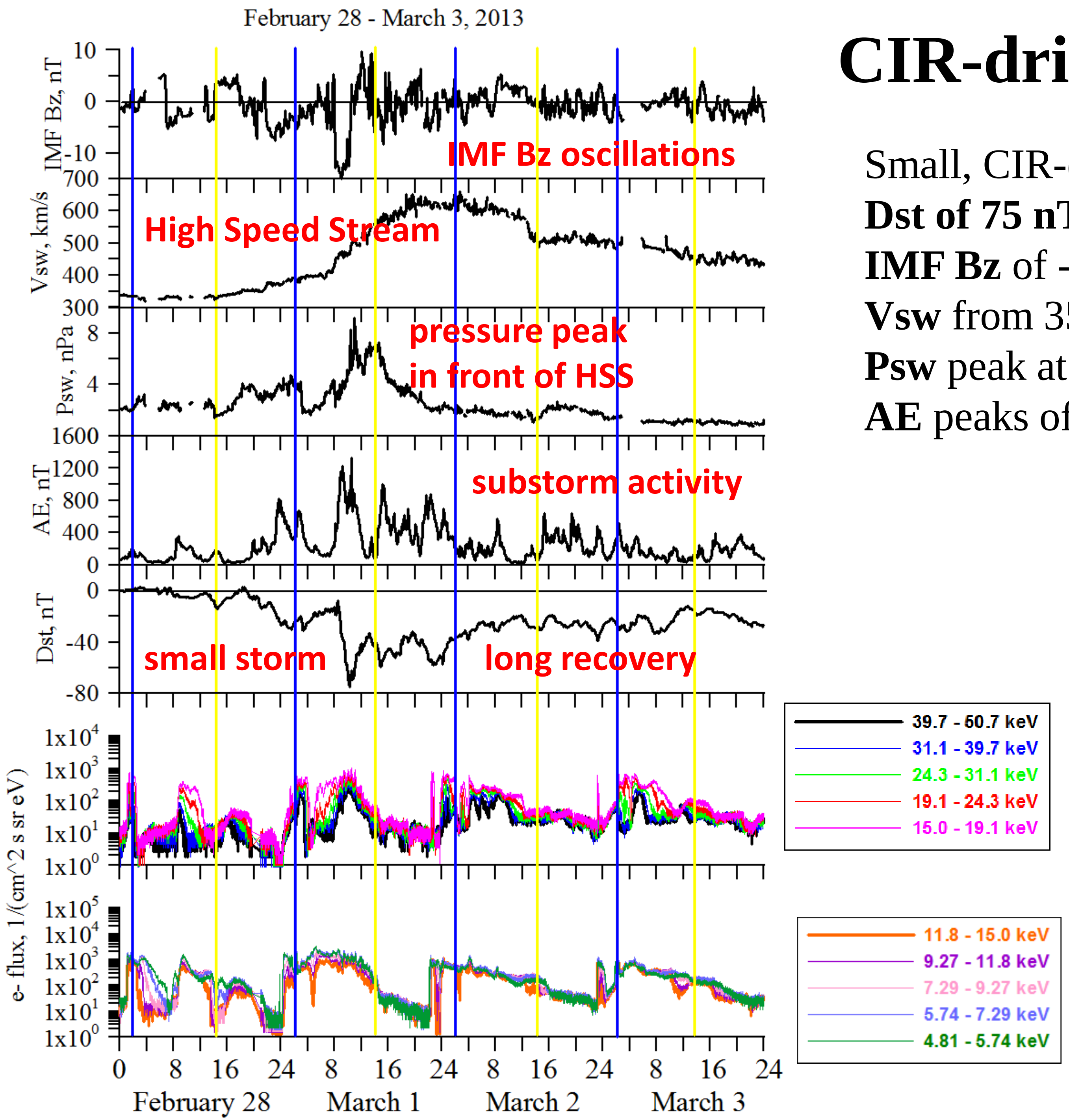
- **Flux increases** are related to **AE peaks** only (less than 200 nT, small, isolated substorms)

- 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

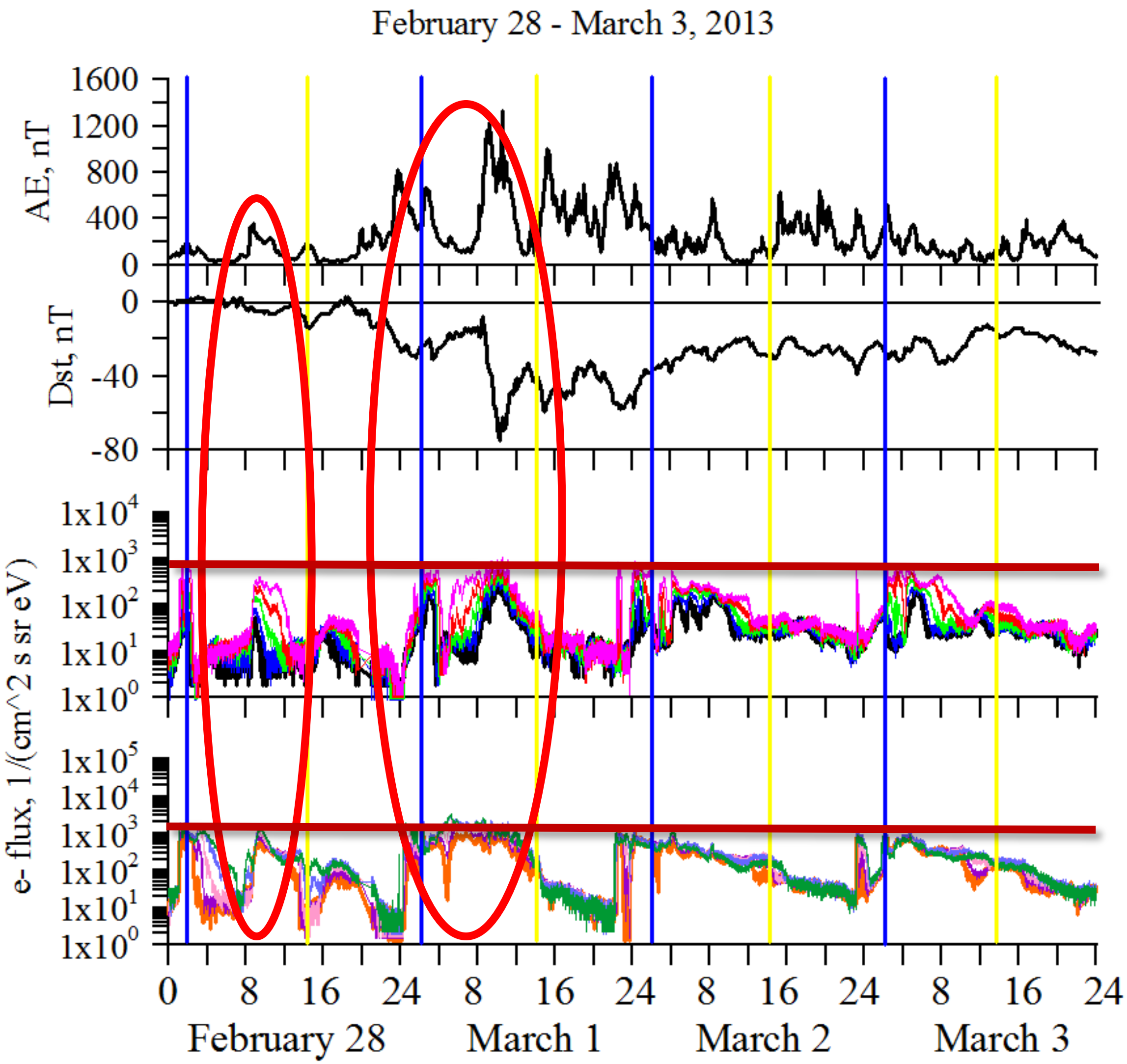
Not a unique case

CIR-driven storm



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

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



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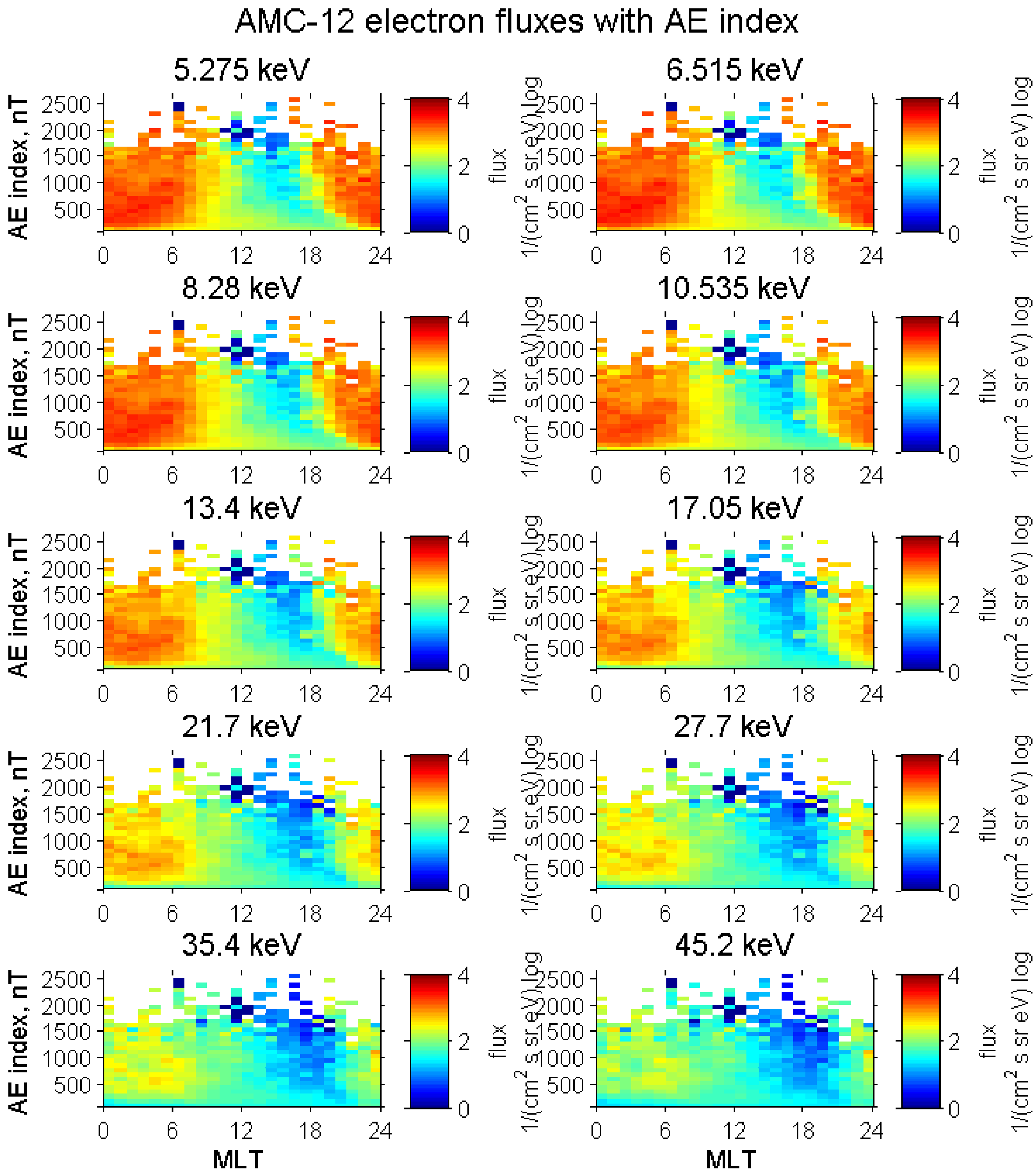
AMC12 electron data

- 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)

AMC 12
CEASE-II
ESA data,
2010-2014

The higher the energy, the less distributed the flux peak

No distinct dependence 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/

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

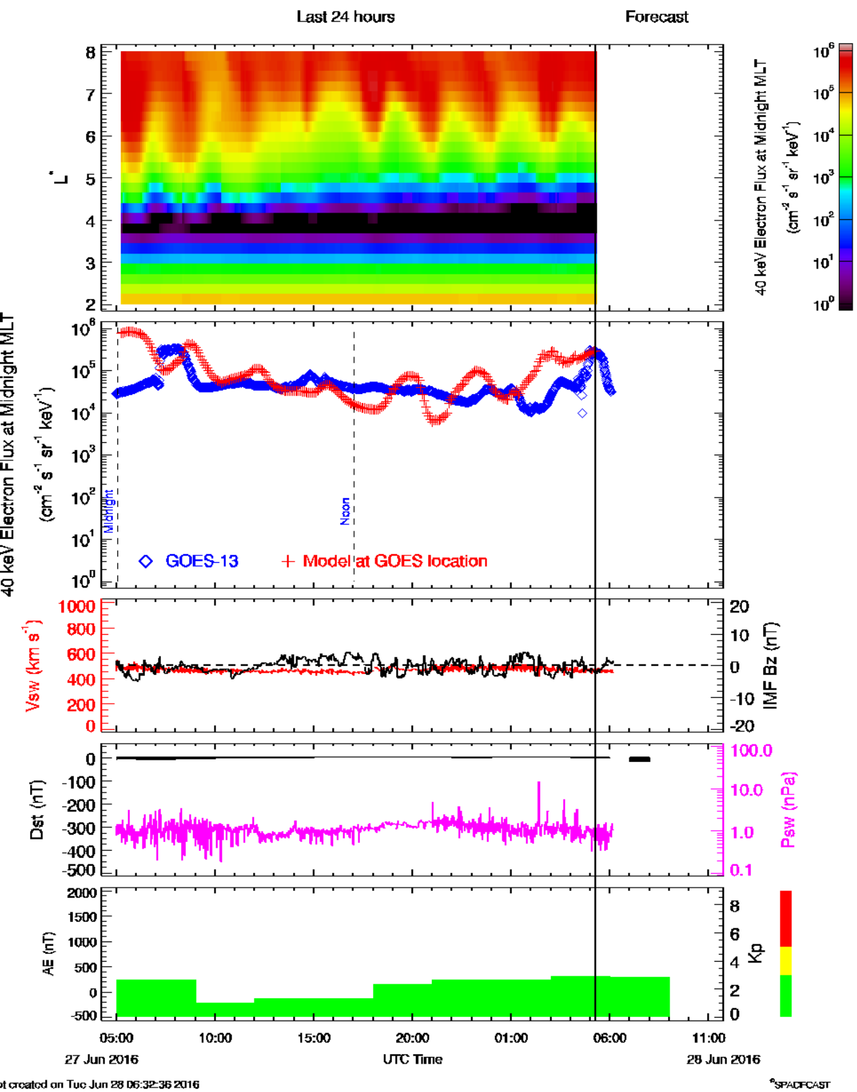
IMPTAM long-term output of omni-directional electron fluxes compared statistically to GEOS-13 MAGED fluxes for energies of 40, 75 and 150 keV.

GOES MAGED fluxes are the only available data on electrons with energies less than 200 keV which can be compared to IMPTAM output in near-real time.

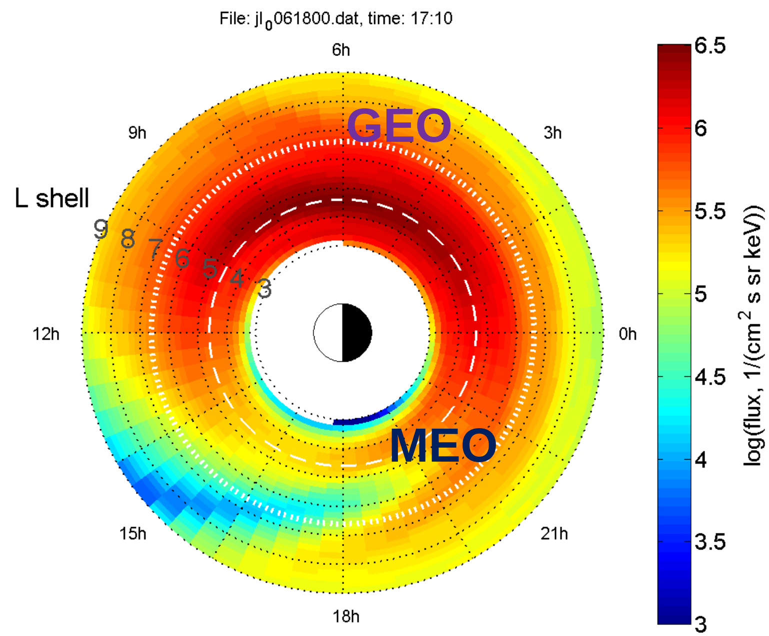
Time period: September 2013 - March 2015.

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
Strong diffusion (L=6-10): *Chen et al*. [2005]
Weak diffusion (L=2-6): *Shprits et al*. [2007]

IMPTAM output compared to GOES MAGED 40 keV e-

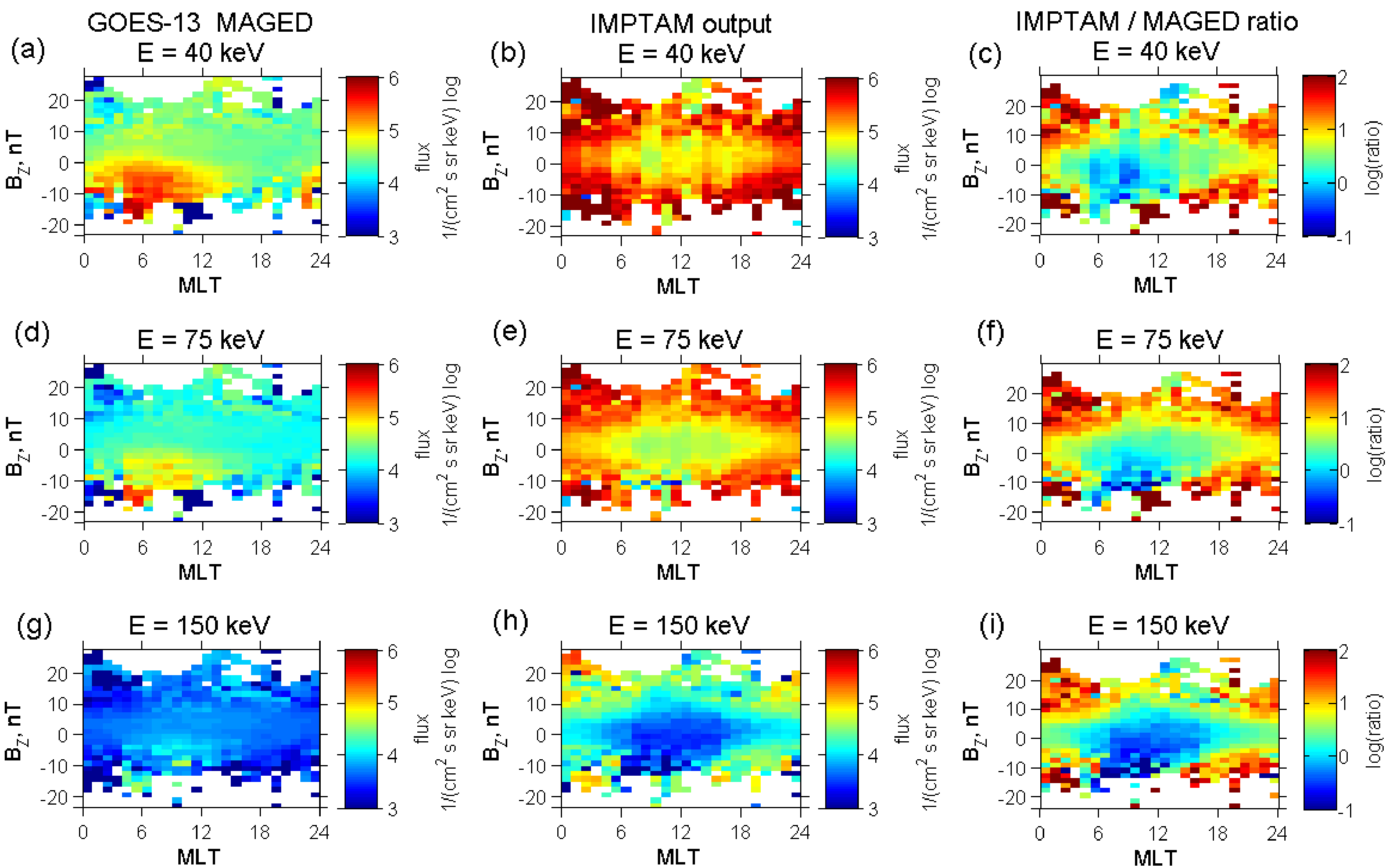


IMPTAM provides the low energy electron flux at all locations and at all satellite orbits, when necessary, in the near-Earth space.

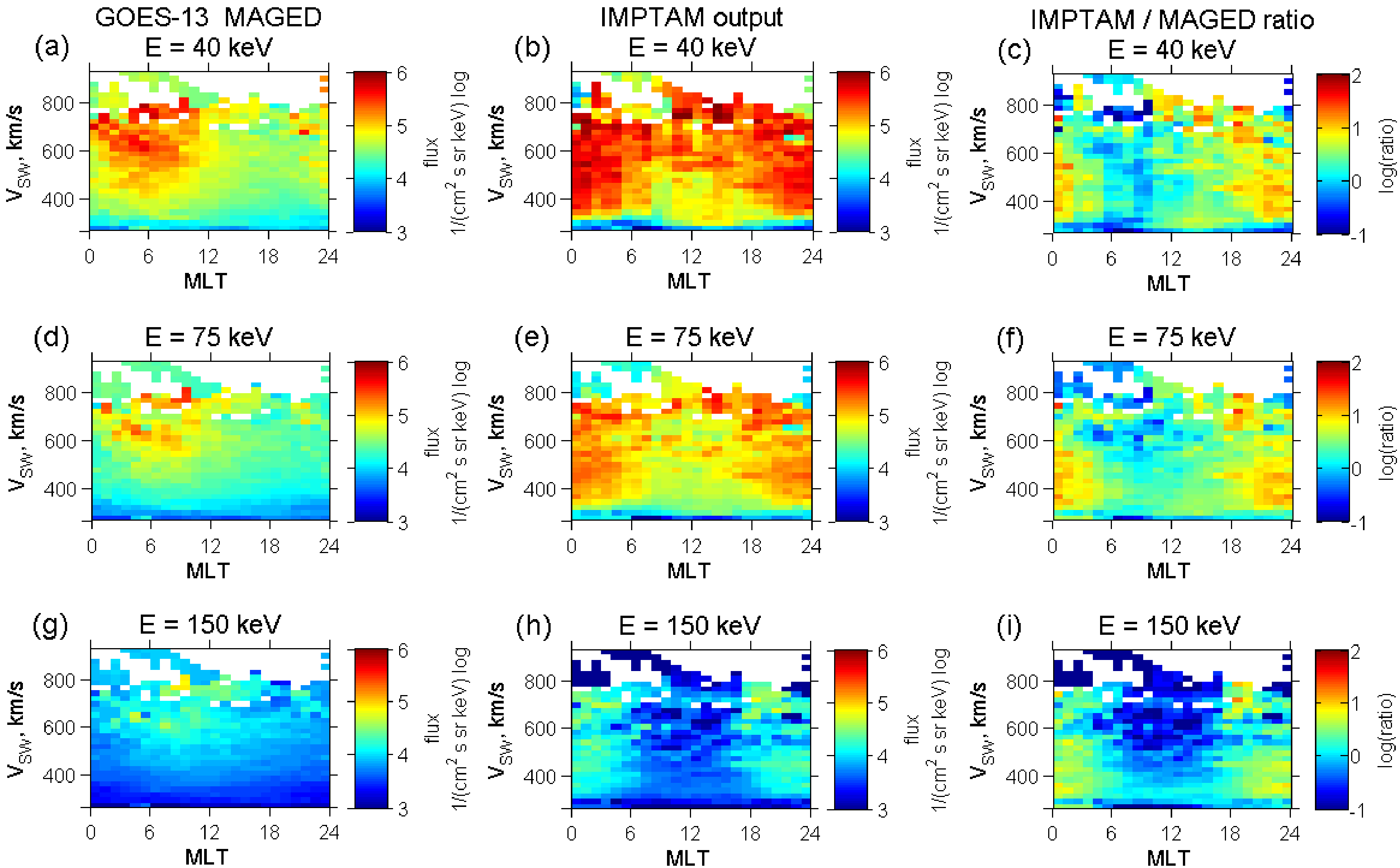


Ganushkina, et al., ***Space Weather*, 2015**.
Ganushkina et al**., *J. Geophys. Res.*, 2014.**
Ganushkina, et al., ***J. Geophys. Res.*, 2013**.

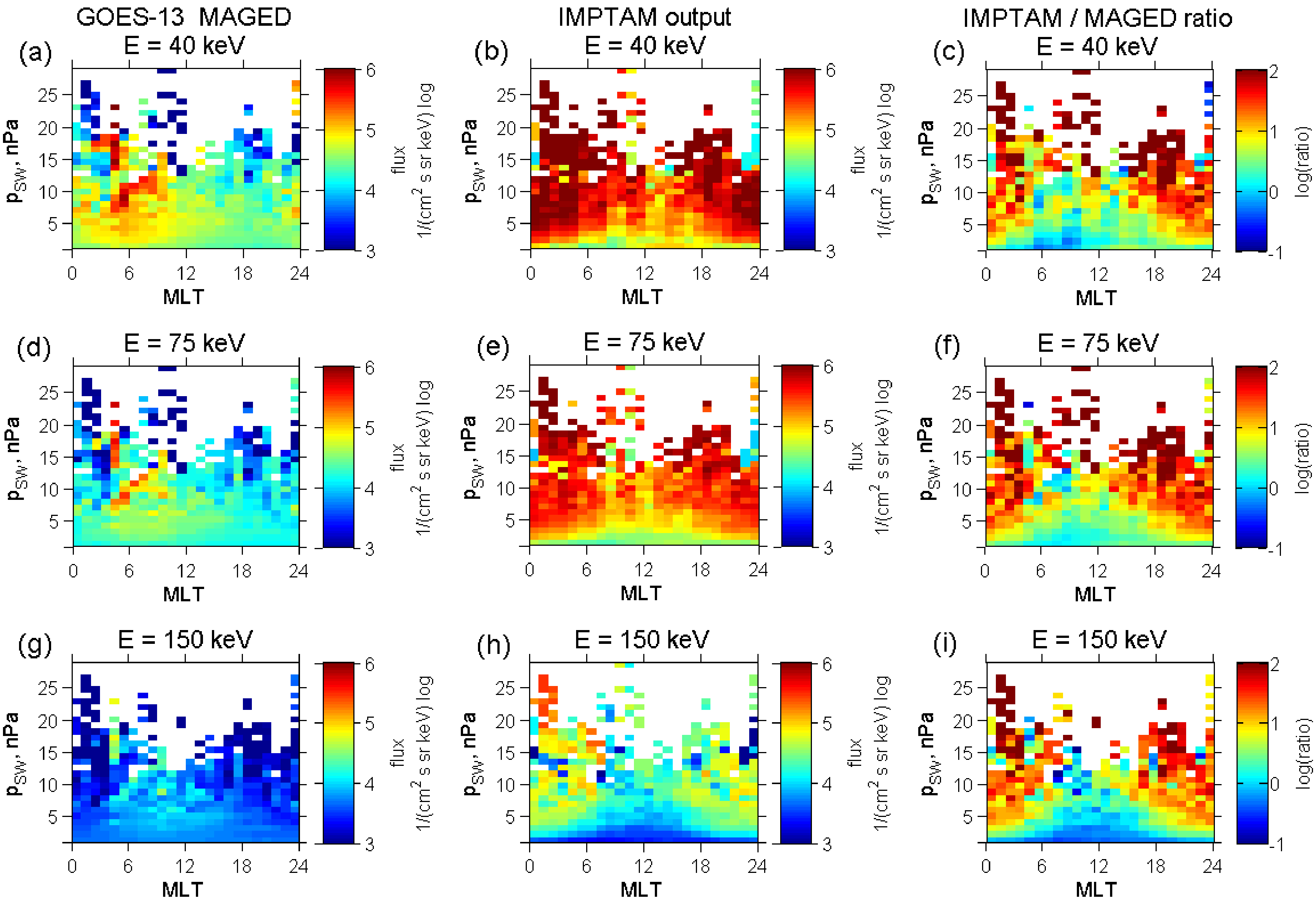
IMPTAM vs GOES 13: IMF Bz



IMPTAM vs GOES 13: Vsw



IMPTAM vs GOES 13: Psw



Notes on IMPTAM performance

In general, the patterns of how the modeled electron fluxes are distributed in MLT dependent on different IMF and solar wind parameters and geomagnetic indices are rather similar to the observed ones.

The location and values of peak fluxes are in a close agreement.

At the same time, the higher modeled fluxes with difference reaching one or two orders of magnitude as compared to the observed ones are obtained for larger values of driving parameters and with the location in the dusk sector.
This is due to the parameterization of models included in IMPTAM and representation of electron losses, especially, on the duskside.

Missing: realistic boundary conditions, proper loss processes, substorms

It is not easy 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?

- **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

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. **S. Dubyagin's talk on Solar Wind Control of the Plasma Sheet Thermal Electrons at r=6-11 Re: Empirical Model**

(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**.

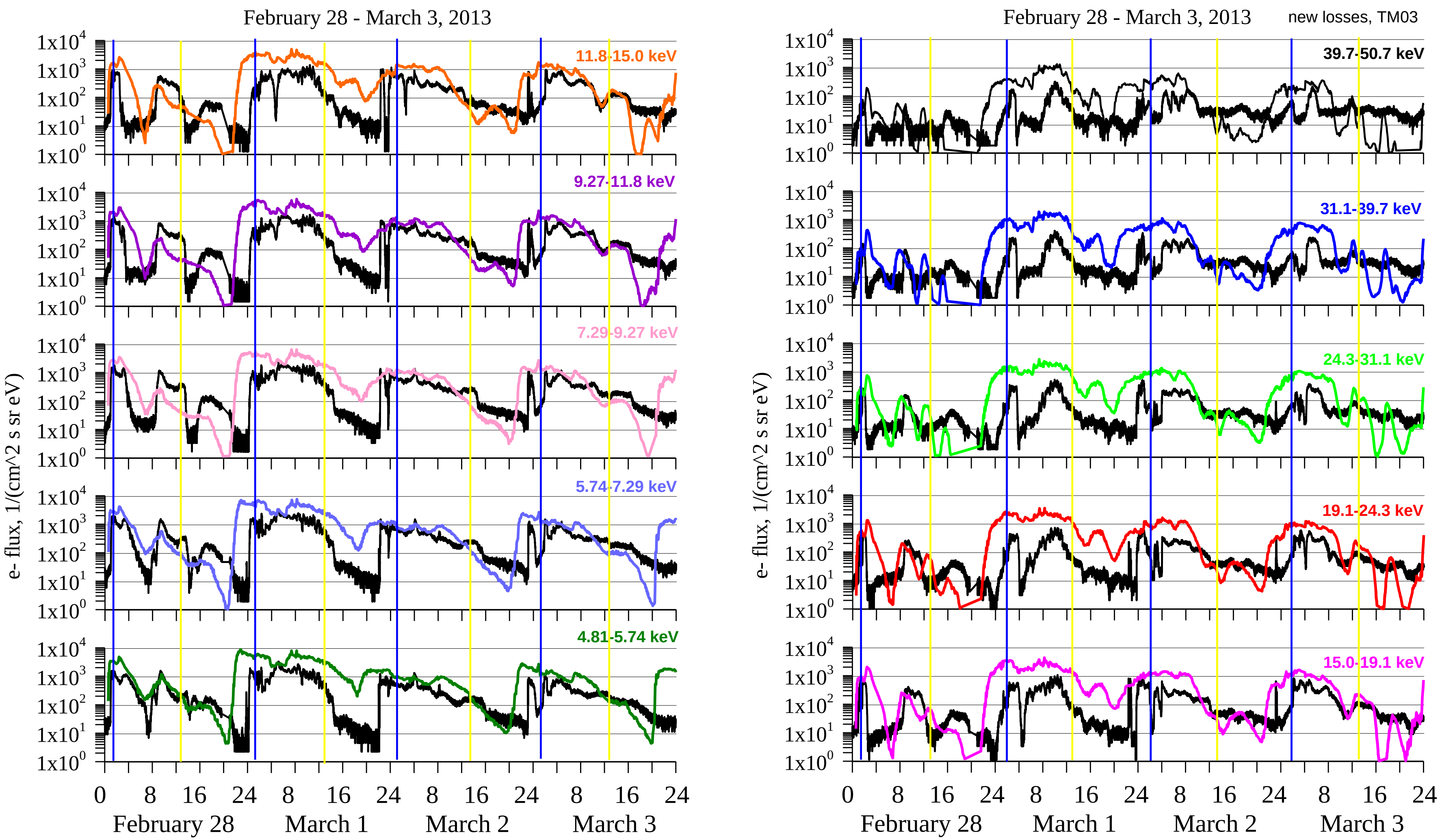
(3) drift velocities;

(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].

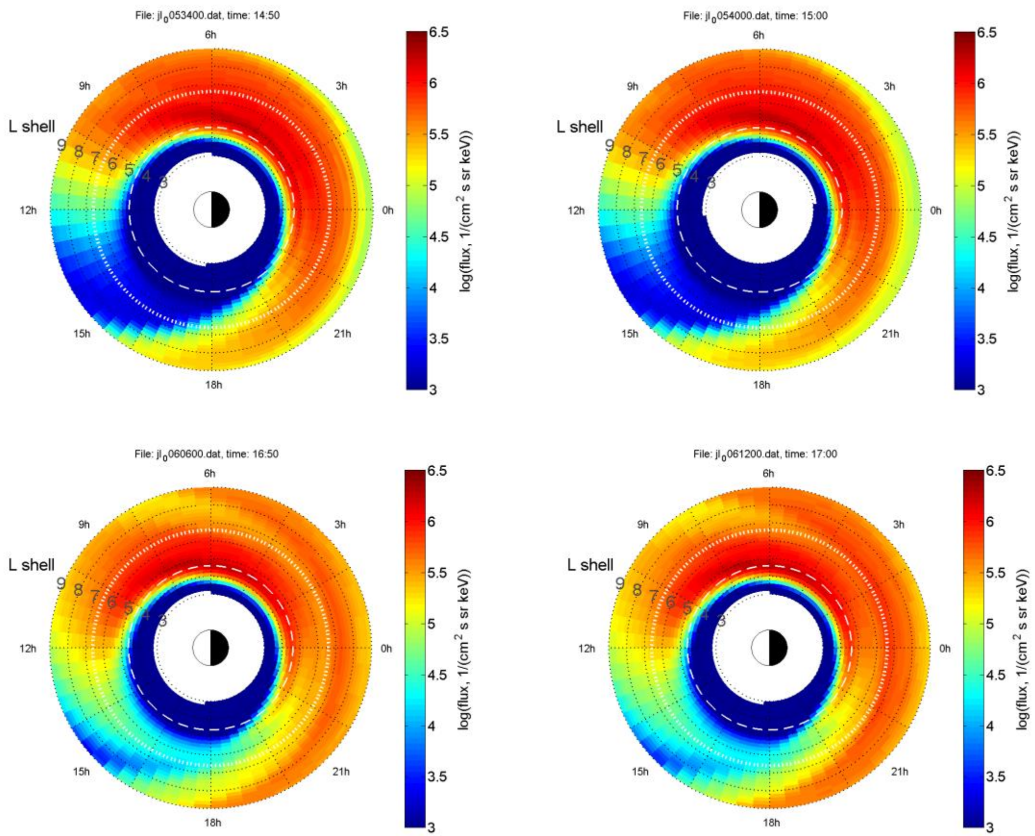
Electron fluxes observed by AMC 12 CEASE II ESA instrument for 15-50 keV energies and modeled

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



IMPTAM at MEO

The IMPTAM output was made as the electron fluxes with energies of 1 to 100 keV at MEO for detected surface charging events at GEO (LANL). It was found that the electron fluxes modeled by IMPTAM at the locations of the observed fluxes at GEO (LANL location) reached their maxima at MEO in about 2 hours and were situated at around 06 MLT with values of 1 order of magnitude higher than at GEO.



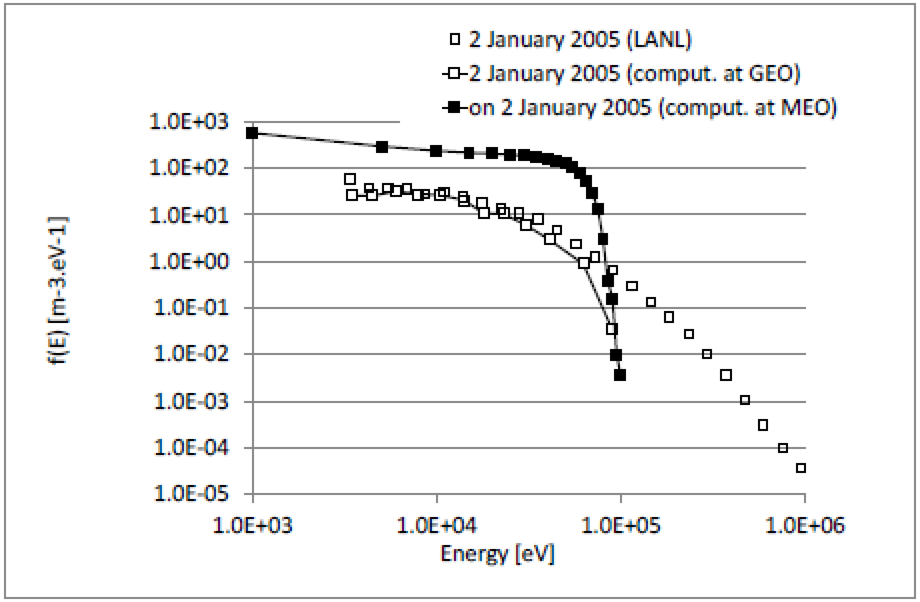
October 25, 2003, surface charging event recoded during the recovery phase of substorm

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

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