



Low energy electrons in the inner Earth's magnetosphere

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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.

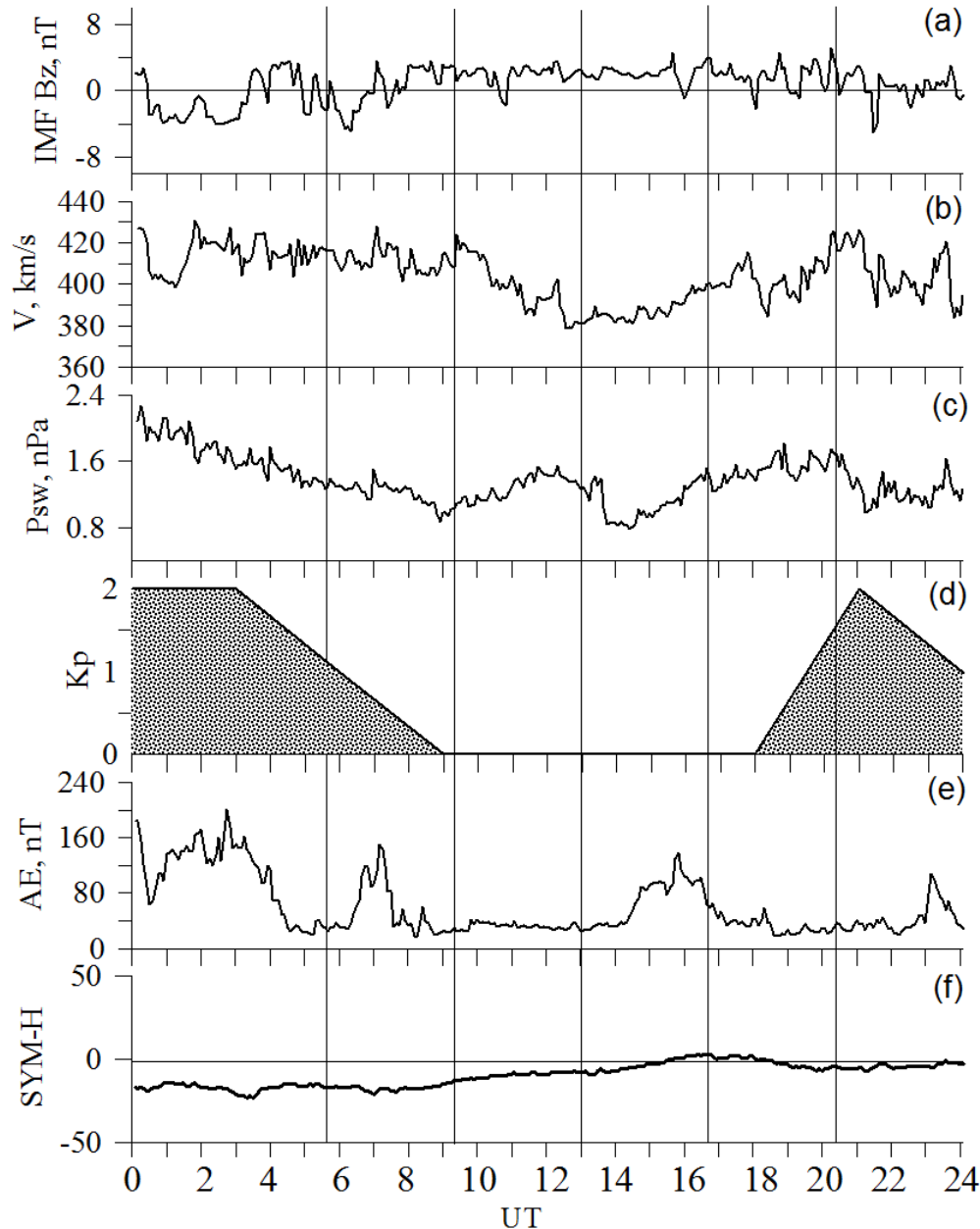
- Surface charging by electrons with < 100 keV can cause significant damage and spacecraft anomalies

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

November 25, 2011

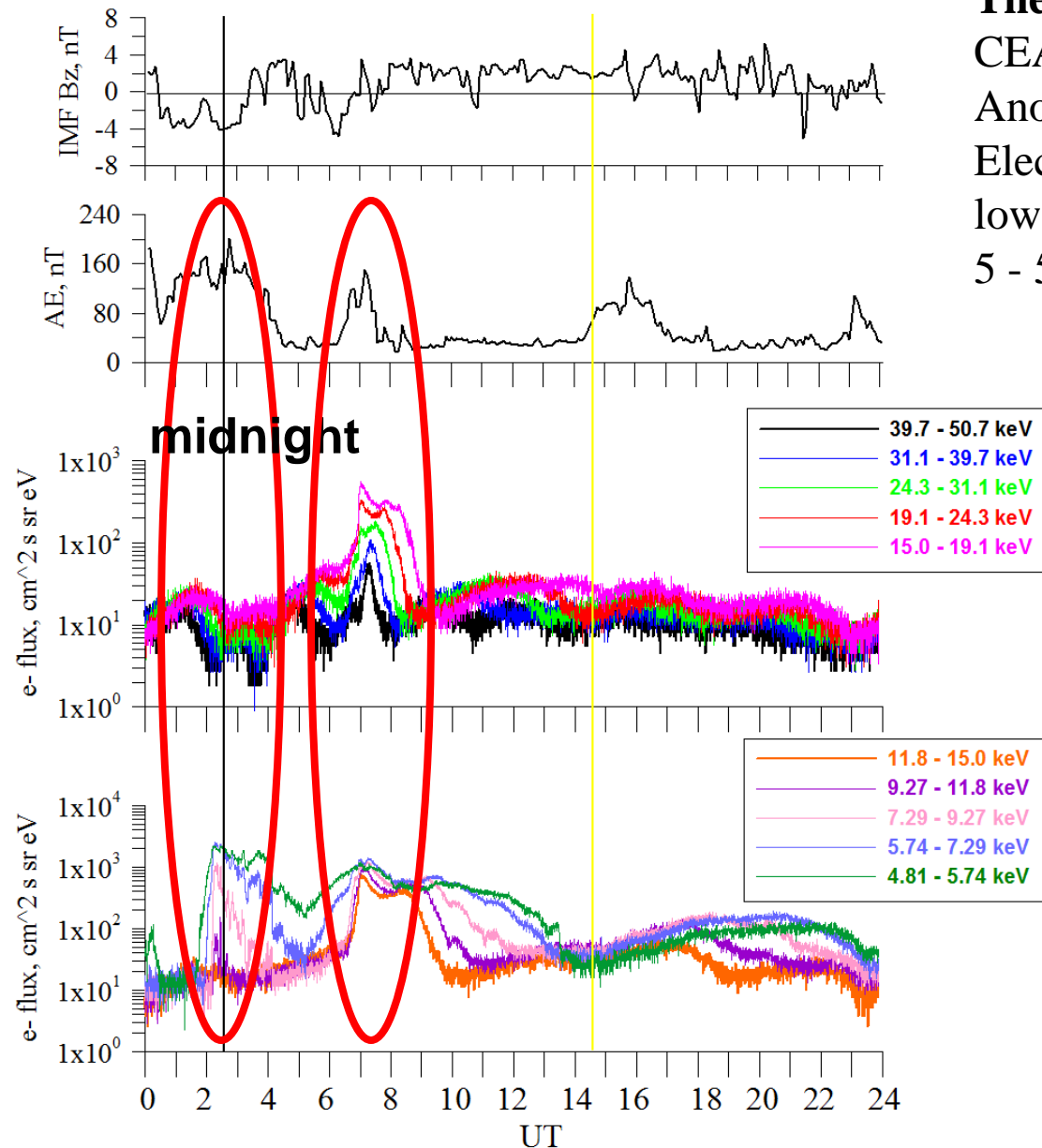


Non-storm variations of low energy electron fluxes at geostationary orbit

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.

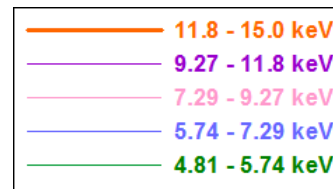
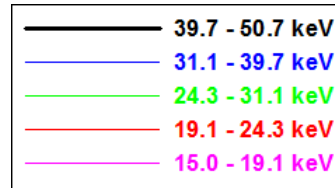
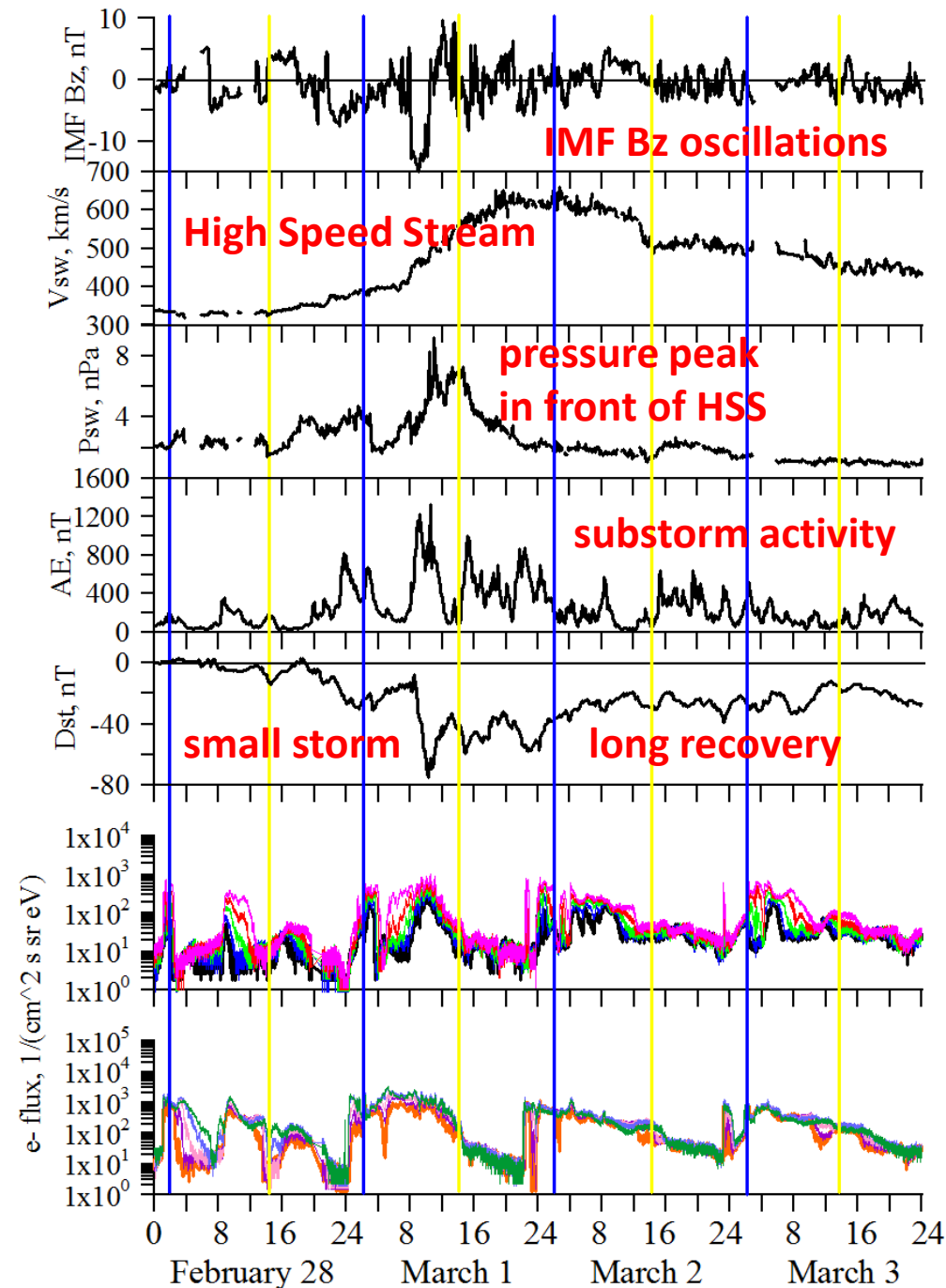
- **Flux increases** are related to **AE peaks** only (less than 200 nT, small, **isolated substorms**)
- The lower the energy, the larger the flux
- Electrons of different channels behaves differently:
 - 1st peak (AE=200 nT) at midnight seen for energies > 11 keV
 - 2nd peak (AE=120 nT) at dawn, increase in all energies

Not a unique case

February 28 - March 3, 2013

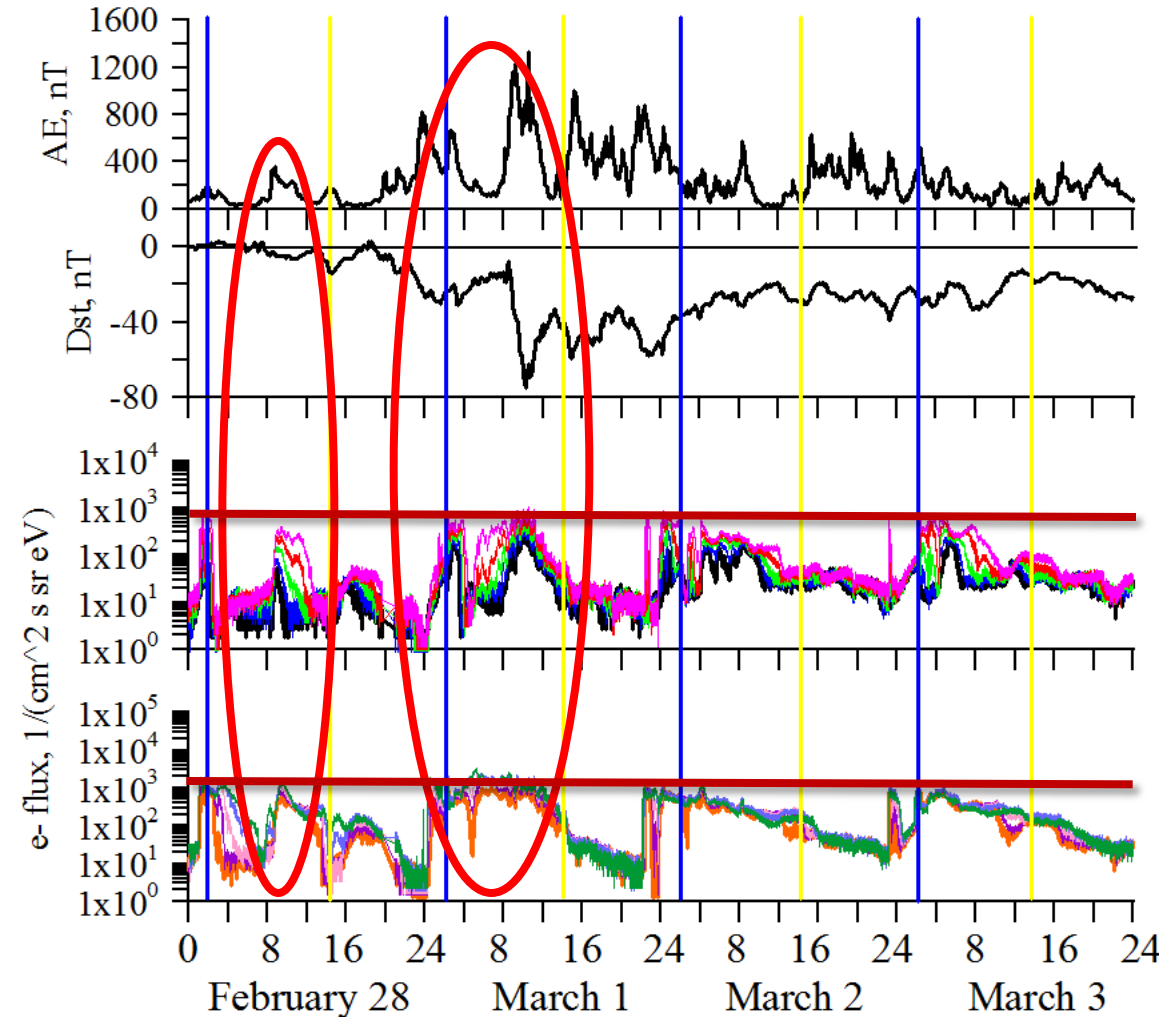
CIR-driven storm

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

February 28 - March 3, 2013



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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

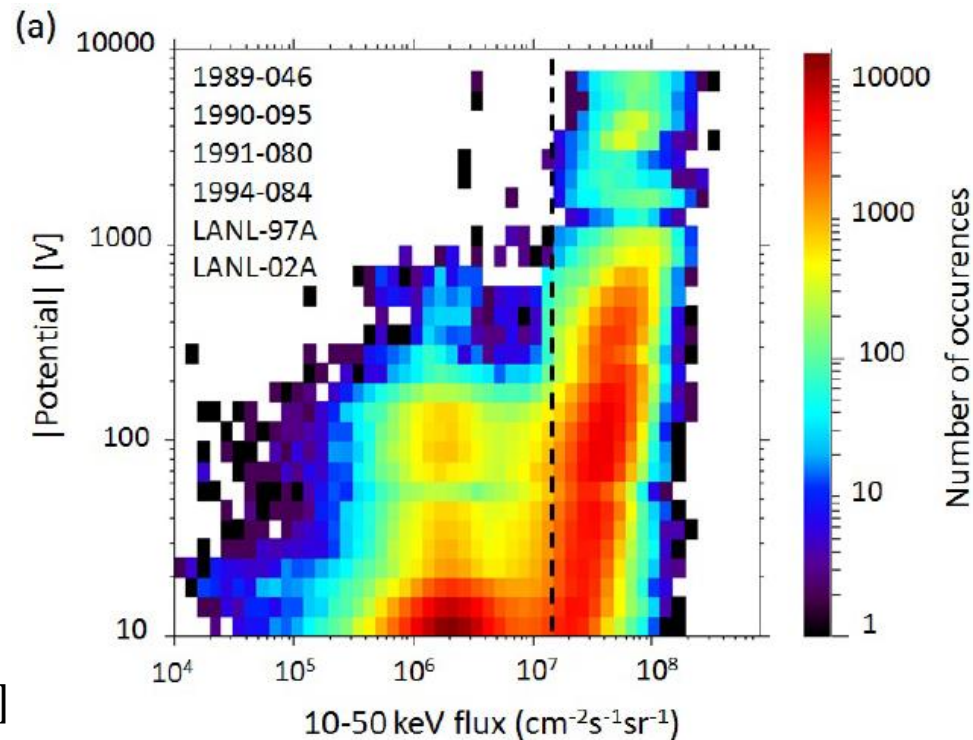
SOPA: from 50 keV to 1.3 MeV

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).

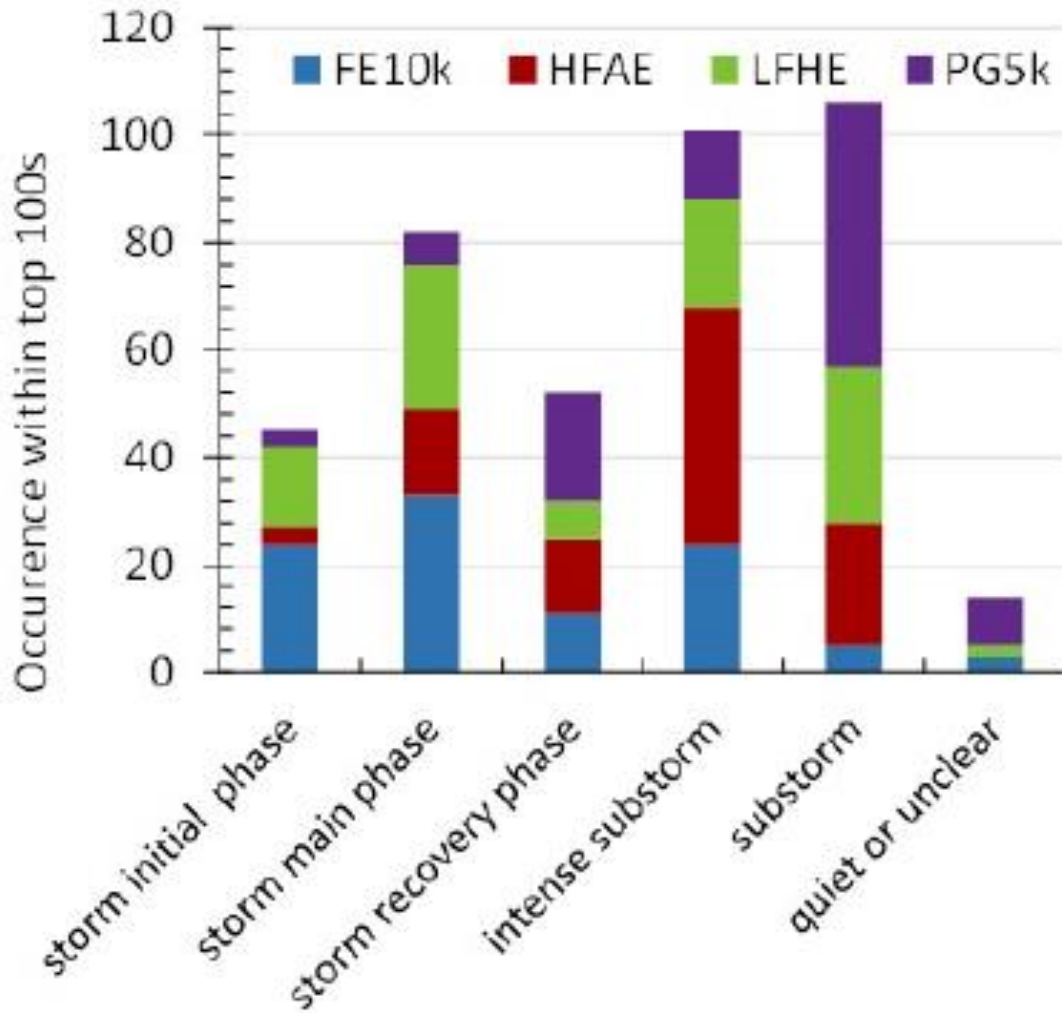
400 events with worst-case environments were identified

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.

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 angle**, 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 B_y and B_z , and W_i , $i = 1, 6$)

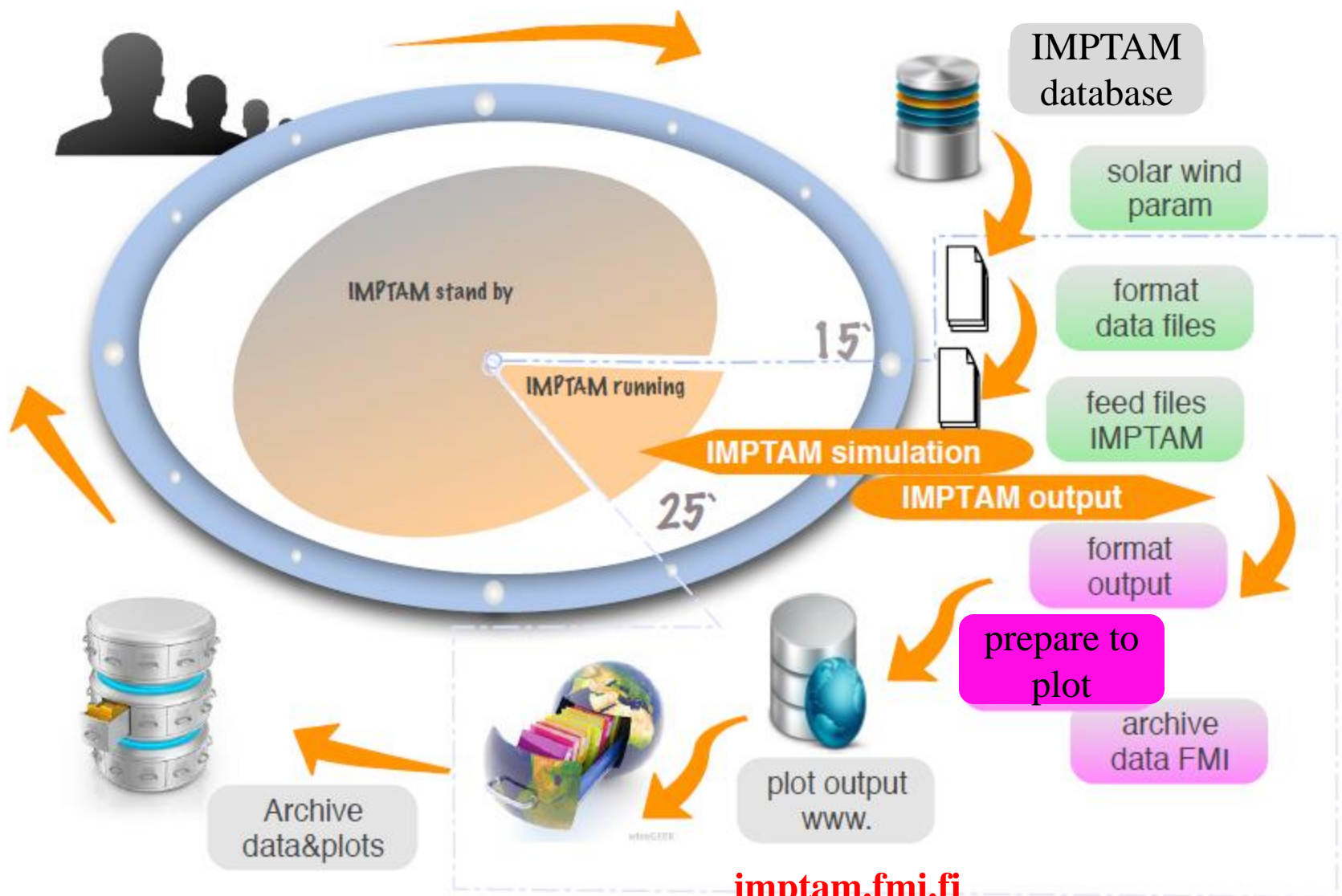
Electric field model: Boyle (V_{sw} , IMF B , B_y , B_z)

Boundary conditions: n and T by Dubyagin et al. (2016) (V_{sw} , IMF B_z , N_{sw})

Losses given as electron lifetimes: newly developed BAS lower and upper band chorus diffusion model (**K_p , magnetospheric magnetic field**)

keV electrons in real time online (IMPTAM model)

Realttime nowcast - hourly procedure

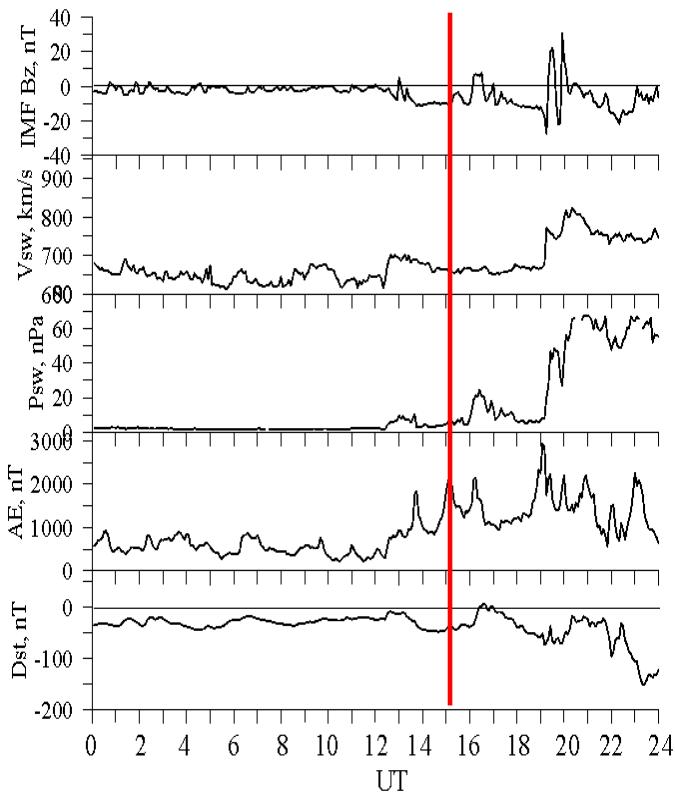


imptam.fmi.fi

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

Severe Events for Surface Charging: May 29, 2003

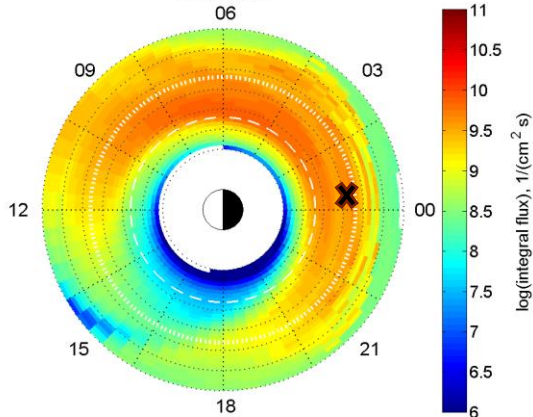
May 29, 2003



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.

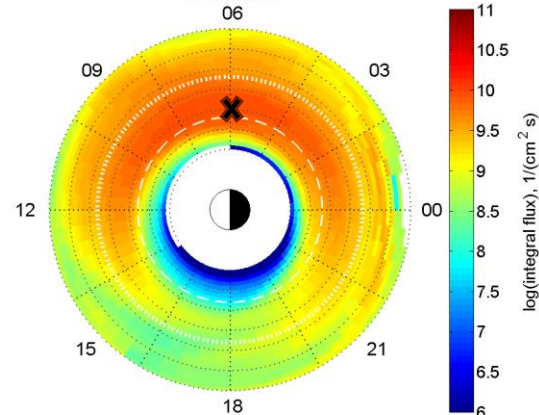
IMPTAM fluxes globally reproduce LANL
Max IMPTAM electron flux at MEO exceeds GEO flux and ECSS and NASA worst-cases by a factor of 2 to 5.

29 May 2003, 15:00UT, 1-300 keV electrons

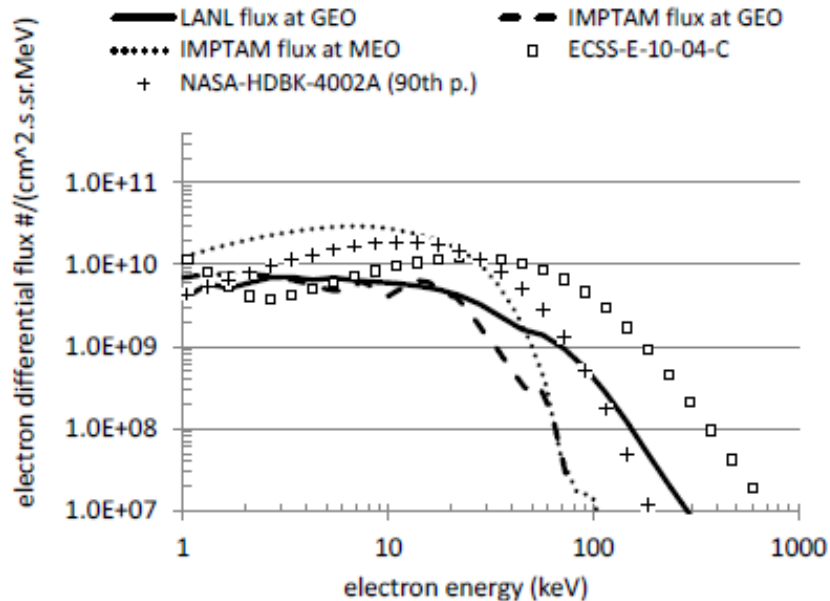


IMPTAM electron fluxes at LANL surface charging event at GEO

29 May 2003, 16:30UT, 1-300 keV electrons

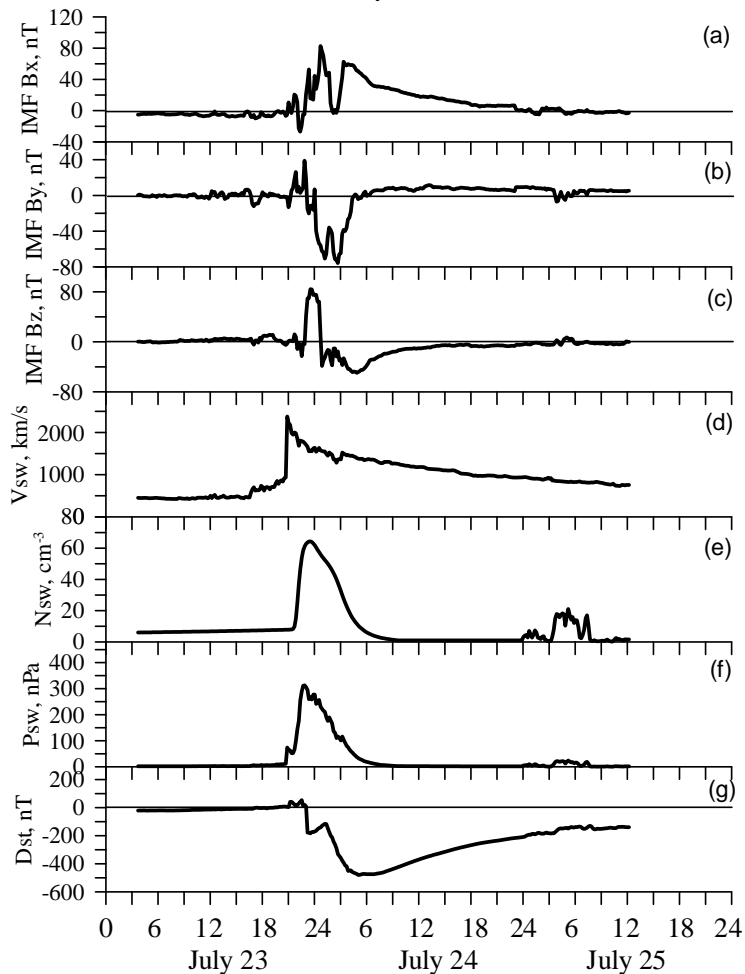


IMPTAM electron fluxes at maximum flux at MEO



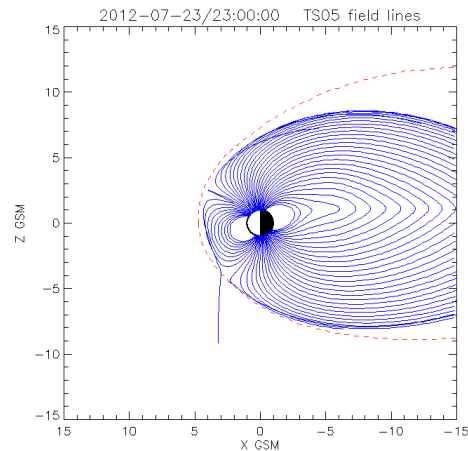
Large CME-driven storm, July 23-24, 2012 (event that missed the Earth)

July 23-24, 2012

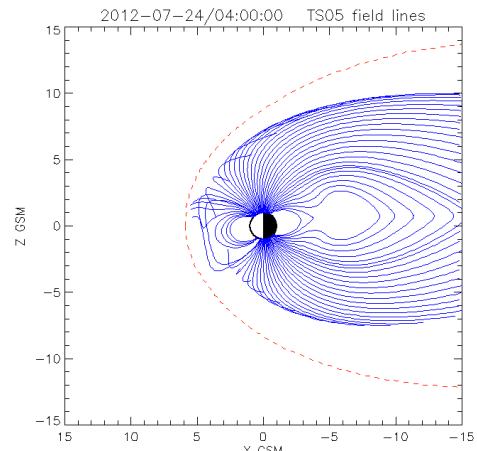


$Dst = -500$ nT, $P_{sw} = 300$ nPa, $V_{sw} = 3000$ km/s

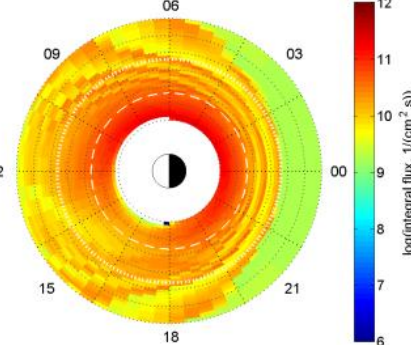
1st Dst drop



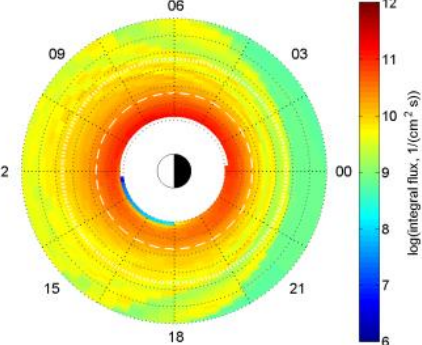
Dst min



23 Jul 2012, 23:00UT, 1 - 300 keV electrons



24 Jul 2012, 04:00UT, 1 - 300 keV electrons

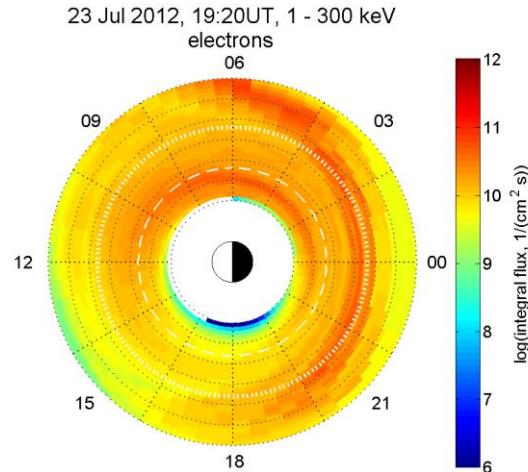


STEREO-A observations,
Wang-Sheerley-Argue, ENLIL model,
Temerin and Li (2006) Dst predictive model

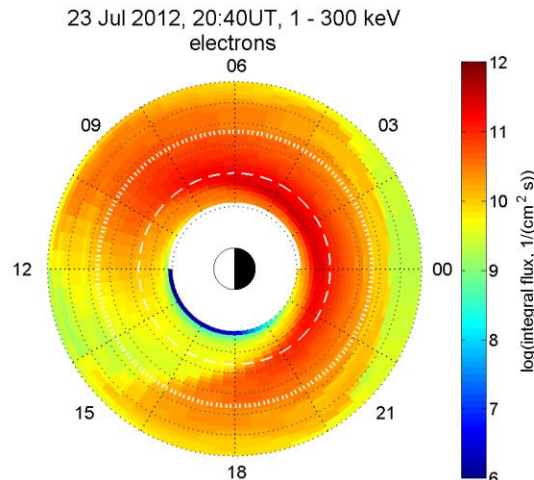
Magnetosphere becomes so compressed on the dayside and so stretched on the nightside that electrons are lost, they happen to be on larger L-shells.

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.



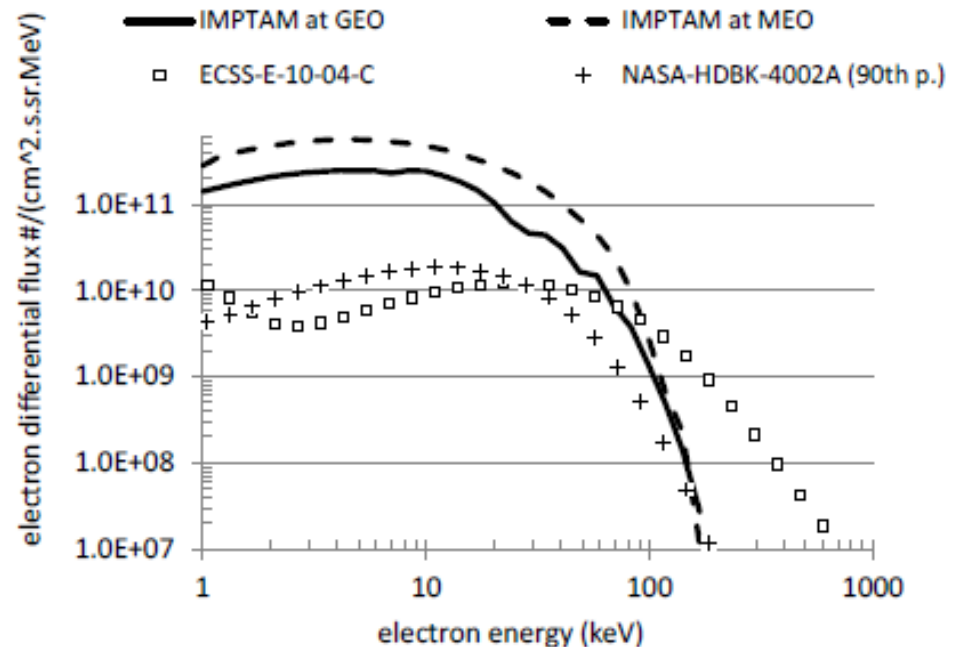
The maximum electron flux reached at GEO:
July 23, 2012, at 1920 UT at MLT 2.4.



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 challenging 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.