
## Participants

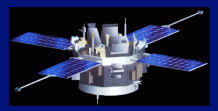
- University of Sheffield
- Finnish Meteorological Institute
- University of Warwick
- Skolkovo Institute of Science and Technology
- University of Michigan
- Space Research Institute, Ukraine
- LPC2E, France
- Swedish Institute for Space Physics

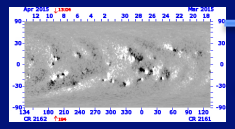
## Collaborators

- Berkeley University
- UCLA

PROGRESS has received funding from the *European Union's Horizon 2020* under grant agreement No 637302.

# PROGRESS

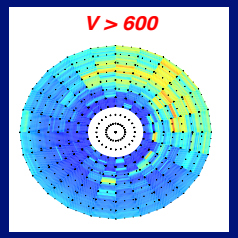




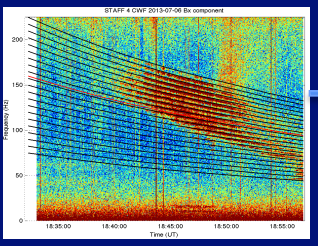
AWSoM → SWIFT →

NARMAX →

Geomagnetic indices Forecast
Solar Wind Parameters Forecast




ERR →



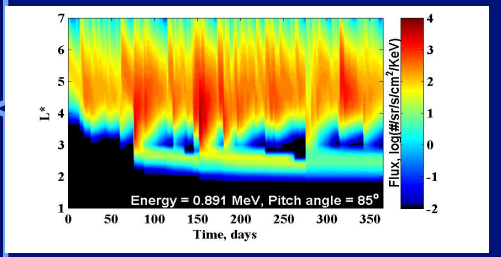
Cluster IMG →

VERB

IMPTAM

→ NB³GEO

Forecast of Radiation Environment in Geospace



# "Physics" based versus data based forecas

## First Principles based forecast

$$S = \int L(x, \dot{x}, t)\,dt$$

$$dL = \sum_i \frac{\partial L}{\partial x_i} dx_i + \sum_i \frac{\partial L}{\partial \dot{x}_i} d\dot{x}_i$$

Assumptions

+

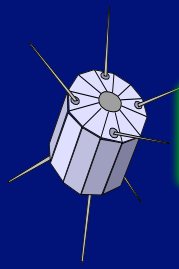
Physical Knowledge

+

First Principles

# “Physics” based versus data based forecast

## First Principles based forecast



L1

$$S = \int L(x, \dot{x}, t)\, dt$$

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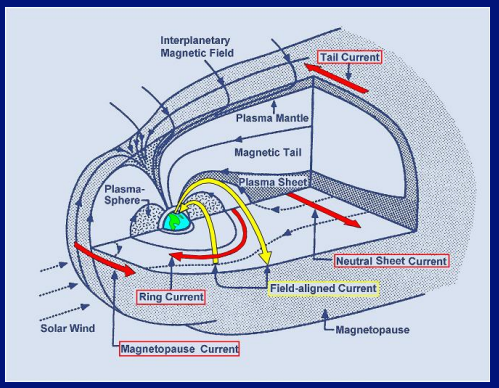
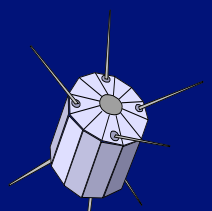



Forecast

# “Physics” based versus data based forecast

## First Principles based forecast of high energy fluxes of Radiation belts



L1

Forecast

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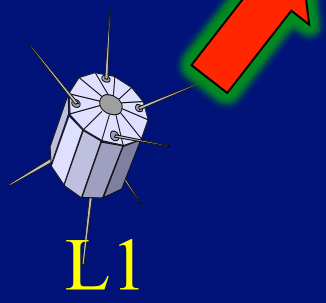
Boundary conditions

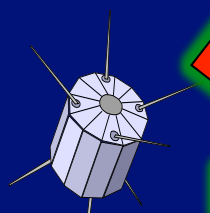


L1

Forecast

# “Physics” based versus data based forecast

## First Principles based forecast of high energy fluxes of Radiation belts



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Boundary conditions

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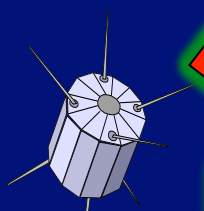
Model of the magnetic field

Forecast

# “Physics” based versus data based forecast

## First Principles based forecast of high energy fluxes of Radiation belts



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Boundary conditions

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Model of the magnetic field

$$S = \int L(x, \dot{x}, t)dt$$

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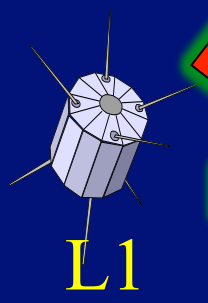
Wave model for the distribution of Hiss, Chorus, EMW, EMIC

Forecast

# “Physics” based versus data based forecast

## First Principles based forecast of high energy fluxes of Radiation belts



L1

$$S = \int L(x,\dot{x},t)dt \qquad dL = \sum_i \frac{\partial L}{\partial x_i} dx_i + \sum_i \frac{\partial L}{\partial \dot{x}_i} d\dot{x}_i$$

Boundary conditions

Model of the magnetic field

Wave model for the distribution of Hiss, Chorus, EMW, EMIC

Forecast

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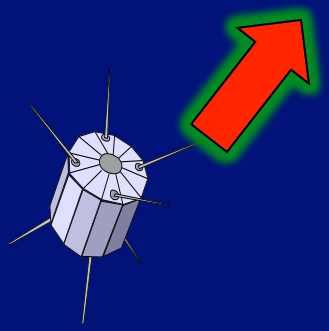
Boundary conditions



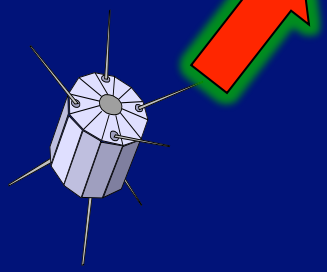
Forecast

# “Physics” based versus data based forecast

## First Principles based forecast of high energy fluxes of Radiation belts

Tsyganenko
Mukai 2003

Boundary conditions



Forecast

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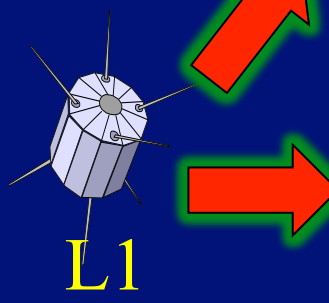



Tsyganenko Mukai 2003

Boundary conditions

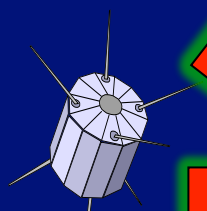
Tsyganenko model

Model of the magnetic field

Forecast

# “Physics” based versus data based forecast

## First Principles based forecast of high energy fluxes of Radiation belts



L1

Tsyganenko Mukai 2003

Boundary conditions

Tsyganenko

Model of the magnetic field

Empirical wave models

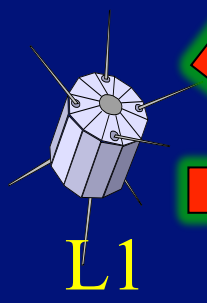
Wave model

Kp, AE

Forecast

# "Physics" based versus data based forecast

## First Principles based forecast of high energy fluxes of Radiation belts




Tsyganenko Mukai 2003

Boundary conditions

Tsyganenko

Model of the magnetic field

Numerical code

Forecast

Empirical wave models

Wave model

$$S = \int L(x, \dot{x}, t)dt$$

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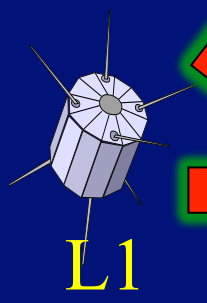
Diffusion coefficients

Kp, AE

Various assumptions

# "Physics" based versus data based forecast

## First Principles based forecast of high energy fluxes of Radiation belts




Tsyganenko Mukai 2003

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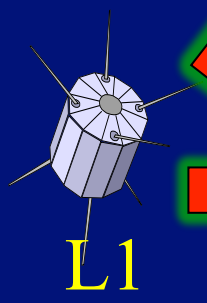


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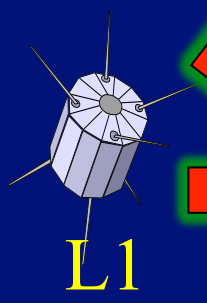


Tsyganenko Mukai 2003

Tsyganenko

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Numerical code

Radial and quasi-linear diffusion

Diffusion coefficients

Various assumptions

Forecast

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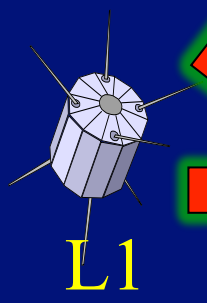

L1

Tsyganenko Mukai 2003

Tsyganenko

Empirical wave models

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Various assumptions

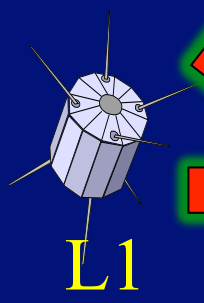
Forecast

?

Effect of large amplitude chorus on 101-102 Kev electrons (Papers by Artemiev, Mozer, Agapitov, Mourenas and Krasnoselskikh 2014-2015)

# "Physics" based versus data based forecast

## First Principles based forecast of high energy fluxes of Radiation belts




Tsyganenko Mukai 2003

Tsyganenko

Empirical wave models

Kp, AE

Numerical code

Radial and quasi-linear diffusion

Diffusion coefficients

Various assumptions

Forecast

*Whenever a theory appears to you as the only possible one, take this as a sign that you have neither understood the theory nor the problem which it was intended to solve.*

***Karl Raimund Popper***

# System Identification Approach

## Analytical Approach

$$S = \int L(x, \dot{x}, t)\,dt$$

$$dL = \sum_i \frac{\partial L}{\partial x_i} dx_i + \sum_i \frac{\partial L}{\partial \dot{x}_i} d\dot{x}_i$$

Assumptions

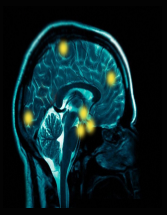
+

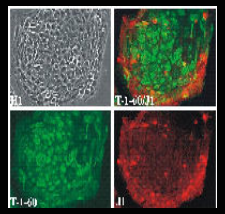
Physical Knowledge

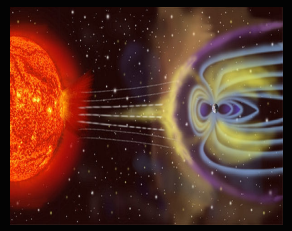
+

First Principles

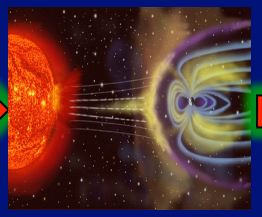
## Black box System







Input Data



Output Data

## Systems Approach

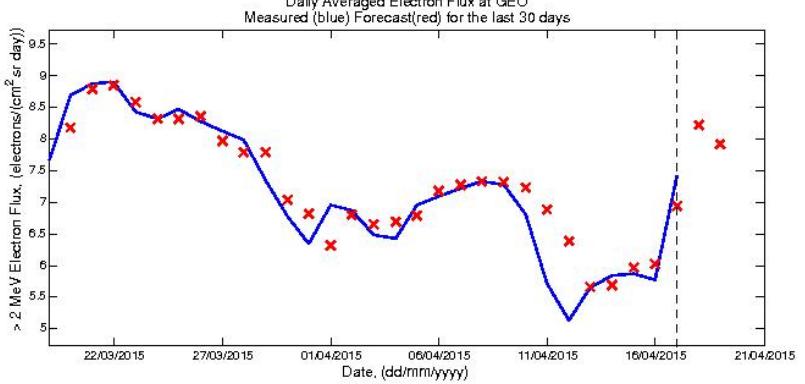
Knowledge of the System

$$S = \int L(x, \dot{x}, t)\,dt$$

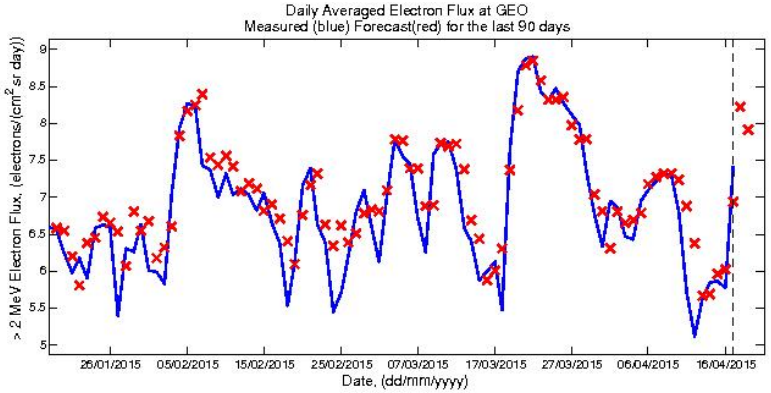
$$dL = \sum_i \frac{\partial L}{\partial x_i} dx_i + \sum_i \frac{\partial L}{\partial \dot{x}_i} d\dot{x}_i$$

The one day ahead forecasts of the relativistic electron fluxes with energies greater than 2 MeV at GEO has been developed in Sheffield and is available in real time:

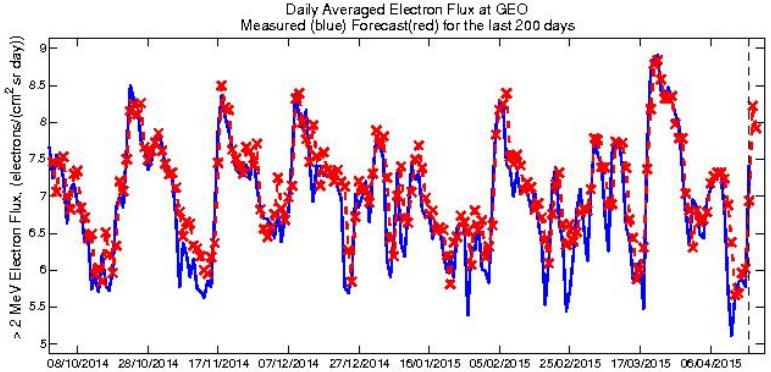
http://www.ssg.group.shef.ac.uk/USSW/2MeV_EF.html.




## Past 90 days




## Past 200 days



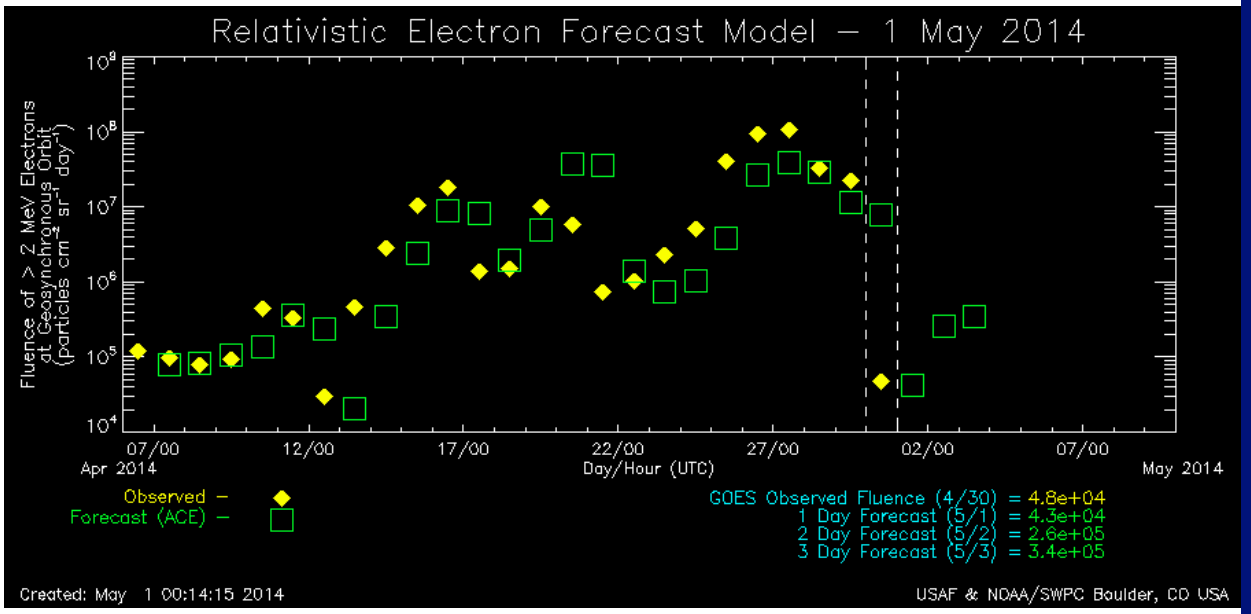
# NOAA REFM Forecast

Space Weather Prediction Center 01/05/2014 21:09

## NOAA / Space Weather Prediction Center

### Relativistic Electron Forecast Model

Presented by the USAF and NOAA/ Space Weather Prediction Center




The impact of high-energy (relativistic) electrons on orbiting satellites can cause electric discharges across internal satellite components, which in turn leads to spacecraft upsets and/or complete satellite failures. The Relativistic Electron Forecast Model predicts the occurrence of these electrons in geosynchronous orbit.
Plots and data are updated daily at 0010 UT. Dashed vertical lines indicate the last vertical value.
When the input parameters are not available, the forecast is not shown.

REFM Verification Plot and Model Documentation

1 to 3 Day Predictions (text file) and corresponding Performance Statistics.
Predictions created using data from the ACE spacecraft.

Historical electron particle data is archived at the
National Geophysical Data Center for Solar-Terrestrial Physics.

Visually impaired users may contact SWPC for assistance.
Please credit SWPC when using these images.

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# Comparison of REFM and SNB$^3$GEO Forecasts (01.03.2012-03.07.2014)

Balikhin, Rodriguez,Boynton, Walker,Aryan, Sibeck, Billings (submitted to SW 2015)

$$PE = 1 - \frac{1}{N}\sum \frac{(Y(t) - Ym(t))^2}{\mathrm{var}(Y)}$$

$$C_{cor} = \frac{1}{N}\sum \frac{(Y(t) - \langle Y(t)\rangle)(Ym(t) - \langle Ym(t)\rangle)}{\sqrt{\mathrm{var}(Ym)\mathrm{var}(Y)}}$$

# Comparison of REFM and SNB$^3$GEO Forecasts

Balikhin, Rodriguez, Boynton, Walker, Aryan, Sibeck Billings, submitted to SW 2015

| Model | Prediction Efficiency Flux | Correlation Flux | Prediction Efficiency Log Flux | Correlation Log Flux |
|---|---|---|---|---|
| REFM | -1.31 | 0.73 | 0.70 | 0.85 |
| SNB$^3$GEO | 0.63 | 0.82 | 0.77 | 0.89 |

# Comparison of REFM and SNB$^3$GEO Forecasts

Balikhin, Rodriguez, Boynton, Walker, Aryan, Sibeck Billings, submitted to SW 2015

**Table 2.** Contingency tables and Heidke skill scores for the REFM predictions.

| Fluence ($cm^{-2}sr^{-1}day^{-1}$) | $> 10^8$ | | $> 10^{8.5}$ | | $> 10^9$ | |
|---|---|---|---|---|---|---|
| REFM HSS | 0.666 | | 0.482 | | 0.437 | |
| Observation: | Yes | No | Yes | No | Yes | No |
| Forecast | | | | | | |
| Yes | 86 | 22 | 23 | 22 | 4 | 7 |
| No | 43 | 510 | 21 | 595 | 3 | 647 |

**Table 3.** Contingency tables and Heidke skill scores for the SNB$^3$GEO predictions.

| Fluence ($cm^{-2}sr^{-1}day^{-1}$) | $> 10^8$ | | $> 10^{8.5}$ | | $> 10^9$ | |
|---|---|---|---|---|---|---|
| SNB$^3$GEO HSS | 0.738 | | 0.634 | | 0.612 | |
| Observation: | Yes | No | Yes | No | Yes | No |
| Forecast | | | | | | |
| Yes | 106 | 33 | 31 | 19 | 4 | 2 |
| No | 23 | 499 | 13 | 598 | 3 | 652 |

$$S = \frac{2(xw - yz)}{y^2 + z^2 + 2xw + (y + z)(x + w)}$$

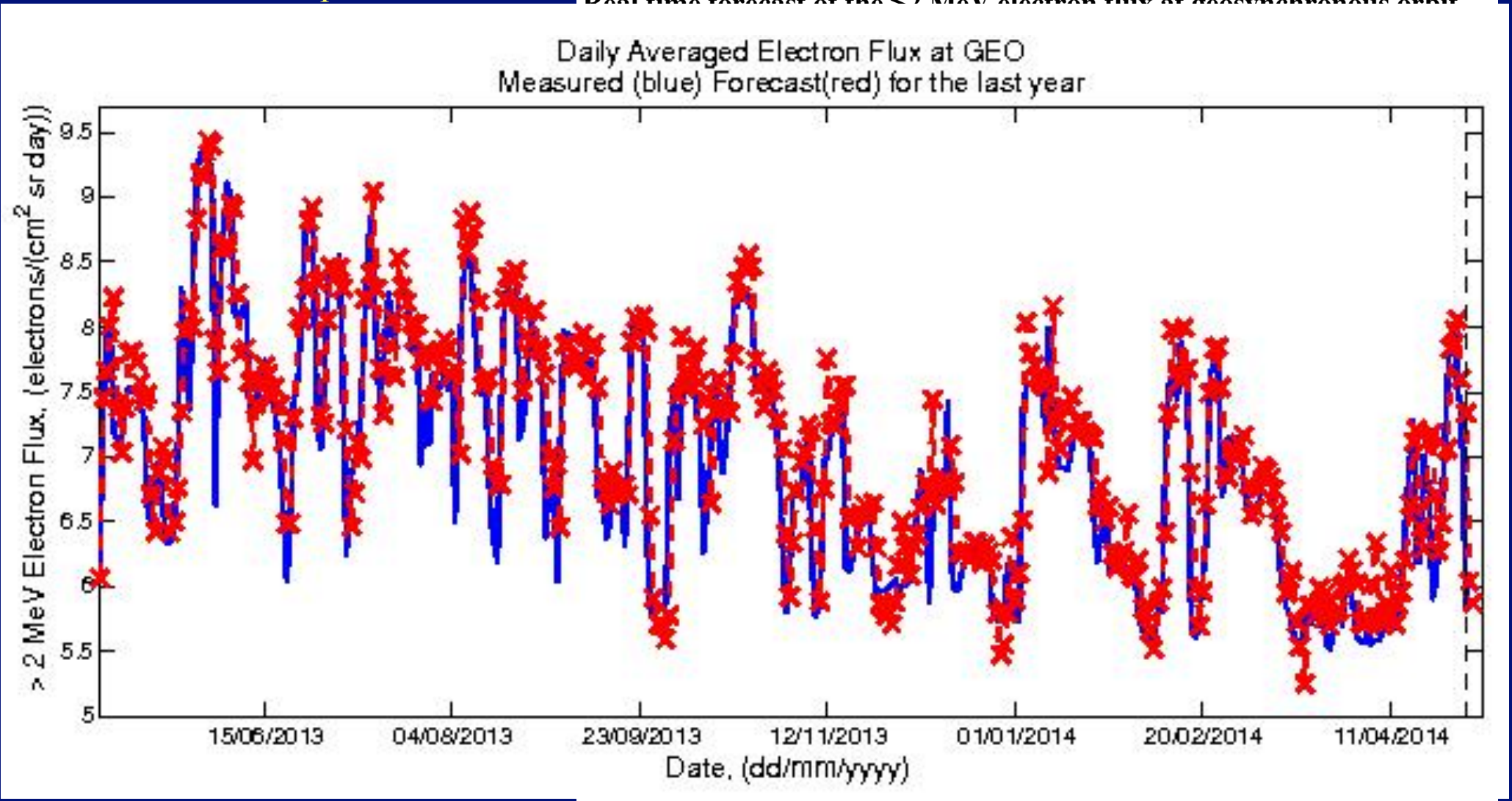
The one day ahead forecasts of the relativistic electron fluxes with energies greater than 2 MeV at GEO has been developed in

The University Of Sheffield.

UNIVERSITY OF SHEFFIELD SPACE WEATHER

Home | Electron Flux | Dst Index | Archive | Contact

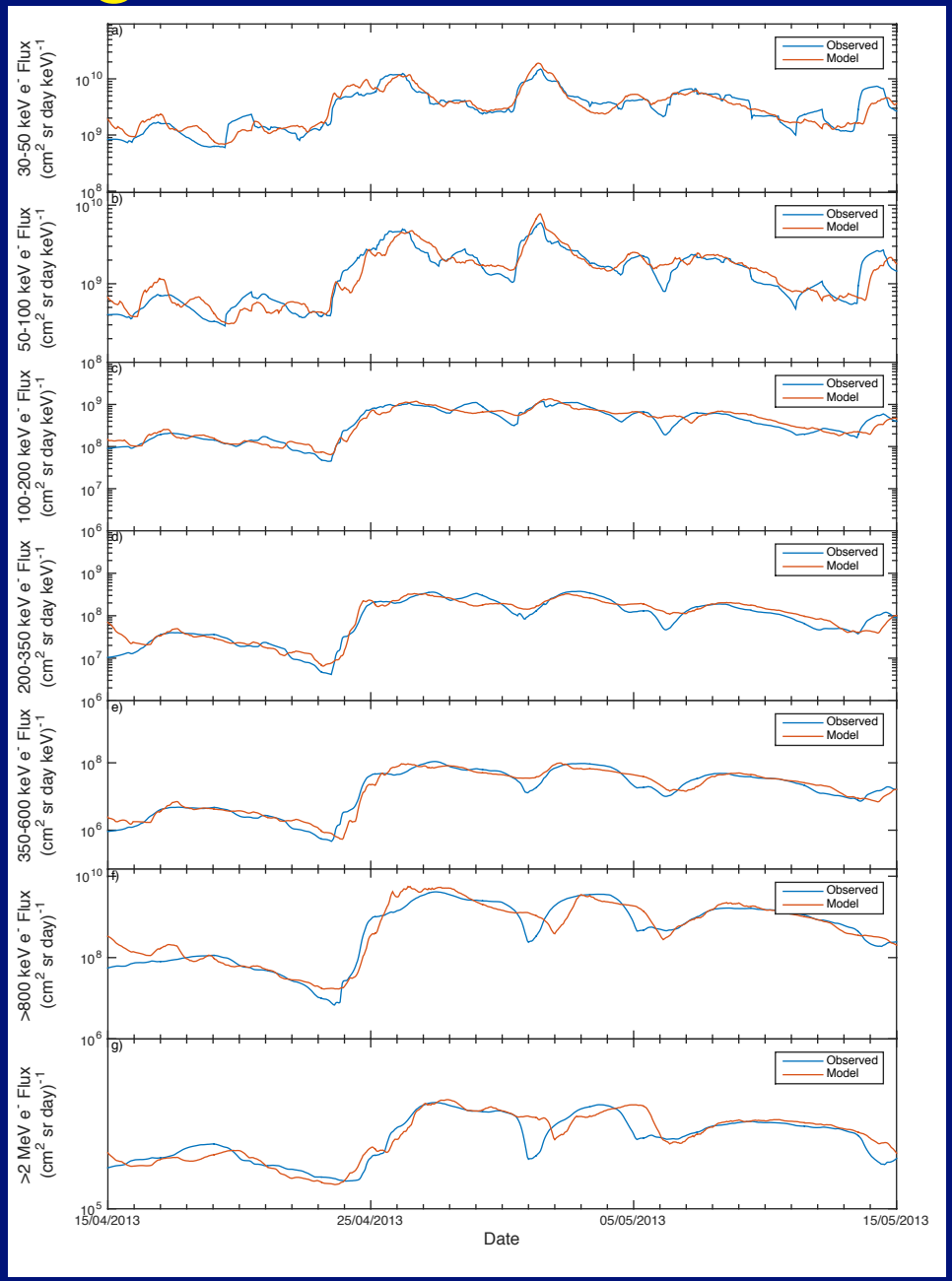
**Real time forecast of the >2 MeV electron flux at geosynchronous orbit**



# Extending SNB$^3$GEO to lower energies

| Model | Forecast Time (hours) | PE (%) | CC (%) | Period |
|---|---|---|---|---|
| 40-50 keV | 10 | 66.9 | 82.0 | 01.03.2013-28.02.2015 |
| 50-100 keV | 12 | 69.2 | 83.5 | 01.03.2013-28.02.2015 |
| 100-200 keV | 16 | 73.2 | 85.6 | 01.03.2013-28.02.2015 |
| 200-350 keV | 24 | 71.6 | 84.9 | 01.03.2013-28.02.2015 |
| 350-300 keV | 24 | 73.6 | 85.9 | 01.03.2013-28.02.2015 |
| > 800 keV | 24 | 72.1 | 85.1 | 01.01.2011-28.02.2015 |
| > 2MeV | 24 | 82.3 | 90.9 | 01.0.12011-28.02.2015 |

# Extending SNB$^3$GEO to lower energies



# PROGRESS: wave models

- Statistical Wave models and physics of wave particle interaction



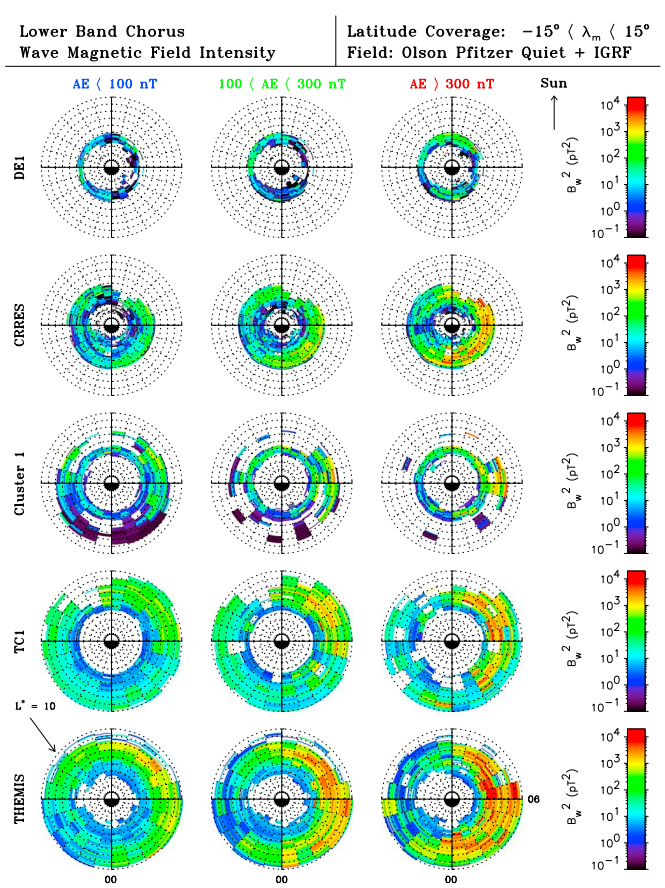
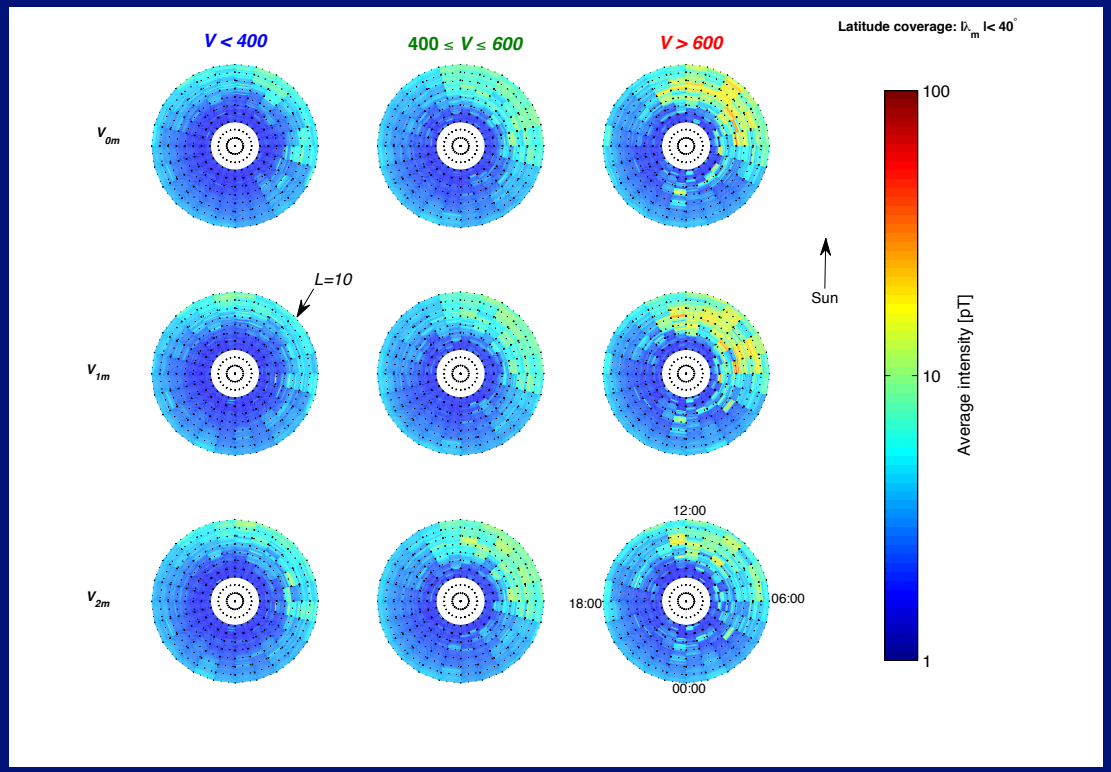
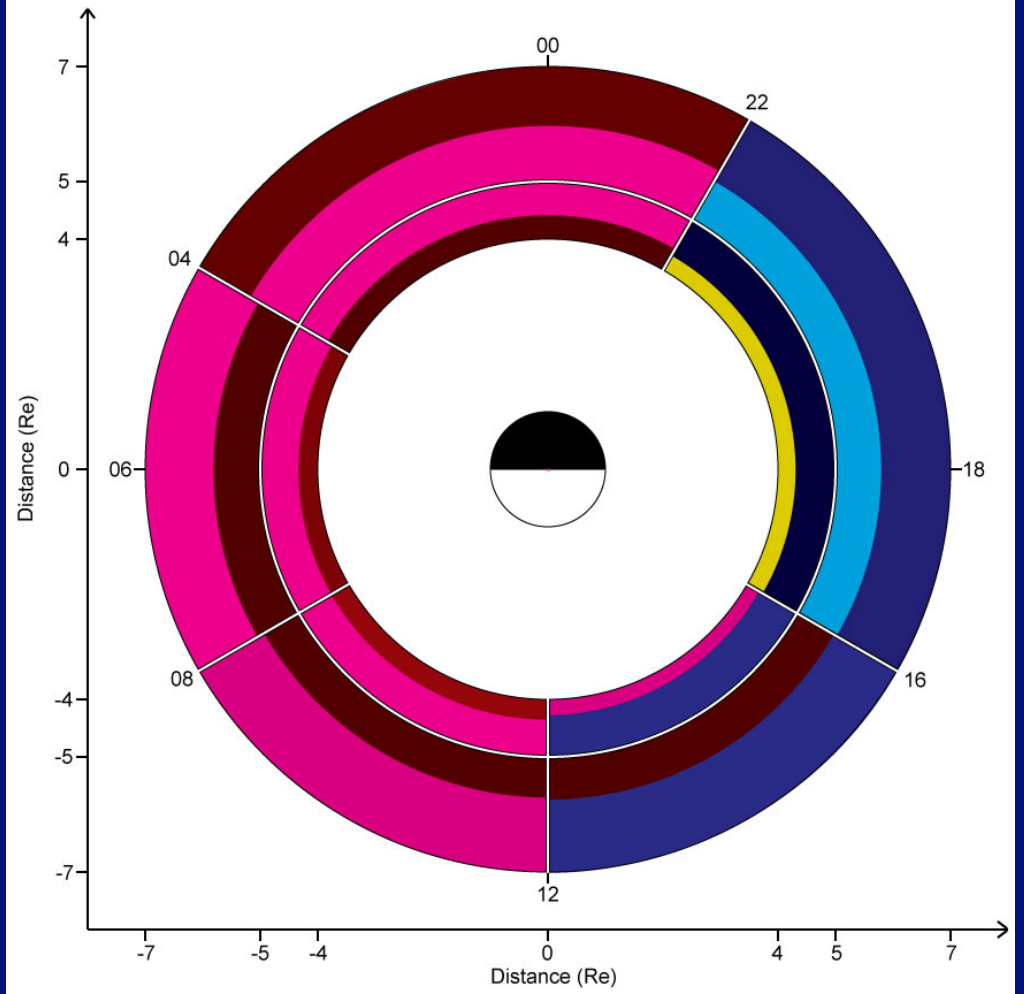



**Figure 2.** Equatorial wave intensity of lower band chorus as a function of $L^*$, MLT and geomagnetic activity for each of the five satellites.

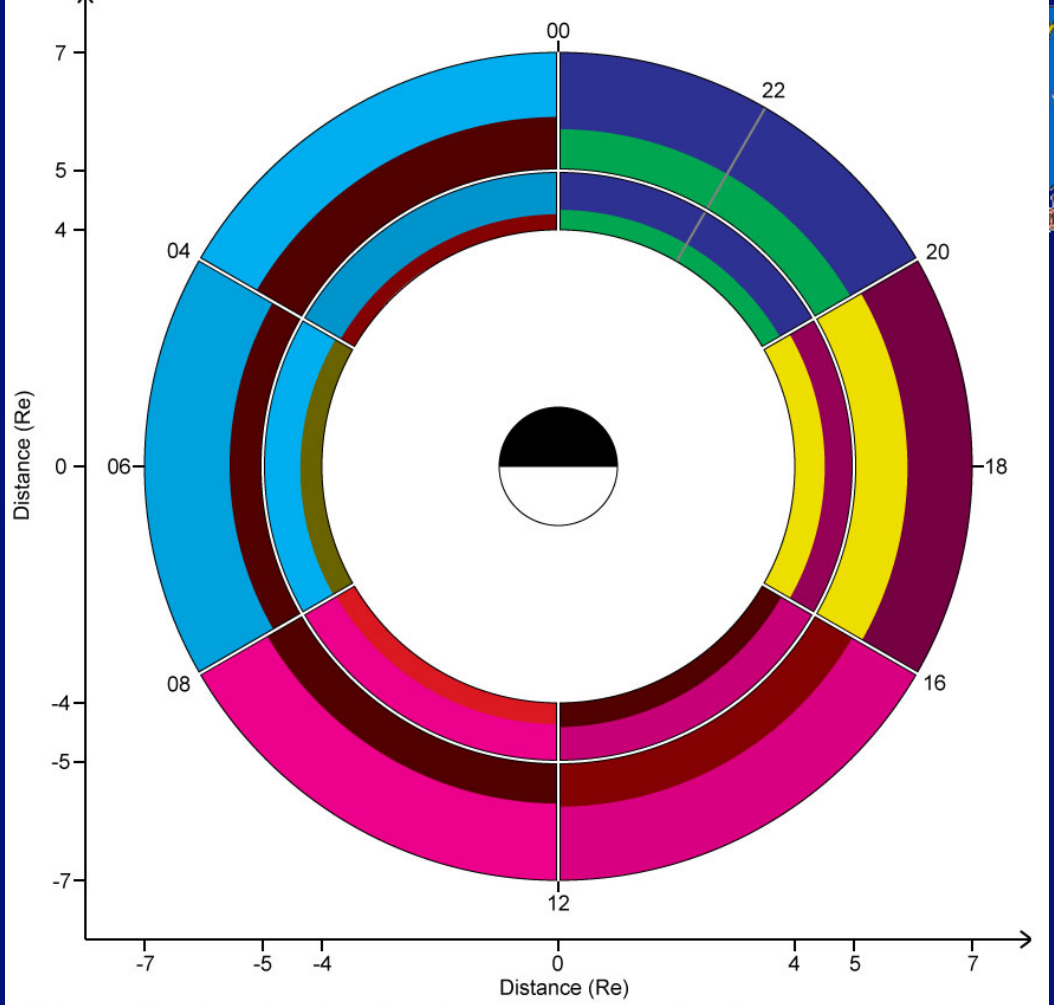


# PROGRESS: wave models LB Chorus



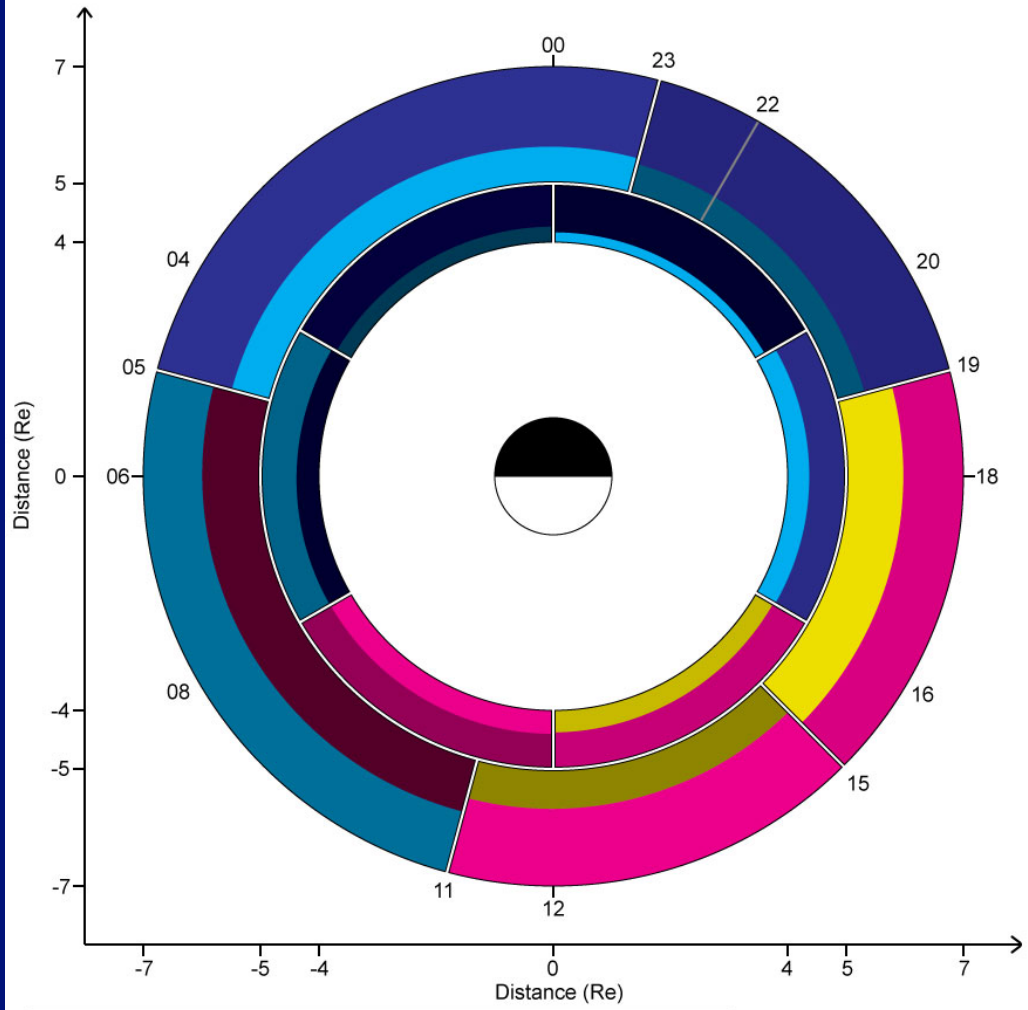

| Time lag (hours) / Input | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Velocity | | | | | | | | | | |
| Density | | | | | | | | | | |
| Pressure | | | | | | | | | | |
| IMF Factor | | | | | | | | | | |
| Dst Index | | | | | | | | | | |
| AE Index | | | | | | | | | | |

# PROGRESS: wave models Hiss




| Time lag (hours) / Input | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Velocity | | | | | | | | | | |
| Density | | | | | | | | | | |
| Pressure | | | | | | | | | | |
| IMF Factor | | | | | | | | | | |
| Dst Index | | | | | | | | | | |
| AE Index | | | | | | | | | | |

# PROGRESS: wave models EMW




| Time lag (hours) / Input | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Velocity | | | | | | | | | | |
| Density | | | | | | | | | | |
| Pressure | | | | | | | | | | |
| IMF Factor | | | | | | | | | | |
| Dst Index | | | | | | | | | | |
| AE Index | | | | | | | | | | |

# Boundary conditions in the plasma sheet for modeling of keV electrons

Previous studies [*Ganushkina et al*., 2013, 2014]:
we set the model **boundary at 10 $R_E$** and use the **kappa electron distribution** function.
Parameters of the kappa distribution function: **number density *n* and temperature *T*** in the plasma sheet given by the empirical model derived from Geotail data by TM03 *Tsyganenko and Mukai* [2003]. The **electron *n* is assumed to be the same as that for ions** in the TM03 model, but **Te/Ti = 0.2** is taken into account (*Wang et al.,* 2012).

Applying this model for boundary conditions has a number of **limitations**:

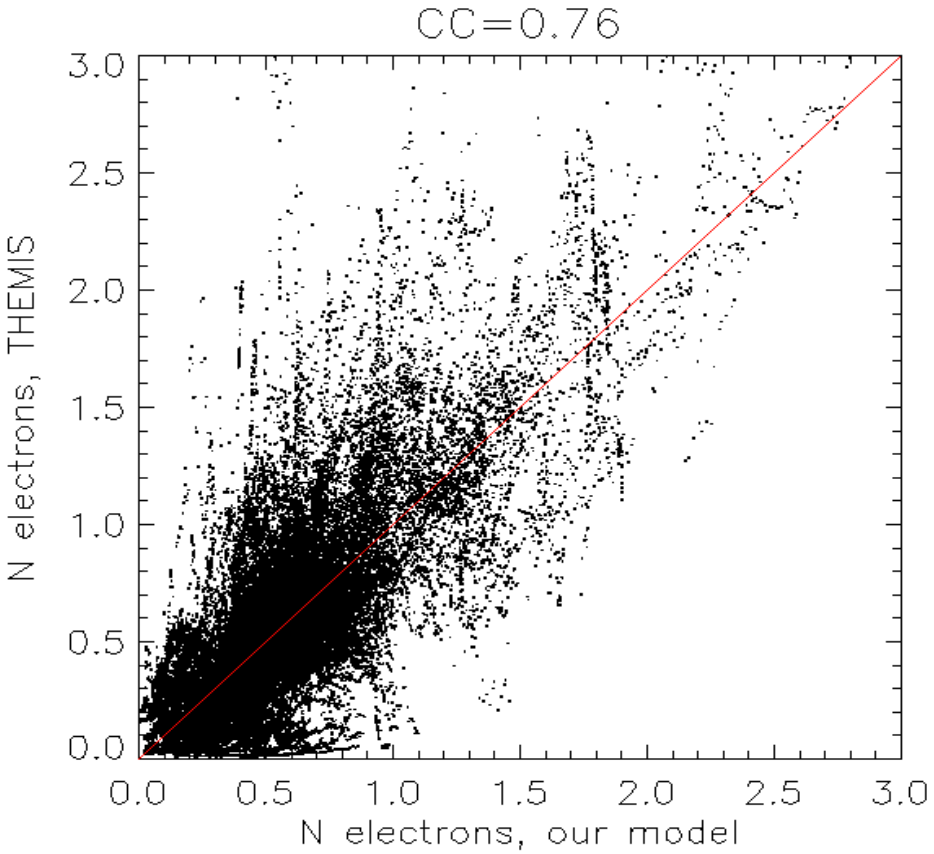
(1) Model was derived from **Geotail data for ions** (limited detector energy range <40keV).

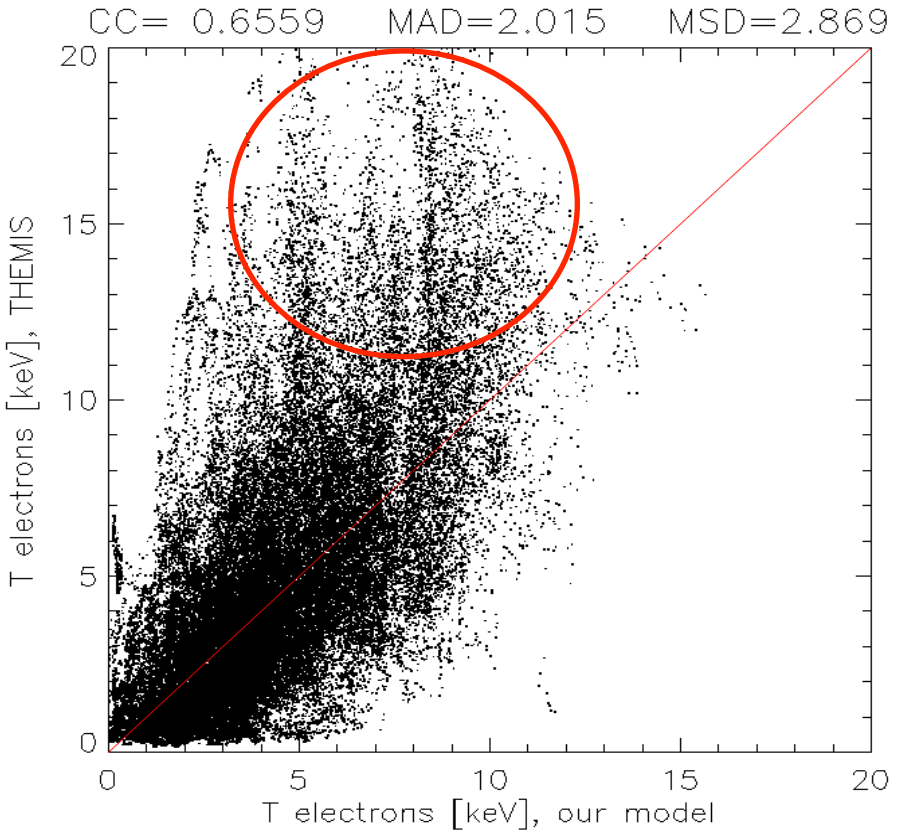
(2) ratio **Te/Ti can vary** during disturbed conditions.

(3) at distances closer than 10 Re, the correlation between Ti and Te might not exist at all and no certain ratio can be determined (*Runov et al.,* 2015).

# Empirical model for plasma sheet electrons at 6-11 $R_e$ based on THEMIS data: Performance

Hot plasma
carried by BBFs
(substorm injections)?

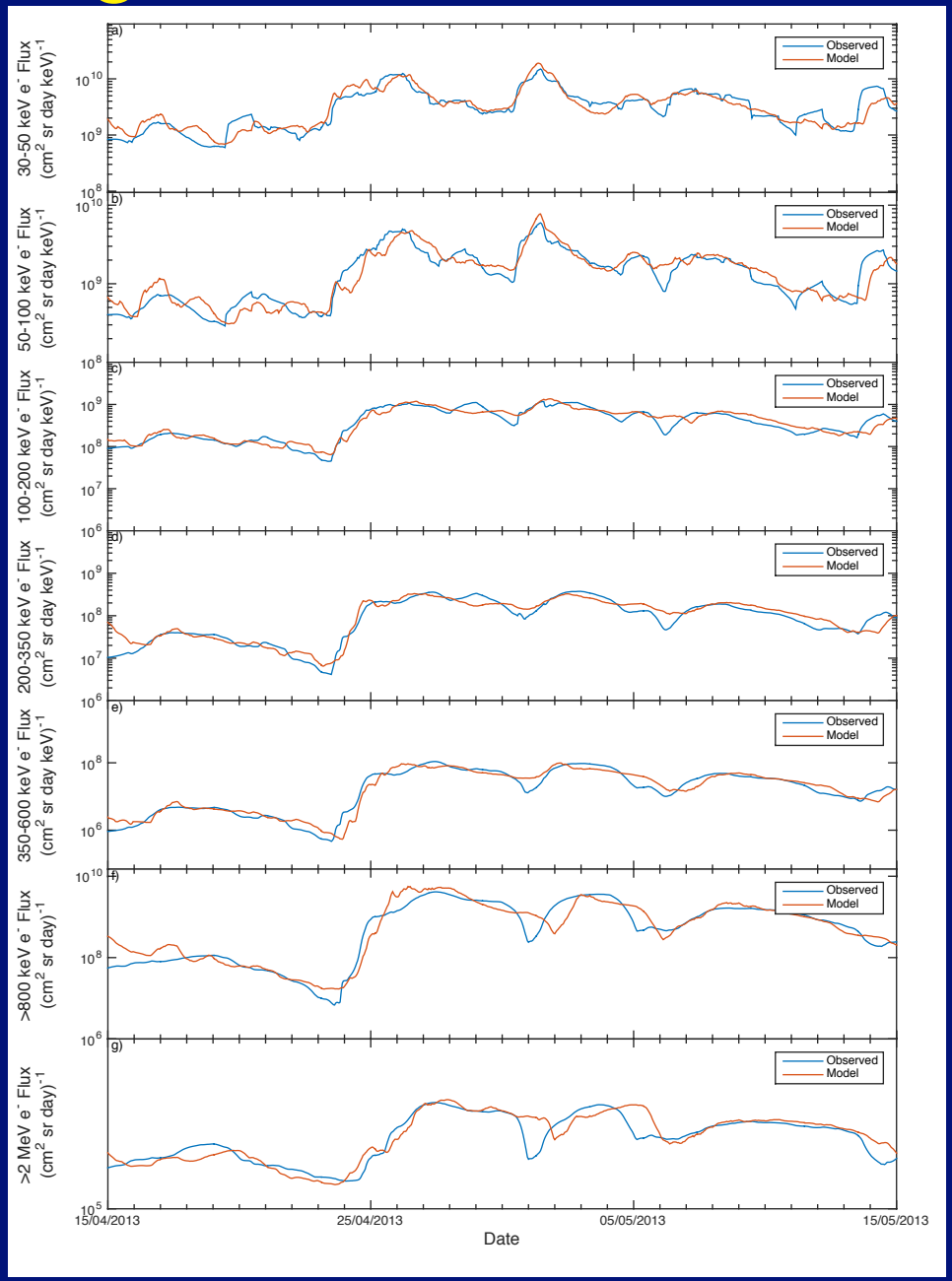


# Extending SNB$^3$GEO to lower energies

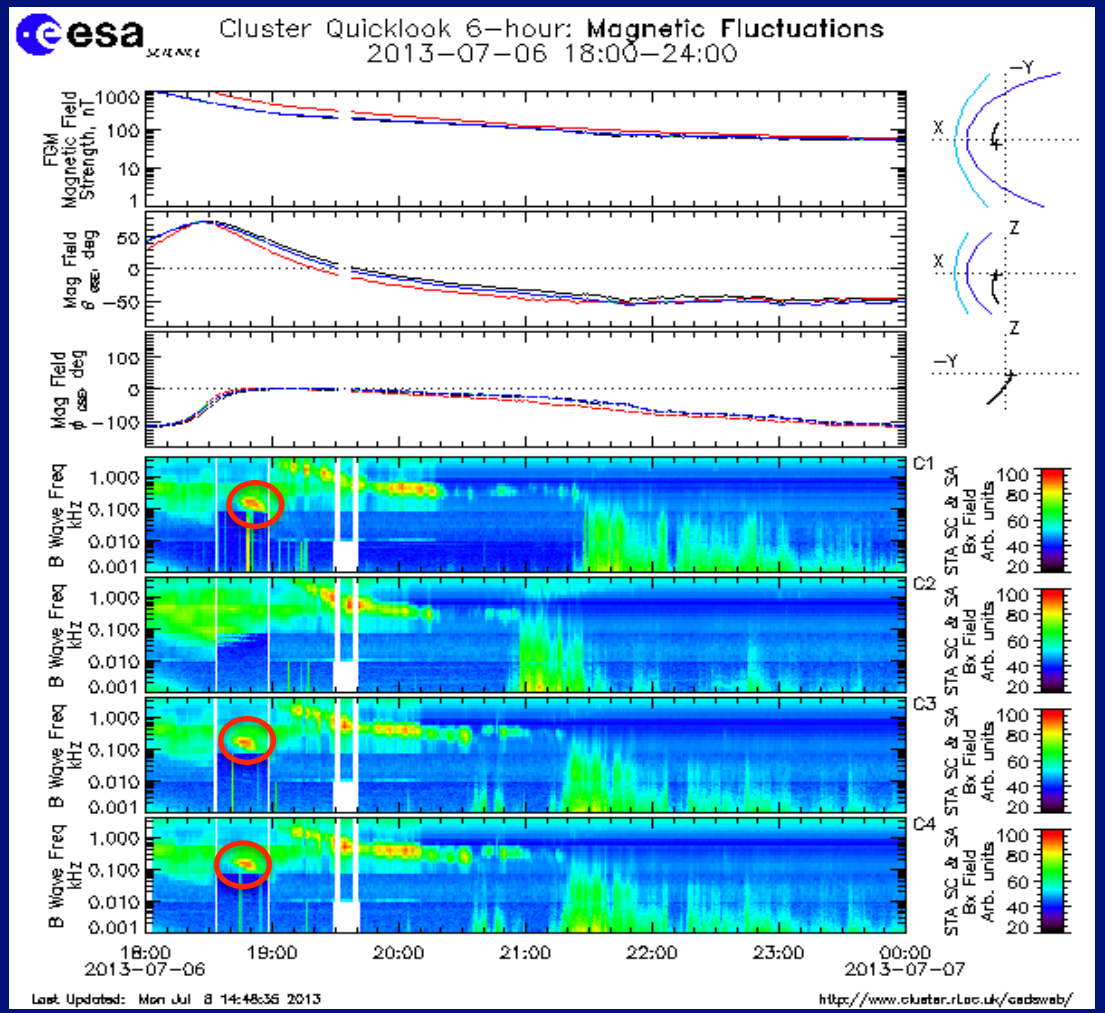
| Model | Forecast Time (hours) | PE (%) | CC (%) | Period |
|---|---|---|---|---|
| 40-50 keV | 10 | 66.9 | 82.0 | 01.03.2013-28.02.2015 |
| 50-100 keV | 12 | 69.2 | 83.5 | 01.03.2013-28.02.2015 |
| 100-200 keV | 16 | 73.2 | 85.6 | 01.03.2013-28.02.2015 |
| 200-350 keV | 24 | 71.6 | 84.9 | 01.03.2013-28.02.2015 |
| 350-300 keV | 24 | 73.6 | 85.9 | 01.03.2013-28.02.2015 |
| > 800 keV | 24 | 72.1 | 85.1 | 01.01.2011-28.02.2015 |
| > 2MeV | 24 | 82.3 | 90.9 | 01.0.12011-28.02.2015 |

# Extending SNB$^3$GEO to lower energies



# EMW Spectral Observations

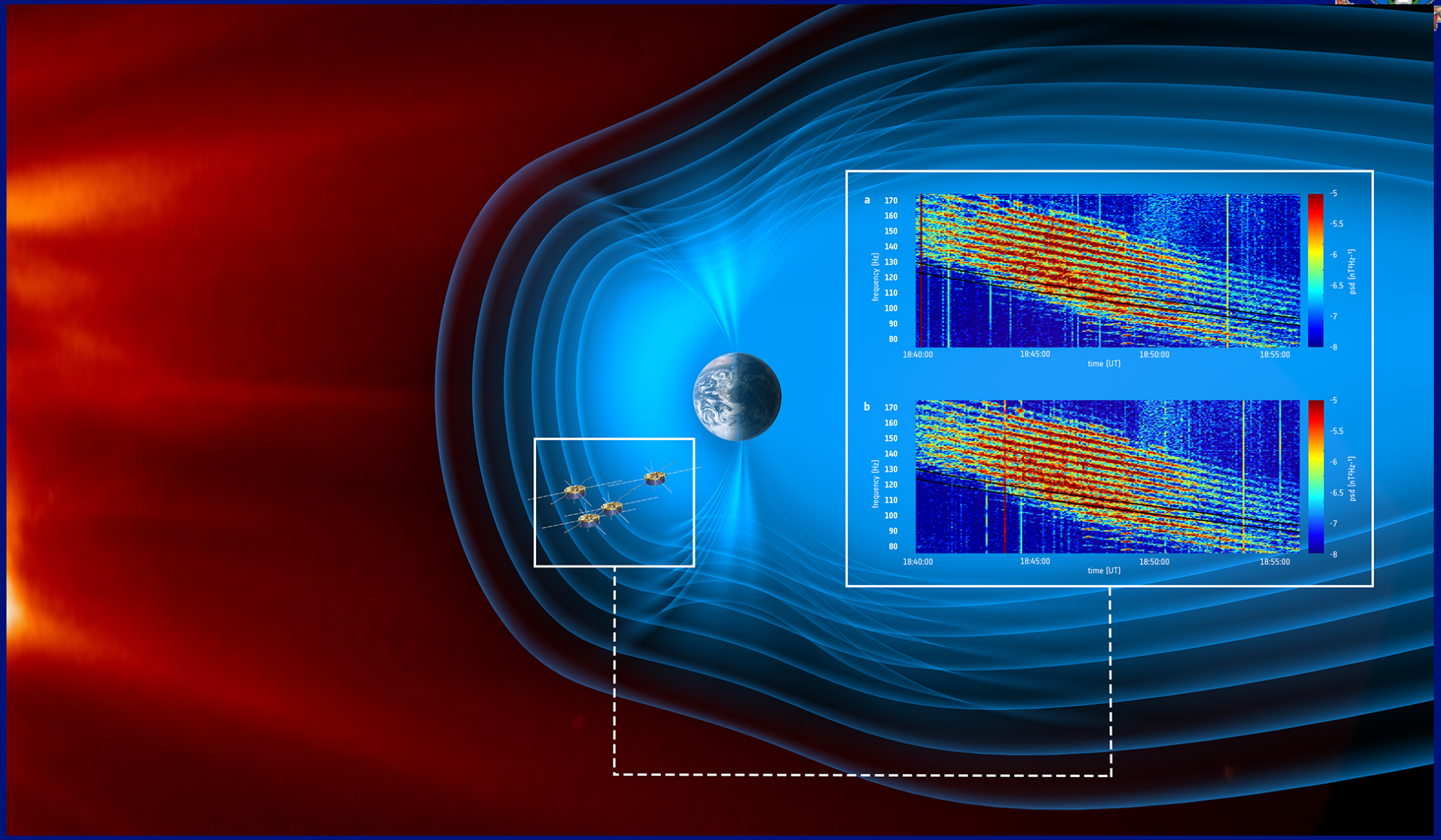
Most studies of the amplitudes of magnetosonic waves assume a continuous spectrum and hence the validity of the quasi-linear theory



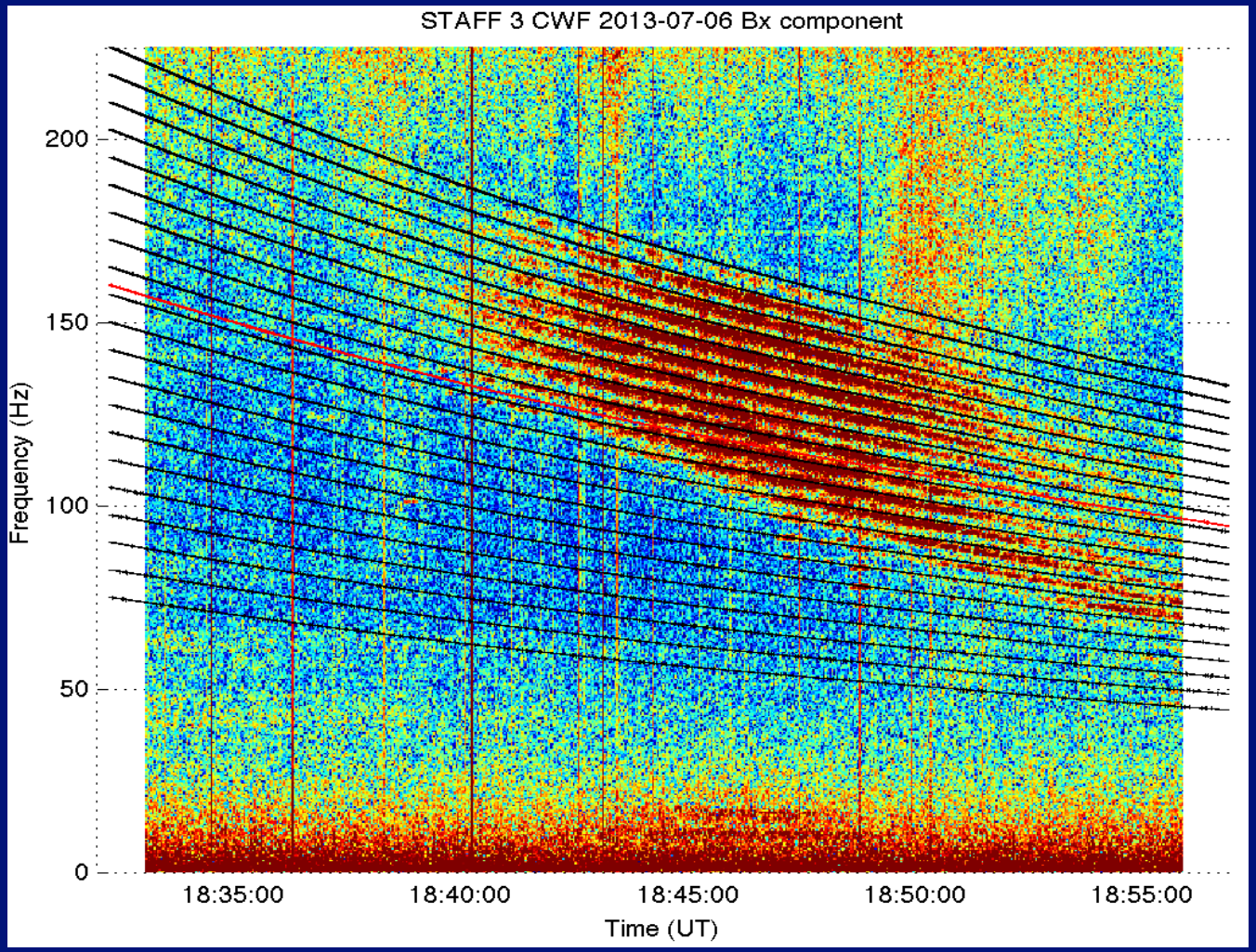

The figure shows an overview of the STAFF spectrum analyser observations on July 6th, 2013. Occurrences o Equatorial magnetosonic waves are indicated by the red circles.

The waves appear continuous in frequency space. Thus, quasi-linear theory is used to estimate their effects on electron acceleration and loss processes.

# Balikhin, Shprits, Walker et al., Nature Comm, 2015



# Balikhin, Shprits, Walker et al., Nature Comm, 2015



# Conclusion:

1) Whenever a theory appears to you as the only possible one, take this as a sign that you have neither understood the theory nor the problem which it was intended to solve. *(KP)*

2) Data are the main source of progress in science and advanced data analysis technique is important tool not only in temporal validation of hypotheses but also to *falsify*=nullify them.

3) PROGRESS project is developing according to the proposed schedule