Specification of electron radiation environment at GEO and MEO for surface charging estimates

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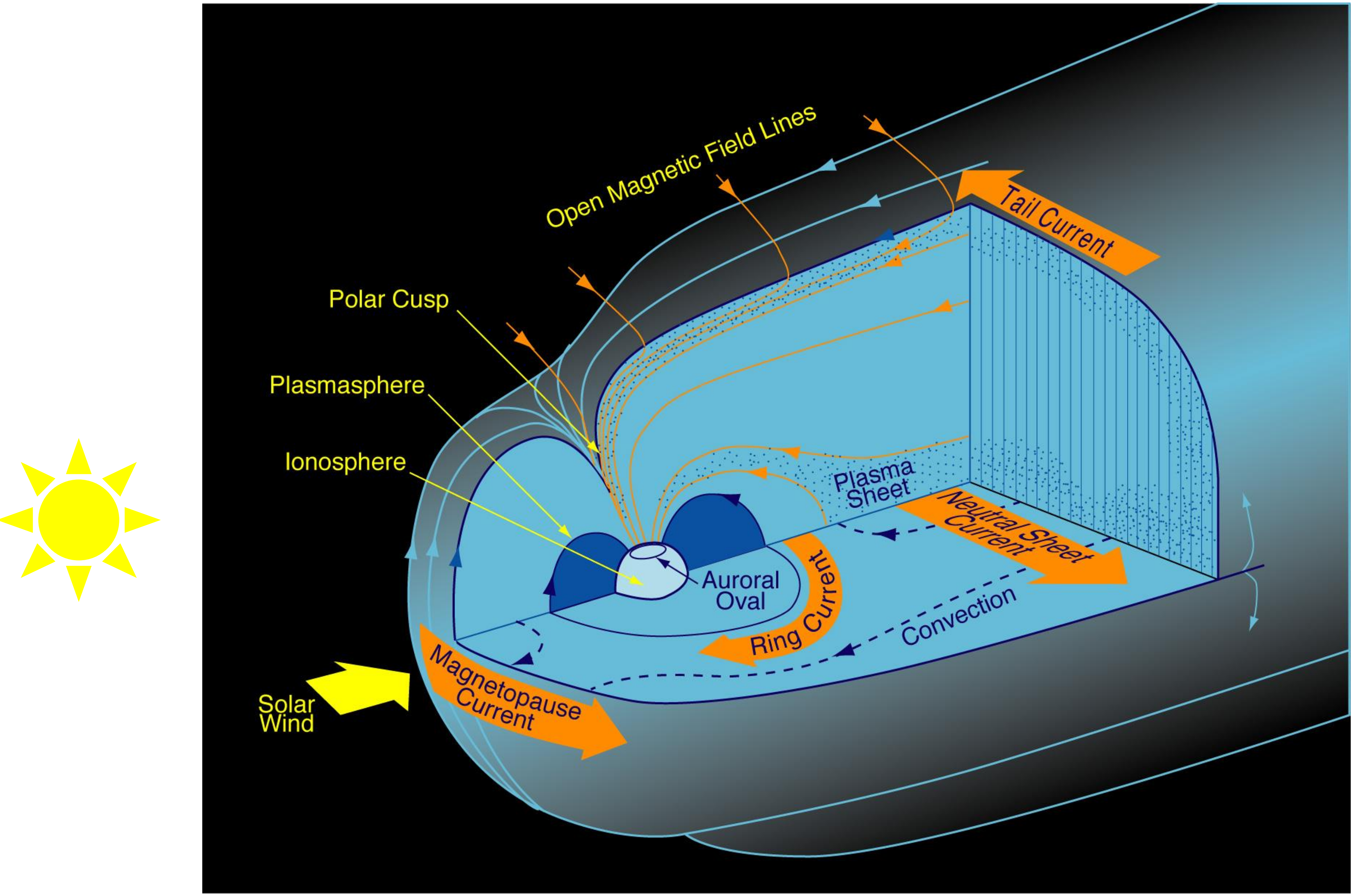
Isradynamics 2018, Dynamical Processes in Space Plasmas

Israel, 22-29 April 2018

Large-scale structure of the Earth’s magnetosphere



What is the interest in studying keV electrons in the inner magnetosphere?

- The distribution of low energy electrons population (10 to few hundreds of keV) constitutes the **seed population** further accelerated to MeV energies, critically important for **radiation belt** dynamics

  Energetic charged particles trapped in the **radiation belts** are a major source of damaging **space weather effects** on space- and ground-based assets.

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

  electrostatic discharges causing **EM interferences** or local degradations, sustained **arcs** and system or mission destruction in the worst cases.

  Individual examples of **permanent losses due to charging in orbit**:

  - loss of the Japanese spacecraft ADEOS-II

  - 8 month outage and drift of Galaxy 15

  - large permanent power losses on PanAmSat 6 and Tempo 2 spacecraft

General definition of the effects of space weather

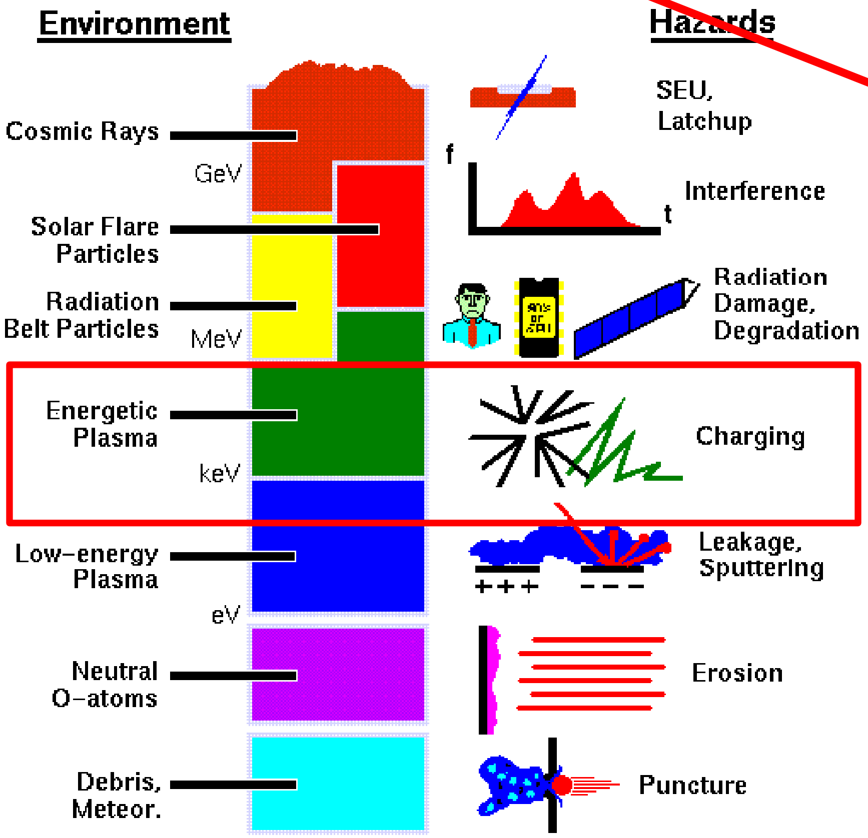
Where do the keV electrons come in?

Time-varying conditions in the space environment that may

- **be hazardous to technological systems in space or on ground**
- endanger human health or life

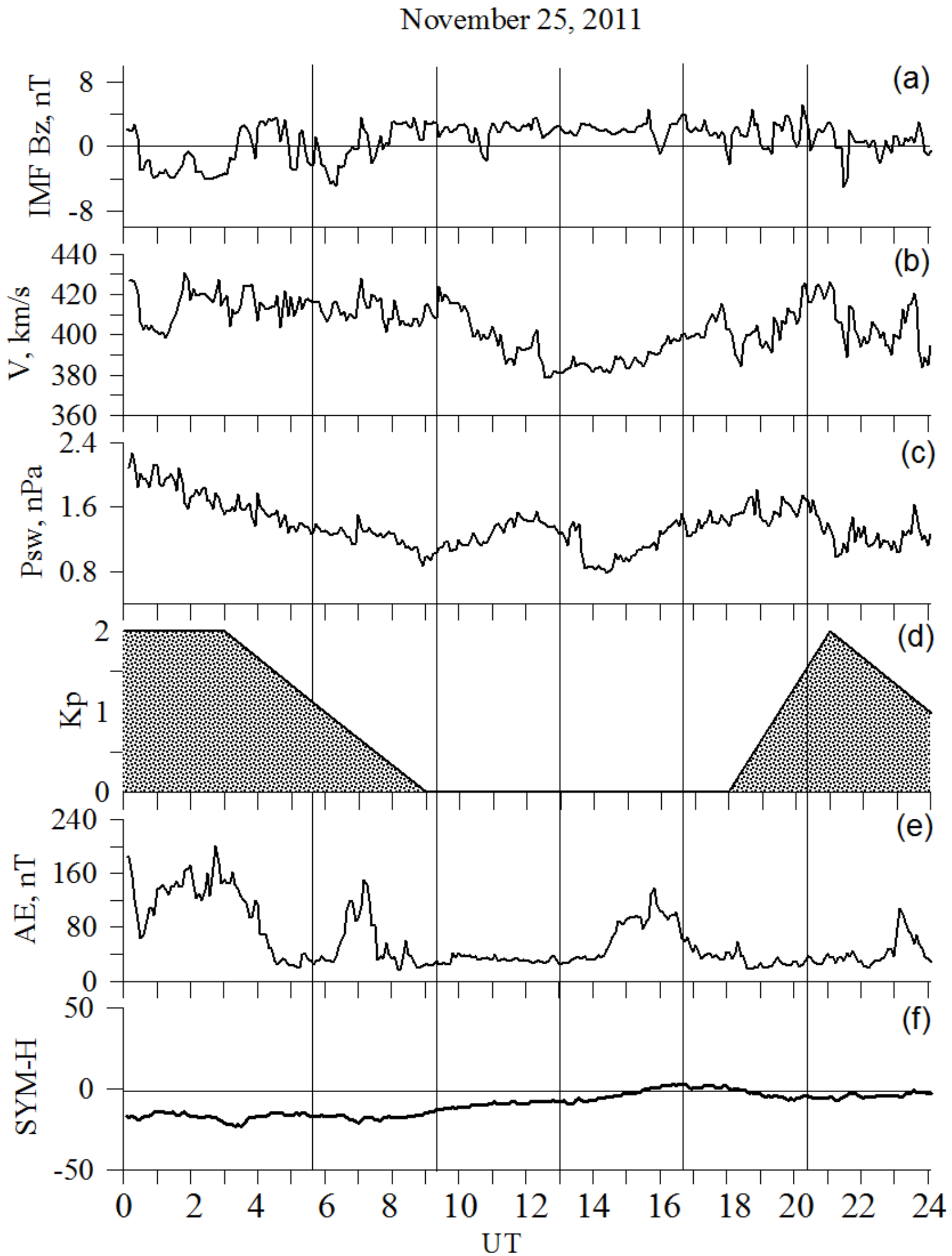
Surface charging can cause significant damage and spacecraft anomalies (*Whipple*, 1981; *Garrett*, 1981; *Purvis et al*., 1984; *Frezet et al*., 1988; *Koons et al*., 1999; *Hoeber et al*., 1998; *Davis et al*., 2008).

Source: European Space Agency, Space Environment and Effects Analysis Section



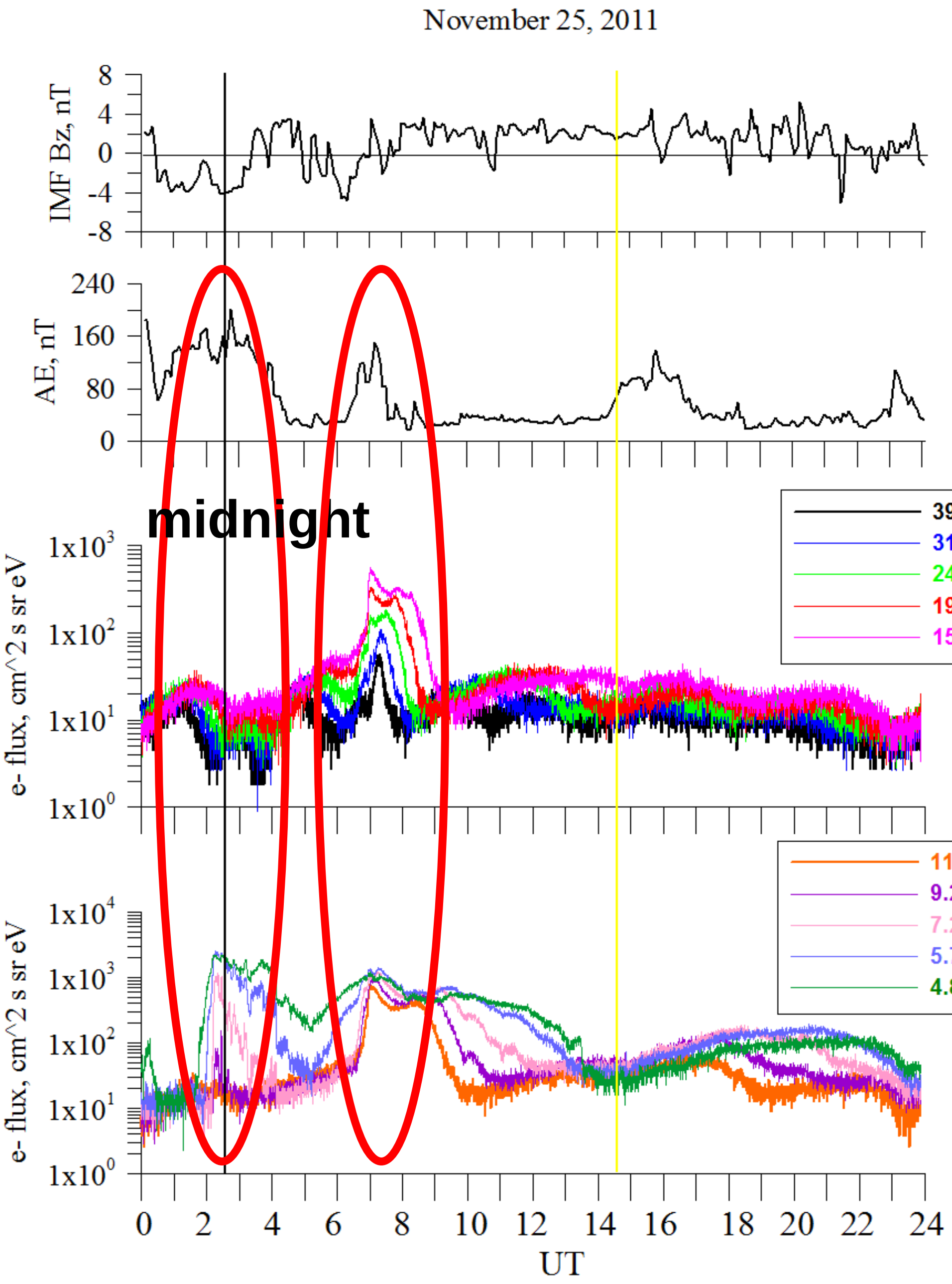
keV electrons for surface charging

Non-storm variations 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.

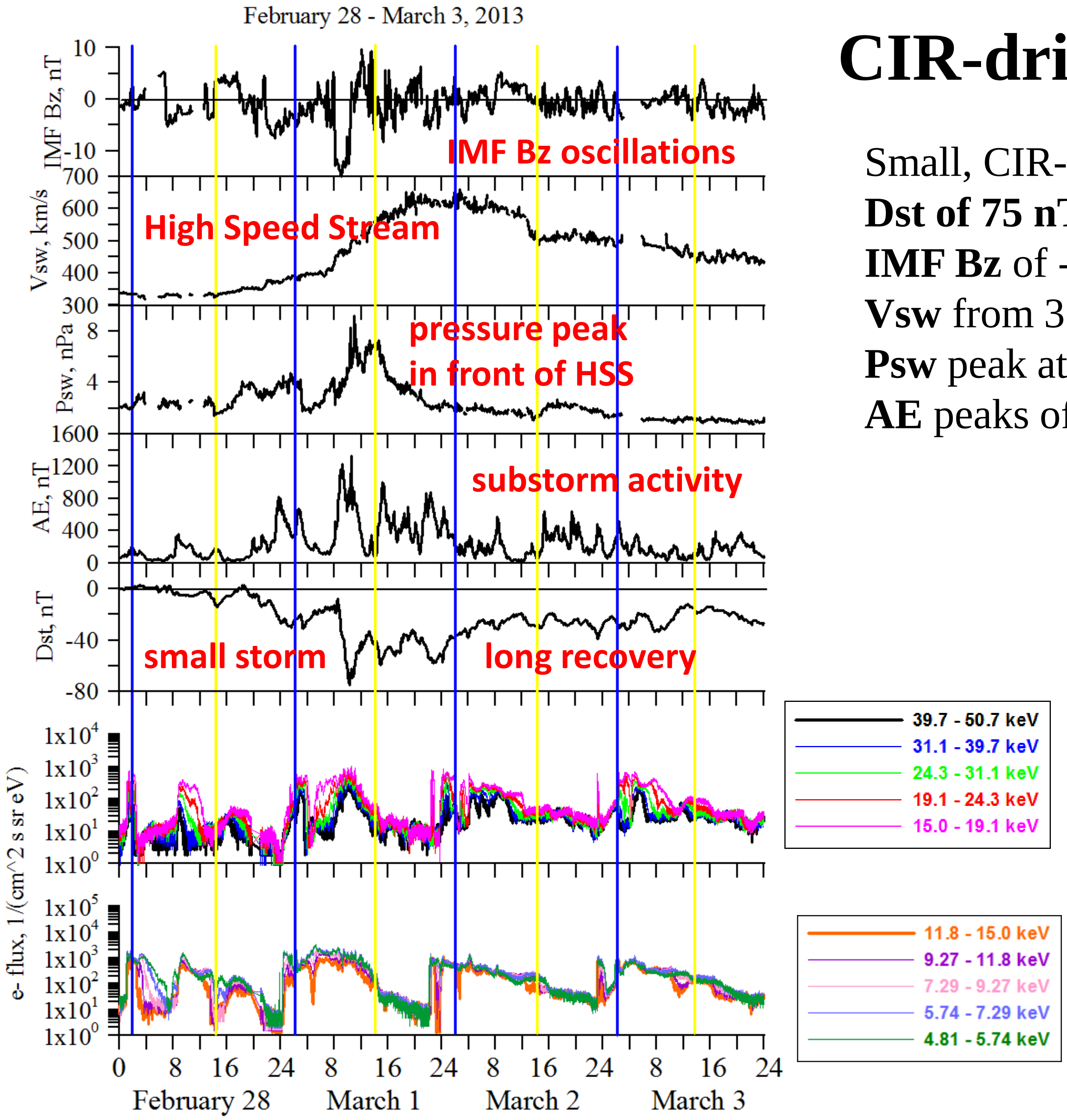
- **Flux increases** are related to **AE peaks** only (less than 200 nT, small, **isolated substorms**)

- 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

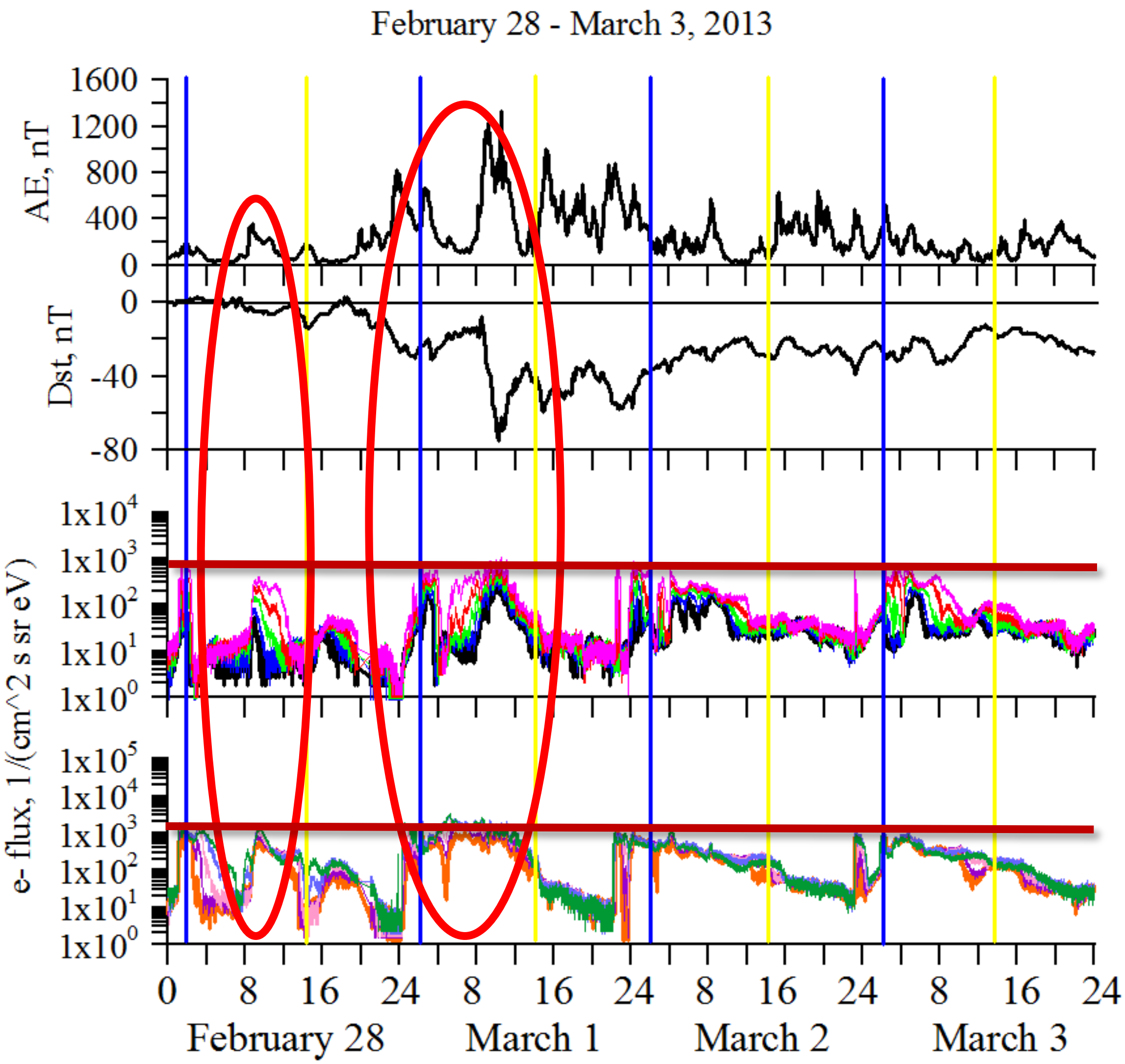
Not a unique case

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

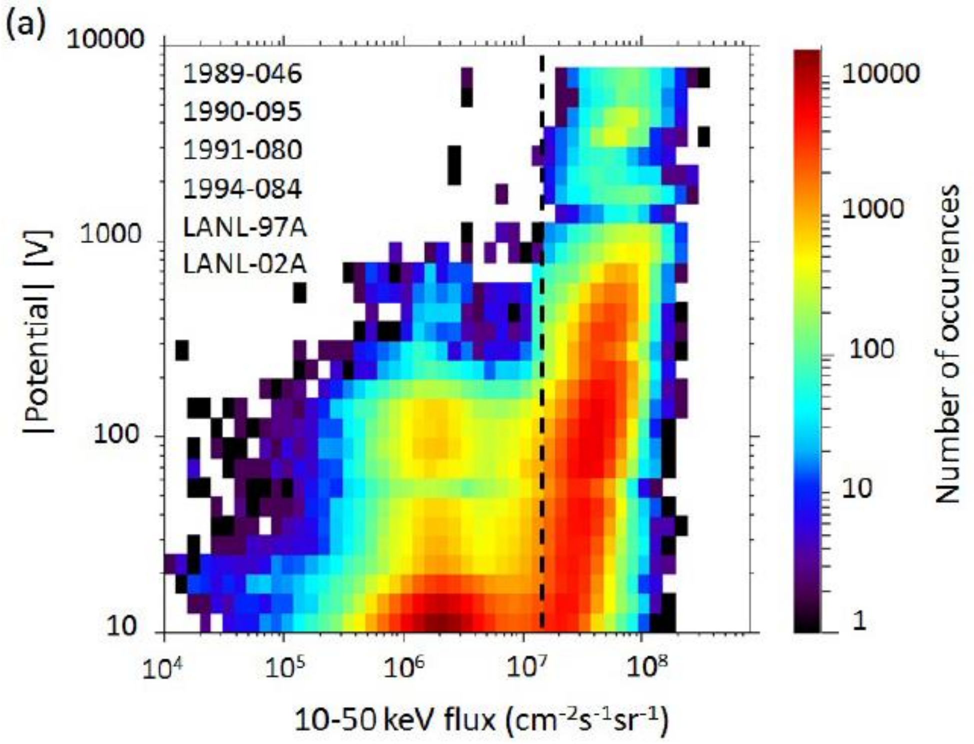
- same order of increase for AE = 800 nT and even for 1200 nT

Analysis of LANL data

Matéo-Vélez et al., Journal of Spacecraft and Rockets, 2016,
Matéo-Vélez et al., Space Weather, 2017

15 years of Los Alamos National Laboratory (LANL) data at GEO from September 1989 to November, 2005 from 6 spinning satellites:
1989-046, 1990-095, 1991-080, 1994-084, LANL-97A and LANL-02A.

LANL data (ions and e-) used:
MPA: from 100 eV to 40 keV
SOPA: from 50 keV to 1.3 MeV
ESP: from 1 to several MeV
The time resolution used is 86 seconds.
The spacecraft potential routinely provided by LANL



The best correlation with potentials is for 10-50 keV electrons (consistent with the 8 keV and 9 keV thresholds from *Thomsen et al.* [2013], *Ferguson et al.* [2015]

The 10 to 50 keV electron flux thresholds as an indicator of surface charging risks at GEO.

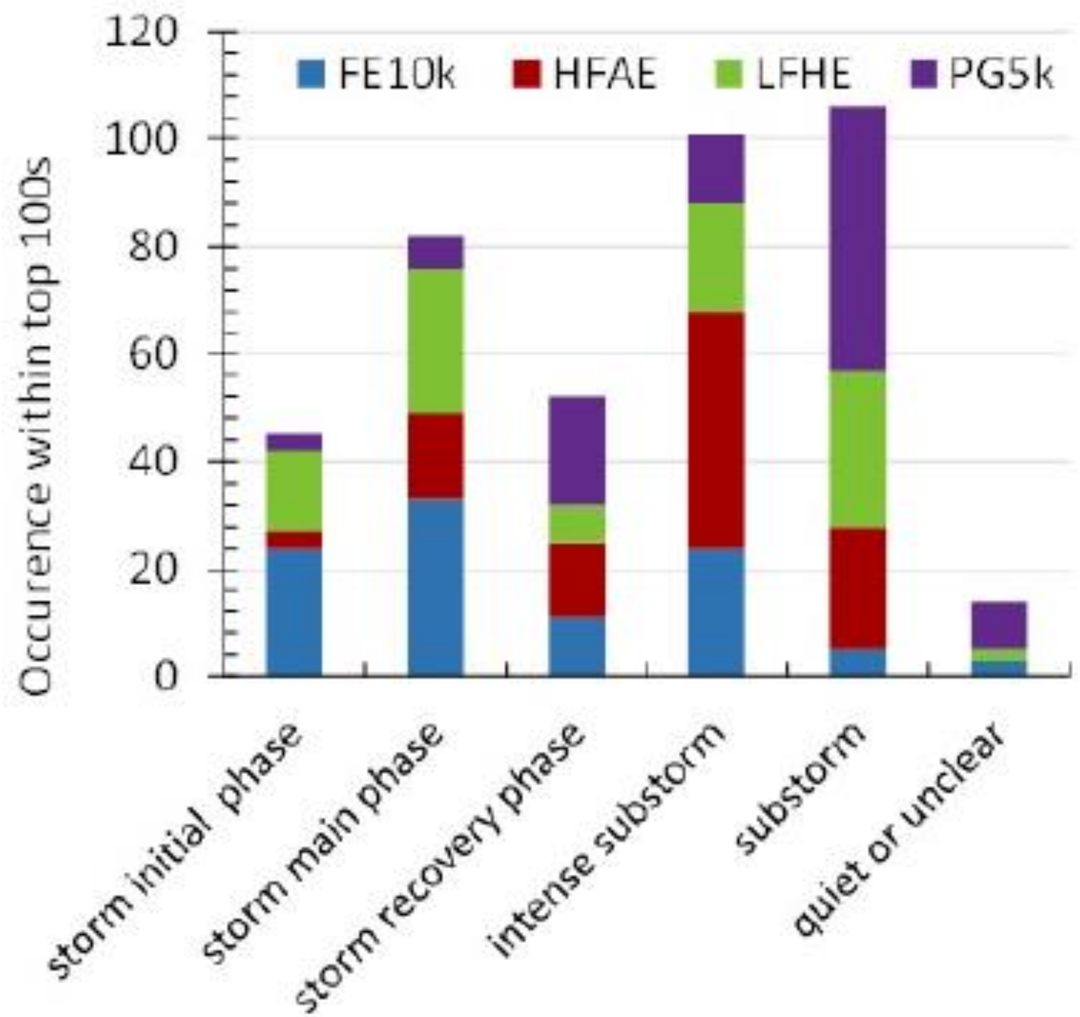
Four criteria for worst-case environments from LANL data

Criteria for defining severe conditions developed based on integral fluxes and measured spacecraft potential.
Fluxes averaged over 15 minutes, because severe conditions need to remain over a few minutes for differential charging to occur in geosynchronous orbit.

(**FE10k**): highest Fluxes of electrons at Energies above 10 keV
(**HFAE**): Highest Fluxes at All Energies (high fluxes at both <50 keV and > 200 keV which is related to charge deposited both at the surface and in the bulk of covering insulators);
(**LFHE**) : high fluxes at low energies together with a Low Flux at High Energy (high fluxes at <50 keV and low fluxes at >200 keV which is related to surface charging);
(**PG5k**) : longest events with a Potential Greater than 5 kV (in absolute) (events associated with large negative potential with plenty of time for differential charging to occur).
400 events with worst-case environments were identified

Comparison done with guidelines given by
1. Standard **ECSS-E-20-06** “Spacecraft charging” of European Cooperation for Space Standardization, *https://www.spacewx.com/Docs/ECSS-E-ST-10-04C_15Nov2008.pdf*
2. **NASA-HDBK-4002A** Mitigating In-Space Charging Effects Guidelines, *http://standards.globalspec.com/std/1309224/nasa-hdbk-4002*

Surface charging events vs. geomagnetic conditions



FE10k events: all storm phases and intense isolated substorms;
HFAE events: substorms;
LFHE events: equally distributed between storms and substorm periods;
PG5k events: storm recovery and moderate substorms.

These results show that
it is not necessary
to have extreme conditions to get severe spacecraft surface charging.

Matéo Vélez et al., Space Weather, *2017*

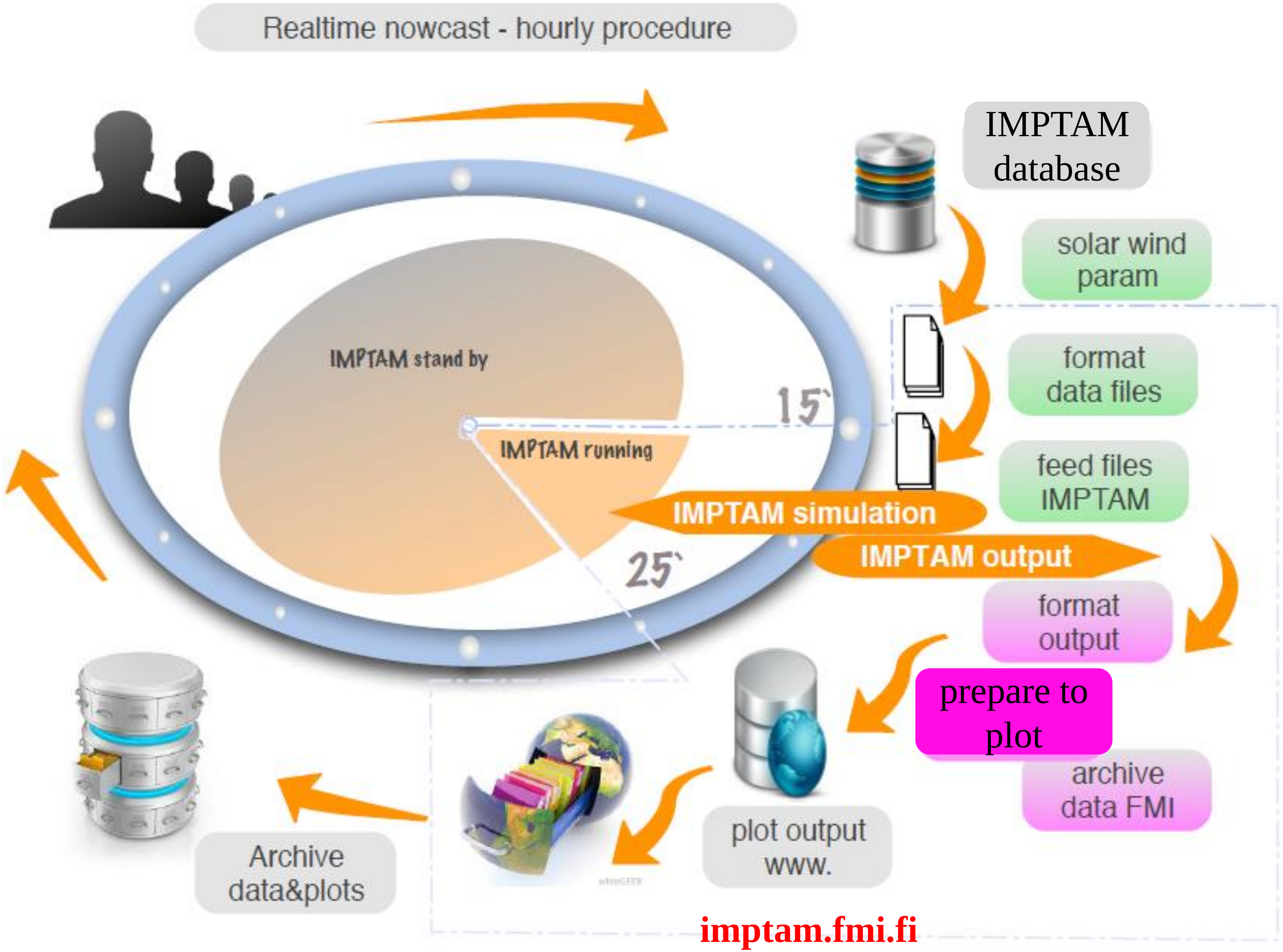
Inner Magnetosphere Particle Transport and Acceleration Model

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: TS05 (Dst, Psw, IMF By and Bz, and Wi, i = 1, 6)
Electric field model: Boyle (Vsw, IMF B, By, Bz)
Boundary conditions: n and T by Dubyagin et al. (2016) (Vsw, IMF Bz, Nsw)
Losses given as electron lifetimes: newly developed BAS lower and upper band chorus diffusion model (**Kp, magnetospheric magnetic field)**

keV electrons in real time online (IMPTAM model)



IMPTAM database

solar wind param

format data files

feed files IMPTAM

format output

prepare to plot

archive data FMI

imptam.fmi.fi

http://csem.engin.umich.edu/tools/imptam/

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**

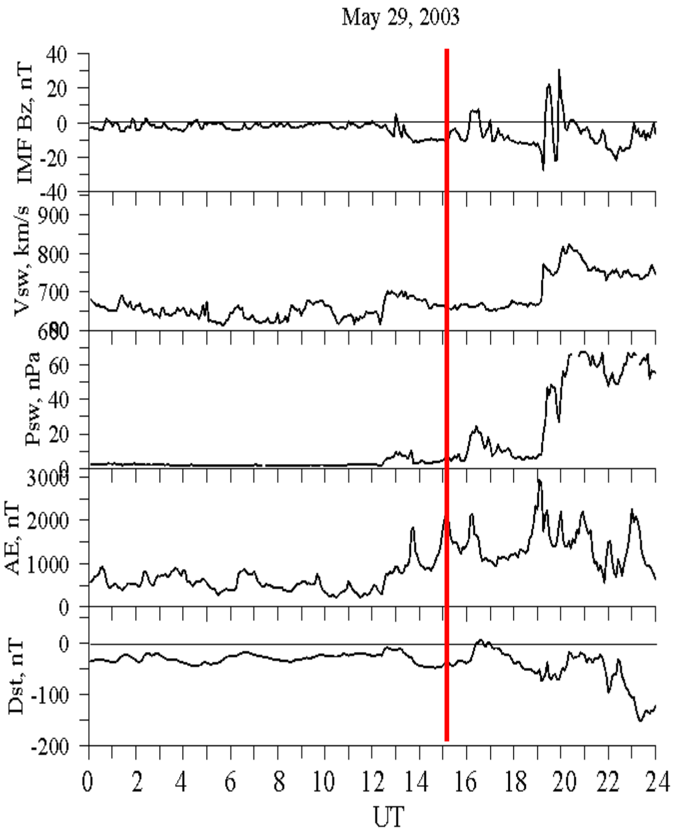
What does the model provide?

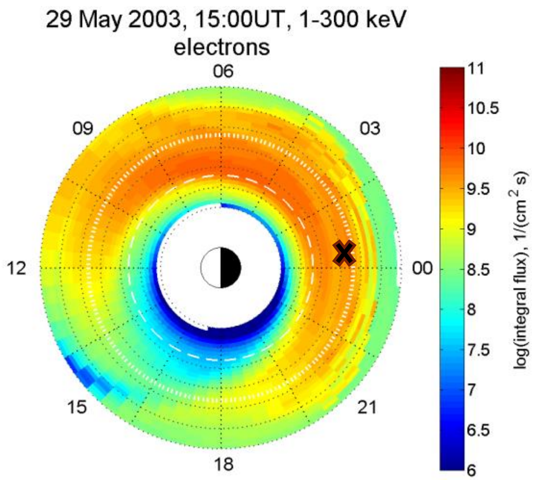
The presented model provides the low energy electron flux at all locations and at all satellite orbits, when necessary, in the near-Earth space.

What are the drivers of the model?

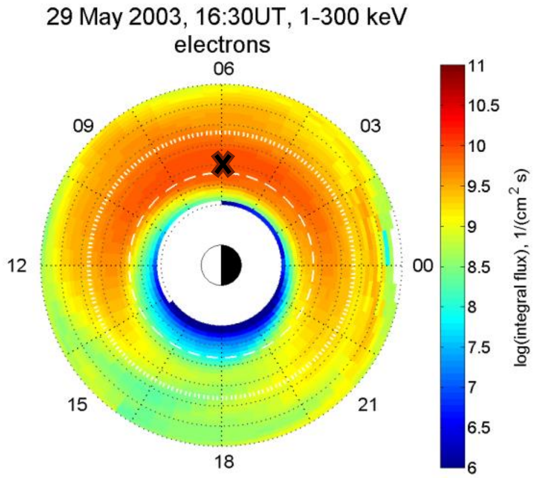
The model is driven by the real time solar wind and Interplanetary Magnetic Field parameters with 1 hour time shift for propagation to the Earth's magnetopause, and by the real time geomagnetic activity index Dst.

Severe Events for Surface Charging: May 29, 2003





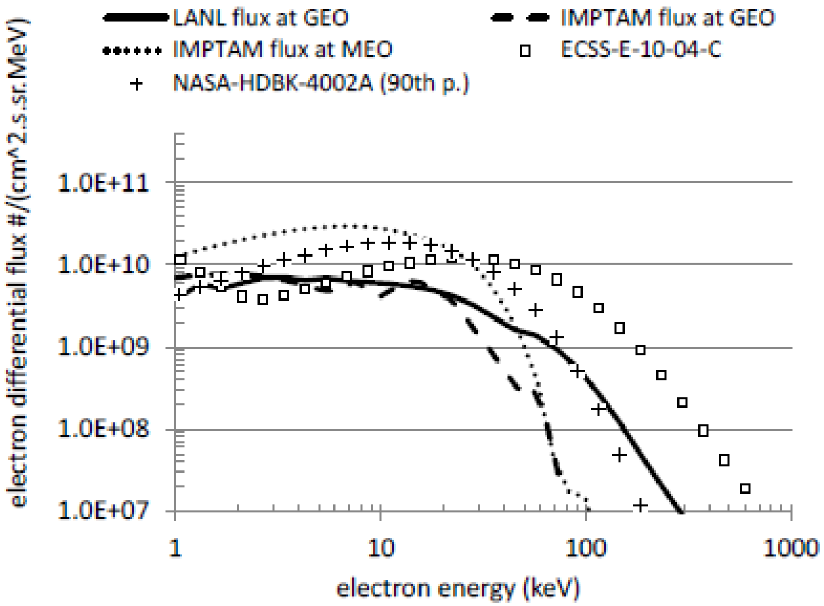
IMPTAM electron fluxes at LANL surface charging event at GEO



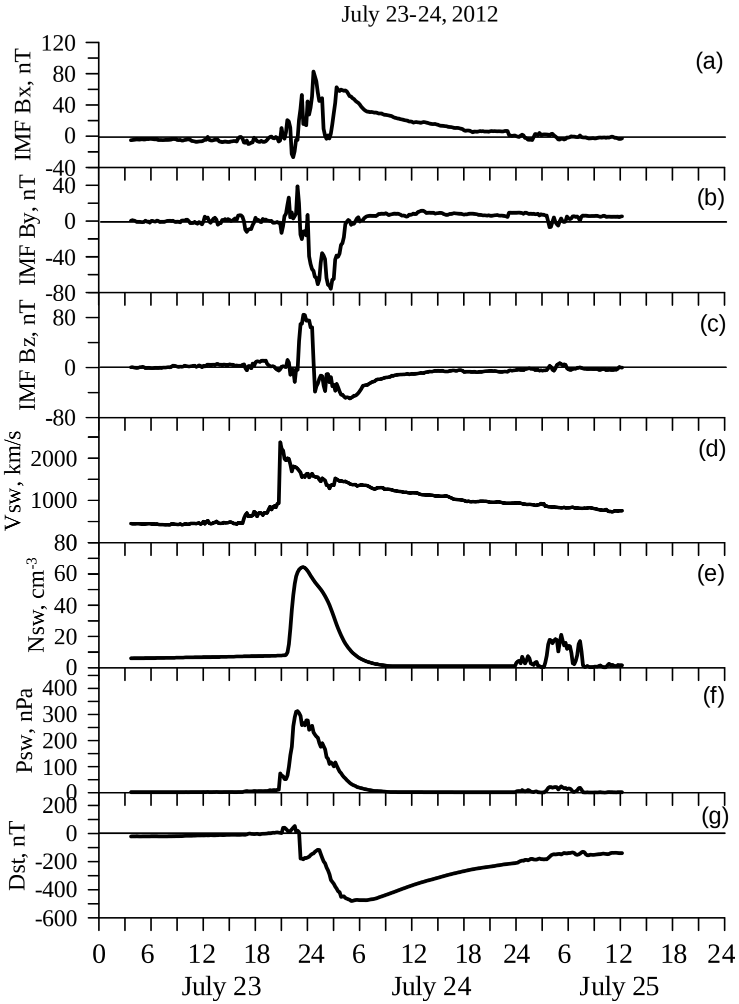
IMPTAM electron fluxes at maximum flux at MEO

Top 100 15 minutes worst case of HFAE, at LANL-1994-084 at 150106 UT, 0.7 MLT; prolonged Dst<0, intense substorm, AE of 2000 nT.

IMPTAM fluxes globally reproduce LANL
Max IMPTAM electron flux at MEO exceeds GEO flux and ECSS and NASA worst-cases by a factor of 2 to 5.



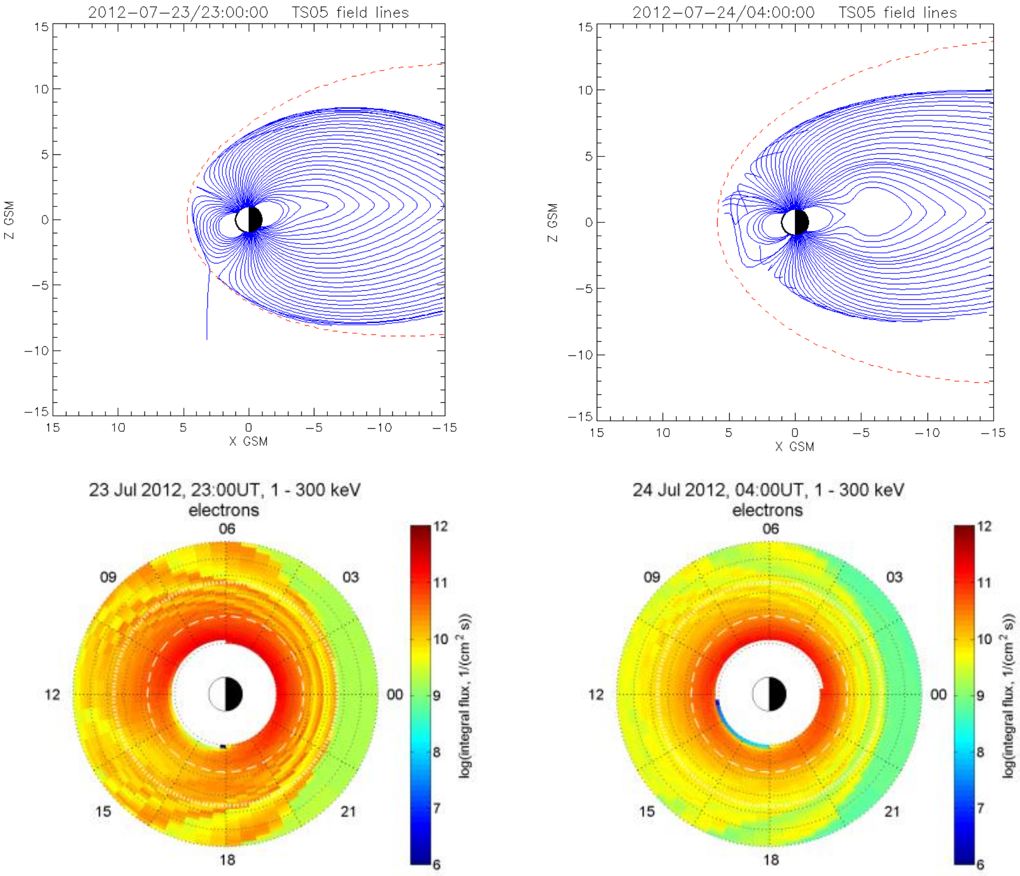
Large CME-driven storm, July 23-24, 2012
(event that missed the Earth)



Dst = -500 nT, Psw=300 nPa, Vsw = 3000 km/s

1st Dst drop

Dst min

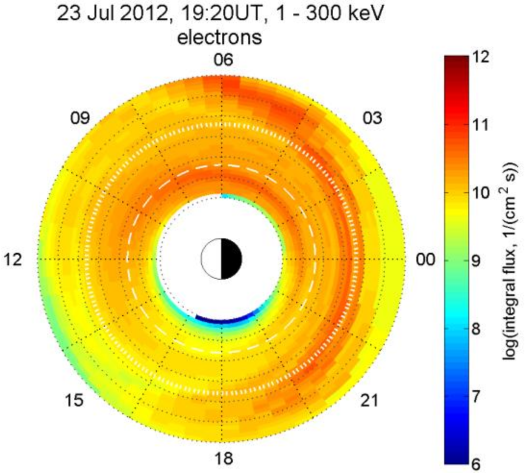


STEREO-A observations,
Wang-Sheerley-Arge, ENLIL model,
Temerin and Li (2006) Dst predictive model

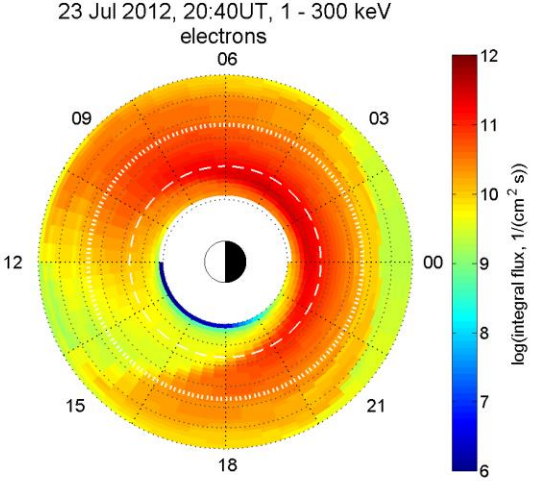
Magnetosphere becomes so compressed on the dayside and so stretched on the nightside that electrons are lost, they happen to be on larger L-shells.

Extreme Events for Surface Charging: July 23-24, 2012

In the beginning of the storm IMPTAM was able to output reasonable electron fluxes at closed magnetic field lines in the inner magnetosphere.

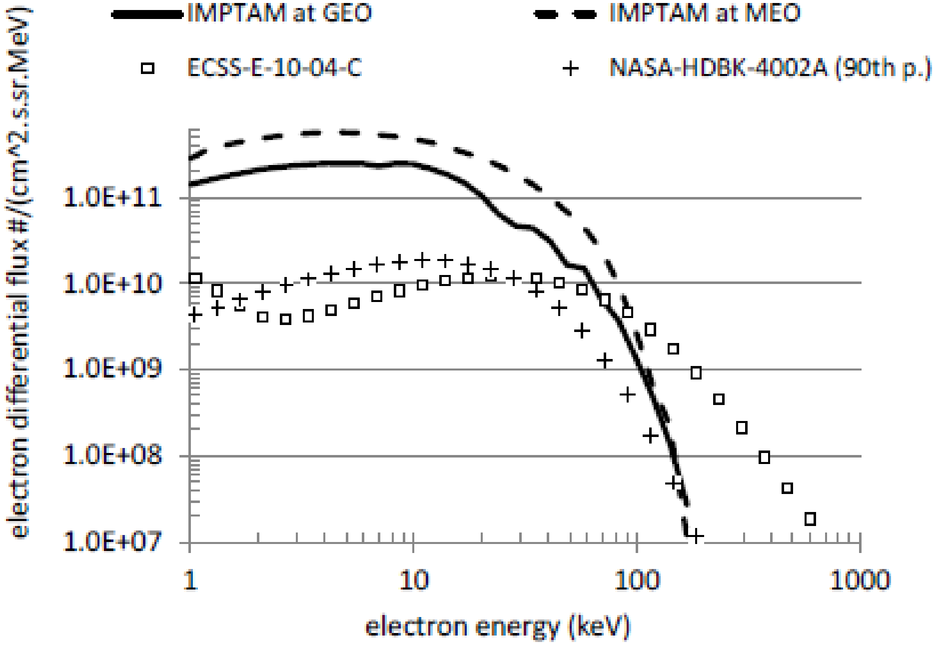


The maximum electron flux reached at GEO: July 23, 2012, at 1920 UT at MLT 2.4**.**



The maximum electron flux reached at MEO: July 23, 2012, at 2040 UT, 6.4 MLT.

Max IMPTAM electron flux at MEO is 6 times higher than that for the similar type of the event (beginning of the storm main phase on April 5, 2004).
The flux is also well above the ECSS and NASA worst-cases.



Summary

- ✓ keV electrons vary significantly with geomagnetic activity. It is challending to model them accurately.
- ✓ It is NOT necessary to have even a moderate storm for significant surface charging event to happen. Substorms are important.
- ✓ All types of the worst-case surface charging events developed based on the analysis of LANL particle data at GEO were modeled using IMPTAM for electrons within 1-100 keV
- ✓ IMPTAM electron fluxes are comparable to the observed fluxes by LANL at GEO
- ✓ Max IMPTAM electron flux at MEO exceeds the GEO flux and the ECSS and NASA standards for worst-cases by a factor of 2 to 10.
- ✓ The event that missed the Earth on July 23-24, 2012 is the kind of space weather extreme conditions that could significantly overpass the ECSS and NASA standards. Caution is advised due to the difficulty of modeling of such events.