Study of the dynamics of electrons in Earth's radiation belts as observed from the Moon using synchrotron radiation

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Context This research explores an innovative approach to remote sensing based on cyclo-synchrotron emissions generated by trapped electrons at radio wavelengths. Although these emissions are undetectable from the ground due to ionospheric absorption (below 10 MHz), they could be observed from space, particularly from the near side of the Moon. In addition to current in-situ measurements, which are limited in both space and time, these synchrotron observations could provide a comprehensive view of the radiation belts and help improve our understanding and modeling of them.

Modeling of cyclo-synchrotron emission

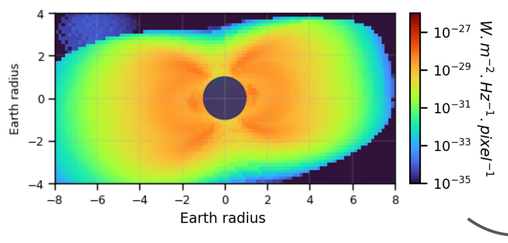
Implementation of cyclo-synchrotron model

Magnetic field geometry | Observation parameters | 3D electron distribution function or PSD (3 dimensions in α_{eq}, E_c, L^*) → Cyclo-synchrotron radiation model → 2D simulated image of the CS emission

Only synchrotron model (E>1 MeV) **Cyclo-synchrotron model (E>100 keV)**

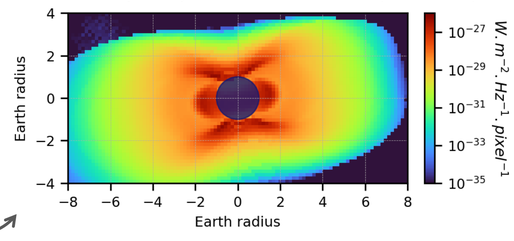
Previous model
Total rad = 4,7 Jy

Simulated synchrotron radiation (>1 MeV)



New model
Total rad = 38,5 Jy

Simulated cyclo-synchrotron radiation (>100 keV)



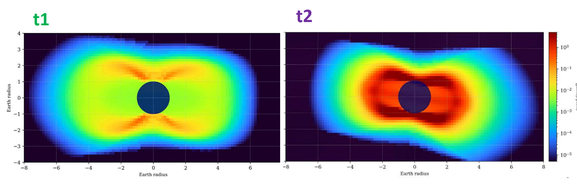
Estimated radiation intensity × 8

Estimated radiation increases when low energy particles are taken into account

Cyclo-synchrotron formalism is essential

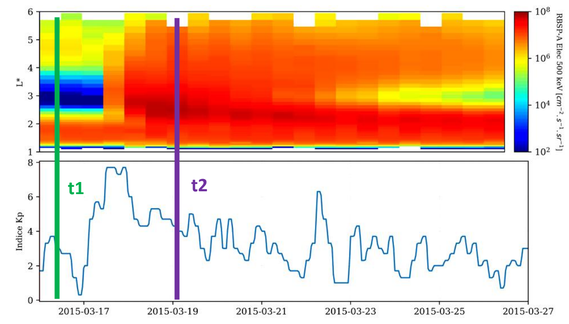
Example of results

2D images of cyclo-synchrotron radiation from the new model and electron distribution from Salammbô



Electron fluxes measured by RBSP

Kp geomagnetic index



Example of results March 2015 at 1 MHz

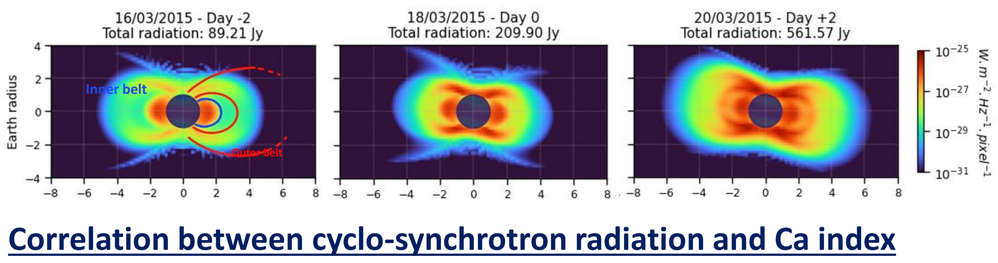
Direct analysis of cyclo-synchrotron images

Evolution of cyclo synchrotron images during geomagnetic storms

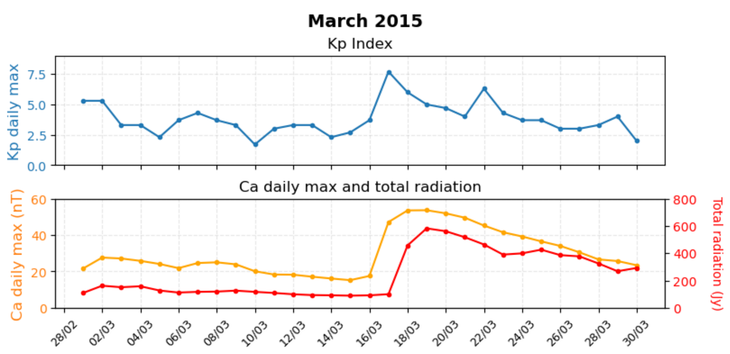
Before storm (D0 –2) : Inner belt dominates, different regions well defined

At storm onset (D0) : Brightening shifts to polar outer belt regions

During storm (D0 +2): Outer belt more diffuse & extended



Correlation between cyclo-synchrotron radiation and Ca index



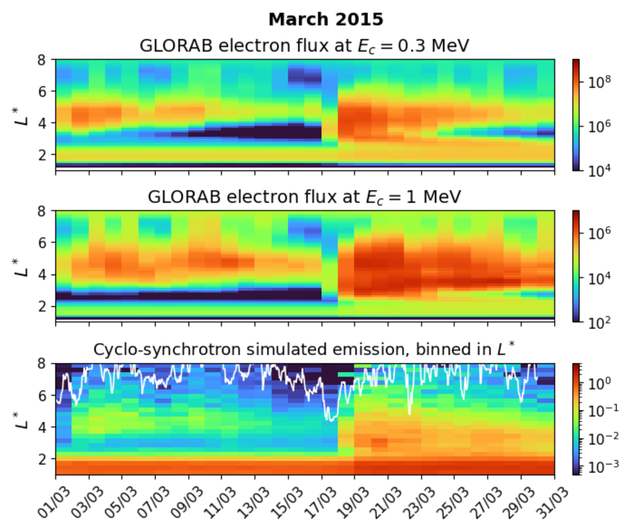
Kp shows moderate correlation

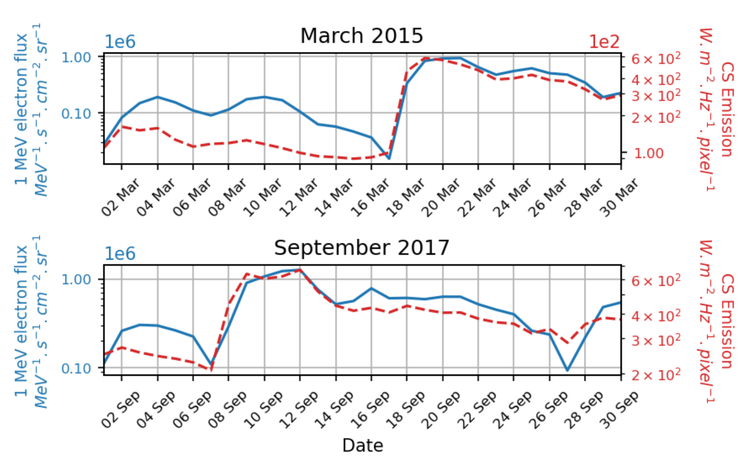
Strongest coupling with Ca

Delays linked to inertia of the belts to accelerate the electrons and time-averaging

Correlation between cyclo-synchrotron radiation at 1 MHz with Kp (top) and Ca (bottom) indices

Correlation between cyclo-synchrotron radiation and electron fluxes





Correlation between cyclo-synchrotron radiation at 1 MHz with electron fluxes

Transformation of 2D images into L^*-time graphs
➔ **Strong correlation between GLORAB electron flux and CS radiation**

Across the four geomagnetic storm periods studied : at 1 MHz CS emission from 1 MeV give the best correlations (**r = 0,94** for March 2015 and **0,92** for September 2017)

Reconstruction of 3D electron distribution

Introduction to the inverse problem

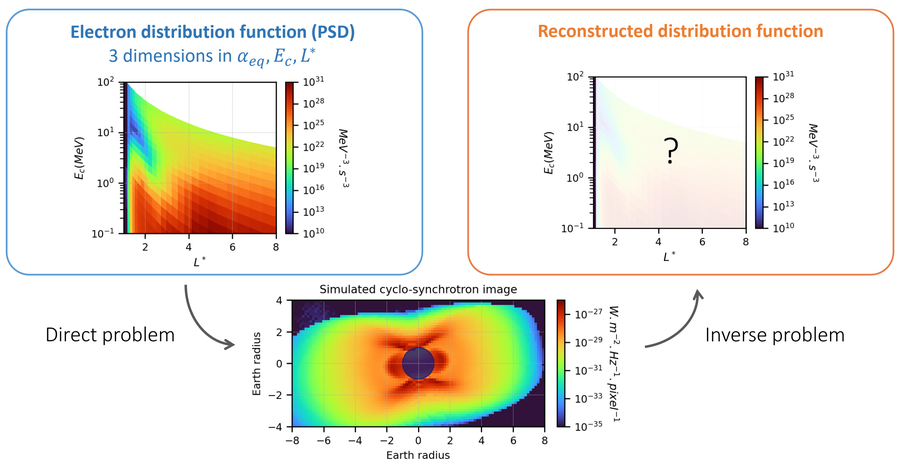
Direct problem:

Magnetic field geometry | Observation parameters | 3D electron distribution function or PSD (3 dimensions in α, E_c, L^*) → CS direct model → 2D simulated image of the CS emission

Inverse problem:

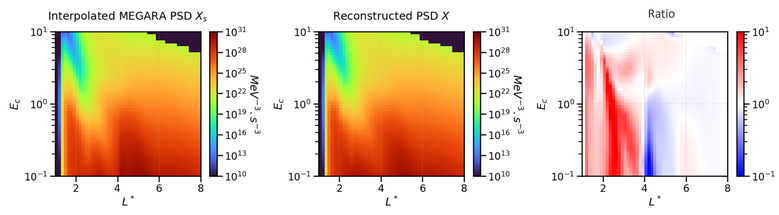
NO OBSERVATION → 2D simulated image of the CS emission → Inversion methods → 3D electron distribution function

Development of an inversion method enabling the 3D reconstruction of electron distributions from 2D images generated by the direct Cyclo-Synchrotron model



PCA-based methods

Given the ill-posed nature of this problem, several strategies have been explored, including regularised inversions and a non-linear reformulation. To stabilise the inversion and reduce its dimensionality, we have developed a method based on principal component analysis (**PCA**) based on a long-term simulation of Salammbô model (1979-2025). This approach enables the accurate reconstruction of electron distributions under various geomagnetic conditions.

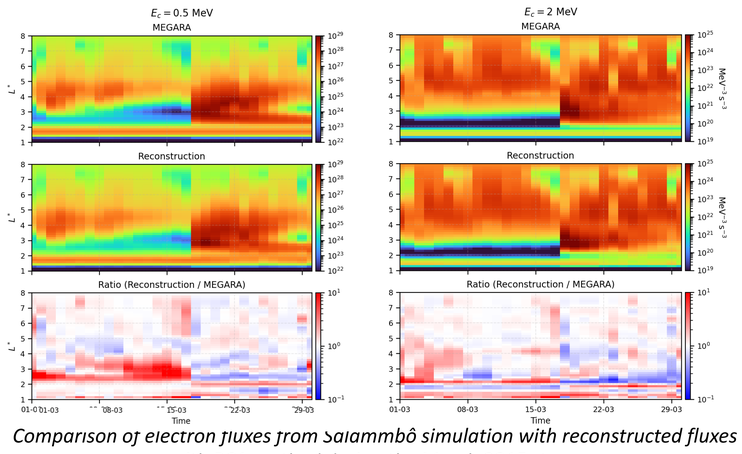


Example of inversion with PCA method for 10 March 2015

Method able to capture radiation belt dynamics

Example of March 2015 for 2 MeV and 0.5 MeV

Non-uniform reconstruction quality, varying along:
- Energy
- Position
- Geomagnetic activity



Comparison of electron fluxes from Salammbô simulation with reconstructed fluxes with PCA method during the March 2015 storm

Acknowledgements

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