

# Radiation Belts observed by CARMEN/SAC-D

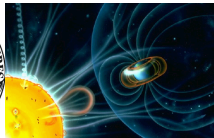
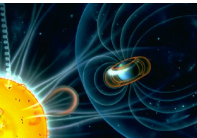
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# Overview

- 1 Space Weather: Earth Radiation Belts and South Atlantic Anomaly
- 2 ICARE-NG in CARMEN-1
- 3 Global map for electron flux
- 4 PDF of fluxes at four different regions
- 5 Distribution of Particles Flux according with L and energy
- 6 Summary and Conclusions

# Space Weather

## Space Weather Impacts on Earth

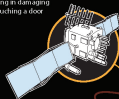
### Global Positioning System (GPS)

Geomagnetic storms can impact the accuracy and availability of GPS by changing the ionosphere, the electrically charged layer of the atmosphere. A GPS signal must pass through from satellite to ground receiver. The ionosphere is the largest source of error in GPS positioning and navigation. These ionospheric disturbances are ever present but can become severe during geomagnetic storms, resulting in range error in excess of 100 feet, or even resulting in loss of lock on the GPS signal entirely. These errors can have significant impacts on precision uses of GPS such as navigation, agriculture, oil drilling, surveying, and timing.



### Satellite Operations

There are thousands of satellites in orbit around Earth with applications in television and radio, communications, meteorology, national defense, and much more. Space weather can affect these satellites in many ways. Solar radiation storms can cause spacecraft orientation problems by interfering with star trackers and by causing errors or damage in electronic devices. Geomagnetic storms can create a hazardous charging environment for satellites resulting in dangerous electrostatic discharge, much like touching a door knob and getting that spark on a dry winter day. Geomagnetic storms also cause heating of the atmosphere, essentially causing it to expand, which results in more drag or slowing down of an orbiting satellite. In a worst case, space weather can cause the satellite to fail.



### Space Operations

Astronauts and their equipment in space are bombarded with charged particle radiation. This radiation causes tissue or cell damage in humans. Space weather and solar radiation storms are of particular concern for activities outside the protection of Earth's atmosphere and magnetic field.



NOAA Education [www.education.noaa.gov](http://www.education.noaa.gov)

NOAA Space Weather Prediction Center [www.spaceweather.gov](http://www.spaceweather.gov)

### Aurora

The Aurora Borealis (Northern Lights) and Aurora Australis (Southern Lights) are the result of electrons colliding with Earth's upper atmosphere. The electrons are energized through acceleration processes in the downward tail (nightside) of the magnetosphere. The accelerated electrons follow the magnetic field of Earth down to the polar regions where they collide with oxygen and nitrogen atoms and molecules in Earth's upper atmosphere. In these collisions, the electrons transfer their energy to the atmosphere, first exciting the atoms and molecules to higher energy states. When they relax back to lower energy states, they release their energy in the form of light. The aurora typically forms 50 to 300 miles above the ground. Earth's magnetic field guides the electrons such that the aurora forms two ovals approximately centered at each magnetic pole.

Electrons accelerated in the tail of the magnetosphere travel down the magnetic field lines.

Electrons collide with the upper atmosphere 50 to 300 miles above Earth.

Electrons exchange energy with the atmosphere exciting the atmospheric atoms and molecules to higher energy levels. When the atoms and molecules relax back to lower energy levels, they release their energy in the form of light.

### THE COLORS OF THE AURORA

- Deep red from high altitude atomic oxygen
- Magenta from high altitude molecular nitrogen in sunlight
- Greenish yellow from lower altitude atomic oxygen
- Magenta from low altitude molecular nitrogen (not shown in the picture)



### Aviation

Aircraft use High Frequency (HF) radio communication to stay in touch with ground controllers in remote areas such as over the oceans or over the poles. Solar flares can "black out" the use of HF on the dayside of Earth, and solar radiation storms can "black out" use of HF near the poles, impacting the aircraft's ability to stay in touch with the ground. Impacts to GPS systems can also significantly affect airline operations.



### Power Grids

Geomagnetic storms result in electric currents in the magnetosphere and ionosphere as the area shaped by Earth's magnetic field is compressed and disturbed. The disturbed conditions create additional currents in long conductors on the ground such as overhead transmission lines or long pipelines. In the most extreme cases, these currents can cause voltage instability or damage to power system components, potentially resulting in temporary service disruptions, or even a widespread power outage.

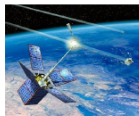


\*Image source: Aurora Borealis taken from the International Space Station in April of 2012.



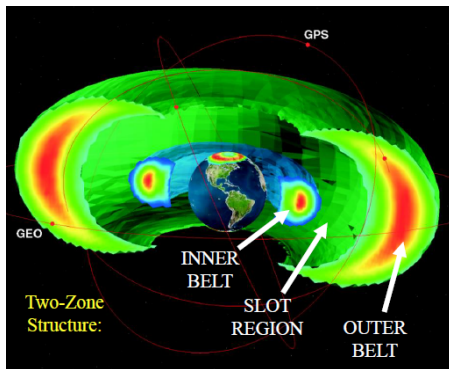
## Service Level Activities

- Organize WMO Members to deliver coordinated services responding to ICAO requirements
- Prepare for extreme events in a multi-hazard Disaster Risk Reduction approach
- Analyze requirements for applications including ionospheric disturbances (radio propagation and GNSS), satellites, and ground infrastructure (power grids)
- Provide training on delivery and use of services



Many other institutions have Space Weather programs: NASA, ESA, UN (Outer Space), Met Office, NOAA, COSPAR, etc

# Radiation Belts & Space Weather

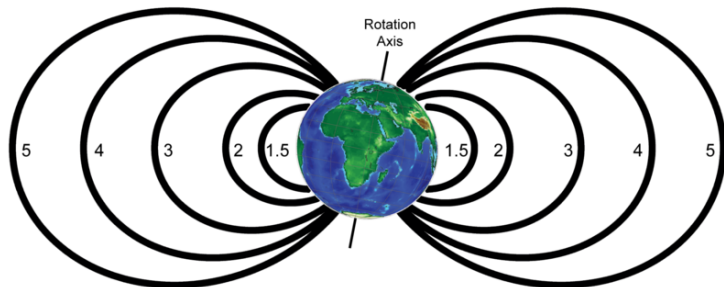


- Radiation belts
  - energies  $>100$  keV
  - two-zone structure
- Inner belt: fairly stable
- Outer belt: can change on the time scale of an hour

## Radiation belts

- Inner:  $\sim 0.2-2 R_E$
- Outer:  $\sim 3-9 R_E$
- Flux of energetic particles strongly dependent on Space Weather conditions in the outer belt

# L shells on Earth



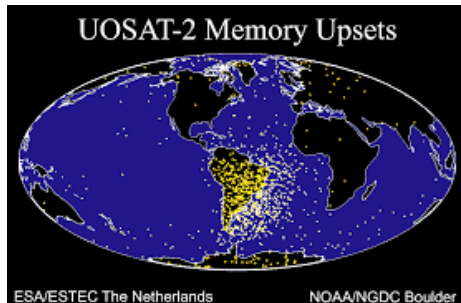
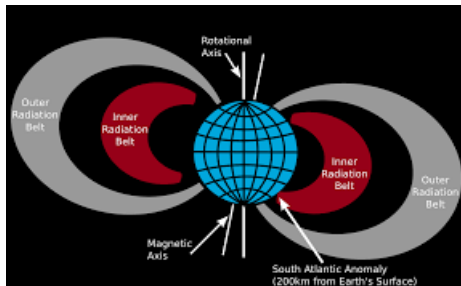
## L parameter

- For a centered dipole magnetic field model:

$$r = L \cos^2(\lambda) R_E$$

- Constant altitude runs over different particle populations

# South Atlantic Anomaly



Caused by non-concentricity of Earth and its magnetic dipole

- SAA is the near-Earth region where the Earth's magnetic field is weakest, relative to an idealized Earth-centered dipole field.
- Memory upsets and many other consequences on satellites passing through SAA.

# ICARE-NG, CARMEN-1, SAC-D

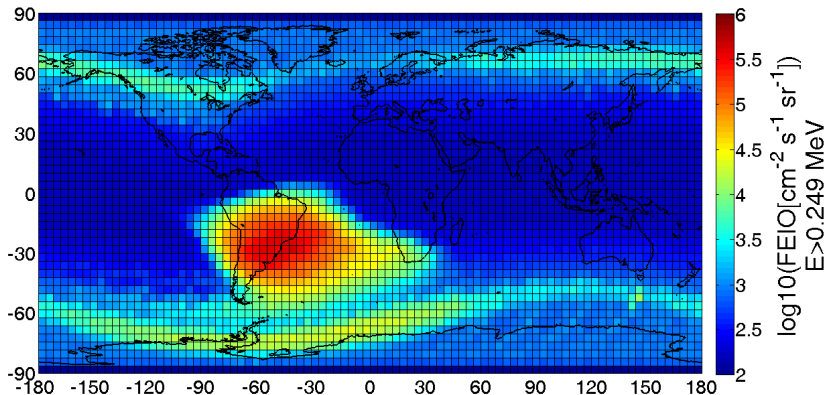
## The particle detectors

- Three detectors to measure electron and proton fluxes
- Energy range for electrons: 250keV to 3.2 MeV
- Energy range for protons: 12.8 MeV to 190 MeV
- FEIO (44 channels):  
Omni-directional Integral  
Electron Flux



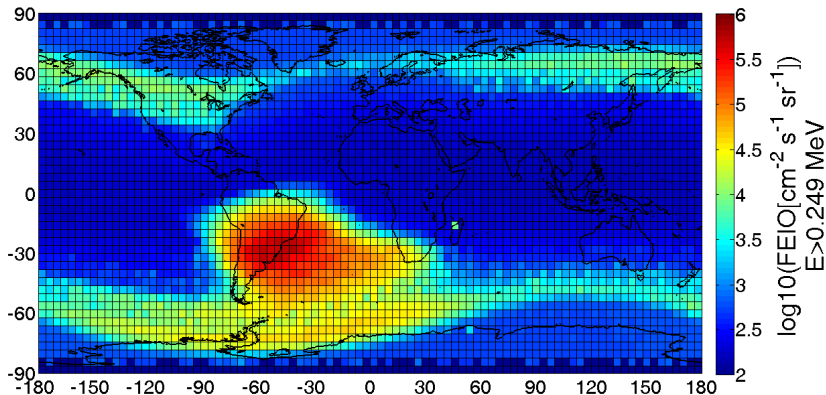


# Global map for electron flux (low energies, 2011-2012)



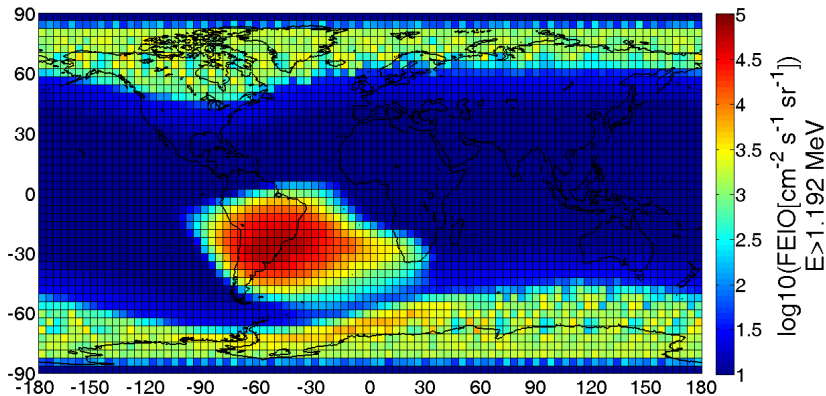
- FEIO (Omni-directional Integral Electron Flux)
- $E > 249$  keV
- From 2011 to 2012

# Global map for electron flux (low energies, 2014-2015)



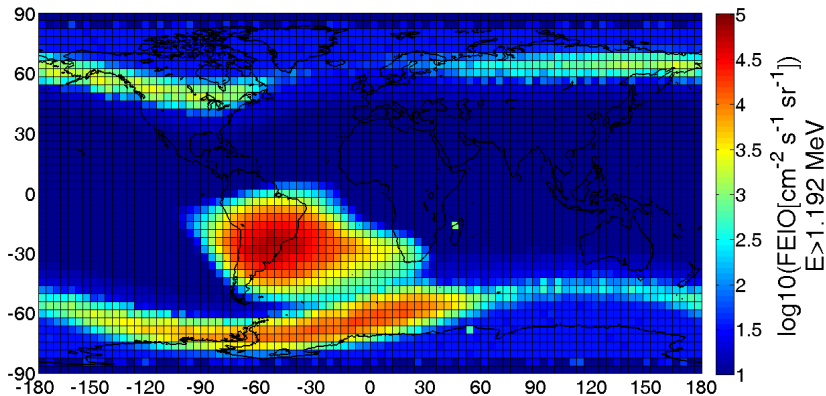
- FEIO (Omni-directional Integral Electron Flux)
- $E > 249$  keV
- From 2014 to 2015

# Global map for electron flux (high energies, 2011-2012)



- FEIO (Omni-directional Integral Electron Flux)
- $E > 1.192$  MeV
- From 2011 to 2012

# Global map for electron flux (high energies, 2014-2015)

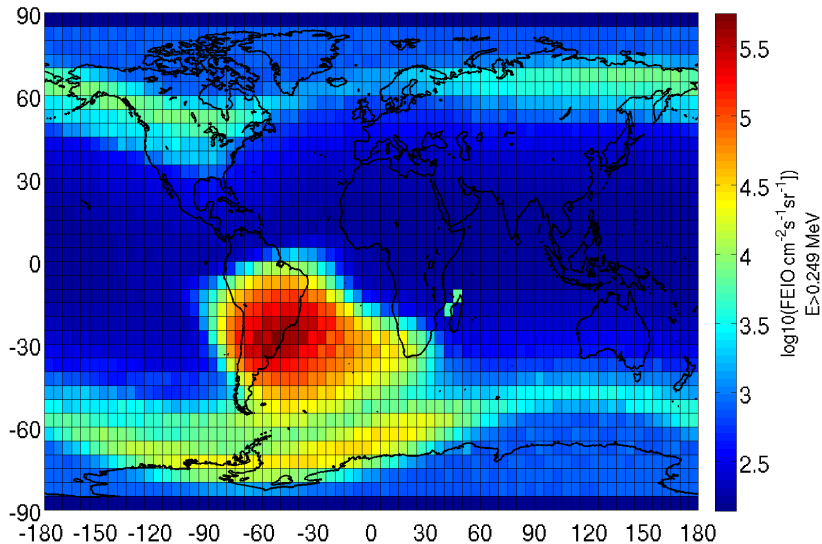


- FEIO (Omni-directional Integral Electron Flux)
- $E > 1.192$  MeV
- From 2014 to 2015

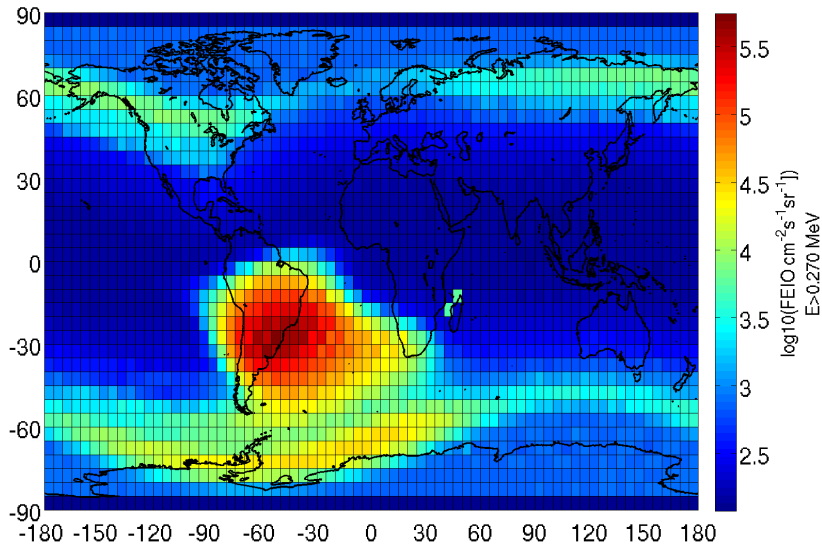
# South Atlantic Anomaly

Different energies at SAA (full mission)

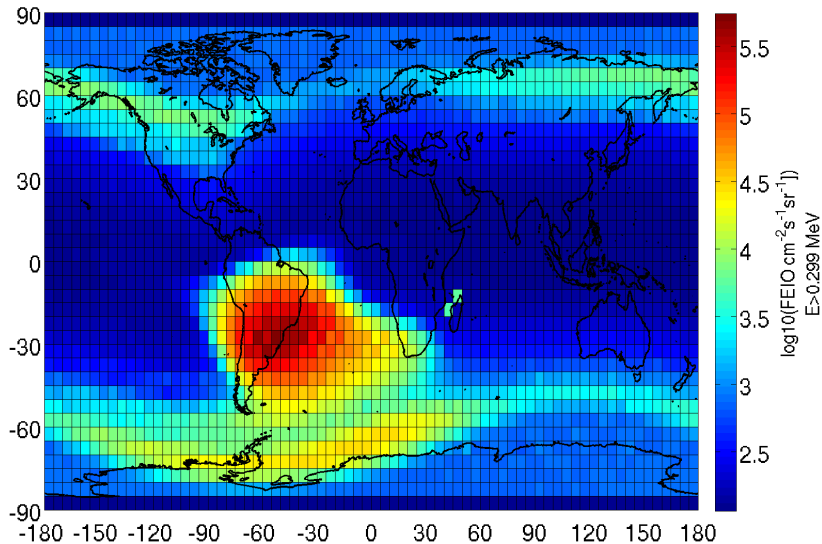
## Different energies at SAA (full mission)



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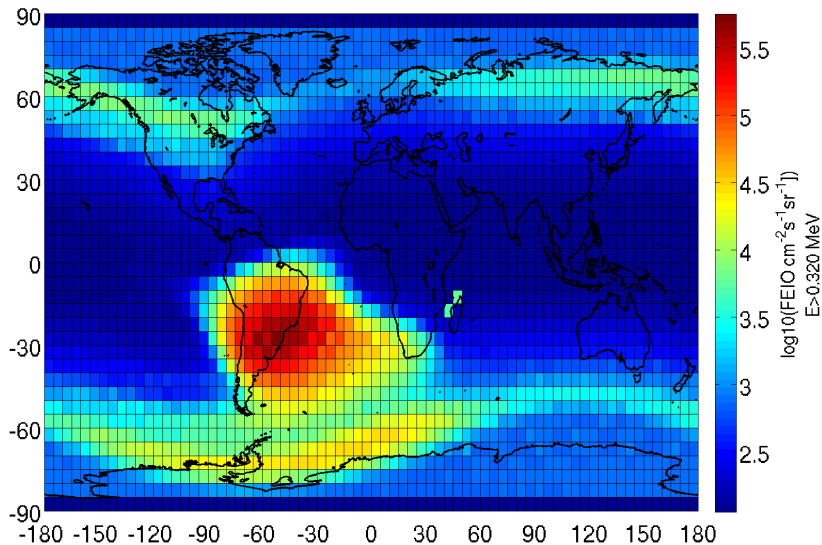


## Different energies at SAA (full mission)

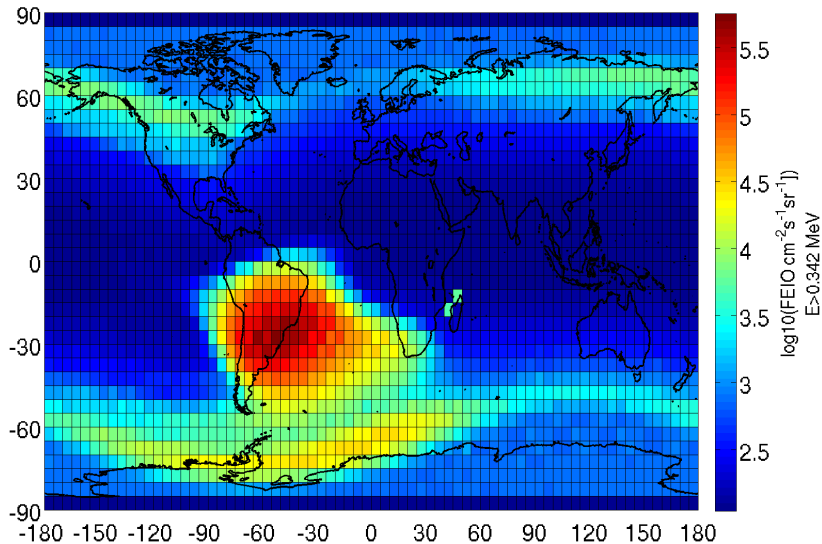




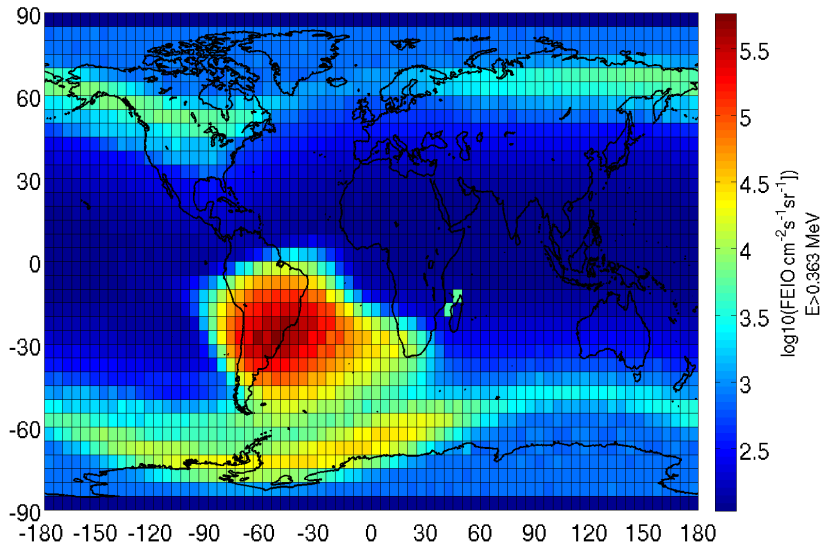
# Different energies at SAA (full mission)



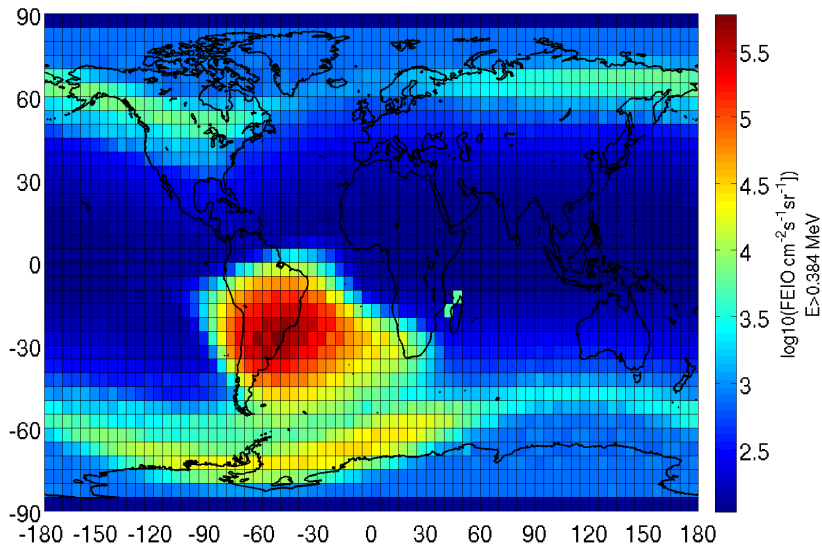
# Different energies at SAA (full mission)



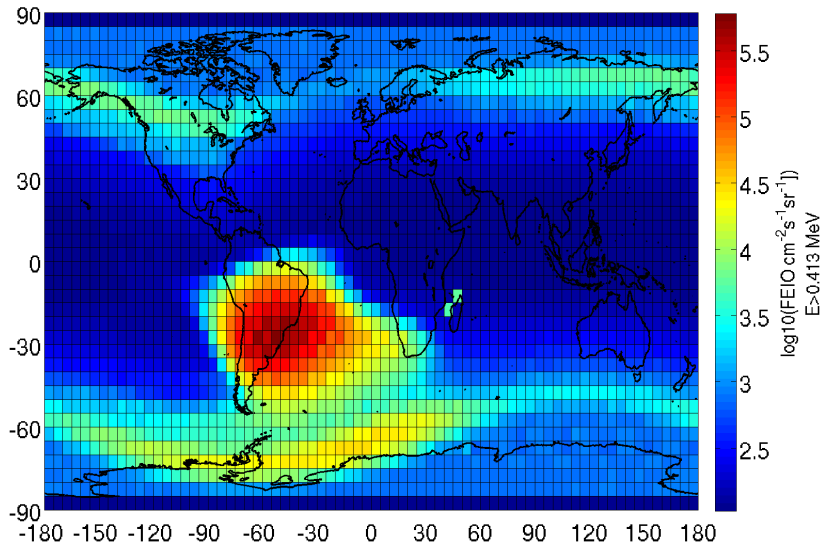
## Different energies at SAA (full mission)



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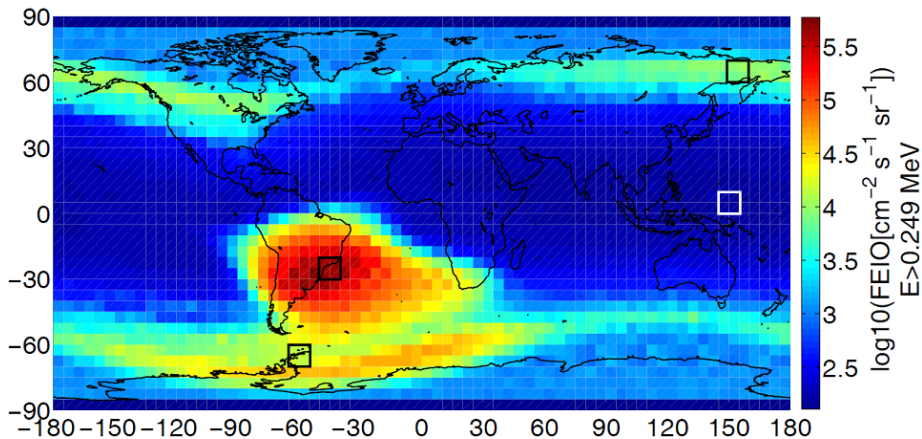
## Different energies at SAA (full mission)



# Fluxes at four different regions

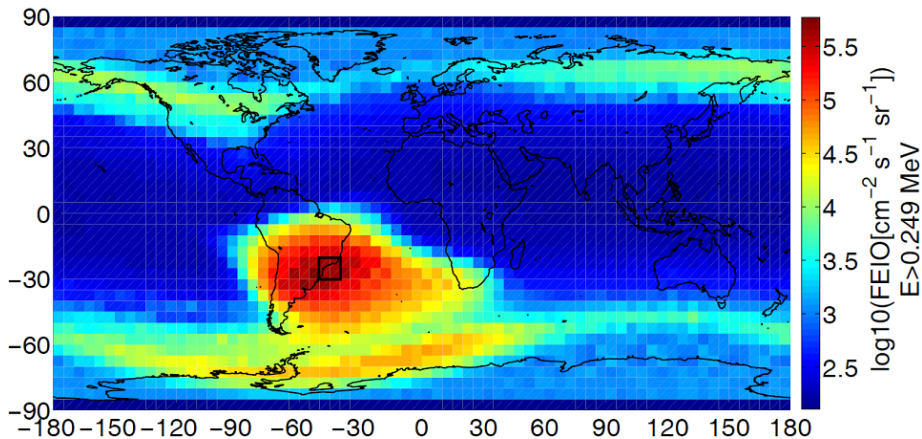
## Analysis of Fluxes Distribution

## Four different regions



- FEIO (Omni-directional Integral Electron Flux)
- Full mission (from Aug/30/2011 to Jun/06/2015)

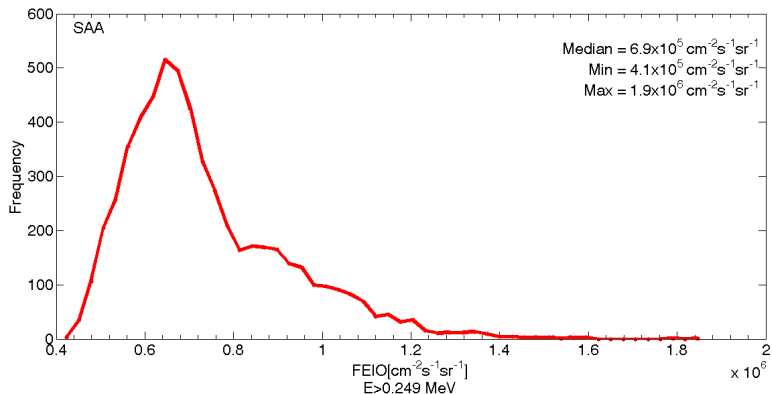
## Region 1: AAS, from Aug/30/2011-Jun/06/2015



- Latitude: -30 to -20 deg, Longitude: -50 to -40 deg
- Region 1 corresponds to  $L \sim 1.35$

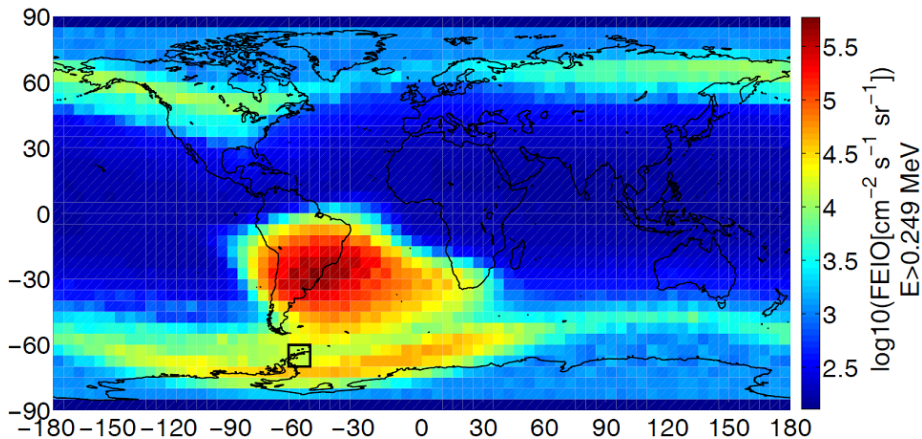


# Observed Distribution of fluxes at SAA (full mission)



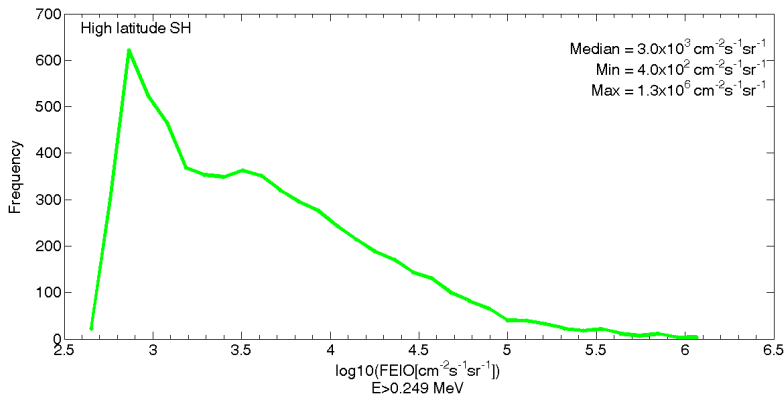
- Region 1 ( $L = 1.35 \pm 0.1$ )
- PDF near to a log-normal for fluxes  $\sim (4 - 8) \times 10^5 \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$
- Larger tail for fluxes  $> 10^6 \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$

## Region 2: South High Latitude Polar



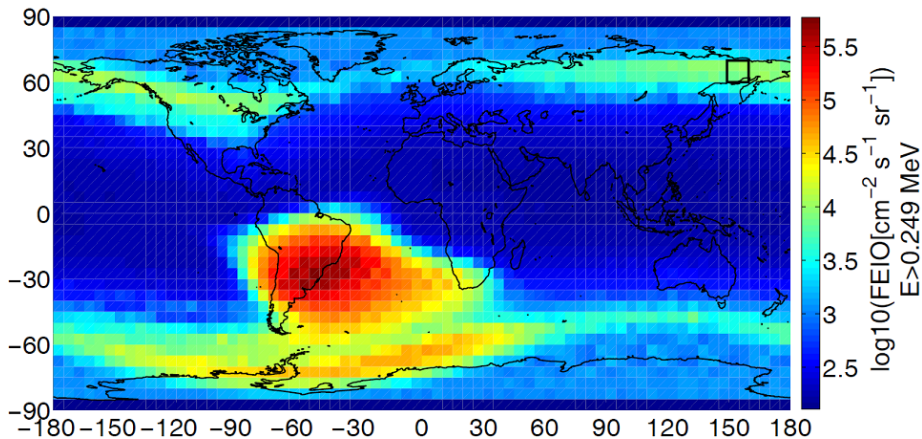
- Latitude: -70 to -60 deg, Longitude: -65 to -55 deg
- Region 2 corresponds to  $L \sim 3$

# Observed Distribution of fluxes at SHL (full mission)



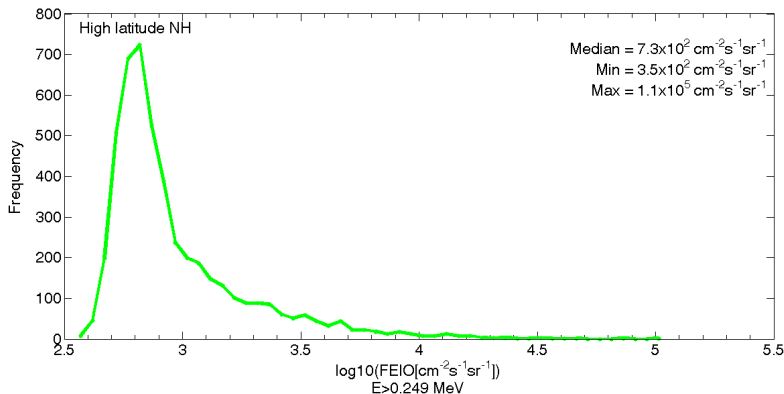
- Region 1 ( $L = 3.0 \pm 0.5$ )
- PDF covers a huge range ( $10^2$  to  $10^6 \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ )
- Near to a superposition of two log-normal
- Larger tail for fluxes  $> 10^4 \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$

## Region 3: North High Latitude



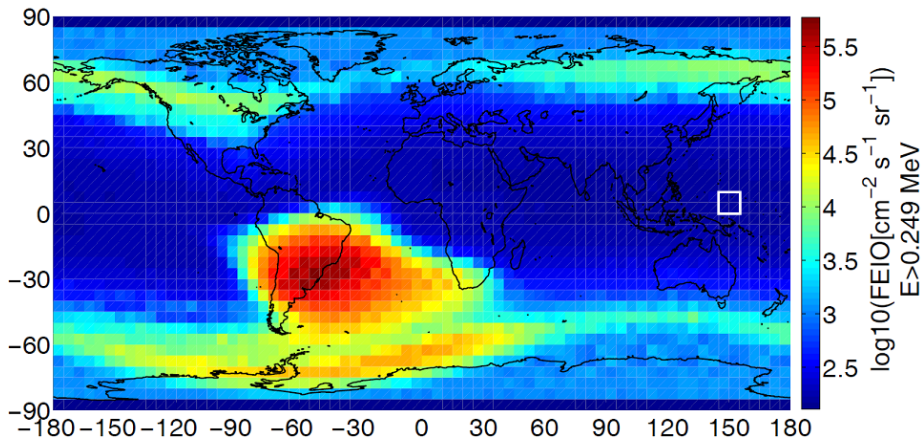
- Latitude: 60 to 70 deg, Longitude: 150 to 160 deg
- Region 3 corresponds to  $L \sim 4.5$

# Observed Distribution of fluxes at NHL (full mission)



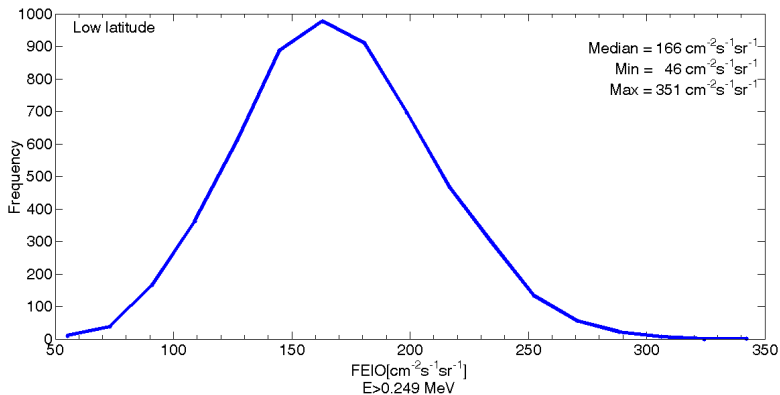
- Region 3 ( $L = 4.5 \pm 1.5$ )
- PDF covers a huge range ( $10^2$  to  $10^5 \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ )
- Near to a log-normal
- Larger tail for fluxes  $> 10^3 \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$

## Region 4: Low Latitudes



- Latitude: 0 to 10 deg, Longitude: 145 to 155 deg
- Region 4 corresponds to  $L \sim 1.05$

# Observed Distribution of fluxes at Low Latitude (full mission)



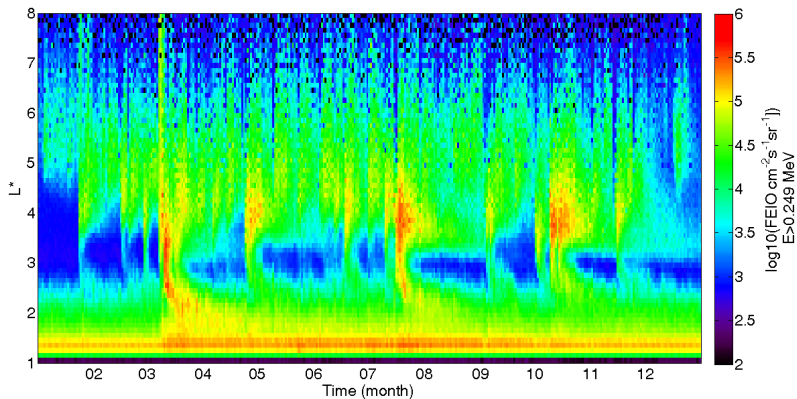
- Region 3 ( $L = 1.05 \pm 0.01$ )
- PDF covers a range between  $\sim 50$  to  $\sim 350 \text{ cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$ )
- Near to a normal

## Particles according with L/energy

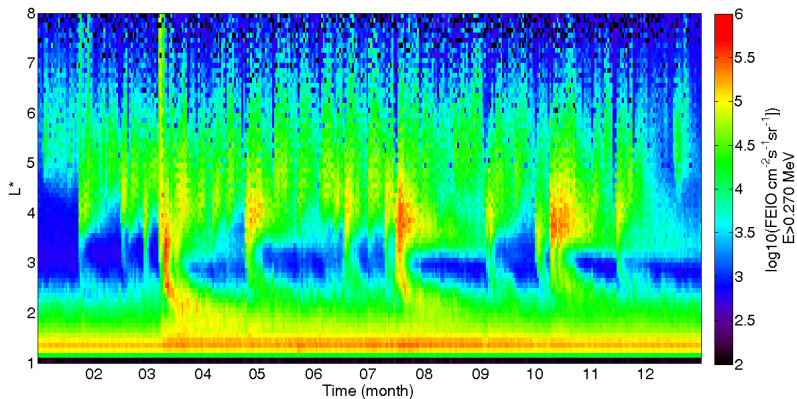
The answer of the fluxes of particles for an extreme Space Weather event is presented in a Poster in this conference [Lanabere et al.]



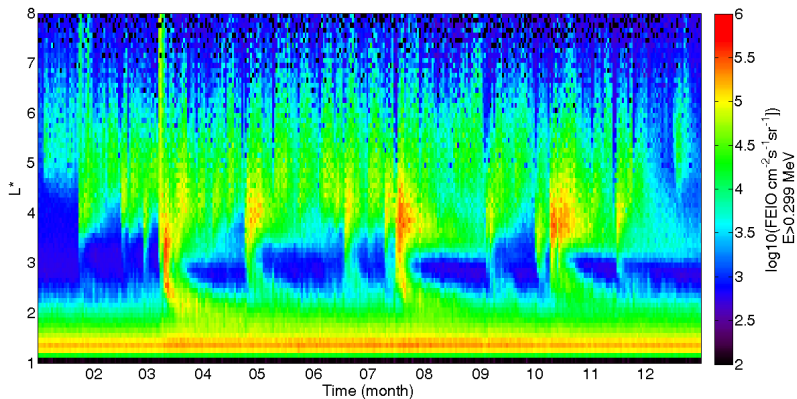
# Distribution of particles, according with L and energy



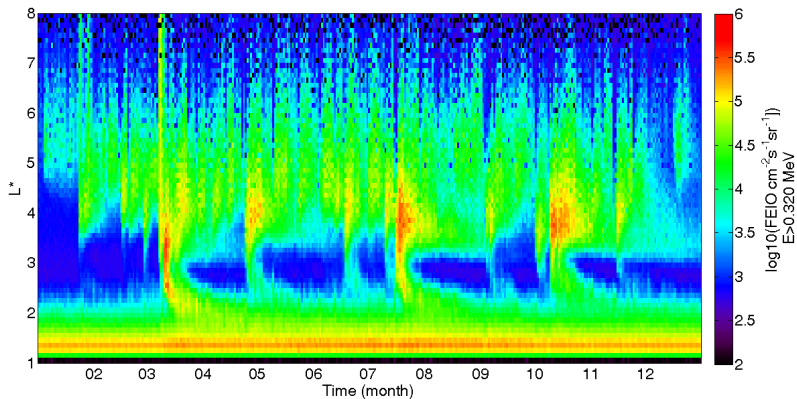
# Distribution of particles, according with L and energy



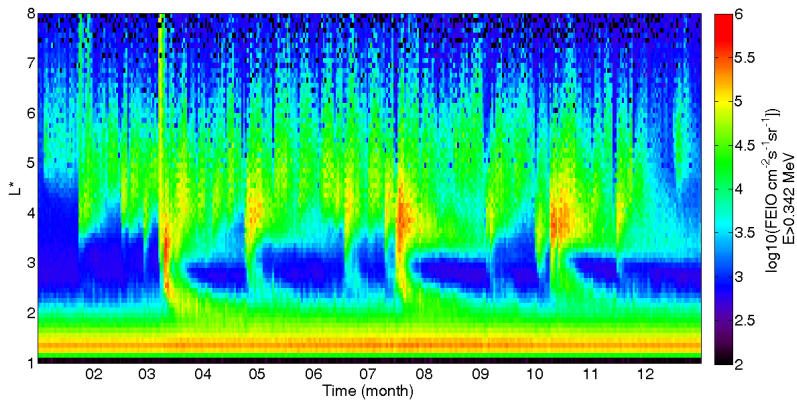
# Distribution of particles, according with L and energy



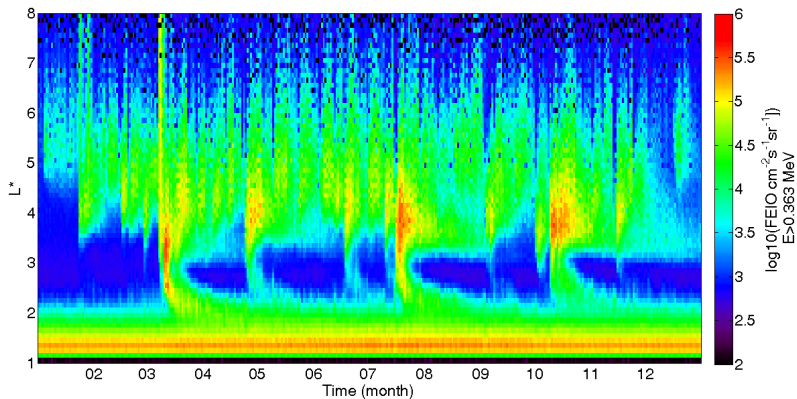
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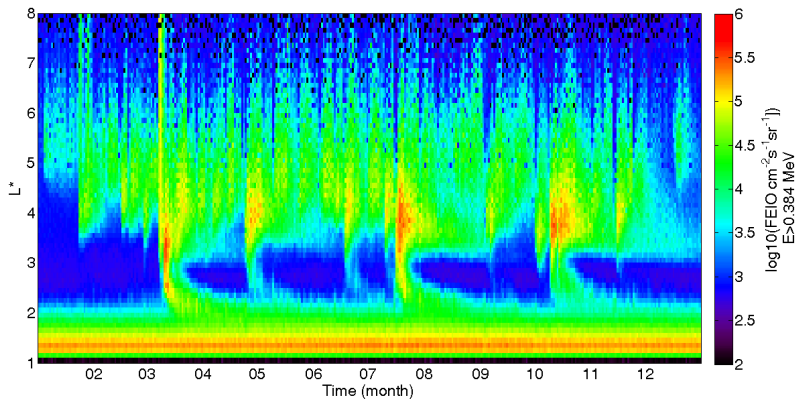
# Distribution of particles, according with L and energy



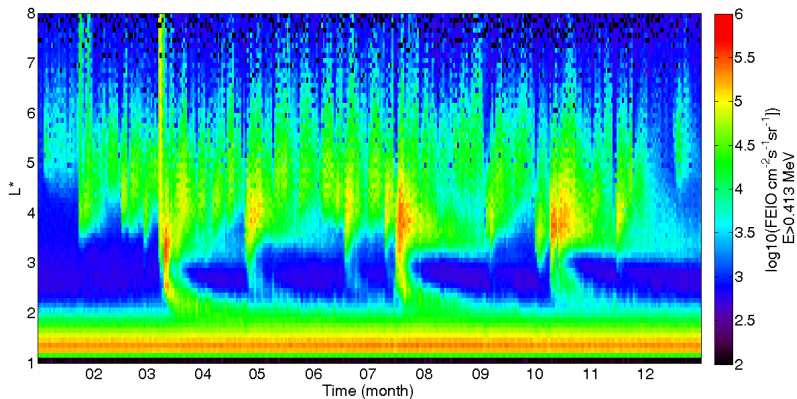
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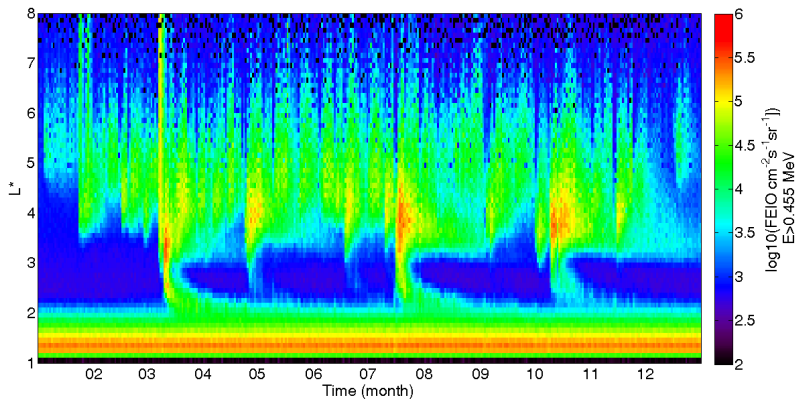


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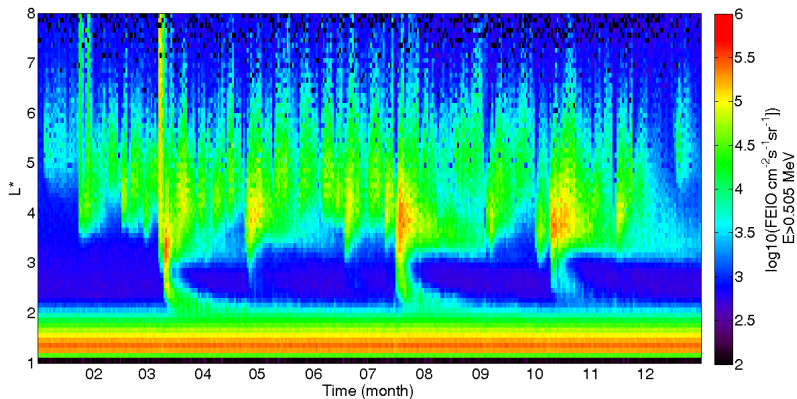




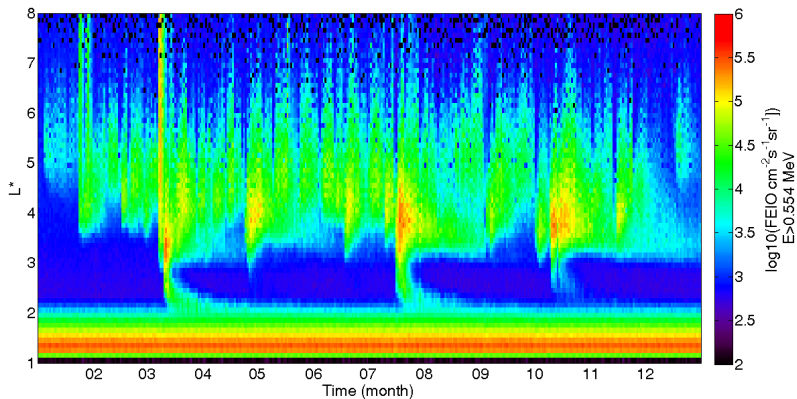
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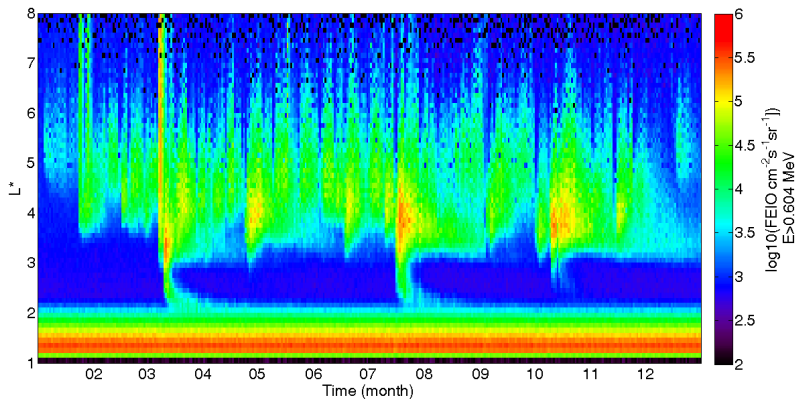
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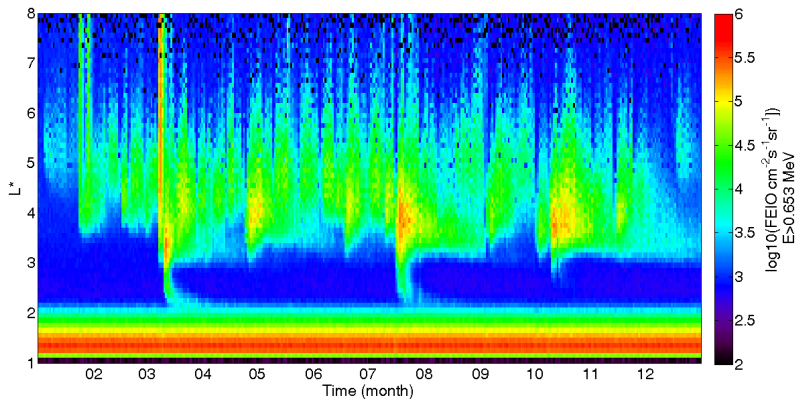
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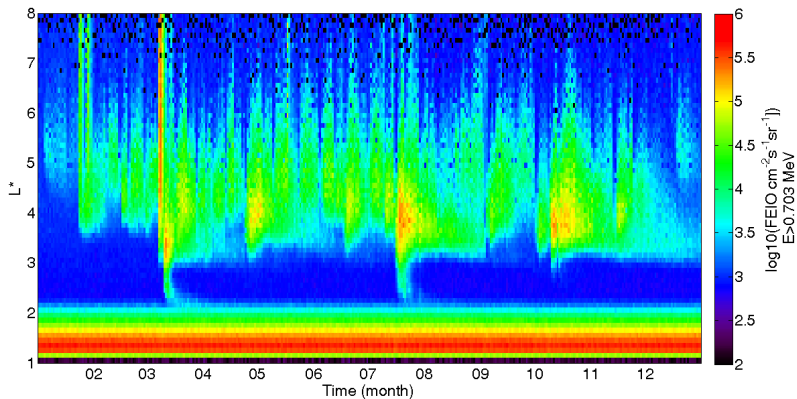
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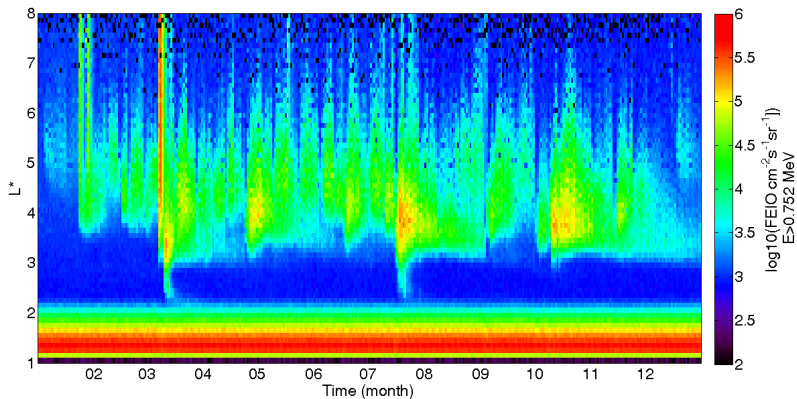
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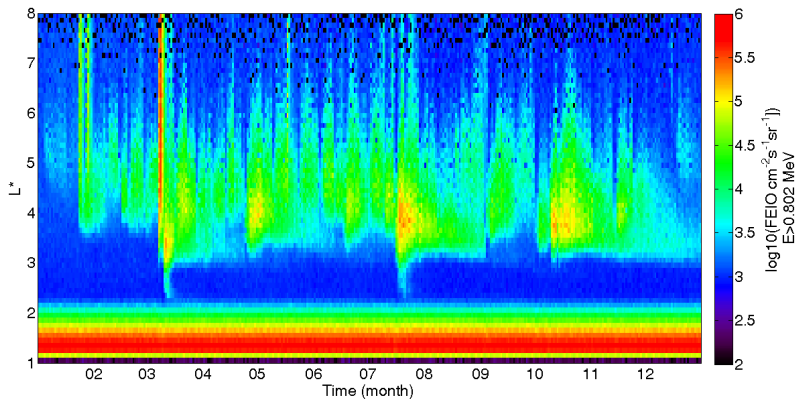
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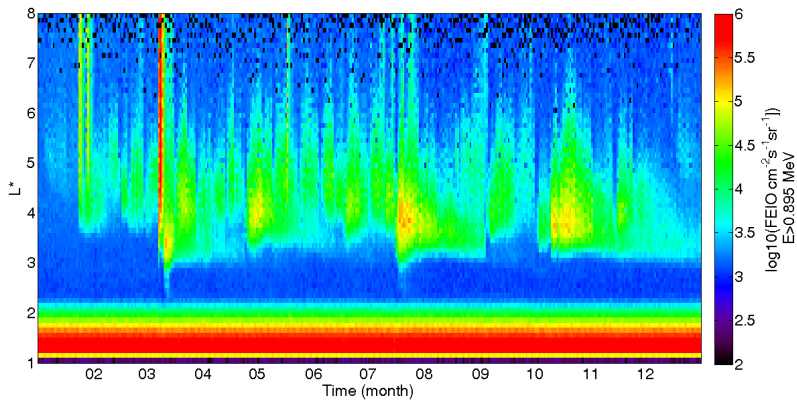


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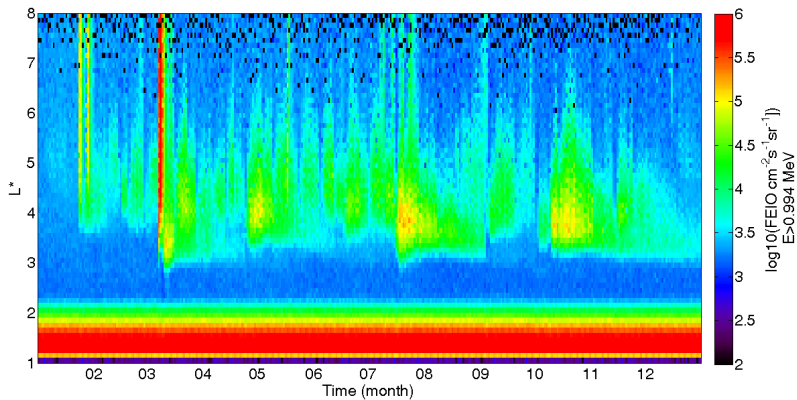




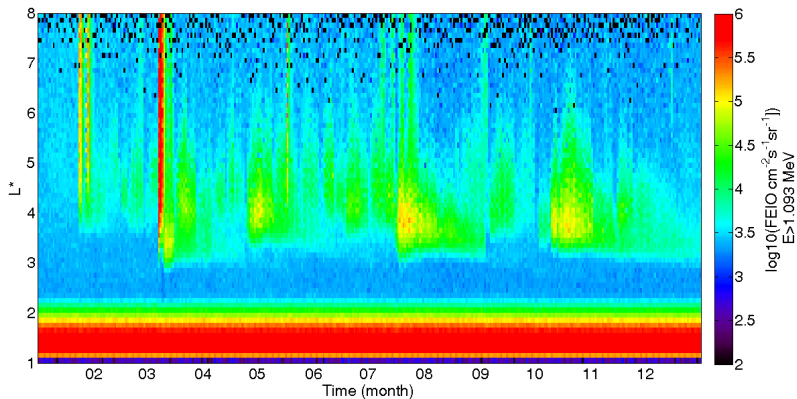
# Distribution of particles, according with L and energy



# Distribution of particles, according with L and energy



# Distribution of particles, according with L and energy



# Summary and Conclusions

- The dynamics of the radiation belts strongly depends on Space Weather activity
- We constructed a global map of e- fluxes for  $E > 259$  keV:  
migration of AAS to the South
- For e- fluxes AAS moves to the North-West when E increases  
(from 259 keV to 413 keV)
- We analyzed the PDF of fluxes for four regiones:
  - ▶ AAS: PDF near to log-normal, with larger tail
  - ▶ South Polar: PDF as superposition of two log-normal, with larger tail
  - ▶ North Polar: PDF near to log-normal, with larger tail
  - ▶ Low Latitude: PDF near to a Normal
- We analyzed the distribution of particles on L and energies, we quantify the answer of the outer radiation belt to extreme Space Weather events

Many Thanks for your attention !!