Space Weather Effects in the Ring Current

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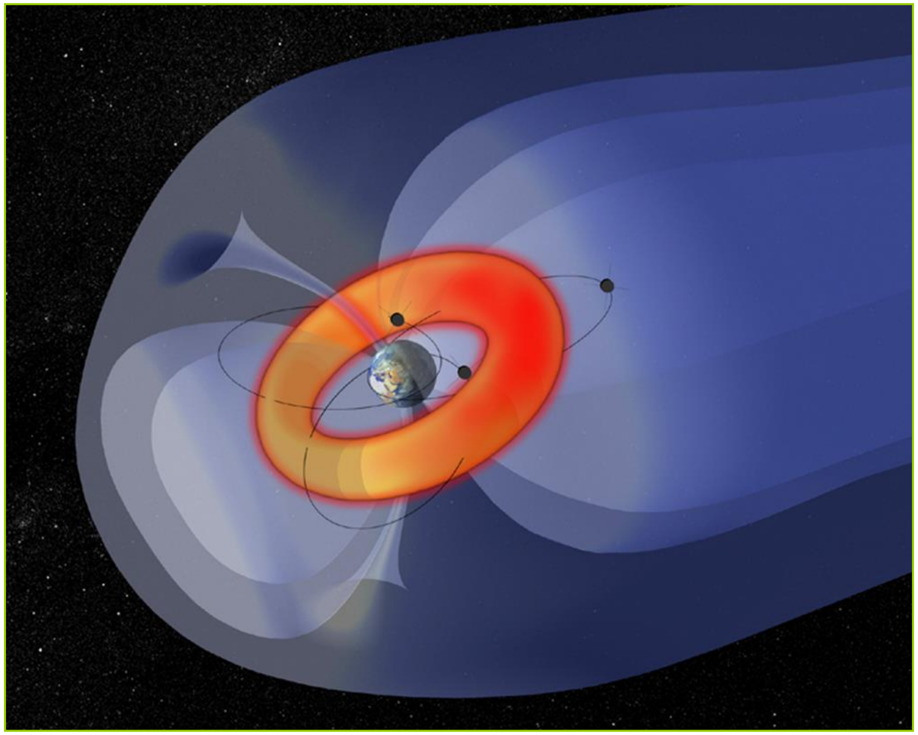
General structure of ring current

The symmetric ring current is one of the oldest concepts in magnetospheric physics:
A current of a ring shape flowing around the Earth was first introduced by *Stormer* (1907) and supported by *Schmidt* (1917). *Chapman and Ferraro* (1931, 1941) used a ring current concept for the model of a geomagnetic storm.



Ring current, simplified view:
- toroidal shaped electric current
- flowing westward around the Earth
- with variable density
- at geocentric distances between 2 and 9 Re.
- H+, O+, He+, e, 1-400 keV

Quiet time ring current:
of ~1-4 nA/m^2
Storm time ring current:
of ~7 nA/m^2

The first mission, which clarified the ring current energy and composition was AMPTE mission of the late 1980s.

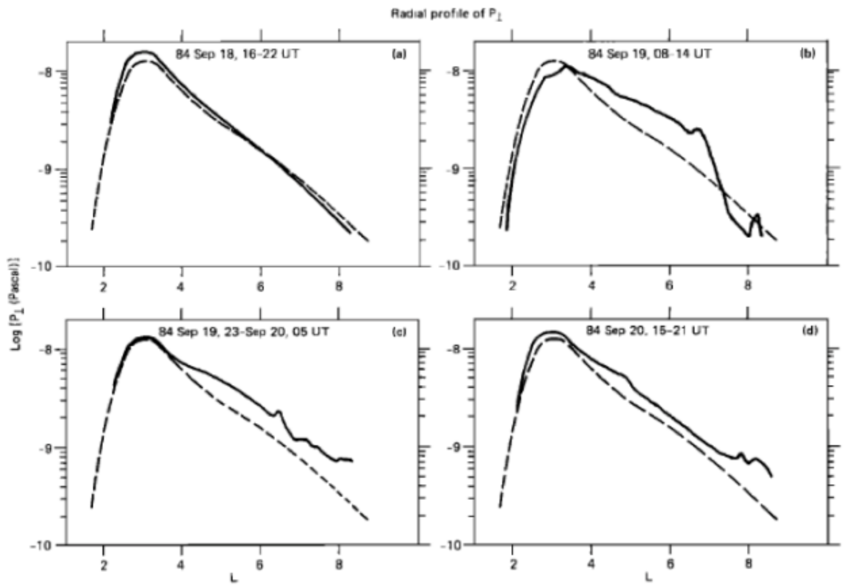
General structure of ring current: Observations

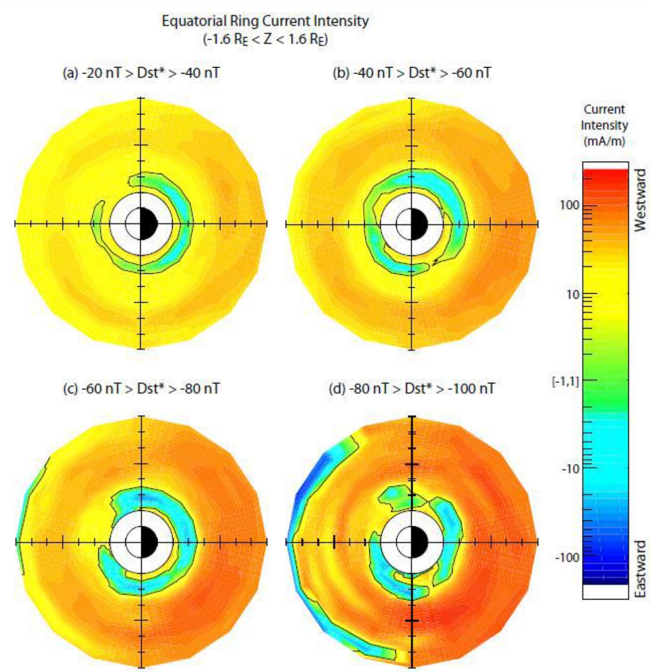
There have been numerous in-situ observations of the ring current:

- **particles measurements** giving plasma pressure and current estimated from it (*Frank*, 1967; *Smith and Hoffman*,1973; *Lui et al*., 1987; *Spence et al*., 1989; ***Lui and Hamilton* (1992);** *De Michelis et al*., 1997; *Milillo et al*., 2003; *Korth et al*., 2000; *Ebihara et al*., 2002; *Lui*, 2003);

- deriving the current from the **magnetic field measurements** (***Le et al*., 2004**; *Vallat et al*., 2005; *Ohtani et al*., 2007);

- **remote sensing of energetic neutral atoms** (ENAs) emitted from the ring current (information about ring current morphology, dynamics and composition) (*Roelof* , 1987; *Pollock et al*., 2001; *Mitchell et al*., 2003; *Brandt et al*., 2002a; *Buzulukova et al*., 2010; *Goldstein et al*., 2012).



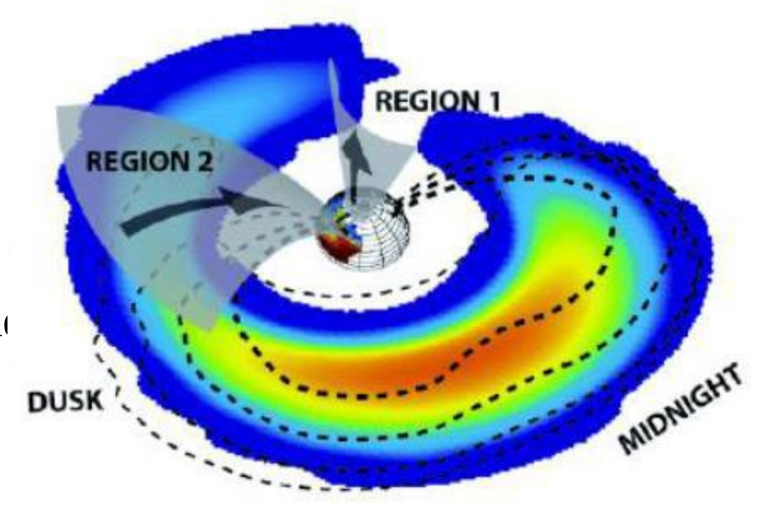


Ring current morphology

The ring current almost always is not a ring. The concept of the partial ring current and its closure to the ionosphere was early suggested by Alfven in 1950’s.

- Magnetosphere is **essentially asymmetric**, compressed by the solar wind dynamic pressure on the dayside, and stretched by the tail current on the night-side.
- **Plasma pressure** distribution during disturbed time becomes **highly asymmetric** due to plasma transport and injection from the night-side plasma sheet to the inner magnetosphere.
- The resulting plasma distribution presents a gradient in the azimuthal direction resulting in the **spatial asymmetry of the ring current.**

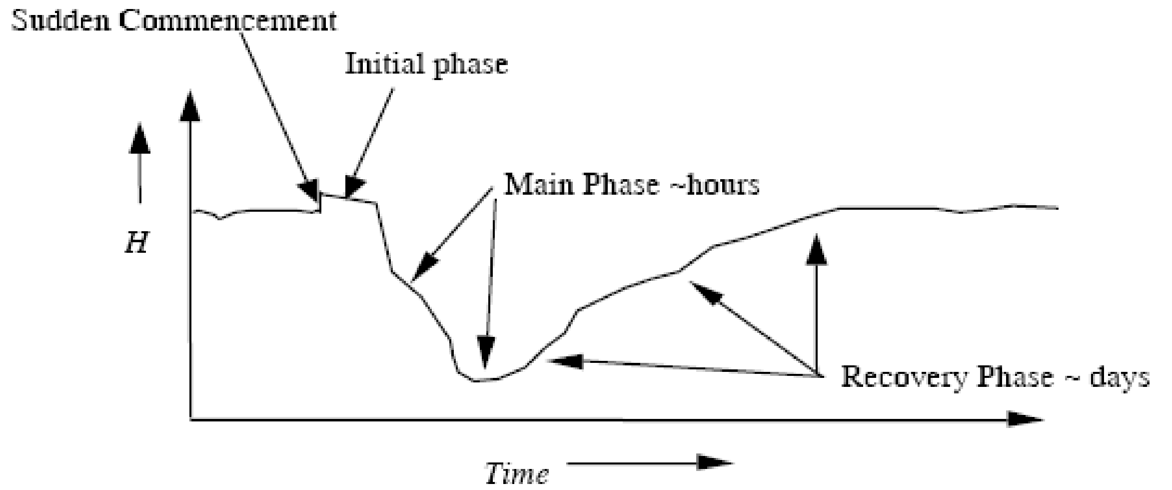
The remnant of the perpendicular current must **flow along a field line** to complete a closure of the current



Current systems associated with the partial ring current as deduced from the ENA measurements (*Brandt et al.*, 2008)

Ground effects from the ring current

It has long been known that the **horizontal component, H**, of the geomagnetic field **is depressed** during periods of great magnetic disturbances and that the recovery to its average level is gradual.



1741: **Celsius** observed large magnetic disturbance in Uppsala **Graham** observed the same in London simultaneously

These large magnetic field disturbances were called **"magnetic storms",** they showed to be **non-local.**
Gauss and **Weber** founded a network of observatories expanded by British and Russians, it was found that magnetic storms are **worldwide** phenomena.

Akasofu and Chapman, (1961); *Kamide and Fukushima (*1971); *Kamide* (1974): Ring current is a measure of the ground disturbance of the magnetic field.
Sugiura (1964), *Iyemori* (1990): : The averaged magnetic field depression observed at low latitudes is used to derive the **Dst index**.

General definition of the effects of space weather

Where does the ring current come in?

Time-varying conditions in the space environment that may

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

Where can we get the modeled Dst index?

1. From physics-based (and semi-empirical) models, which include current systems
   Global magnetospheric magnetic field models like **Tsyganenko models**
   MHD models (with inner magnetosphere represented) like **SWMF**
   Kinetic models like our own **IMPTAM**

2. From linear (or nonlinear) prediction filter based on solar wind parameters alone (*Burton et al*., 1975; *Fenrich and Luhmann*, 1998; *Vassiliadis et al*., 1999; *O'Brien and McPherron*, 2000; *Lundstedt et al*., 2001; *Watanabe et al*., 2002; *Temerin and Li*, 2006; *Boynton et al*., 2011).

Dst index is not a measure of the ring current only

From semi-empirical global magnetospheric magnetic field models

Magnetic field measured on the ground contains contributions from all current systems, No other way to separate them but to use magnetospheric models.

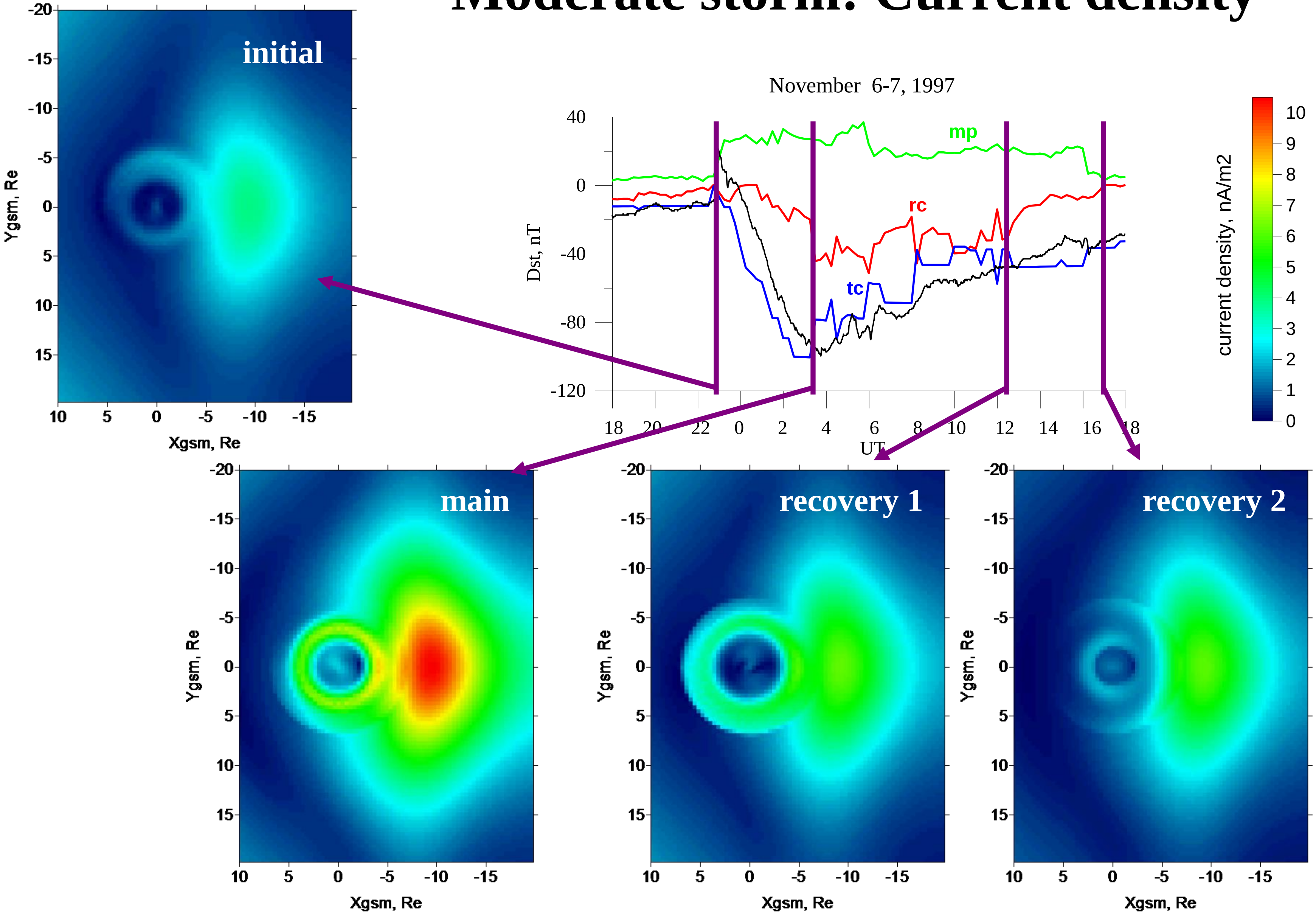
Other current systems' contributions (significant or largest) during main phase:

- ***cross-tail current*** (*Alexeev et al., 1996; Dremukhina et al., 1999; Turner et al., 2000; Alexeev et al., 2001; Ohtani et al., 2001; Maltsev, 2004; Ganushkina et al., 2004; Kalegaev et al., 2005)*

- ***partial ring current*** *(Liemohn et al.*, 2001; *Liemohn, 2003)*

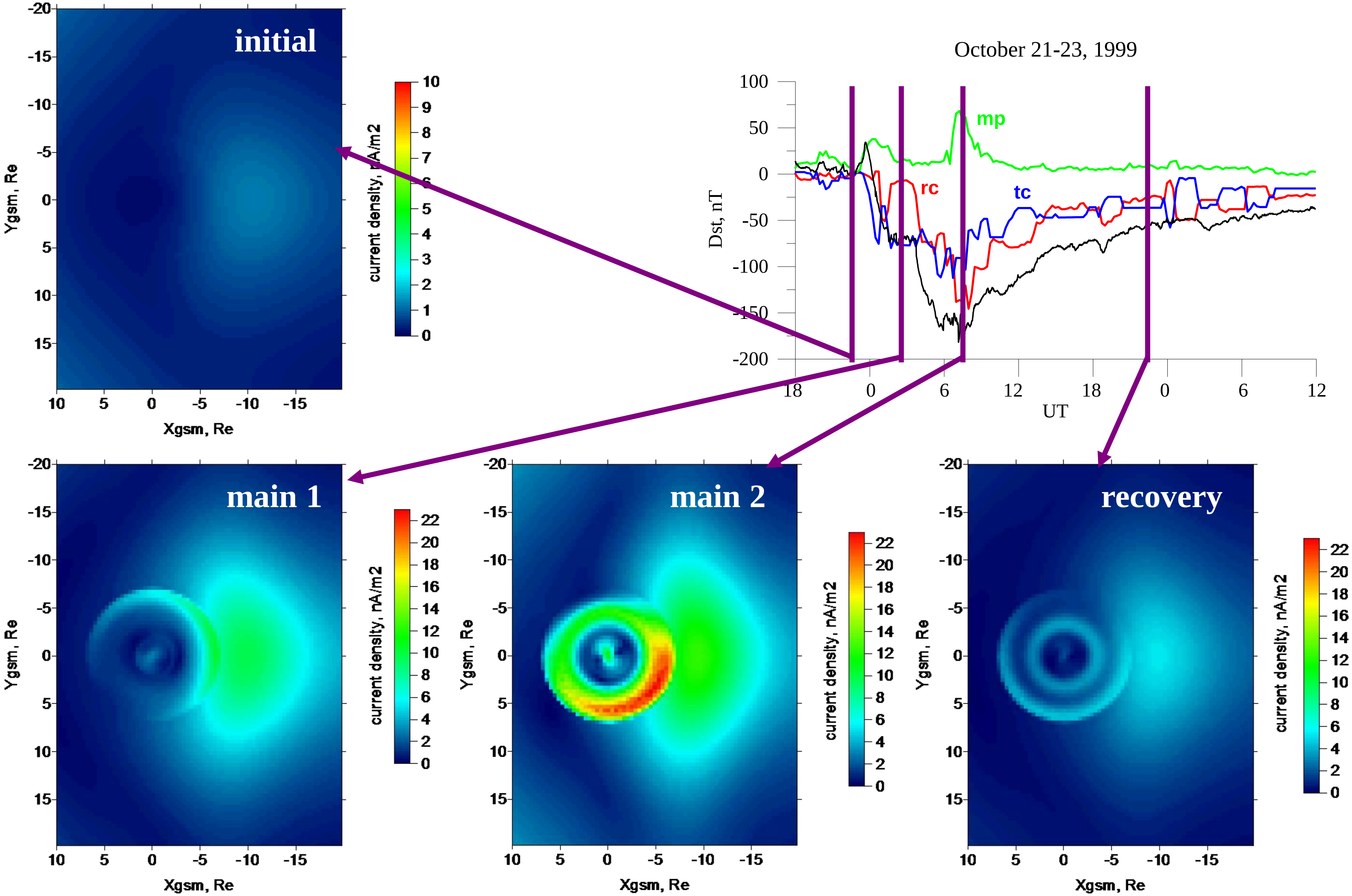
- ***substorm current wedge*** (*Friedrich et al., 1999; Munsami , 2000)*

Moderate storm: Current density



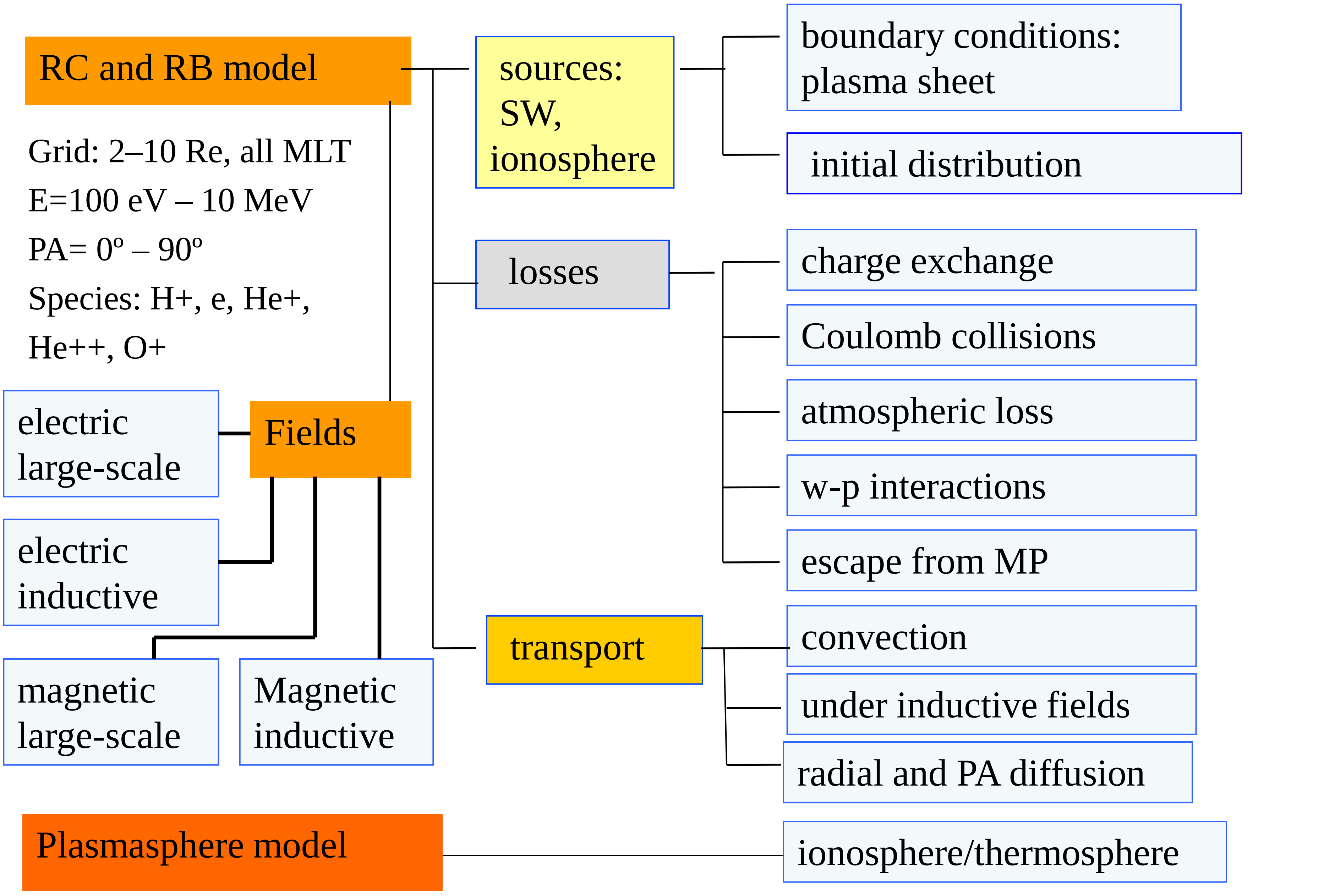
Event-oriented magnetic field model, From *Ganushkina et al.*, AnnGeo, 2010

Intense storm: Current density



Event-oriented magnetic field model, From *Ganushkina et al.*, AnnGeo, 2010

Inner Magnetosphere Particle Transport and Acceleration Model



Formation of storm-time ring current: Convection vs substorms

Points	Counter-Points
Dst development is reduced with substorm occurrence.	Dst is a magnetic index and is affected by other current systems (e.g., SCW).
Good Dst prediction from solar wind parameters alone.	Solar wind conditions for enhanced convection are also favorable to frequent substorm occurrence.
Simulations show enhanced convection alone is sufficient for ring current buildup.	Enhanced convection is effective in ring current buildup only initially (~3 hr).
Ring current buildup comes with repeated convection reduction and strengthening.	Substorms reduce convection and help in converting particles in open drift paths to closed ones.

Drivers of inner magnetosphere

♦ Relative importance of large-scale convection and substorm-associated electric fields for ring current development is still an open issue

- Storms as superposition of substorms (*Chapman, 1962; Akasofu, 1966*);

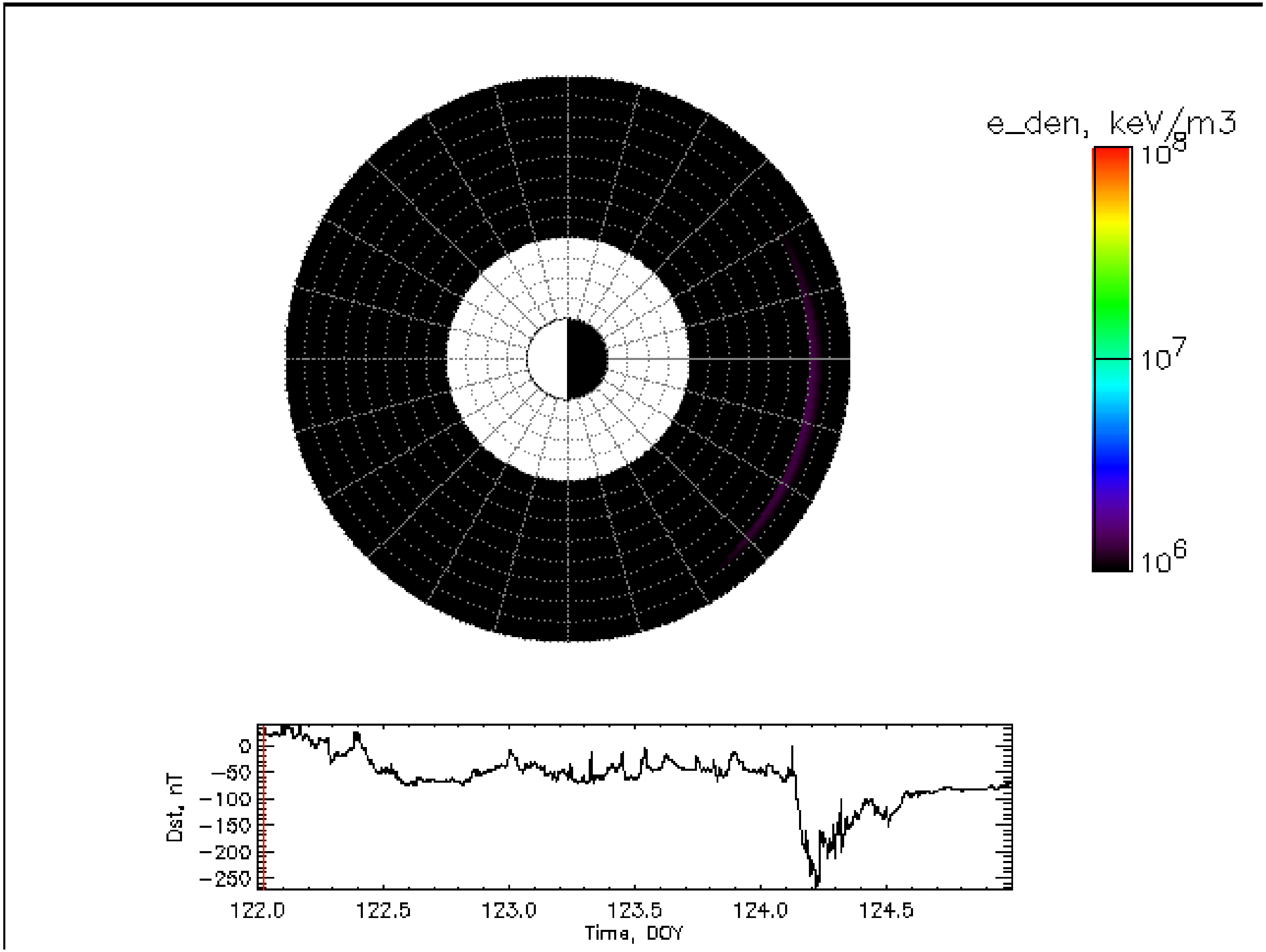
- Substorm occurrence is incidental to storm main phase (Kamide, 1992);

- Convection paradigm (*Takahashi et al., 1990; Kozyra et al., 1998; Ebihara and Ejiri, 2000; Jordanova et al., 2001; Liemohn et al., 2001*);

- **Concurrent action of convection and substorm-associated field variations** (*Fok et al., 1999; Ganushkina et al., 2005*)

Accurate representation of substorm-associated fields is missing

Ring current development during storm on May 2-4, 1998: IMPTAM simulations (*Ganushkina et al.*, 2005)



Model-dependent Dst calculations during storms

1. Using **Dessler-Parker-Sckopke relationship**:

The energy in the ring current can be expressed by $\frac{\Delta \vec{B}}{B_E} = -\frac{2}{3}\frac{W_{RC}}{W_{mag}}\hat{k}$, where

$W_{mag} = \frac{4\pi}{3\mu_0} B_E^2 R_E^3$ is the total energy in the Earth's dipole magnetic field above the surface, B_E is the magnetic field at the Earth's surface, R_E is one Earth radii (6371 km).

$\Delta \vec{B}$ is the change in B measured at the surface of the Earth (Dst).

2. Calculating from the model ring current by **Biot-Savart law**:

The magnetic disturbance parallel to the earth's dipole at the center of the earth ΔB induced by the azimuthal component of $J_\perp$, is given by

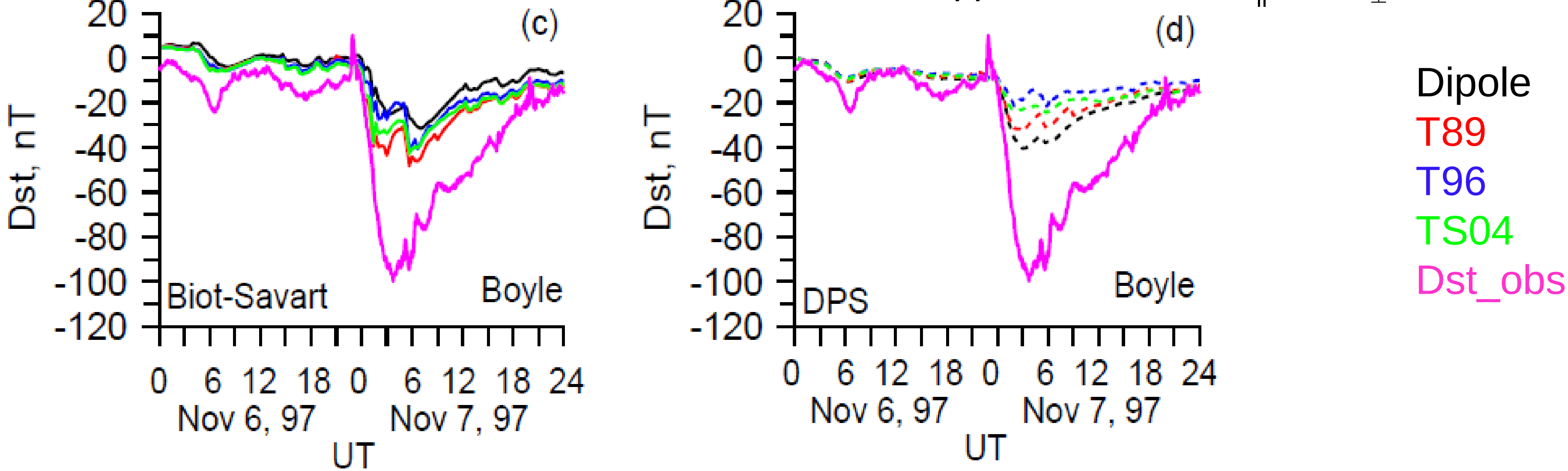
$$\Delta B = \frac{\mu_0}{4\pi}\int_r \int_\lambda \int_\phi \cos^2 \lambda J_\phi(r, \lambda, \phi) dr d\lambda d\phi$$

$$\vec{j}_\perp = \frac{\vec{B}}{B^2} \times \left(\nabla P_\perp + \frac{P_{II} - P_\perp}{B^2}\left(\vec{B}\cdot\nabla\right)\vec{B} \right)$$

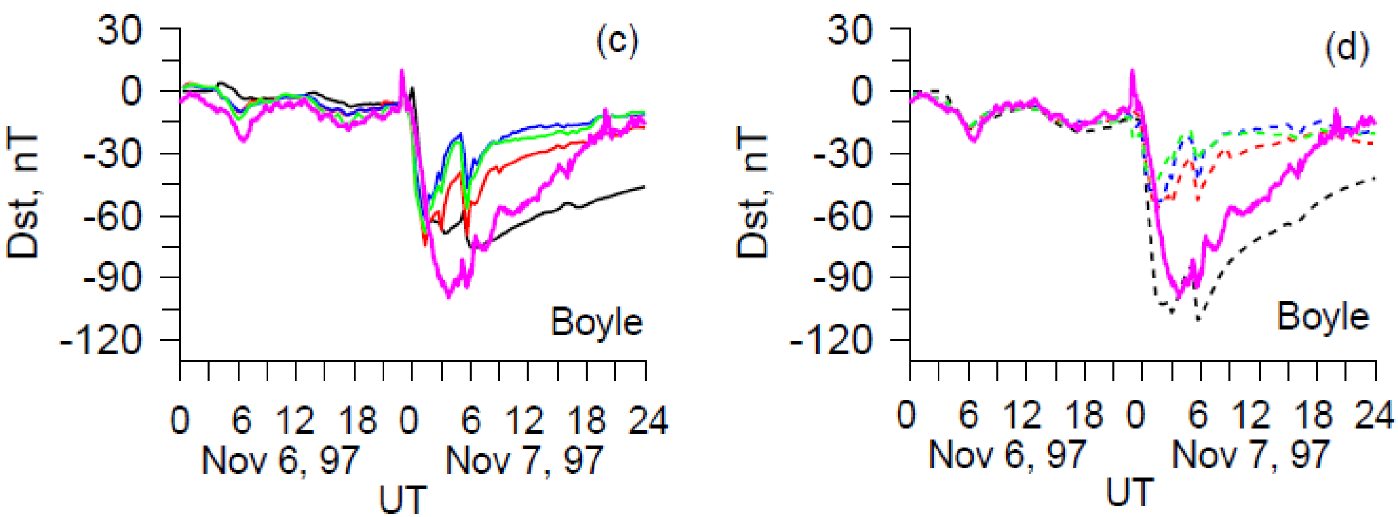
Dst index is not a measure of the ring current only

From kinetic inner magnetosphere models

kappa at 6.6 Re, n, $T_{||}$ and $T_{\perp}$ from LANL



kappa at 10 Re, T and n from Tsyganenko and Mukai (2003)



From *Ganushkina et al.*, AnnGeo, 2012

Near-Earth tail current is important and must be considered

1. Change the boundary position from 6.6 Re to 10 Re:
further decrease of modeled Dst

Time-dependent model boundary outside of 6.6 RE allows to take into account the particles in the transition region (between dipole and stretched field lines) forming a partial ring current and near-Earth tail current in that region.

2.Method of Dst calculation: DPS and Bio-Savart approach give close values for dipole magnetic field but can differ of about 50 -100 nT for realistic magnetic field

Calculating the model Dst* by Biot-Savart's law instead of the widely used Dessler-Parker-Sckopke (DPS) relation gives larger and more realistic values, since the contribution of the near-Earth tail current can be present.

Disturbances of ground magnetic field and indices calculated at low latitudes as space weather proxies

Disturbances of the magnetic field in space and on the ground are due to external current systems, which are, their turn, due to solar-wind-magnetosphere interactions.
Separate ground-based stations can “feel” variations of current systems differently, indices (Dst, SYM-H, ASY-H) contain averaged patterns.

To model and to predict these disturbances is to predict ground effects of space weather.

Main challenge: to be able to predict ring current effects (and effects from other current systems) on the ground as one of the space weather proxies, we need **predictions of IMF and solar wind** parameters, days in advance.

Therefore:
End users (whoever they are) of our scientific efforts will not be interested in Dst or magnetic field variations at ground-based stations given by physics-based models.

At present, prediction filters-kind of models will be of interest, since they can give an exact (though, not correct, may be) number at some time moments in a future.

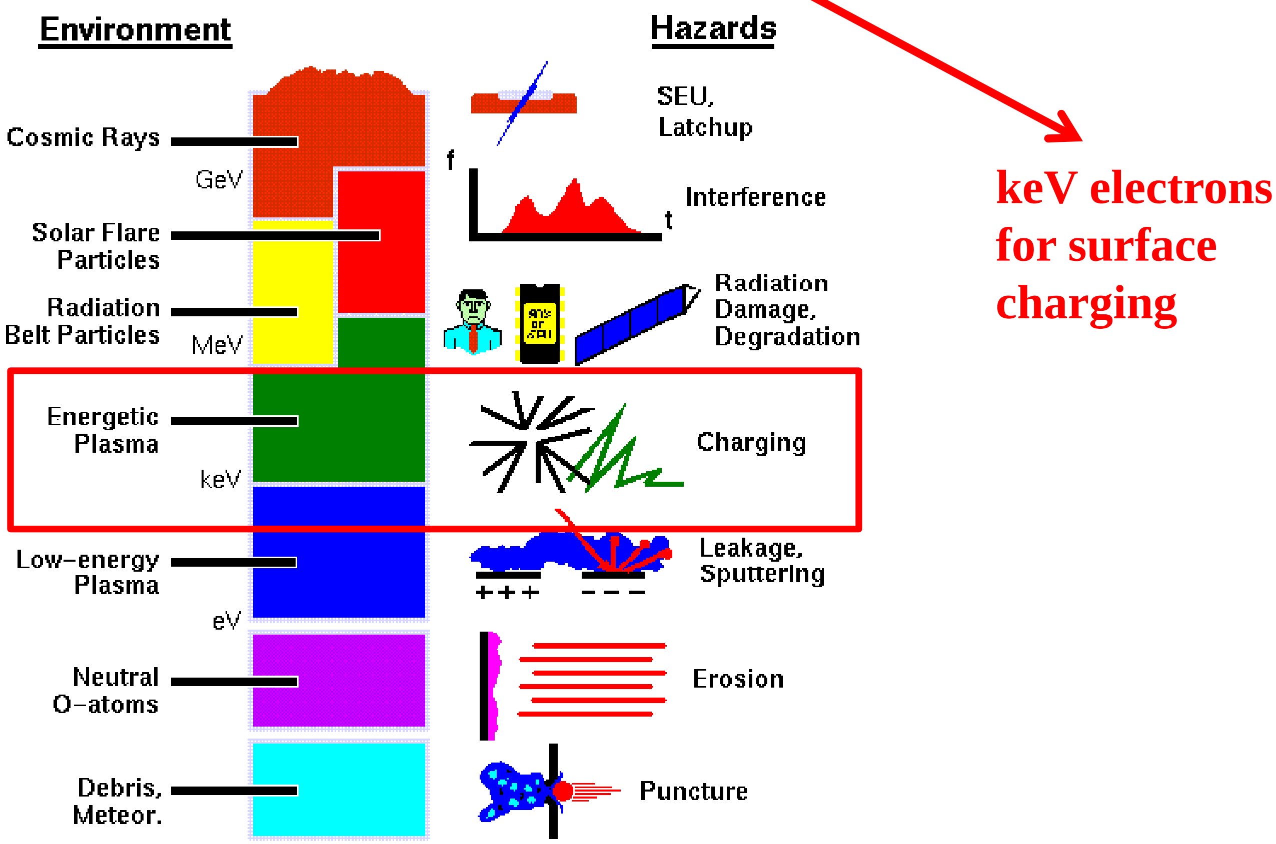
General definition of the effects of space weather

Where does the ring current 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

Ring current is not only ions but also **electrons**



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 as was said by Louis Lanzerotti

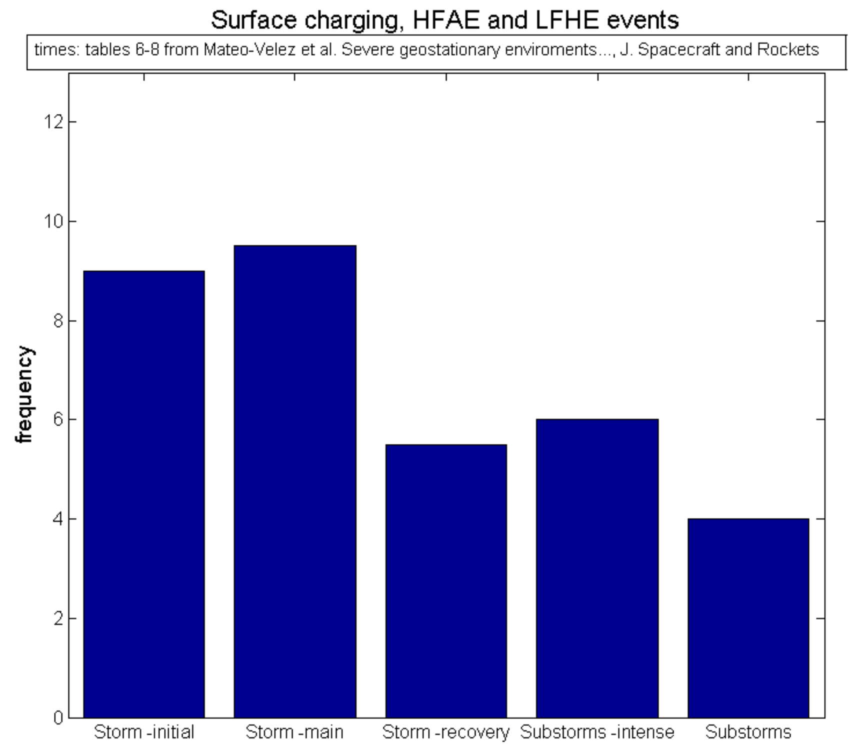
It is **NOT necessary to have even a moderate storm for significant surface charging** event to happen

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!

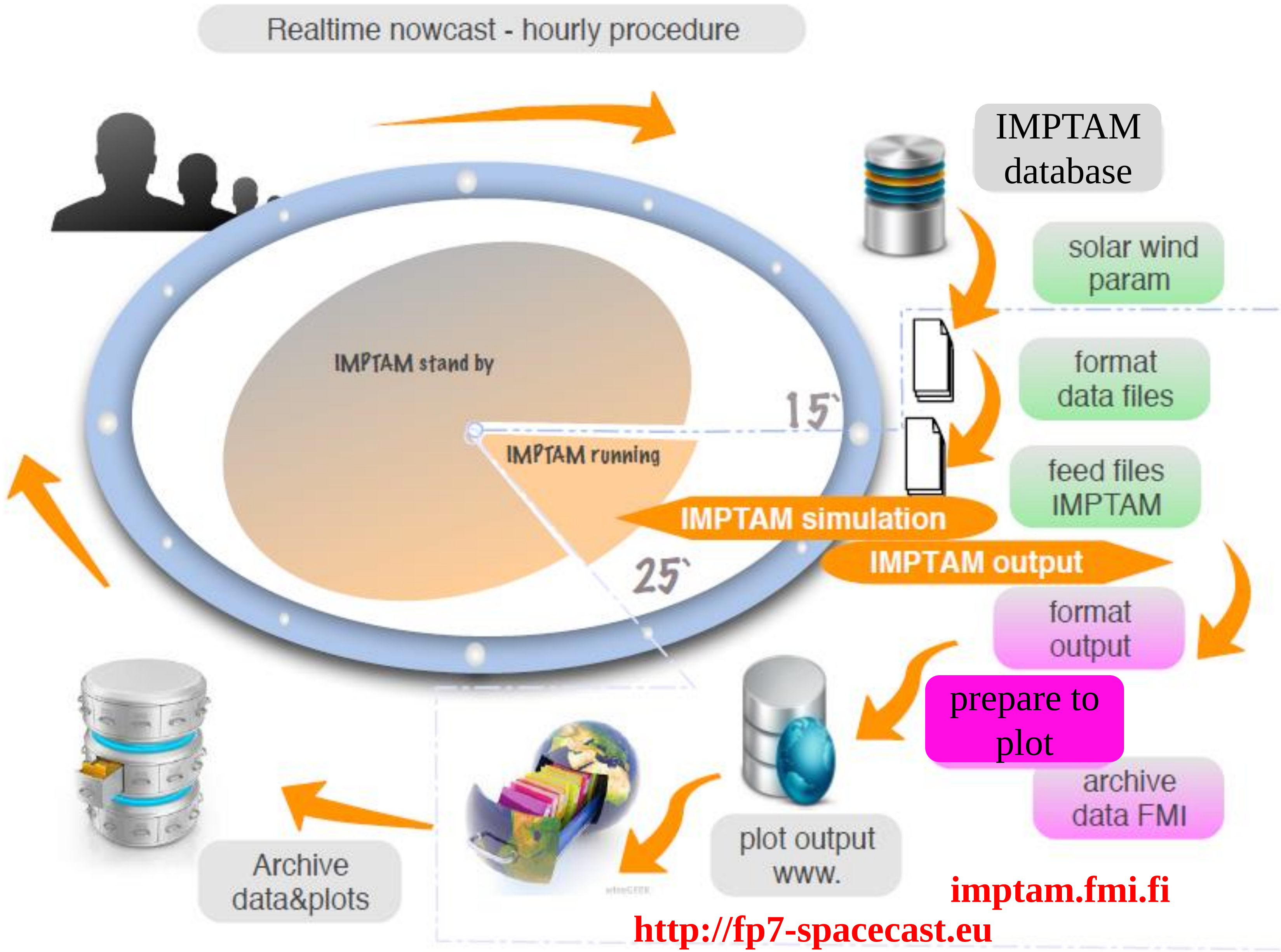
Correct models for electromagnetic fields, boundary conditions, losses are extremely hard to develop

Surface charging events vs. geomagnetic conditions



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

keV electrons in real time online (IMPTAM model)

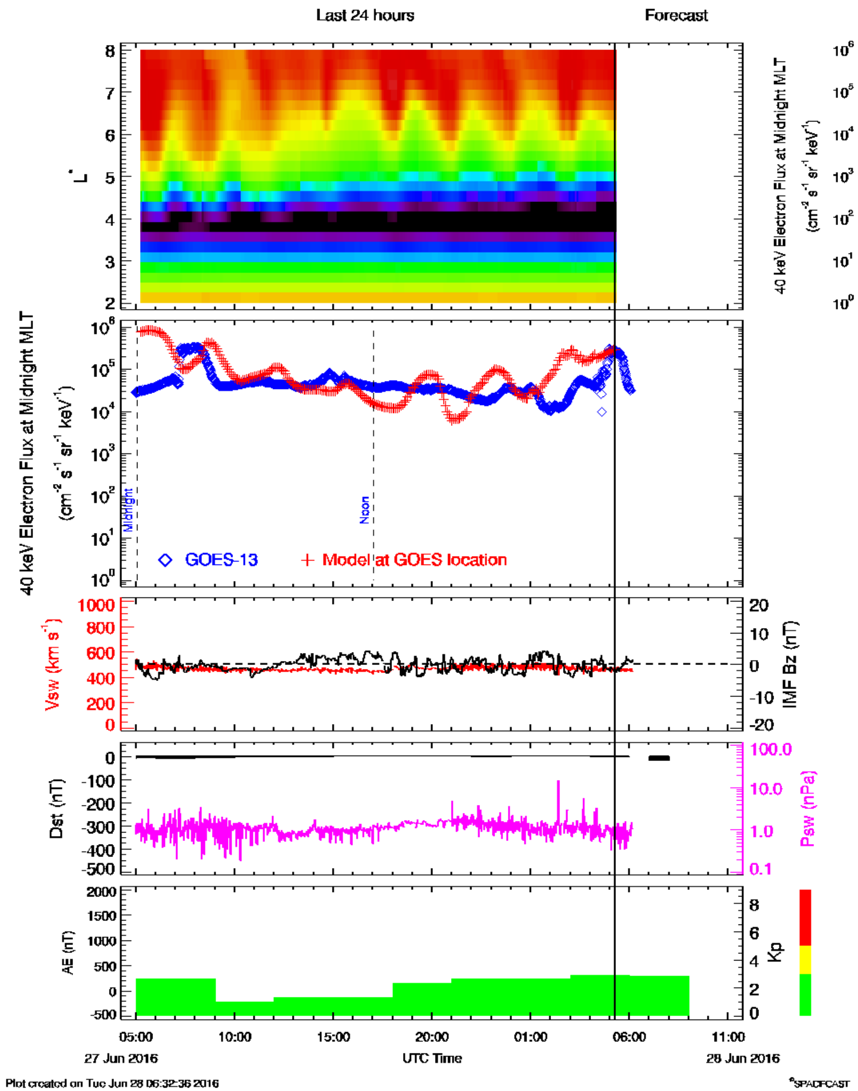


imptam.fmi.fi

http://fp7-spacecast.eu

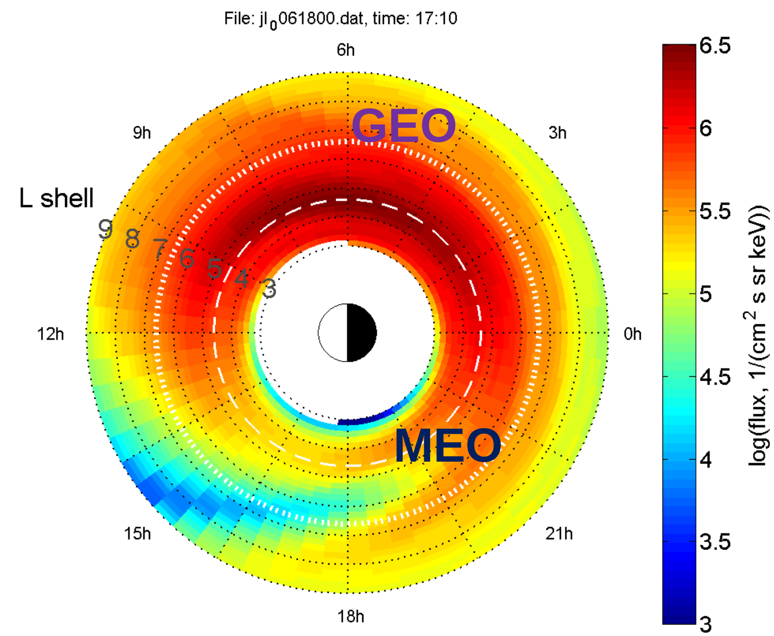
http://csem.engin.umich.edu/tools/imptam/

IMPTAM compared to GOES MAGED 40 keV e- fluxes



IMPTAM: traces **electrons (< 200 keV)** with arbitrary pitch angles (**drift approximation)** from the plasma sheet to the inner L-shells in time-dependent magnetic and electric fields

Taken into account: **radial diffusion and** electron losses as convection outflow and pitch angle diffusion by the **electron lifetimes**

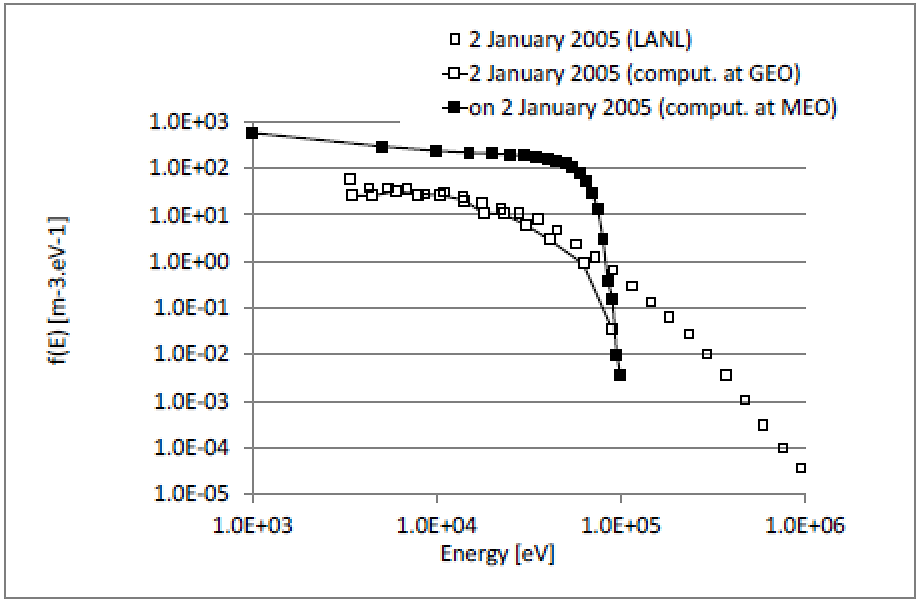


Ganushkina, et al., ***Space Weather***, **2015**.
Ganushkina et al.**, *J. Geophys. Res.*, 2014.**
Ganushkina, et al., ***J. Geophys. Res.***, **2013**.

Selected GEO environments #1

LANL_1994_084 2005/01/02 15h46min12s MLT 04 47

3. IMPTAM computations



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

14th SCTC 2016

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

This is what end-users want: Traffic light