Low energy (< 200 keV) electron fluxes responsible for surface charging

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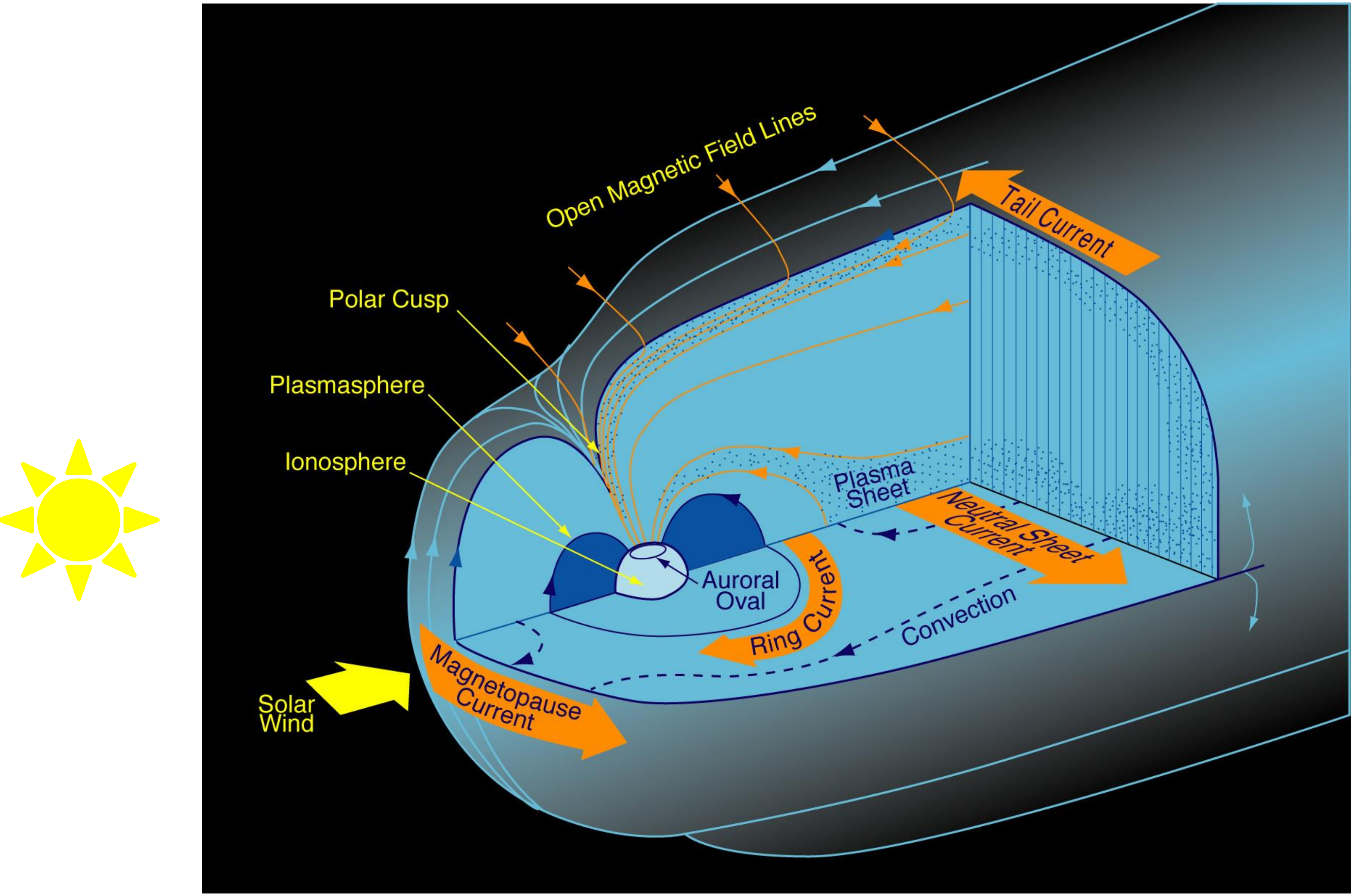
Large-scale structure of the Earth’s magnetosphere

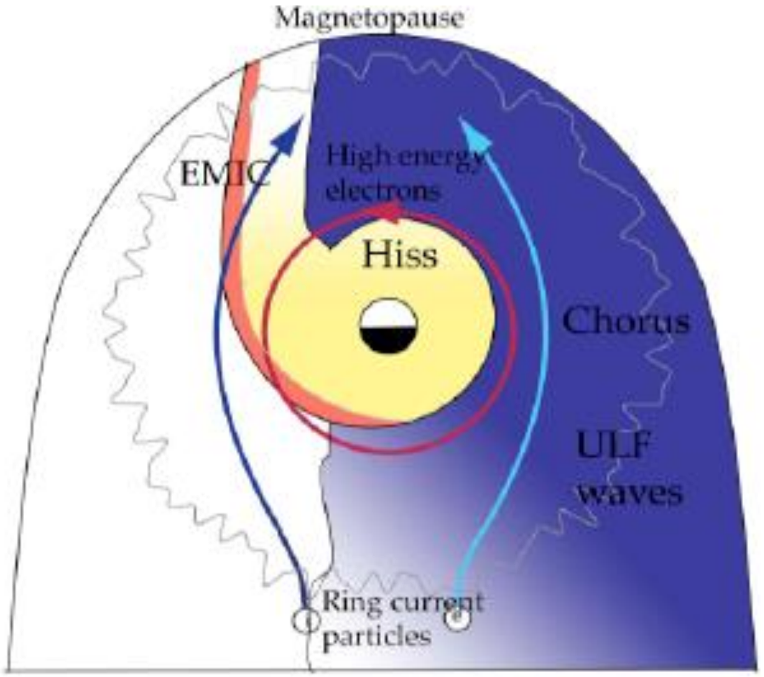


What is the interest in studying keV electrons in the inner magnetosphere?

- 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 (*Horne et al*., 2005; *Chen et al*., 2007)

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

The **plasma sheet electrons** injected into the inner magnetosphere get altered into unstable forms (*Tsurutani and Smith*, 1974; *Meredith et al.*, 2001) exciting through cyclotron resonance (*Kennel and Petschek*, 1966; *Kennel and Thorne*, 1967) various plasma waves (notably **VLF chorus and EMIC waves**) outside the plasmapause. Wave-particle interactions can **either energize or scatter** relativistic particles (*Green and Kivelson*, 2001, 2004; *Chen et al*., 2006; *Shprits et al*., 2006).



Whistler mode chorus waves play an important role in accelerating the seed electron population to relativistic energies in the outer radiation belt (*Horne et al*., 2005; *Chen et al*., 2007).

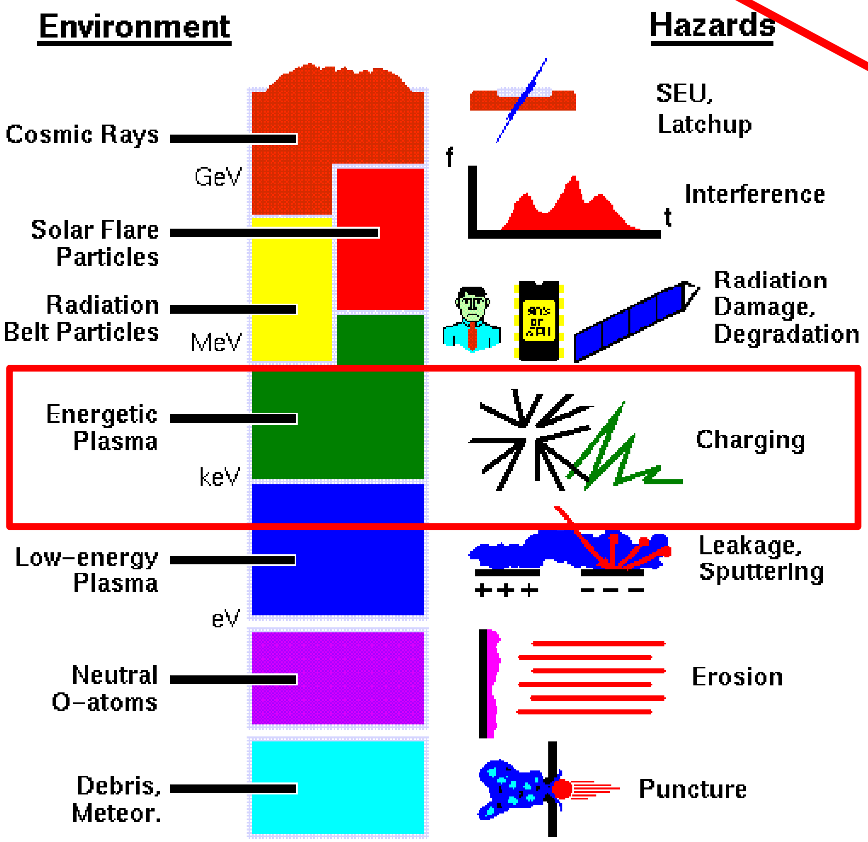
General definition of the effects of space weather

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).



keV electrons for surface charging

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

Surface charging briefly (1)

Surface charging is created from low-energy plasma and photoelectric currents.

The spacecraft surface potential is a function of **the net current to/from the spacecraft surface**.
These currents are from
- solar photon-induced photoelectrons leaving the surface,
- plasma electrons and ions impinging on the surface, and
- charged particles emitted from the vehicle (*e.g.*, from active ion emission).

In a balance, a net current is equal to zero.

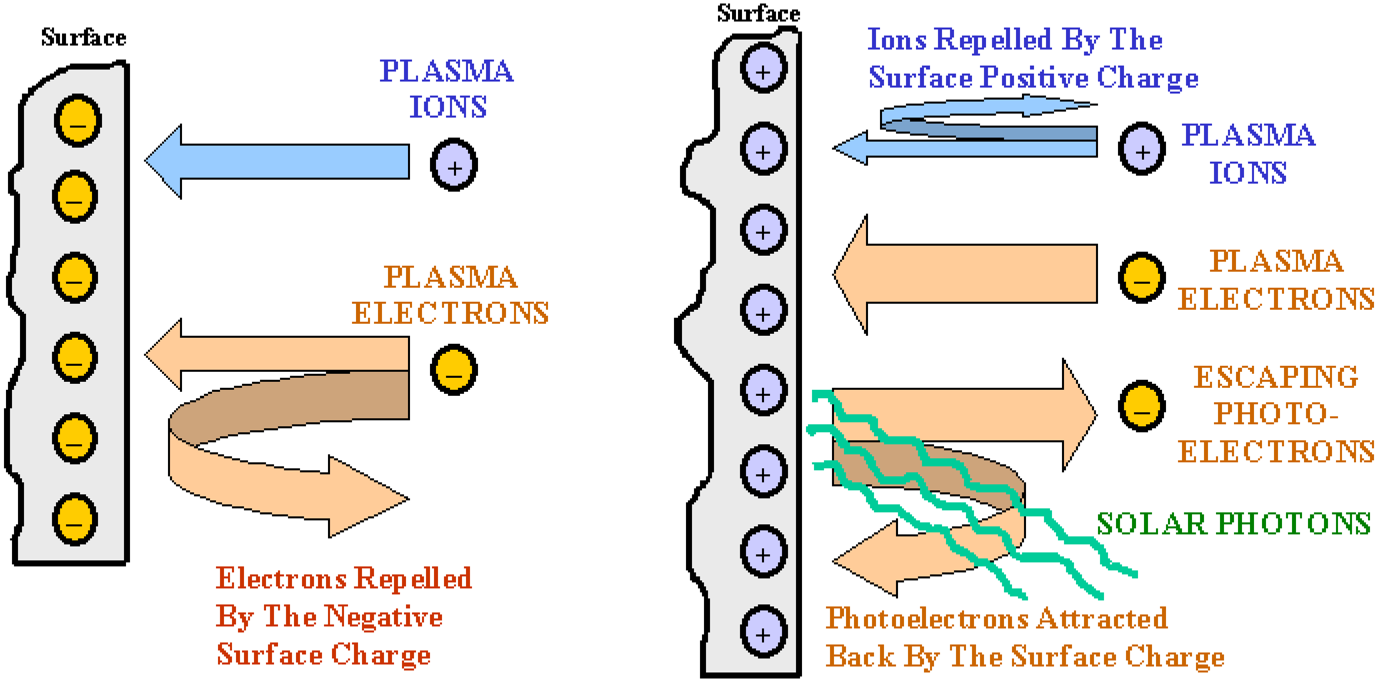
A spacecraft placed in the plasma will assume a floating potential different from the plasma itself.

The satellite's surface materials will be charged in order to have the zero net current between the surfaces and the plasma. Therefore, the **surface will have nonzero voltages**.

The sunlit areas of the satellite's surface are positive and the shadowed areas are negative.

For the conducting surfaces, the potential of the surface is uniform for reaching the equilibrium for zero net current. For insulating materials, this equilibrium can be only on several points on the surface.

Surface charging briefly (2)



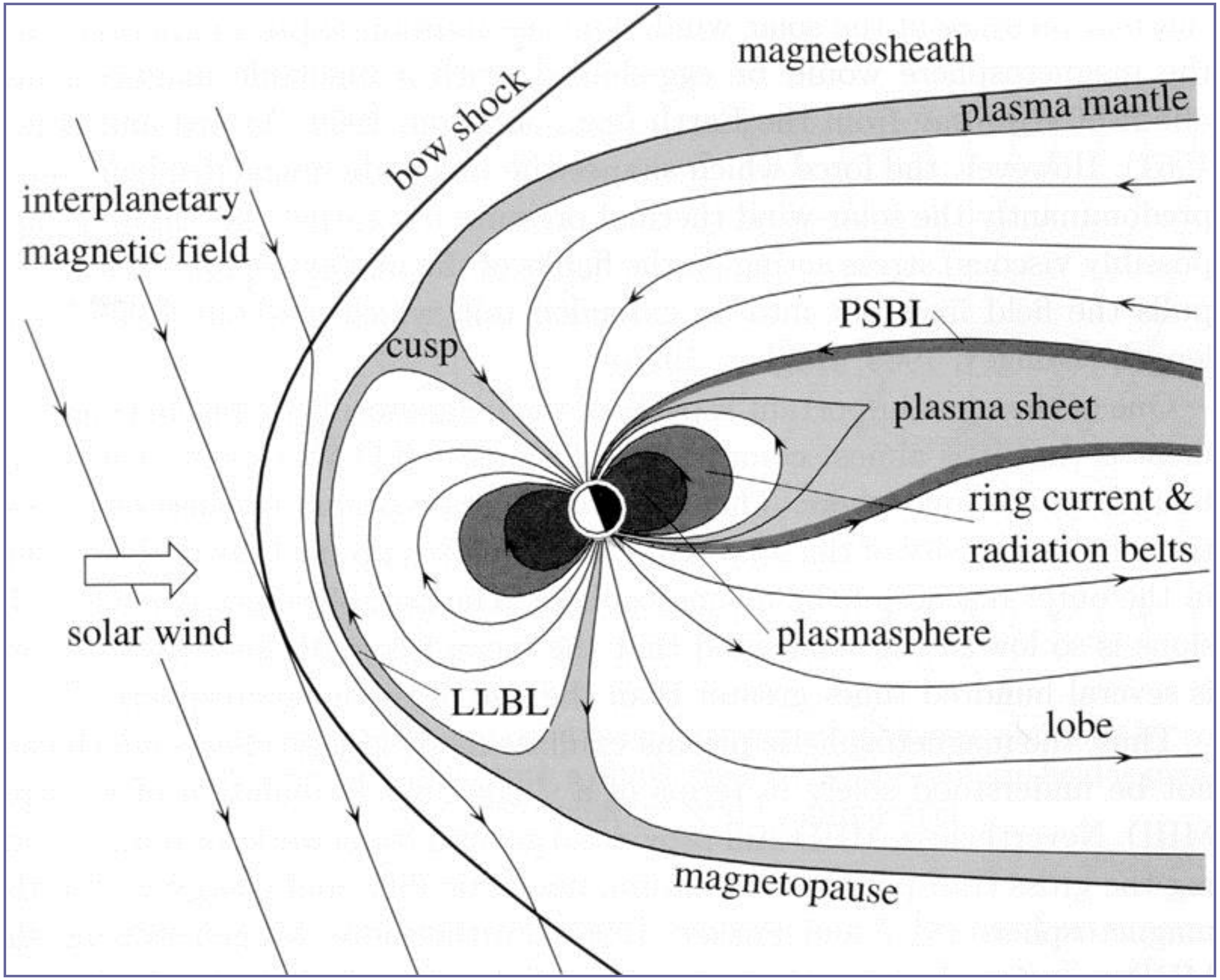
(*a*) **Surface In Shadow**

(*b*) **Surface In Sunlight**

Surface materials can discharge into space or to structure ground. The resulting **electrostatic discharge (ESD)** currents can electromagnetically couple into electronic circuits and subsystems, causing damage.

Spacecraft charging is a function of the space environment characteristics, including sunlight/eclipse, solar activity, geomagnetic activity, electron flux magnitude and spectrum.

Source of keV electrons in the plasma sheet

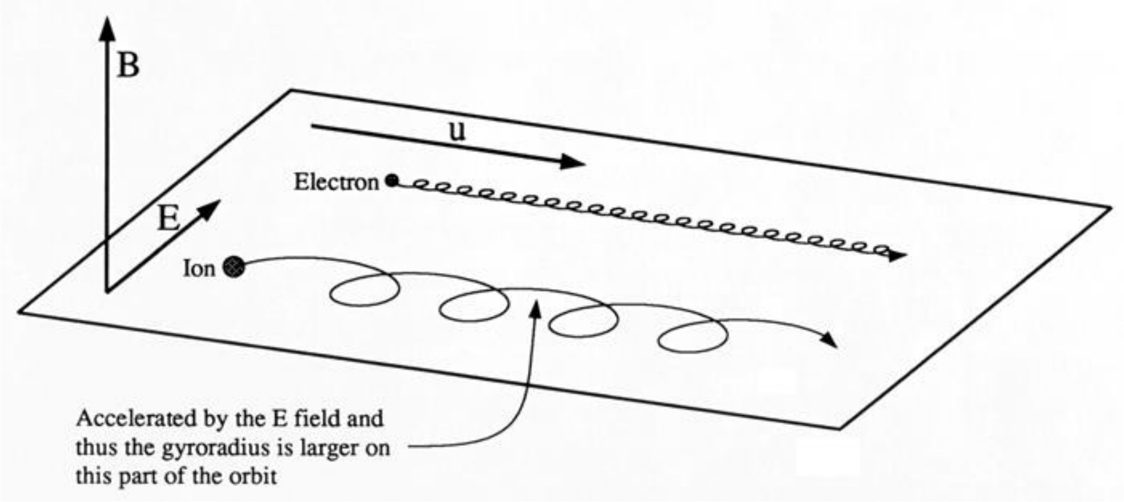


Major particle sources
for the plasma sheet:

- mantle particles entering through the distant tail (they have higher temperatures after energization through current sheet crossing);
- magnetosheath particles entering through the flank magnetopause (they have lower temperatures).

Main energies of electrons in the plasma sheet: from eVs to tens of keVs

keV electron transport and energization

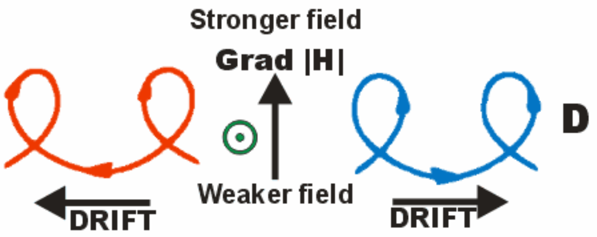


Accelerated by the E field and thus the gyroradius is larger on this part of the orbit

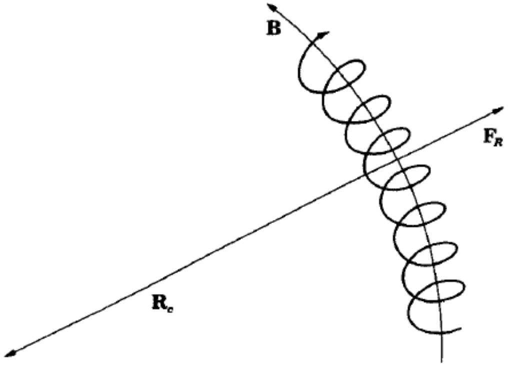
ExB drift in the plasma sheet
$E_\perp$ has a major effect on motion
Drift velocity is ⊥ to **E** and **B.**
No charge dependence, no currents

$$\vec{u}_E = \frac{\vec{E}\times\vec{B}}{B^2}$$

Magnetic drifts closer to the Earth:
Gradient drift: Ions and electrons drift into opposite direction, **⊥ to both B and ∇B**.
Drift velocity is proportional to the perpendicular energy of particle. **More energetic** particles **drift faster**, they have larger gyroradius and experience more of the inhomogeneity of the magnetic field.

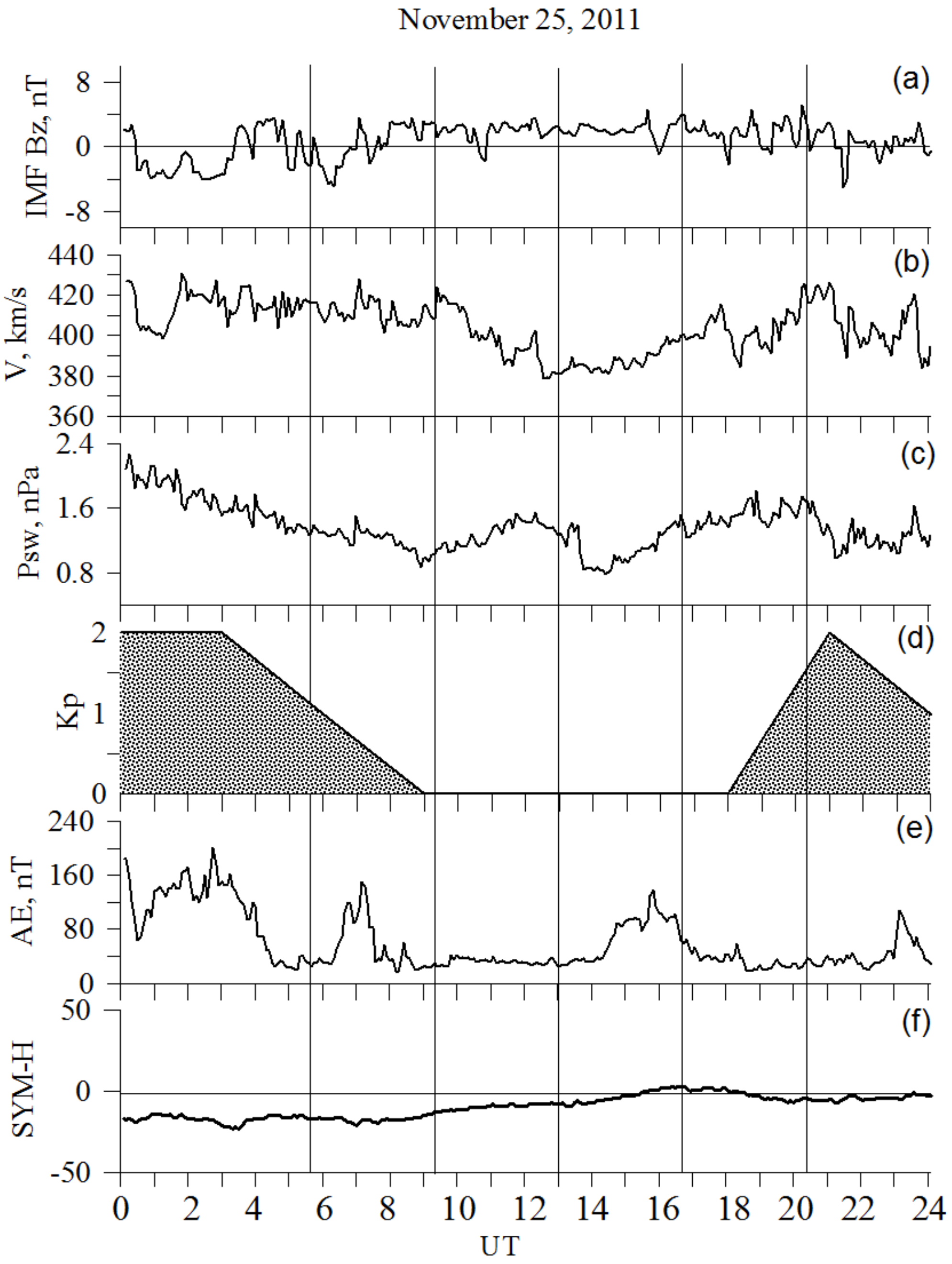


Curvature drift: due to curvature of the magnetic field line
As particles move along the field they undergo **centrifugal acceleration**.
The curvature drift is proportional to the parallel particle energy and perpendicular to the magnetic field and its curvature.



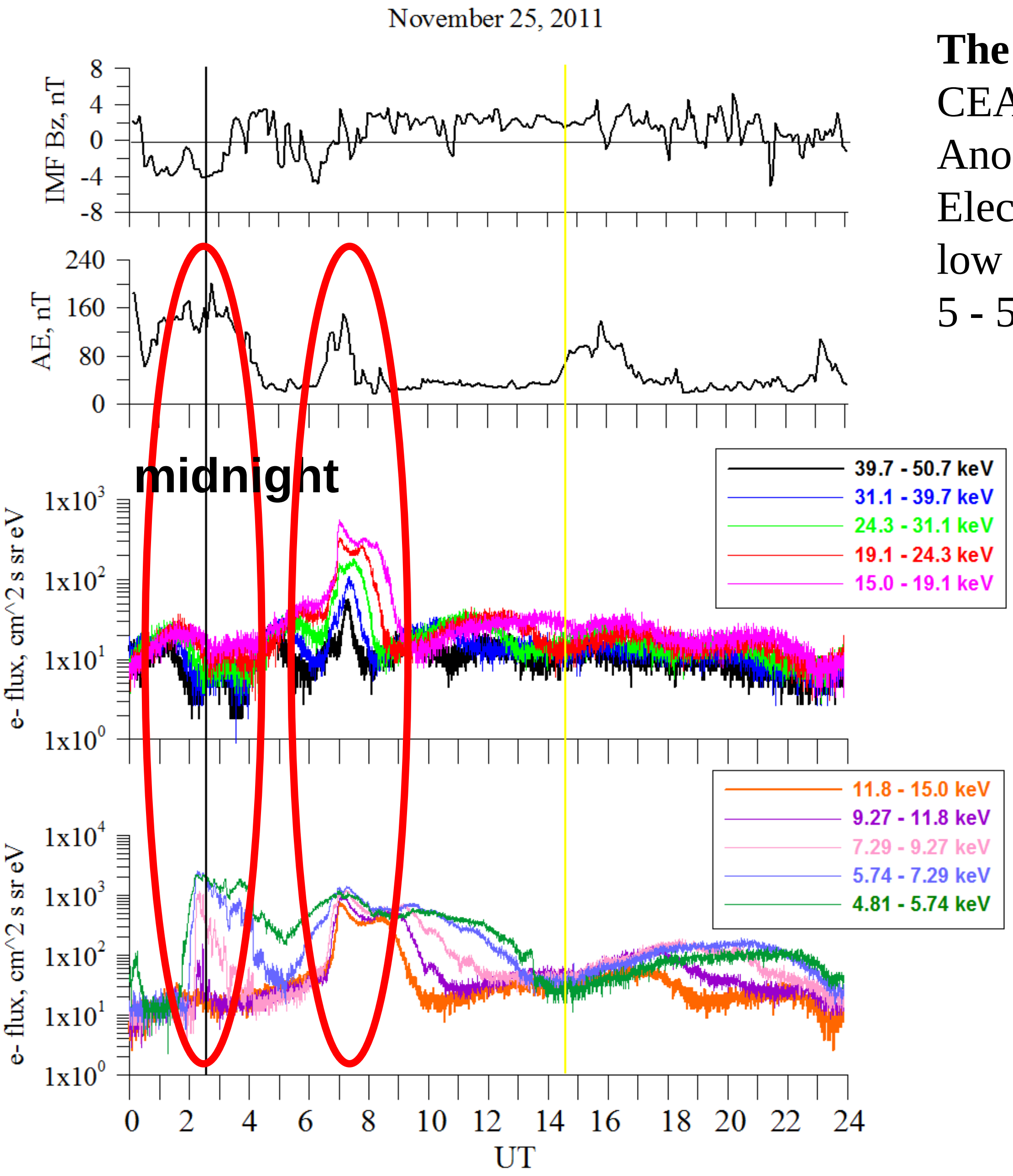
Transport of keV electrons from the plasma sheet to the inner regions: Movie made with modeling results

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

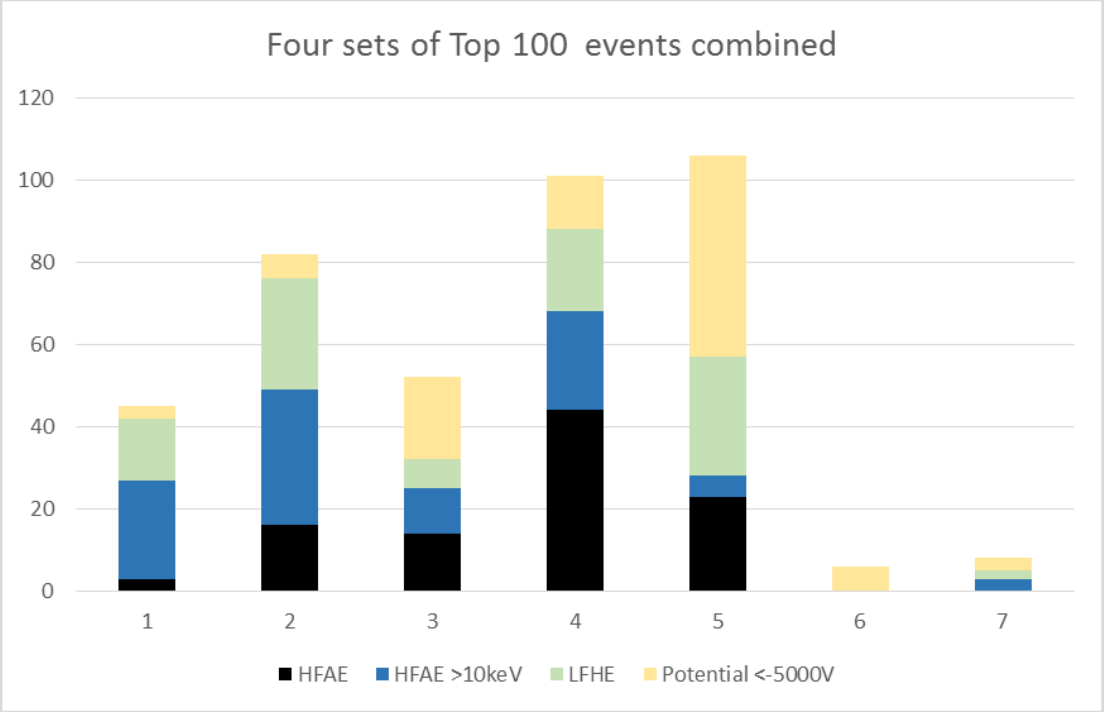
- Electrons of different channels behaves differently:
- 1st peak (AE=200 nT) at midnight seen for energies > 11 keV
- 2nd peak (AE=120 nT) at dawn, increase in all energies

Not a unique case

Space weather is more than storms (Louis Lanzerotti)

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

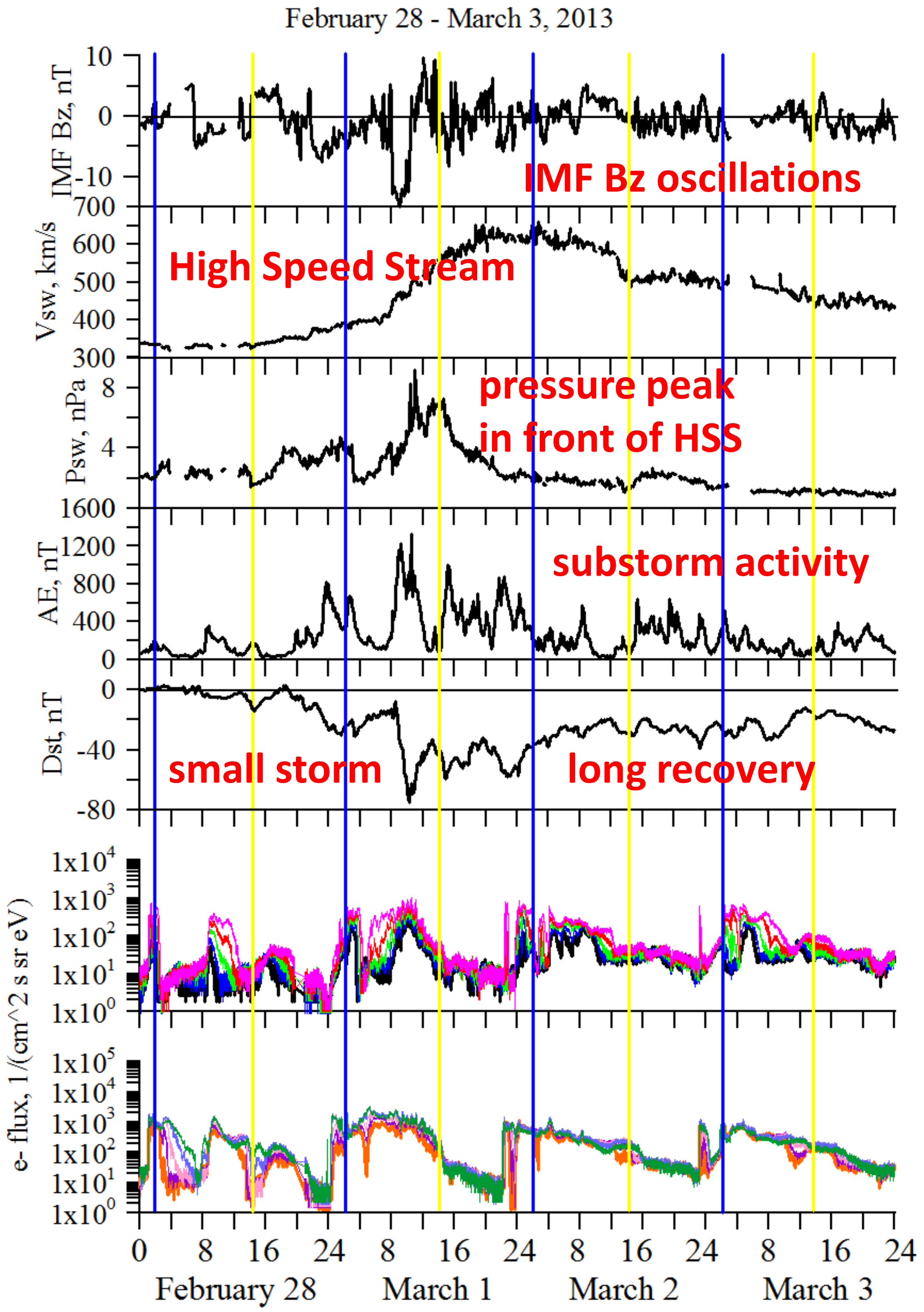
Surface charging events detected at LANL vs. geomagnetic conditions



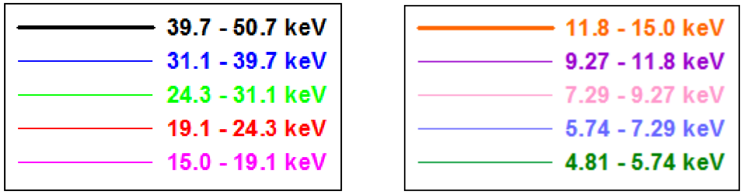
1. storm initial phase;
2. storm main phase;
3. storm recovery phase;
4. intense substorms (AE>=800 nT);
5. isolated substorms;
6. quiet;
7. unclear

The electron flux at the keV energies is largely determined by convective (*Korth et al*., 1999; *Friedel et al*., 2001; *Thomsen et al*., 2002; *Kurita et al*., 2011) and **substorm-associated** (*Fok et al*., 2001; *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!

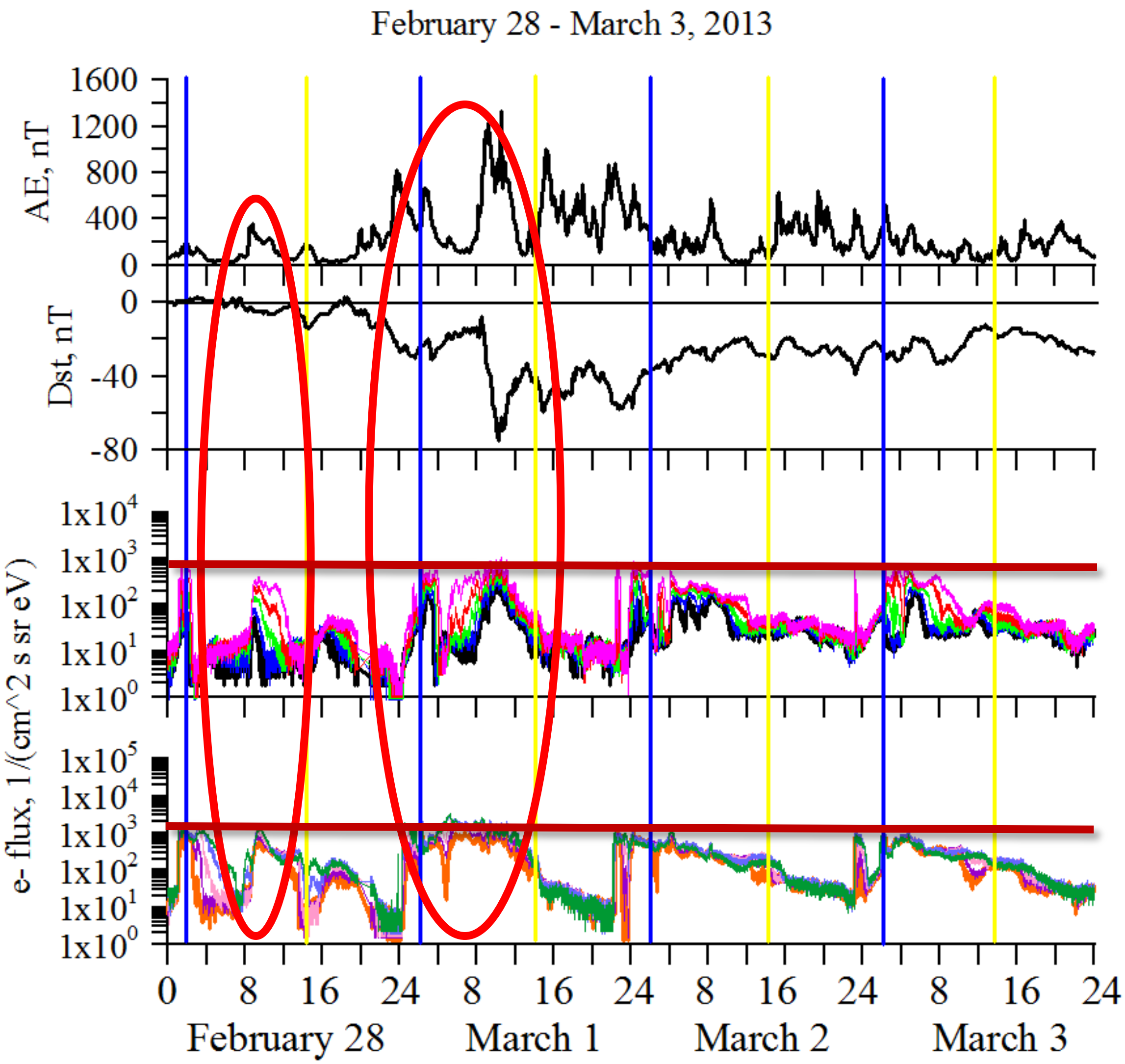
CIR-driven storm



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



AMC12 electron data

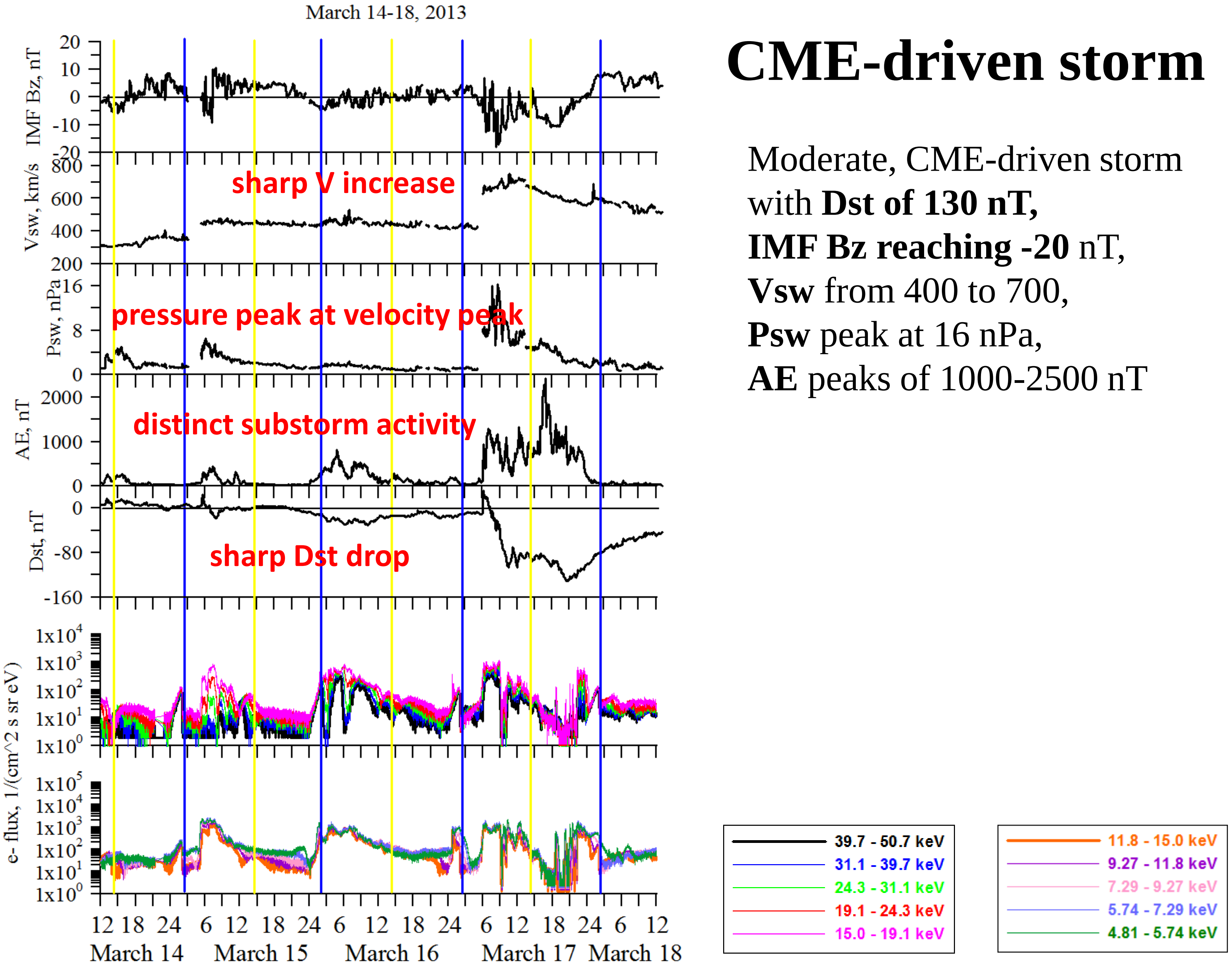
- peaks in both 15-50 keV and 5-15 keV electron fluxes show correlation with AE

- 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

CME-driven storm



sharp V increase

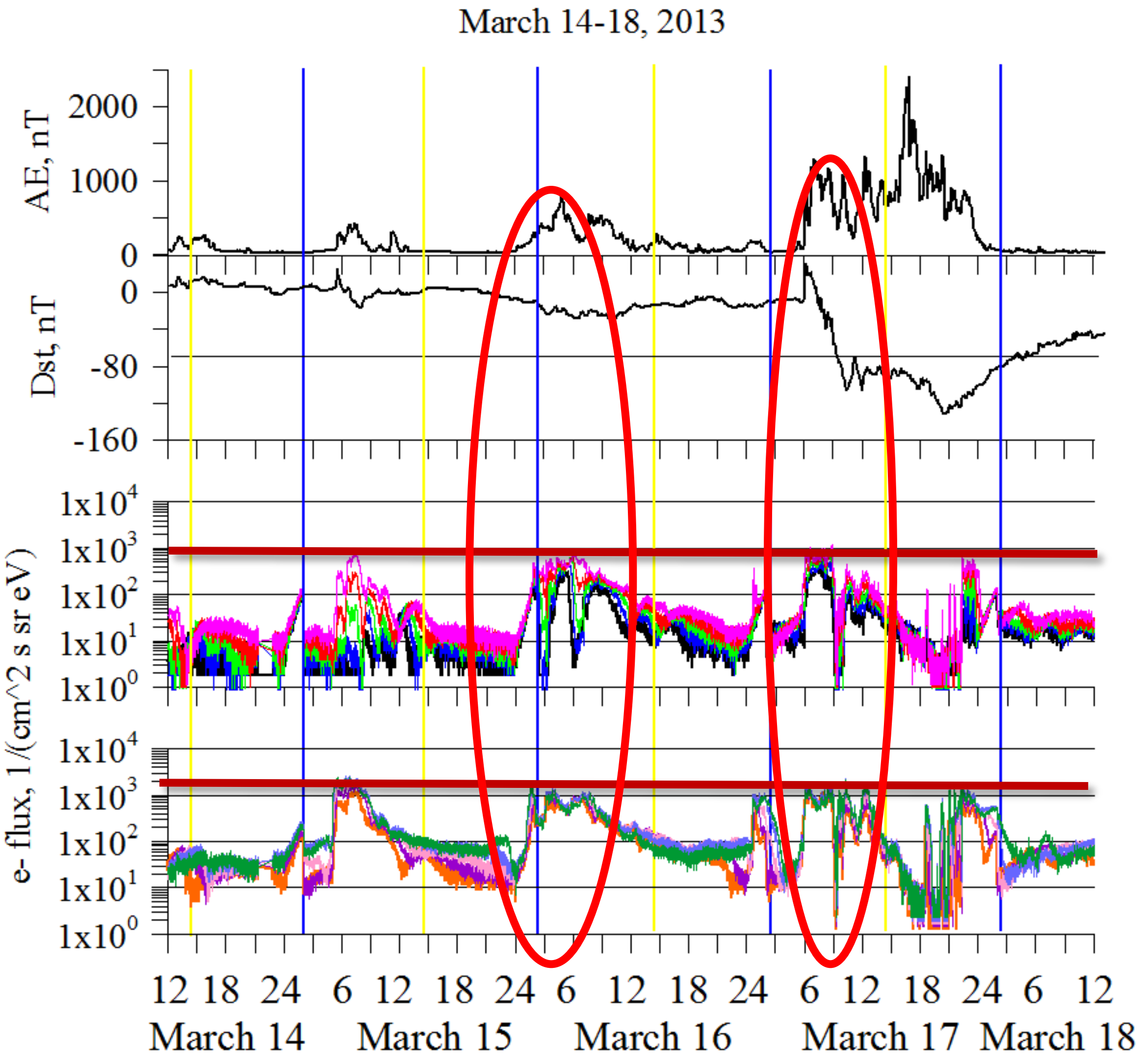
pressure peak at velocity peak

distinct substorm activity

sharp Dst drop

Moderate, CME-driven storm
with **Dst of 130 nT,**
IMF Bz reaching -20 nT,
Vsw from 400 to 700,
Psw peak at 16 nPa,
AE peaks of 1000-2500 nT

Similar increase in electron fluxes during AE = 500 nT and AE=1500 nT

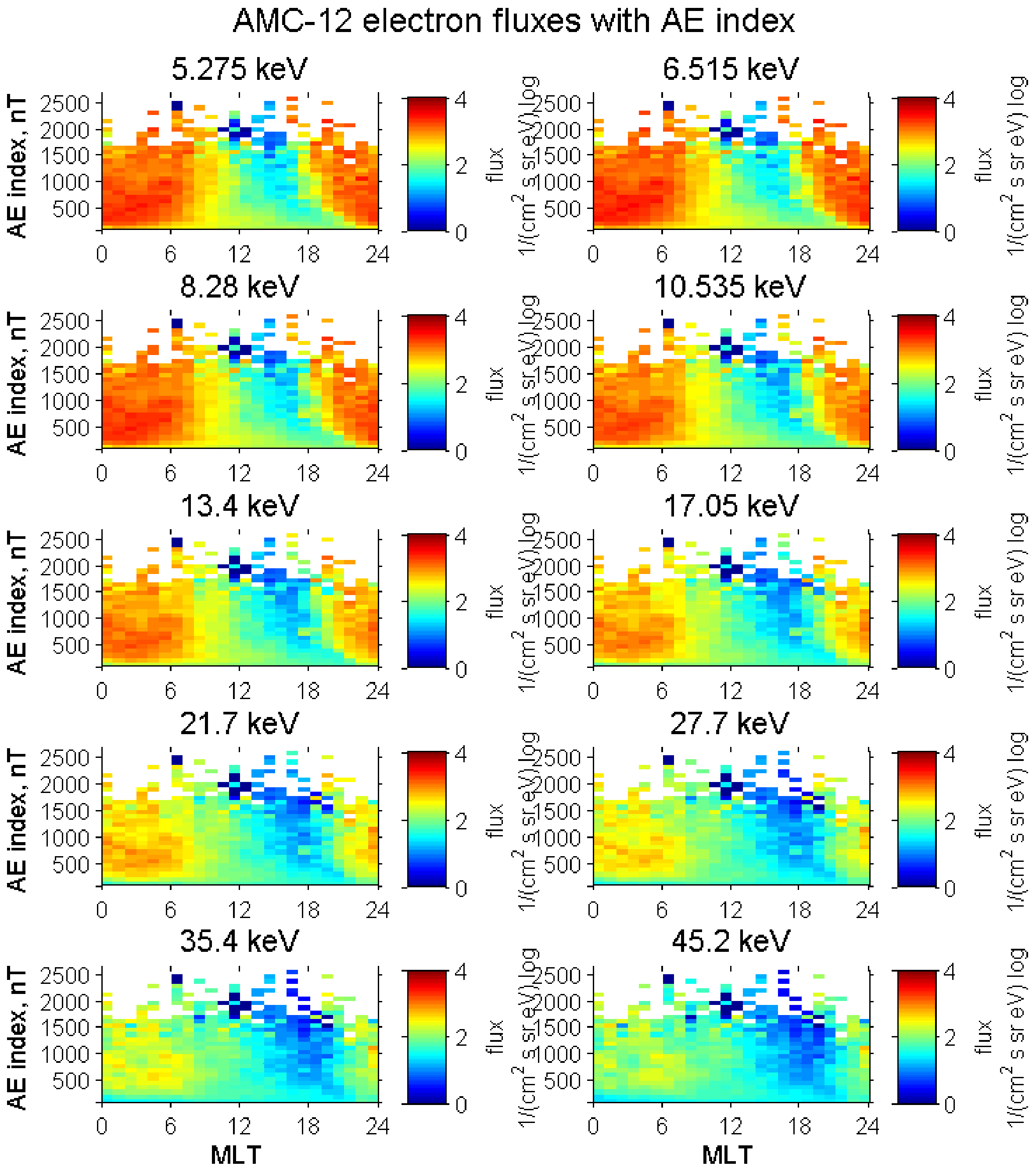


AMC12 electron data

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

- 2 orders of magnitude increase

- during quiet period before storm peaks with AE =500 nT similar to peaks with AE over 1000 nT at storm time



Log(flux)

Flux(MLT, AE)

AMC 12
CEASE-II
ESA data,
2010-2014

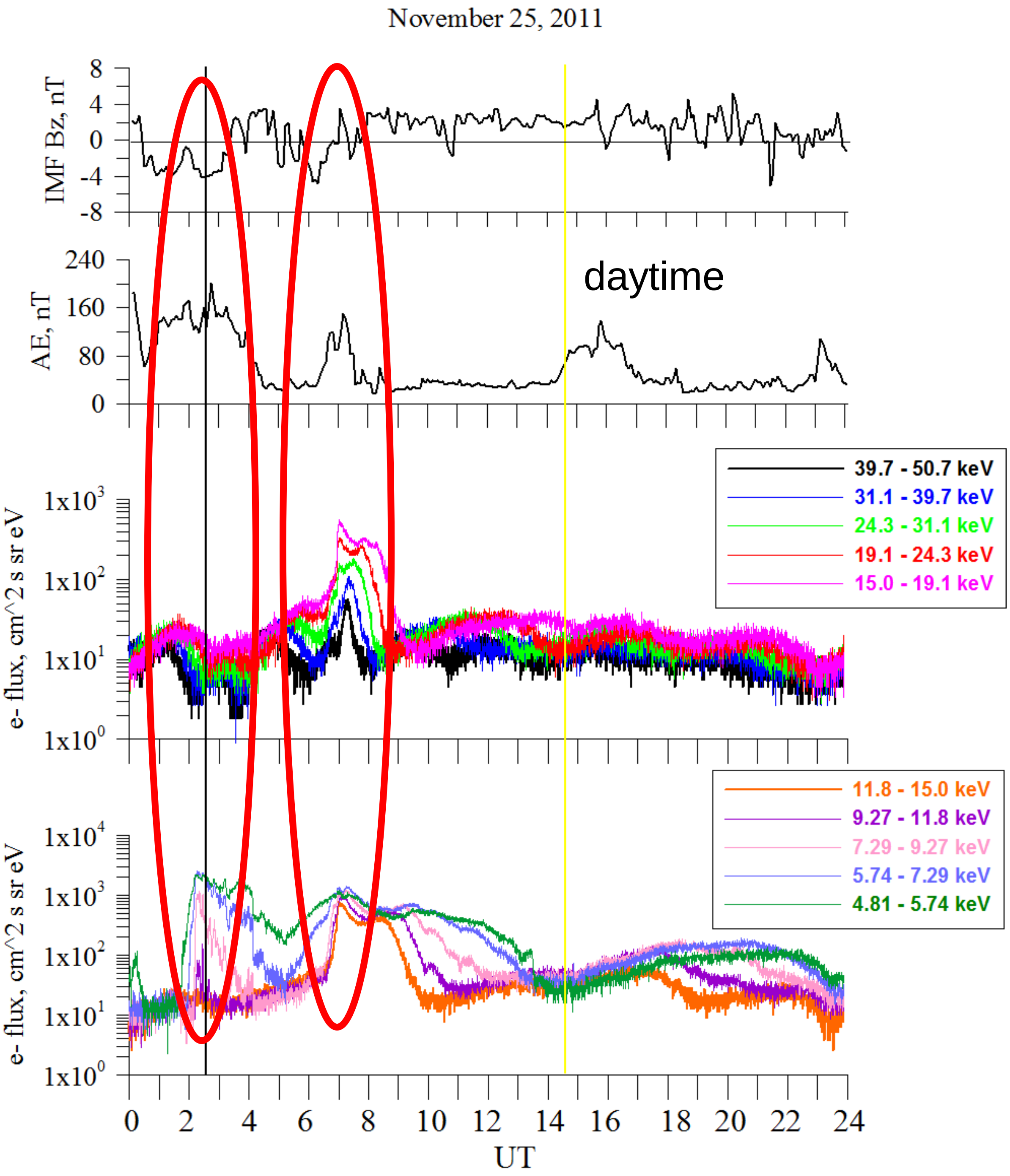
The higher
the energy,
the less
distributed
the flux peak

No distinct
dependence
on AE
strength

Inner Magnetosphere Particle Transport and Acceleration Model

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: 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



Event is rather **quiet**

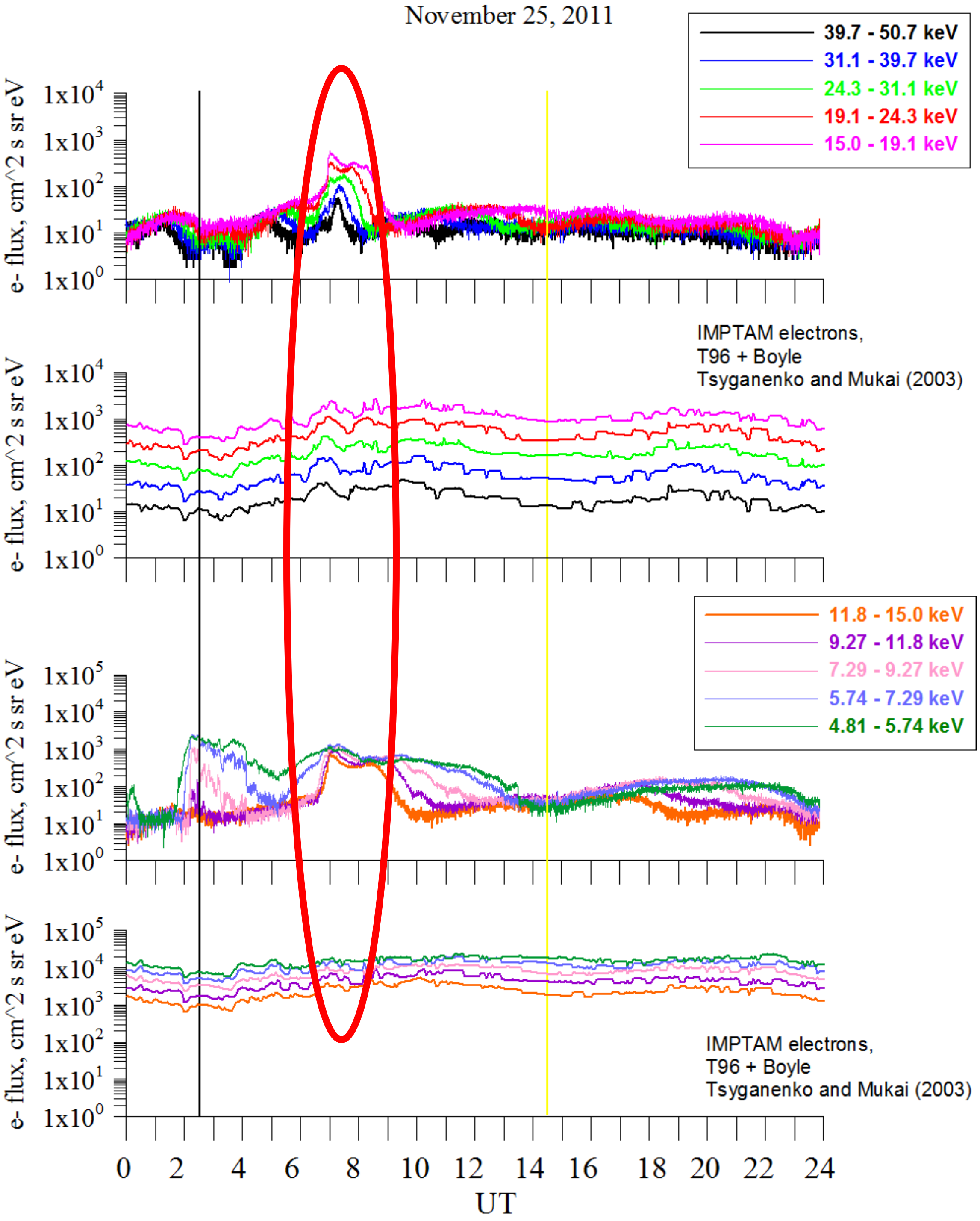
Flux increases are related to **AE index peaks** only

AE peaks are low (less than 200 nT) small, isolated substorms

The lower the energy, the large the flux increase

First peak at midnight seen for energies starting from 11 keV

No flux increases when satellite on dayside



No significant variations in models' parameters –

no changes in modeled electron fluxes

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.

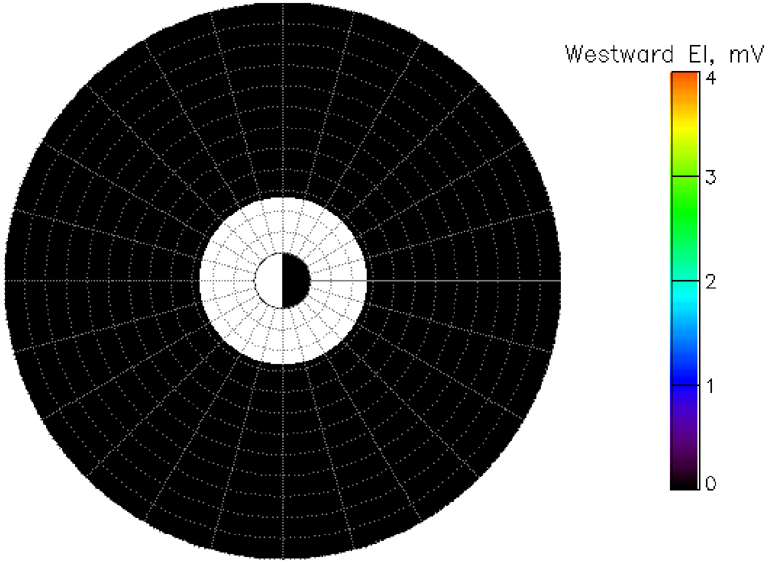
Present IMF and SW dependent models fail to represent the observed peaks associated with substorm activity

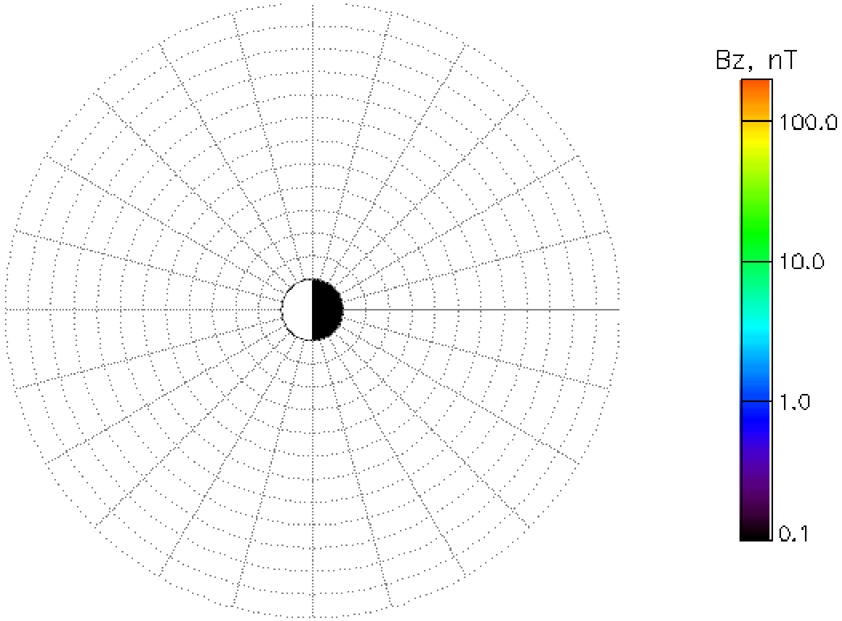
Electric field pulse model

Time varying fields associated with dipolarization in magnetotail, modeled as an electromagnetic pulse (*Li et al., 1998; Sarris et al., 2002*):

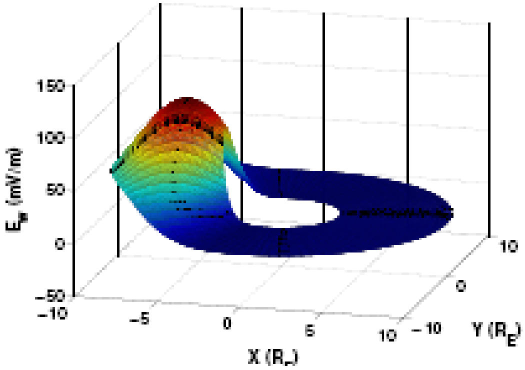
- Perturbed fields propagate from tail toward the Earth;
- Time-dependent Gaussian pulse with azimuthal E;
- E propagates radially inward at a decreasing velocity;
- decreases away from midnight.

Time-dependent B from the pulse is calculated by Faraday’s law.

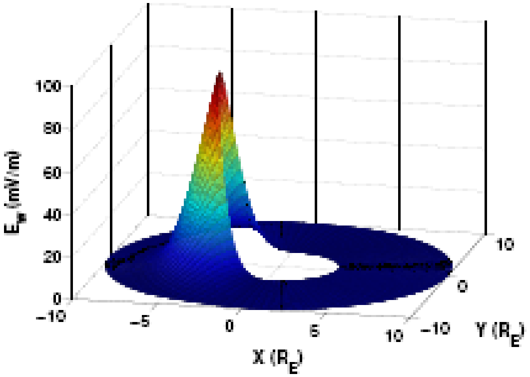




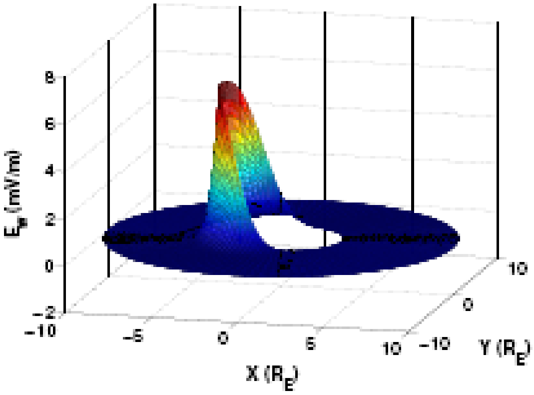
Launching electromagnetic pulses on substorm onsets



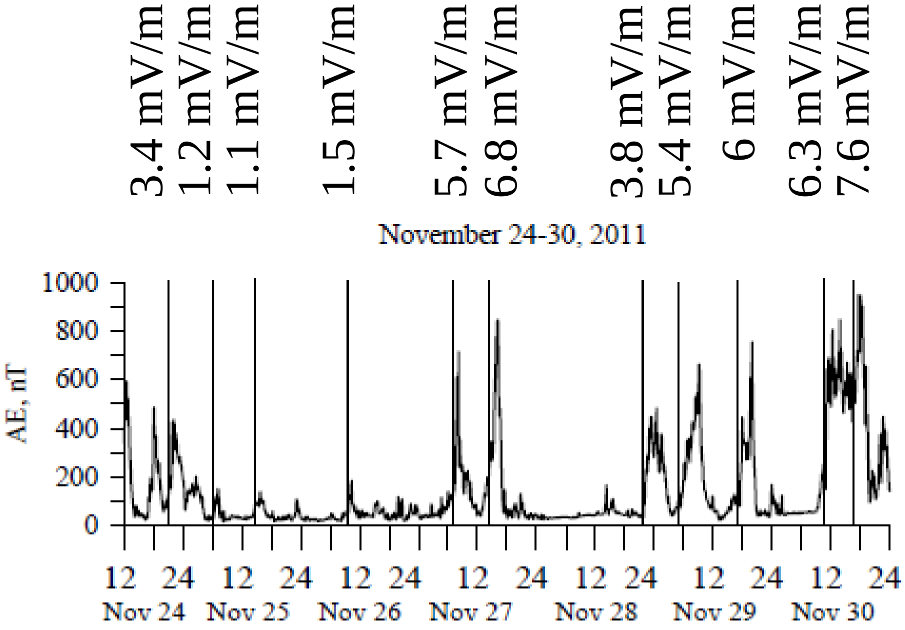
at 10 Re

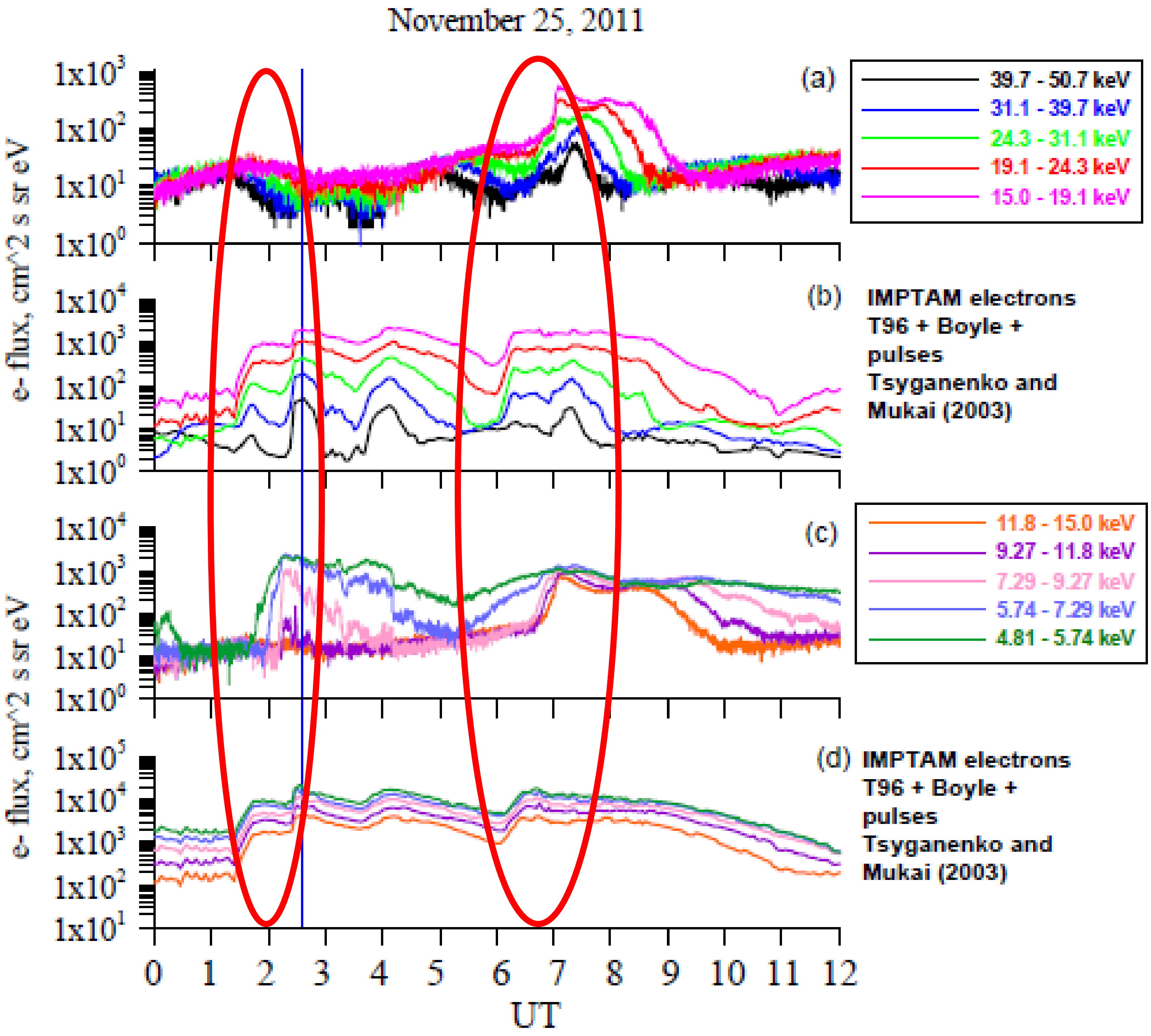


at 7 Re



at 3.5 Re




November 25, 2011
(a)
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
(b)
IMPTAM electrons
T96 + Boyle +
pulses
Tsyganenko and
Mukai (2003)
(c)
11.8 - 15.0 keV
9.27 - 11.8 keV
7.29 - 9.27 keV
5.74 - 7.29 keV
4.81 - 5.74 keV
(d)
IMPTAM electrons
T96 + Boyle +
pulses
Tsyganenko and
Mukai (2003)
e- flux, cm^2 s sr eV
e- flux, cm^2 s sr eV
1x10^0
1x10^1
1x10^2
1x10^3
1x10^4
1x10^5
0 1 2 3 4 5 6 7 8 9 10 11 12
UT

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.

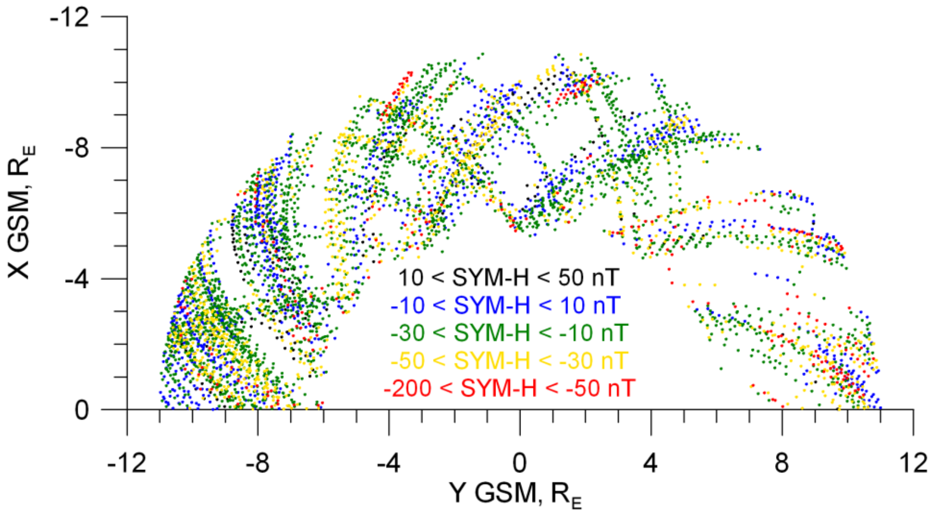
(2) magnetic and electric fields everywhere dependent on time;
The **magnetic field model is Tsyganenko T96 model** [*Tsyganenko*, 1995] with Dst index, solar wind pressure P_{SW}, and IMF B_Y and B_Z as input parameters. The **electric field** is determined using the solar wind speed V_{SW}, the IMF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

New empirical plasma sheet model

Dubyagin et al., JGR, 2016



Analysed THEMIS data 6–11 Re
Data: THEMIS A, D, E probes;
ESA electrons: 30eV - 30 keV;
SST electrons ~25 keV - 300 keV

Electron density model: 7 coefficients

$$N_e = 1.23 - 1.01\cdot r + 0.874\cdot r\phi^2 - 0.82\cdot \phi^2$$

positive → $+\boxed{0.392}\cdot N_{SW}$

positive → $\boxed{+(0.521 - 0.474\cdot r)}\cdot B_S$

Electron temperature model: 9 coefficients

$$T_e = [-0.0215 - 0.426\cdot \phi$$

positive → $\boxed{+0.874}\cdot V_{SW}$

positive → $\boxed{+(0.587 - 0.538\cdot r\phi^2)}\cdot B_S^{0.32}$

negative → $\boxed{-0.489\cdot r}\cdot B_N^{0.36}]^{2.31}$

Density model: 2 input parameters
(1) Solar wind proton density
(2) IMF southward component
Temperature model: 3 input parameters
(1) Solar wind velocity
(2) IMF southward component
(3) IMF northward component

Both models show very good performance
Density: C.C.=0.82; RMS = 0.23 cm-3
Temperature: C.C.=0.75; RMS = 2.6 keV

Electron losses in the inner magnetosphere

Electron losses occur on the time scales of minutes or hours which is much shorter than those times for ions.

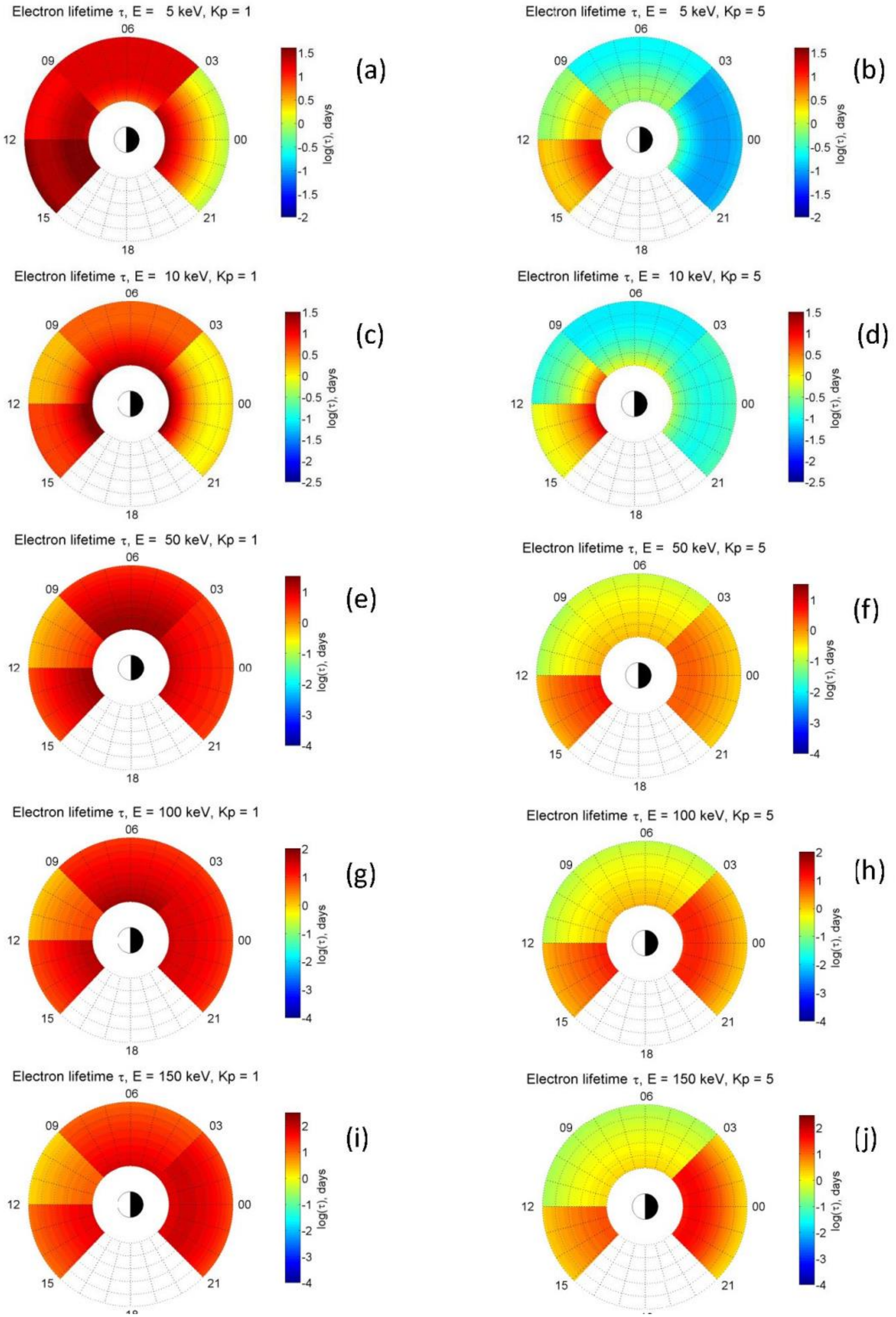
In the inner magnetosphere, the dominating loss process is pitch-angle scattering due to wave-particle interactions.

Chorus waves contribute significantly to the scattering processes of keV electrons **outside the plasmapause**. Electron pitch angle scattering occurs due to interactions with the plasmaspheric **hiss waves** **Inside the plasmasphere**.

It is difficult to quantify globally the electron losses due to interaction with waves, since the rate of pitch-angle diffusion depends on the wave amplitude, wave frequency, and wave normal distributions, as well as the plasma density and background magnetic field.

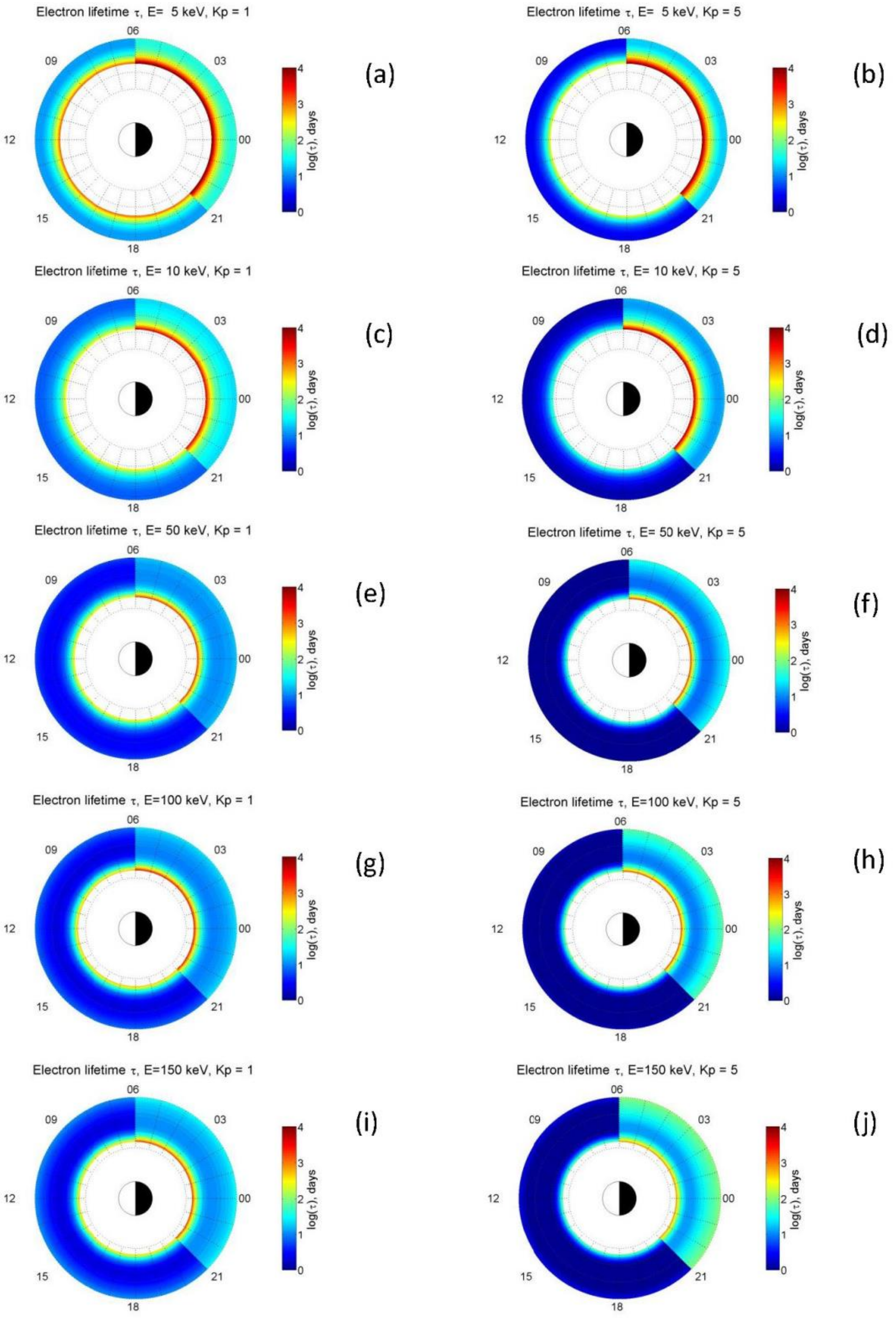
Electron losses, Empirical models

Shprits and Orlova [2014], electron lifetimes due to **chorus waves**. R=3-8 Re. Activity depedence is parameterized by Kp index.



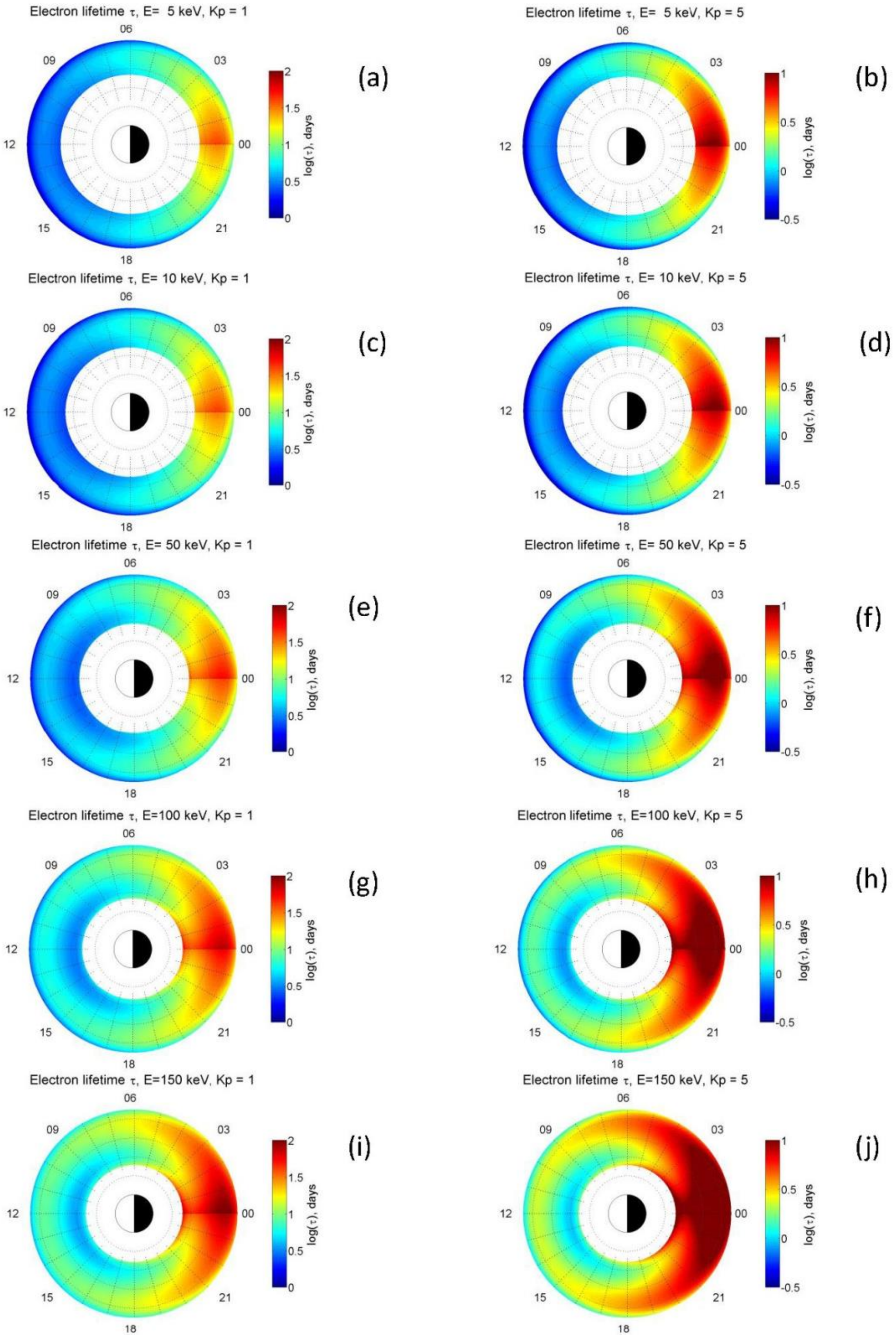
Electron losses, Empirical models

Orlova et al., [2014], electron lifetimes due to plasmaspheric **hiss waves**. CRRES data were used. R=3-6 Re. Activity dependence is parameterized by Kp index.



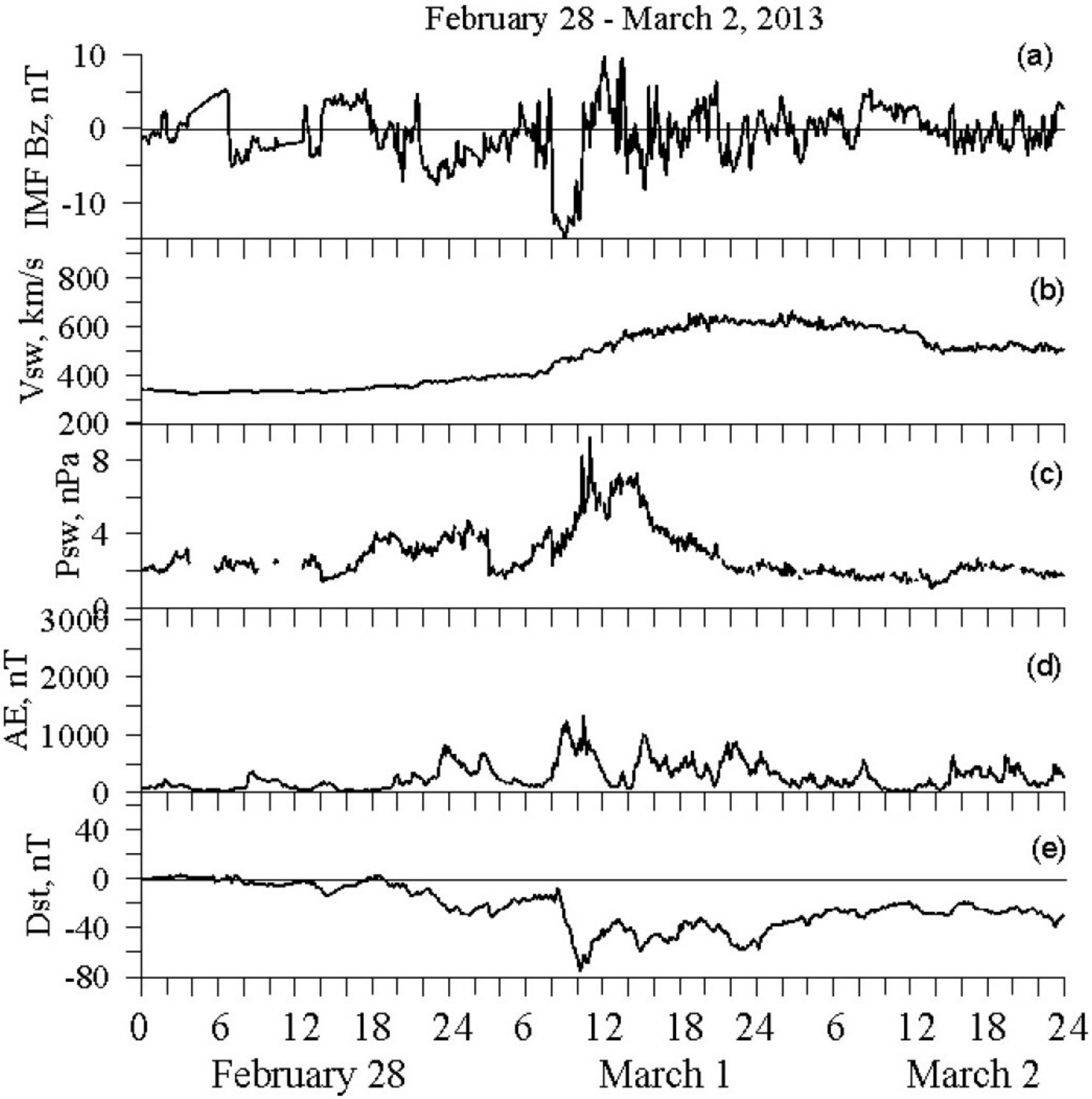
Electron losses, Empirical models

Orlova et al., [2016] electron lifetimes due to plasmaspheric **hiss waves**. Empirical model *Spasojevich et al.*, [2015] of hiss intensity obtained from Van Allen probe data were used. R=1.5-5.5 Re.
Activity dependence is parameterized by Kp index.



Electron lifetime τ, E= 5 keV, Kp = 1 (a)
Electron lifetime τ, E= 5 keV, Kp = 5 (b)
Electron lifetime τ, E= 10 keV, Kp = 1 (c)
Electron lifetime τ, E= 10 keV, Kp = 5 (d)
Electron lifetime τ, E= 50 keV, Kp = 1 (e)
Electron lifetime τ, E= 50 keV, Kp = 5 (f)
Electron lifetime τ, E=100 keV, Kp = 1 (g)
Electron lifetime τ, E=100 keV, Kp = 5 (h)
Electron lifetime τ, E=150 keV, Kp = 1 (i)
Electron lifetime τ, E=150 keV, Kp = 5 (j)

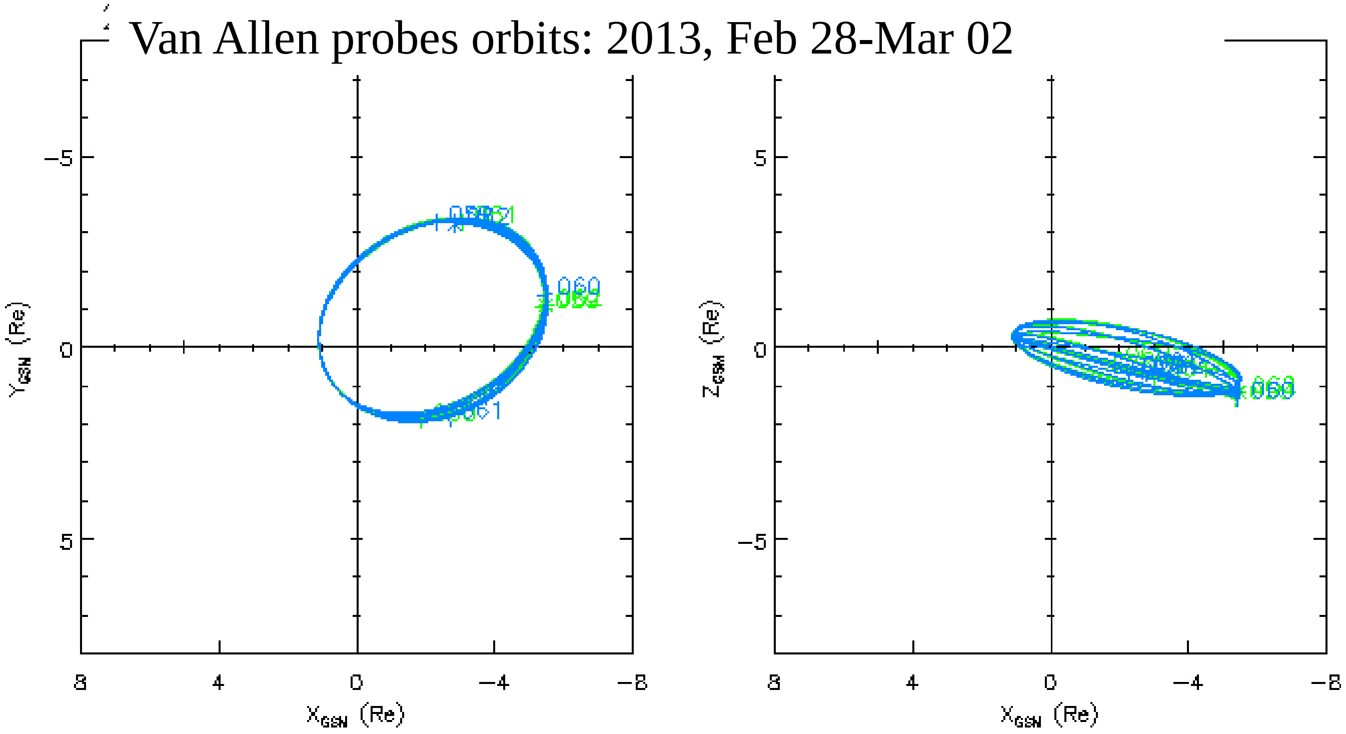
Event overview



Comparison with observations of electron fluxes

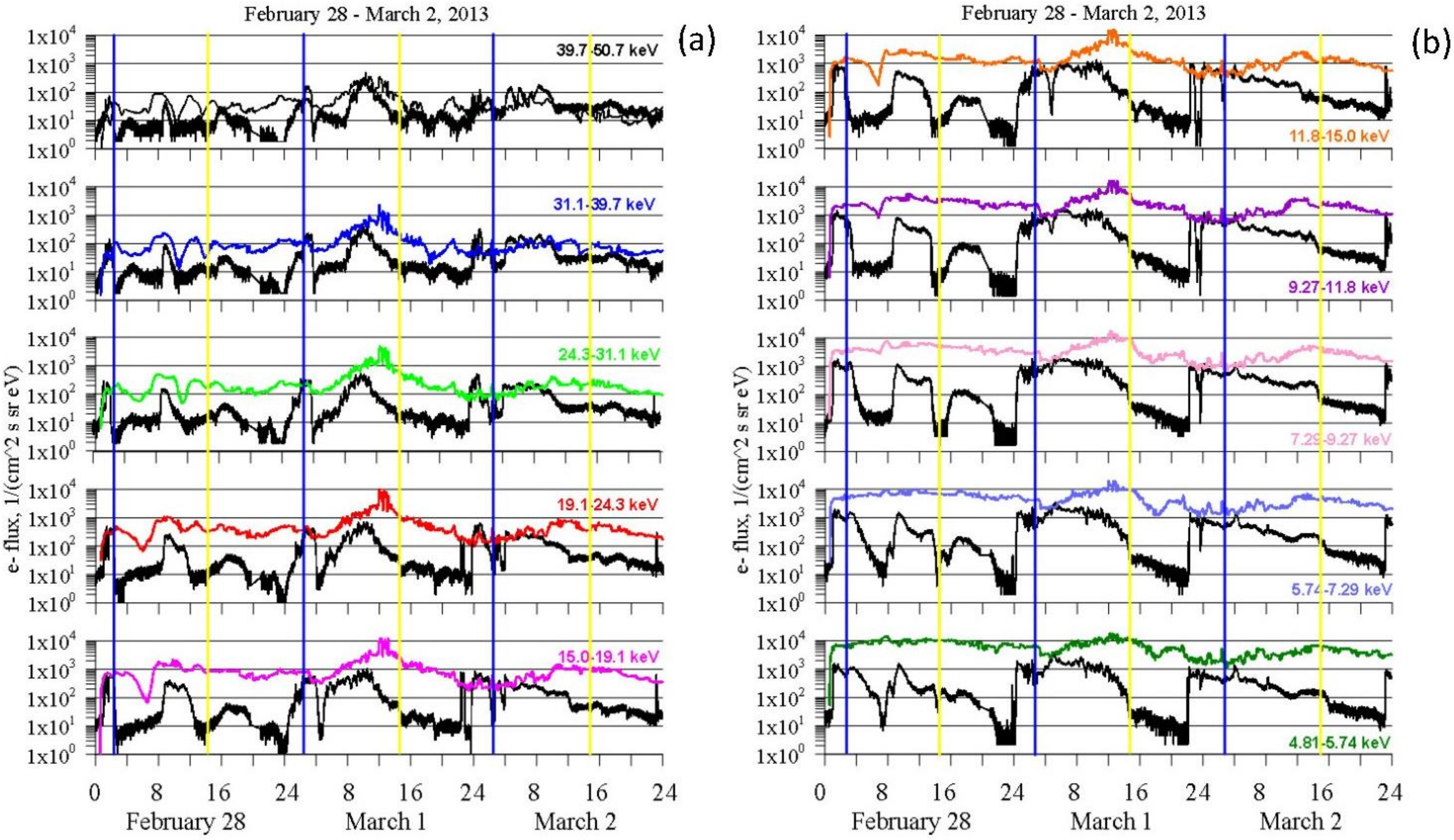
☐ AMC-12 (geosynchronous orbit)
ESA 5- 50keV, 10 energy channels

☐ Van Allen probes (aka RBSP), two probes on slightly elliptic orbits apogee 5.8Re, perigee 1.1 Re
HOPE instrument 30eV - 45keV
MagEIS instrument 30keV - 4MeV



Van Allen probes orbits: 2013, Feb 28-Mar 02

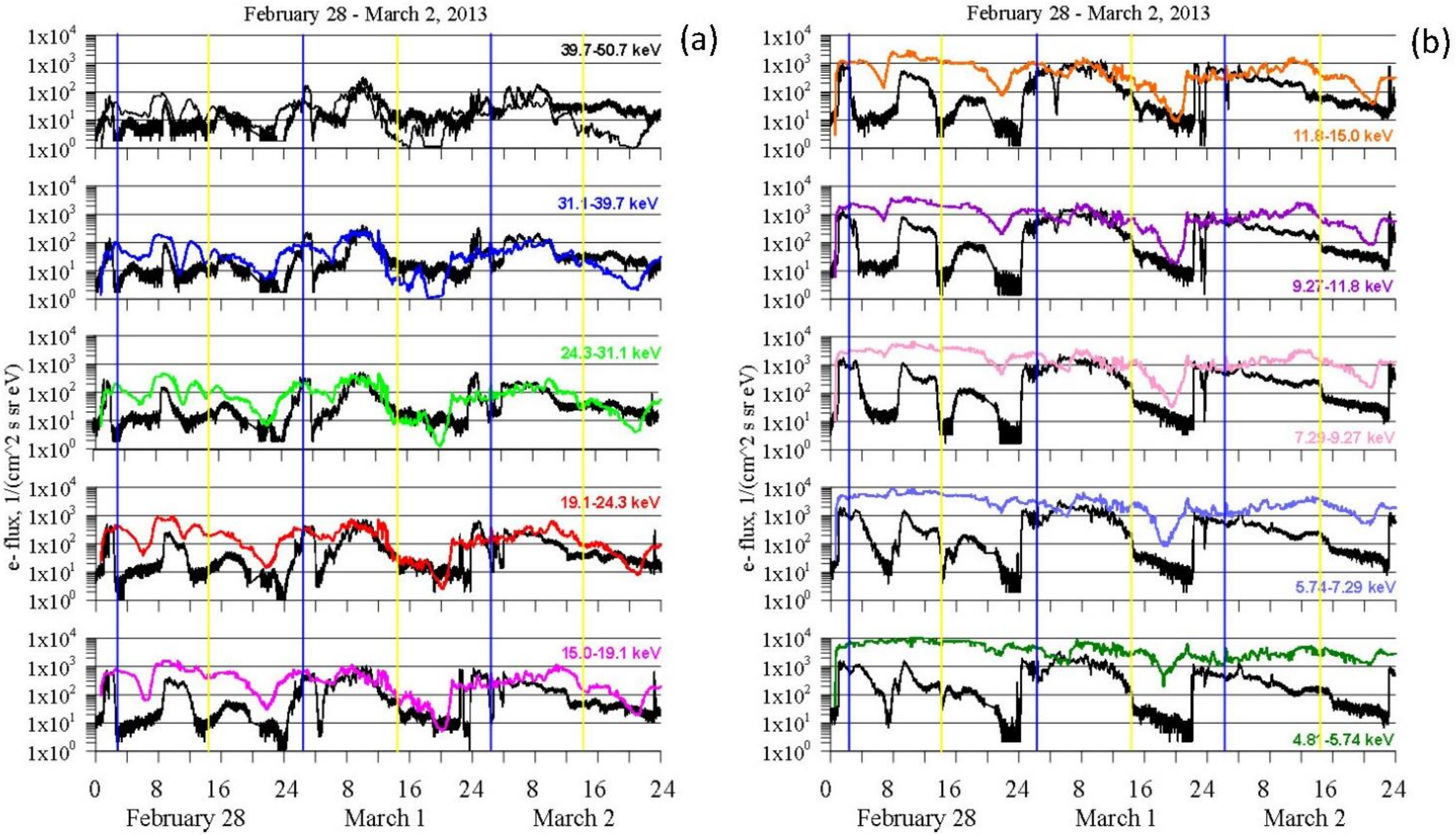
No electron losses included; geosynchronous orbit



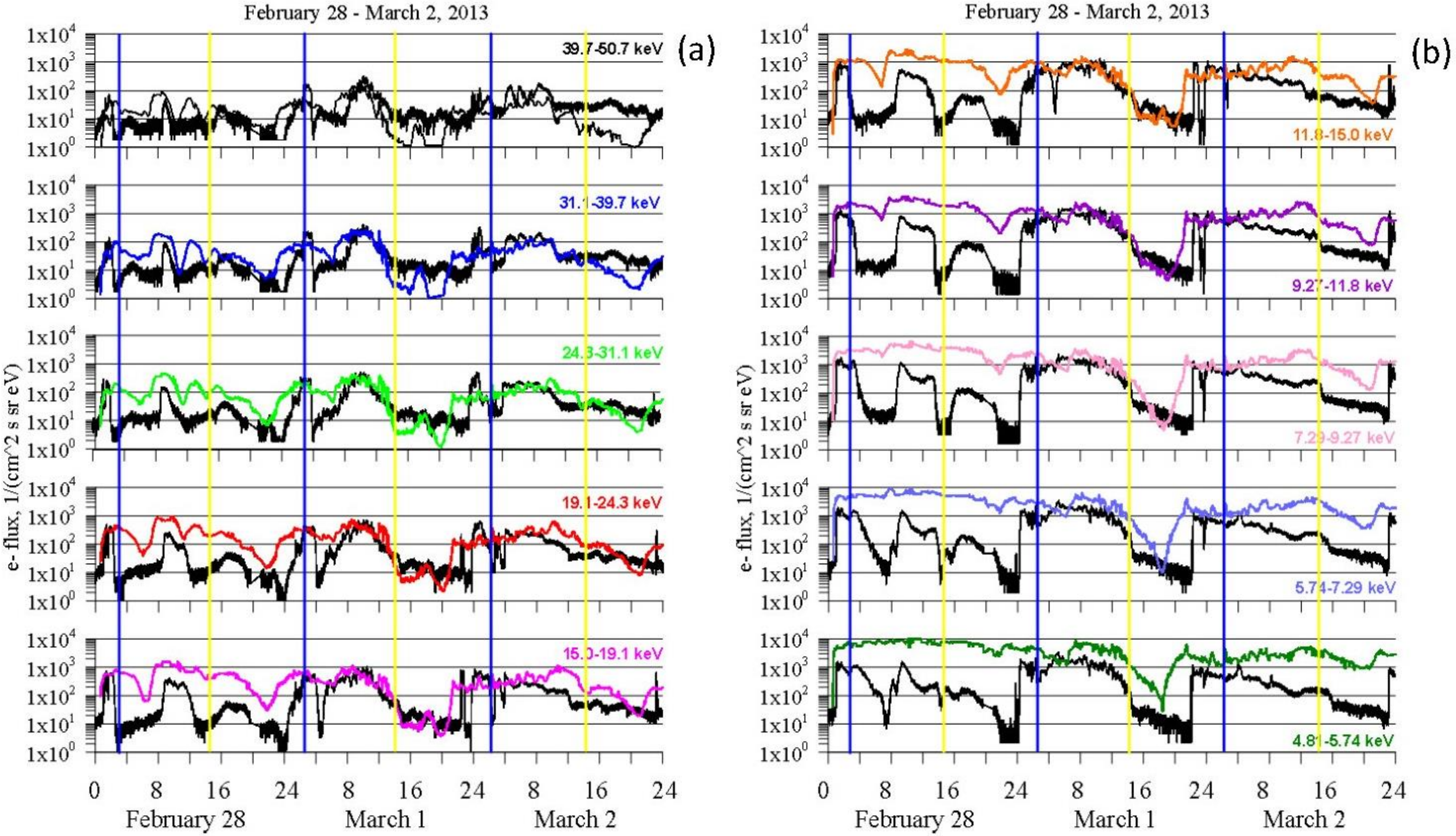
Chorus waves: *Orlova and Shprits* [2014]

Hiss waves: *Orlova et al.*, [2014]

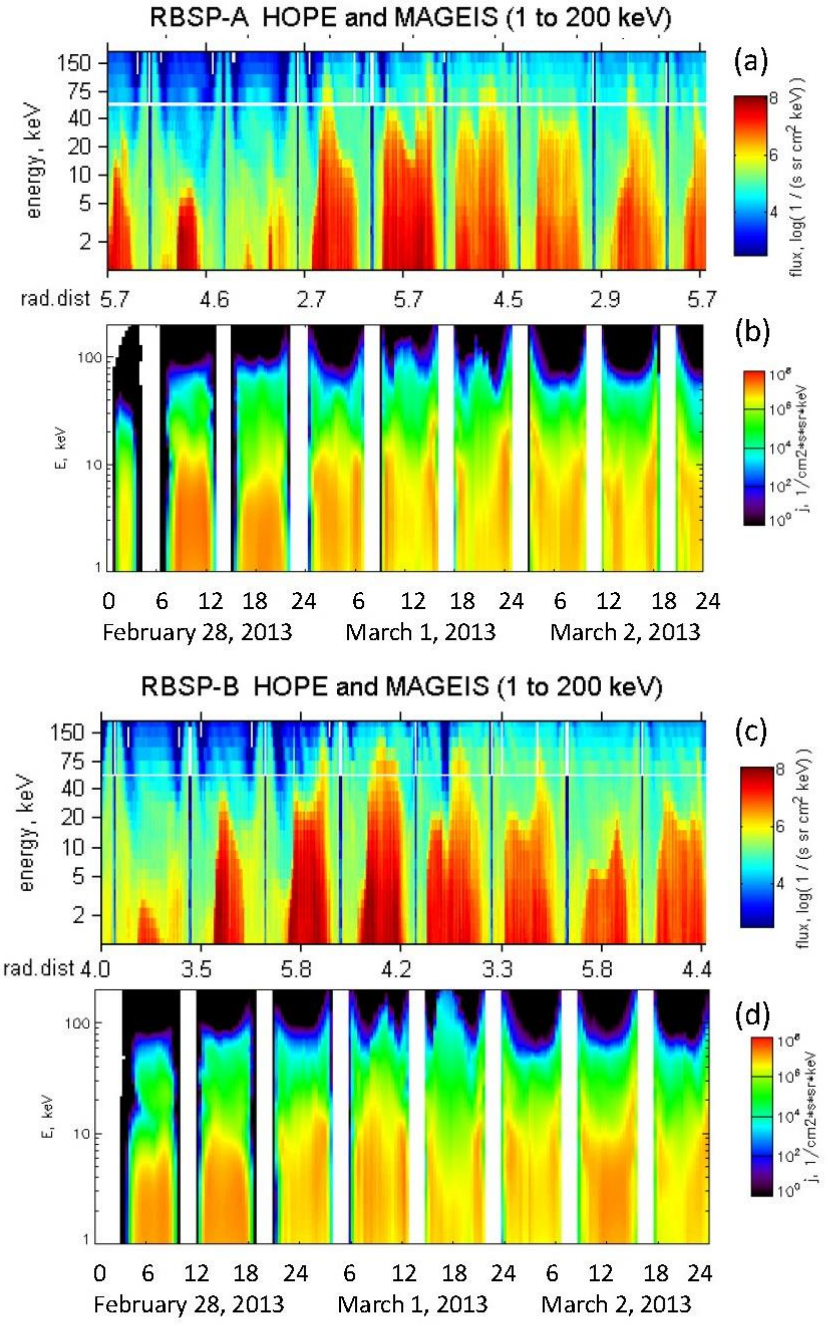
geosynchronous orbit



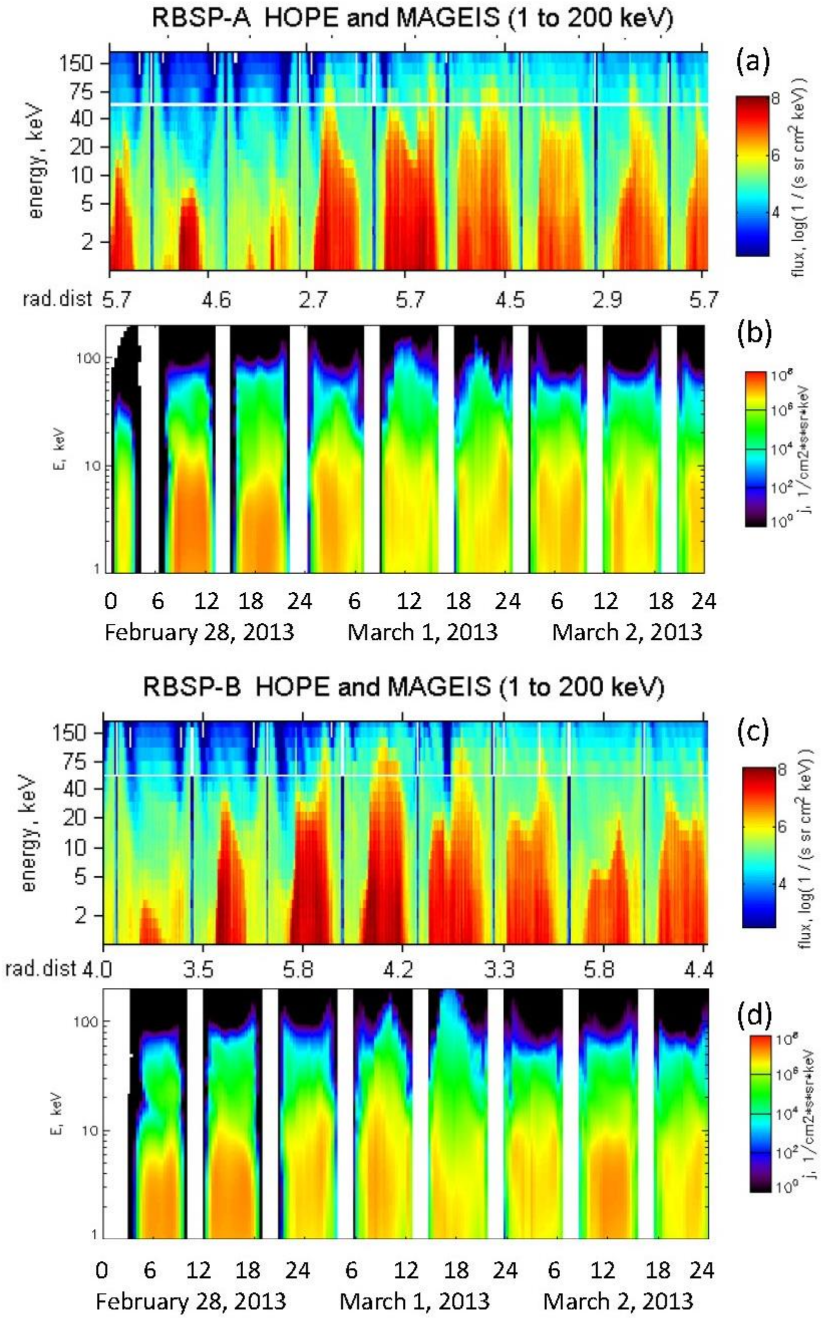
Chorus waves: *Orlova and Shprits* [2014]
Hiss waves: *Orlova et al.*, [2016]
geosynchronous orbit



Orlova and Shprits [2014], *Orlova et al.*, [2014]



Orlova and Shprits [2014], *Orlova et al.*, [2016]



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

imptam.fmi.fi

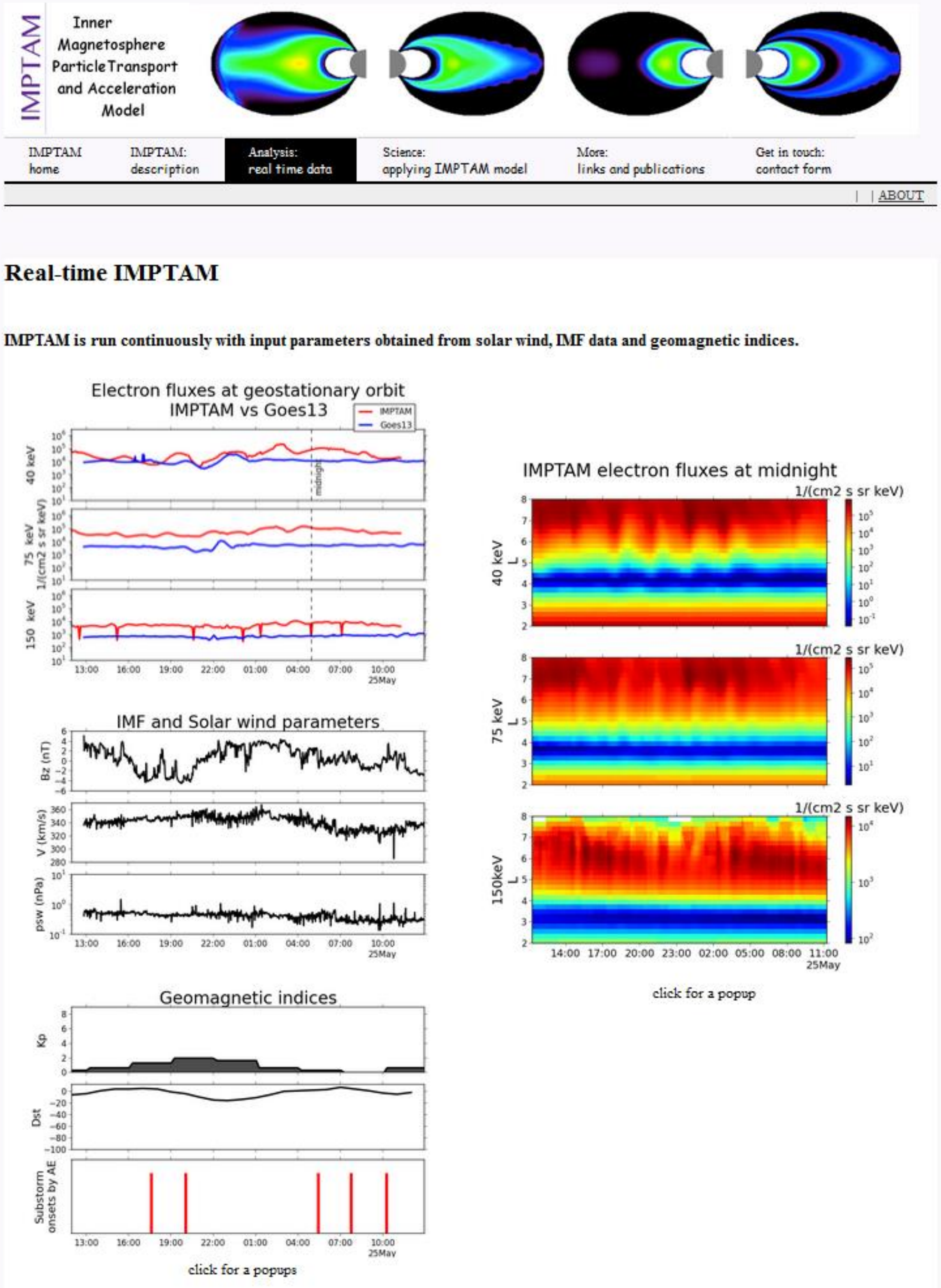
Why this model is important?
Low energy electron fluxes are very important to specify when hazardous satellite **surface charging** phenomena are considered.
They constitute the low energy part of the seed population for the high energy MeV particles in the **radiation belts**

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.

imptam.fmi.fi

Low Energy Electrons Nowcast
40 keV
75 keV
150 keV
Compared to GOES 13 MAGED electron data



Real-time IMPTAM

IMPTAM is run continuously with input parameters obtained from solar wind, IMF data and geomagnetic indices.

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.
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