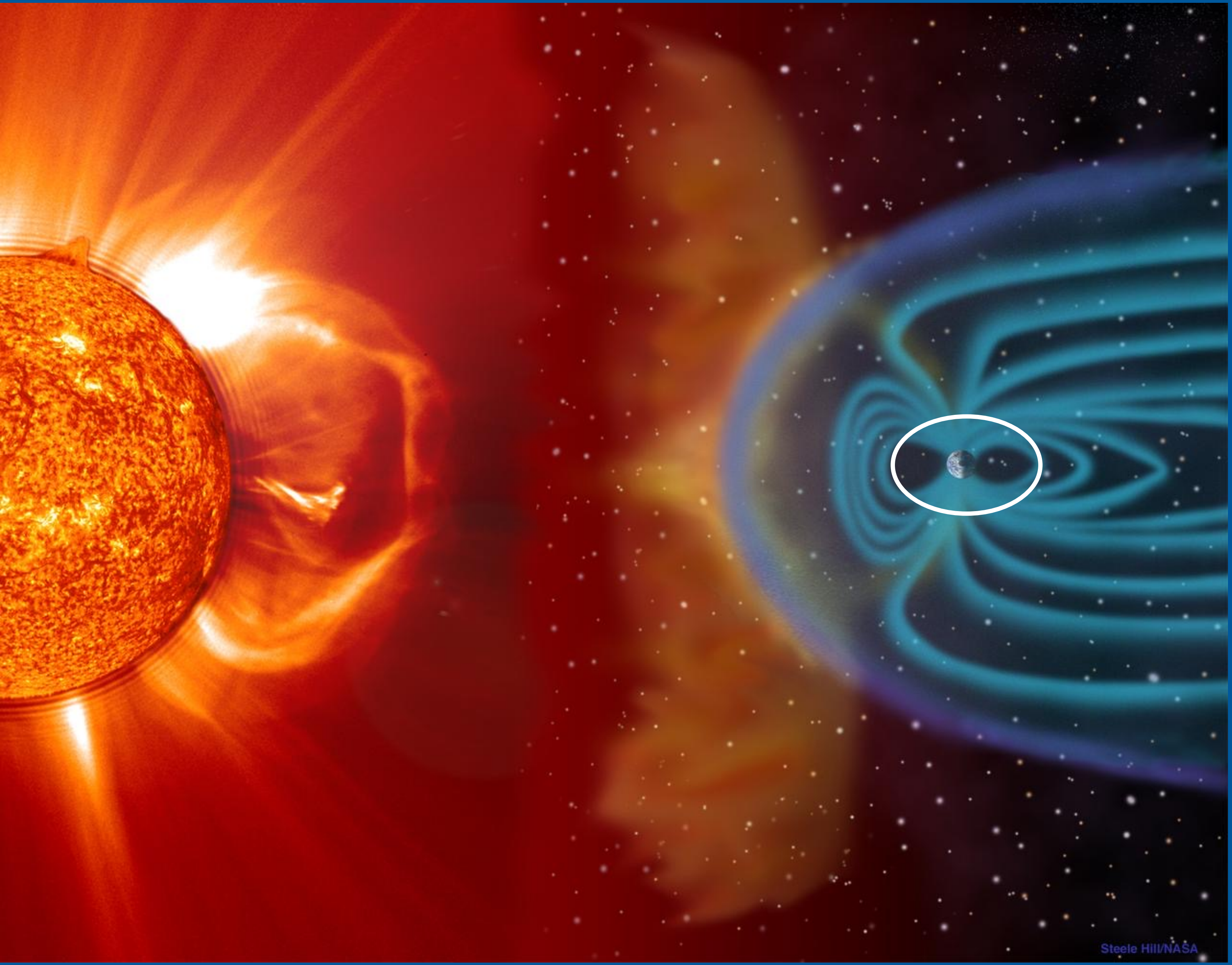


The Solar Wind – Magnetosphere Coupling, Radiation Belts, Plasmasphere

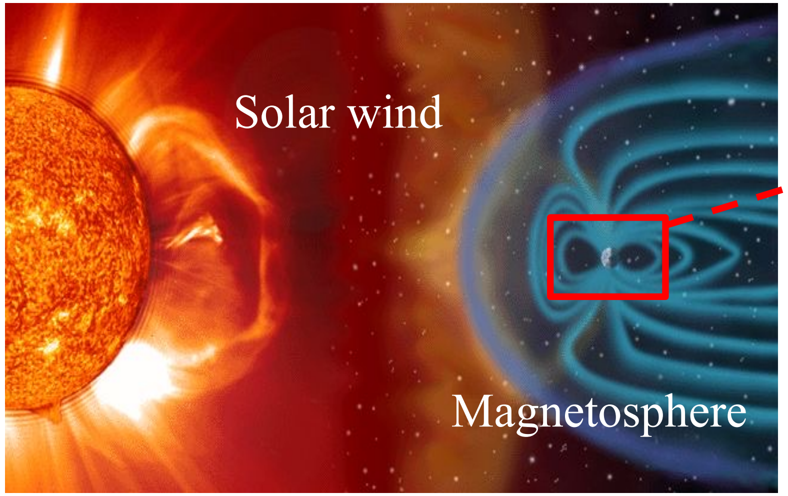
Dedong Wang, Yuri Y. Shprits

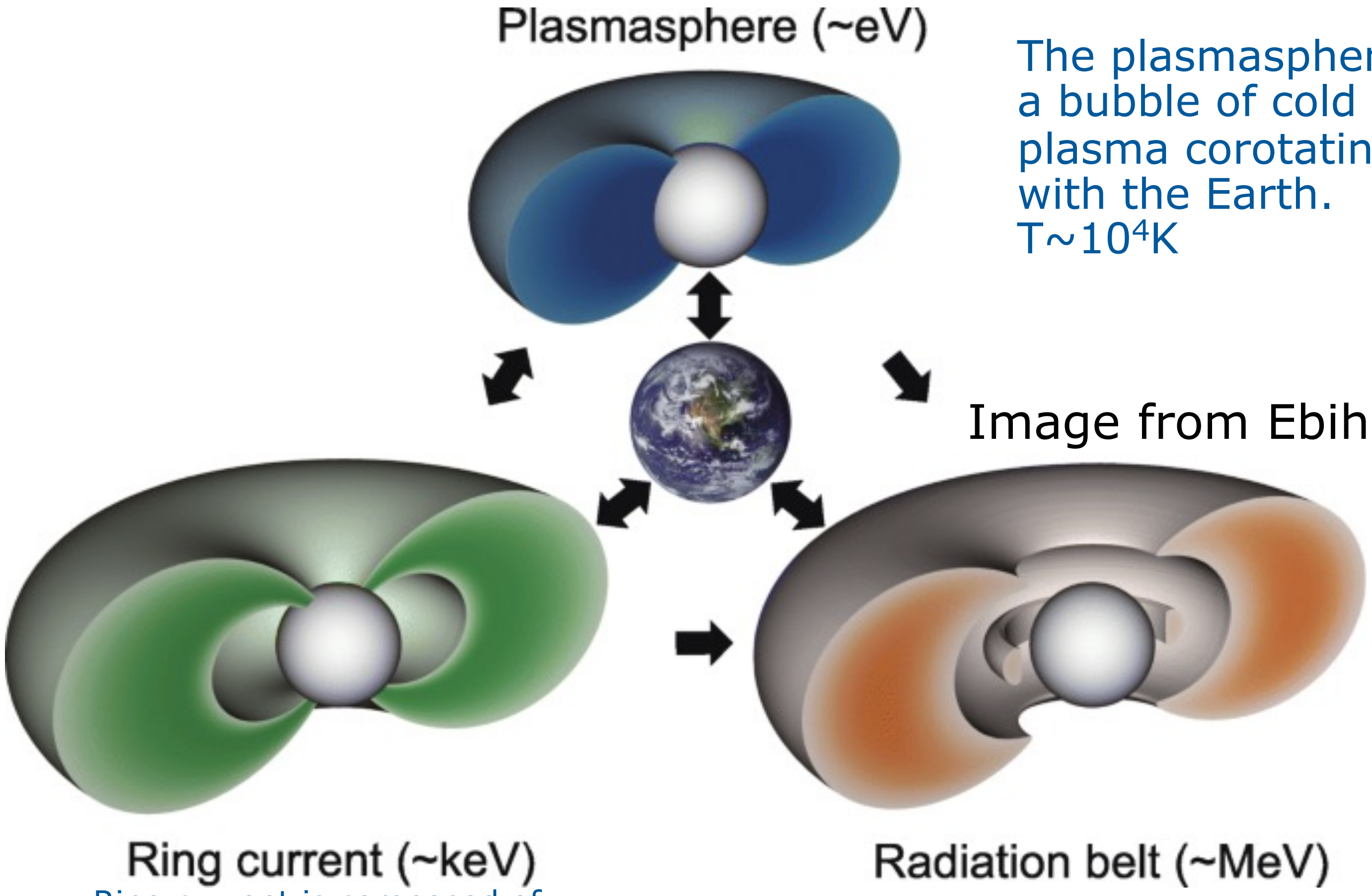
Section 2.7 Space Physics and Space Weather

Department 2 Geophysics
Helmholtz Centre Potsdam
German Research Centre for Geosciences, GFZ

Co-located different populations of particles

The magnetosphere creates a cavity in the magnetic field. However, the magnetosphere is not empty and hosts a number of different particle populations.





The plasmasphere is a bubble of cold plasma corotating with the Earth. T~10^4K

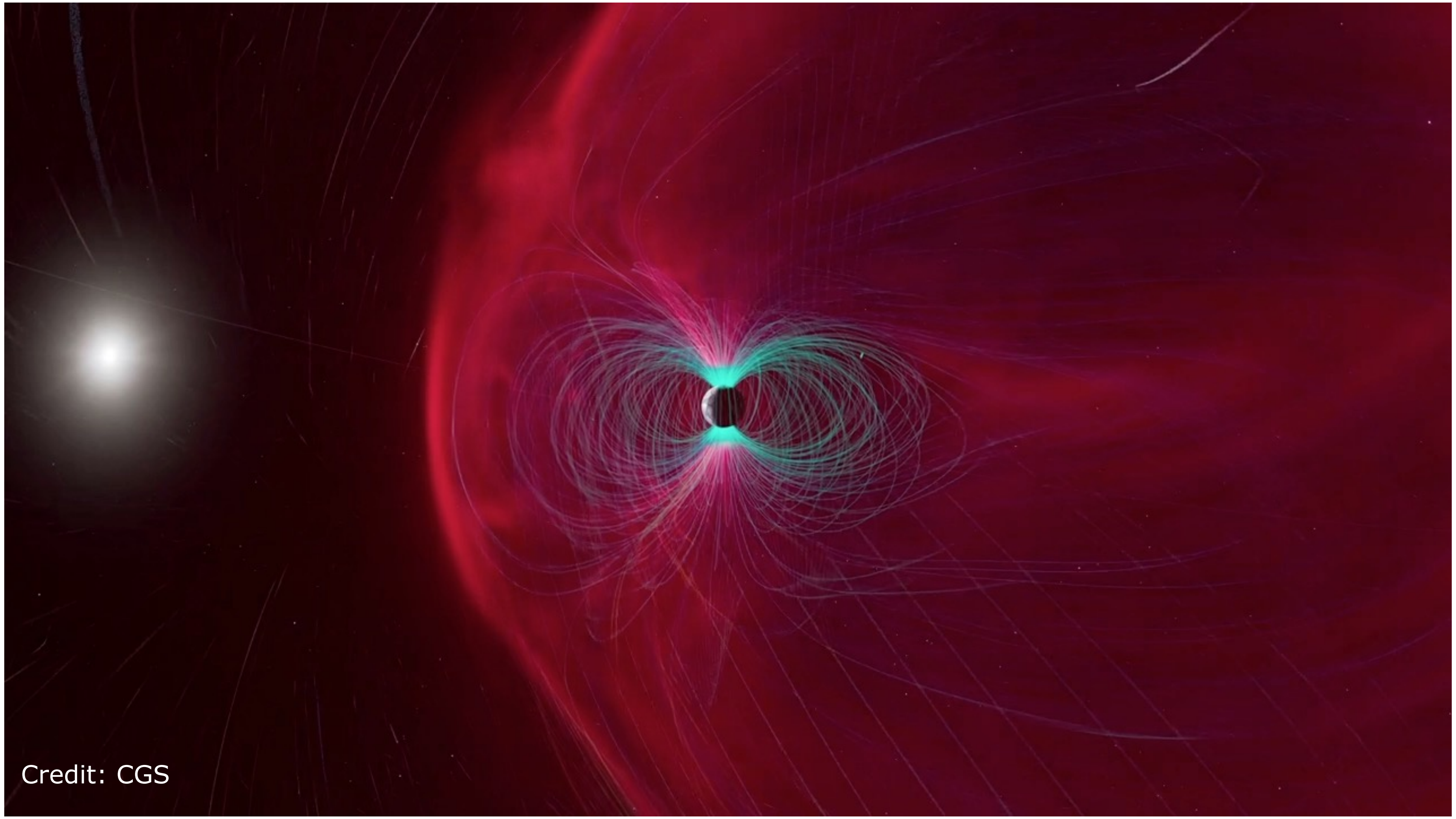
Image from Ebihara, 2019

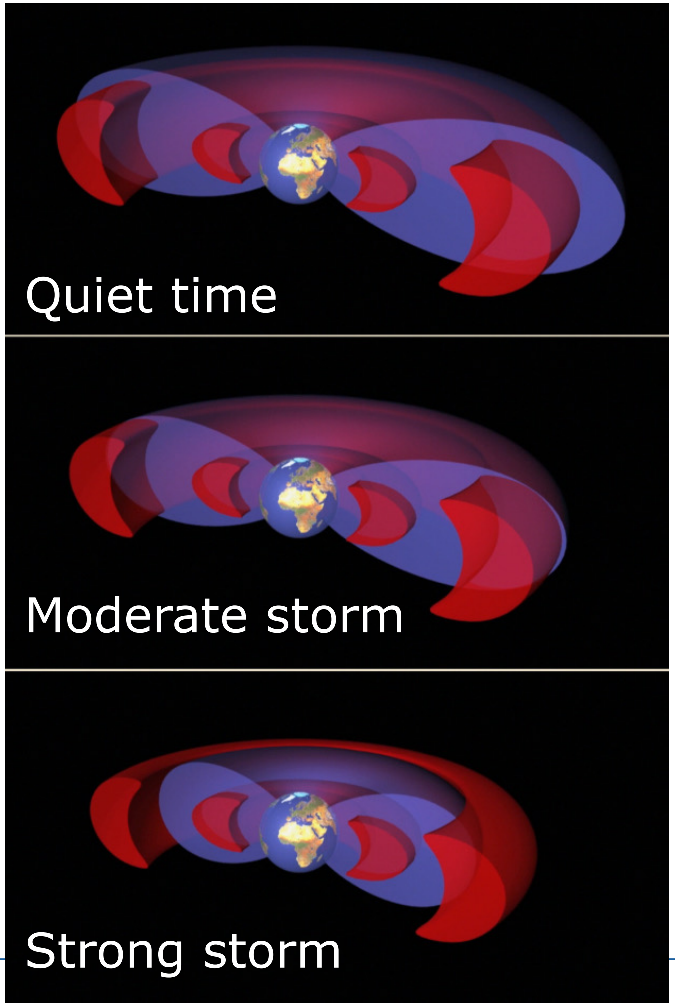
Ring current is composed of energetic ions and electrons that create a negative perturbation on the ground. ~10^7K

The radiation belts – two donut-shaped regions of high radiation encompassing the Earth.

Inner-magnetosphere

Particles at different energies are strongly coupled in this region

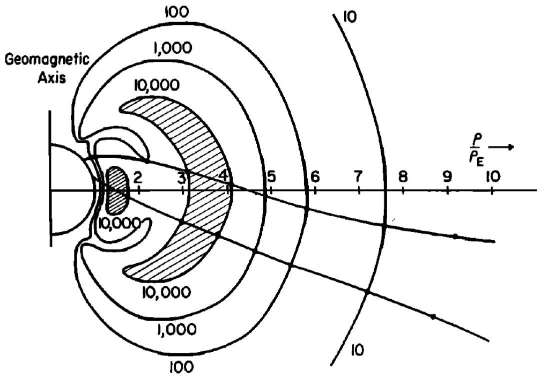




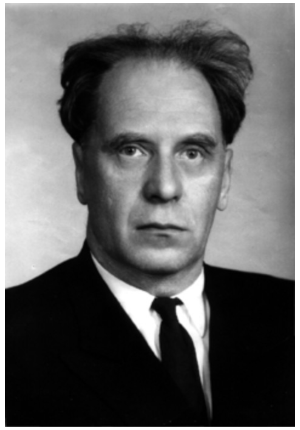
An Achievement of the International Geophysical Year

The Earth's Radiation Belts Discovered in 1958

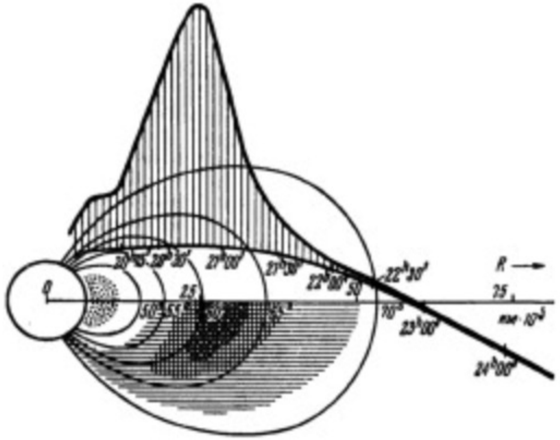
James Van Allen



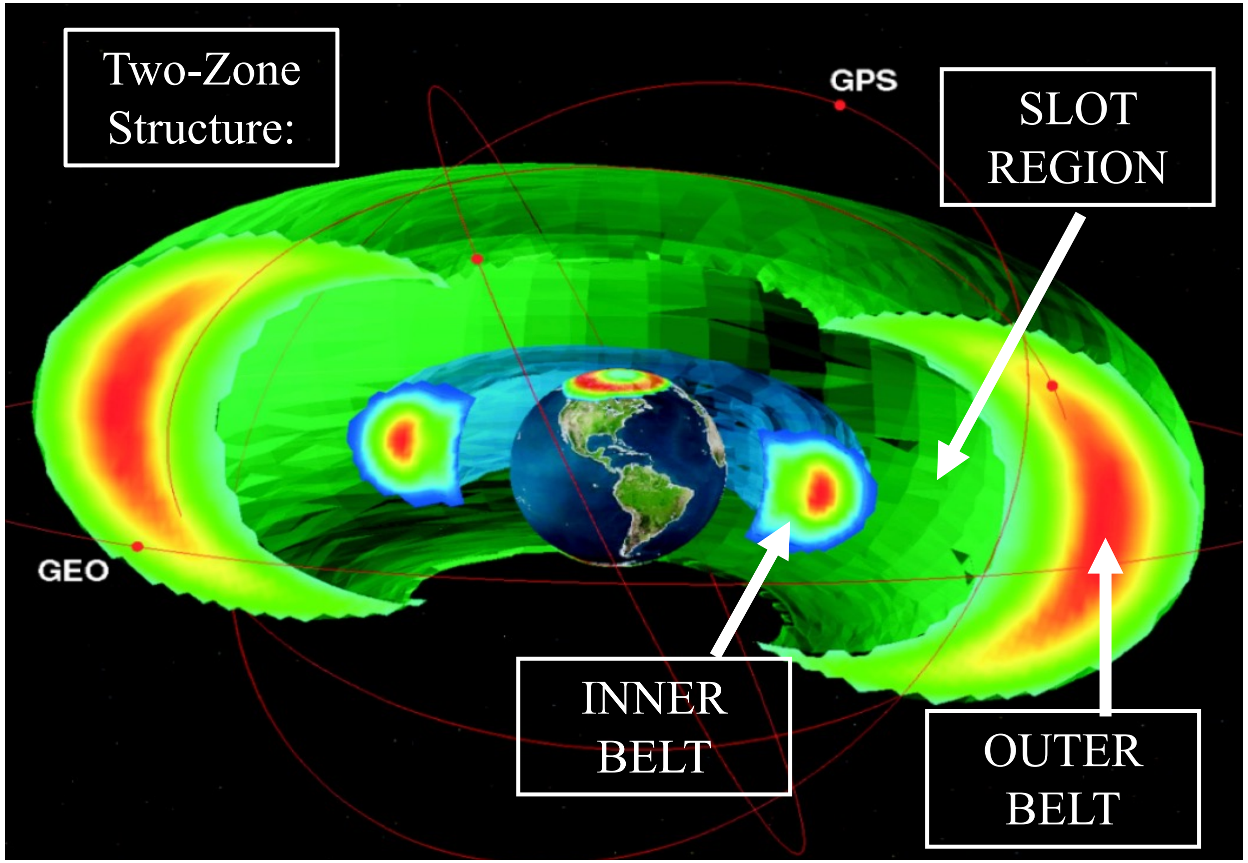
[Van Allen, 1959]



Sergei N. Vernov

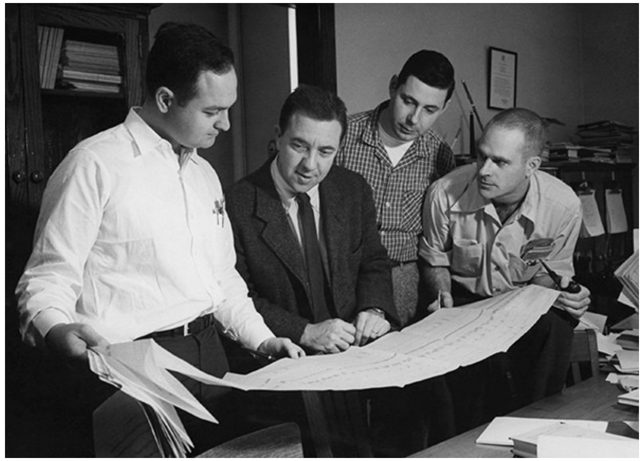


[Vernov et al., 1959]



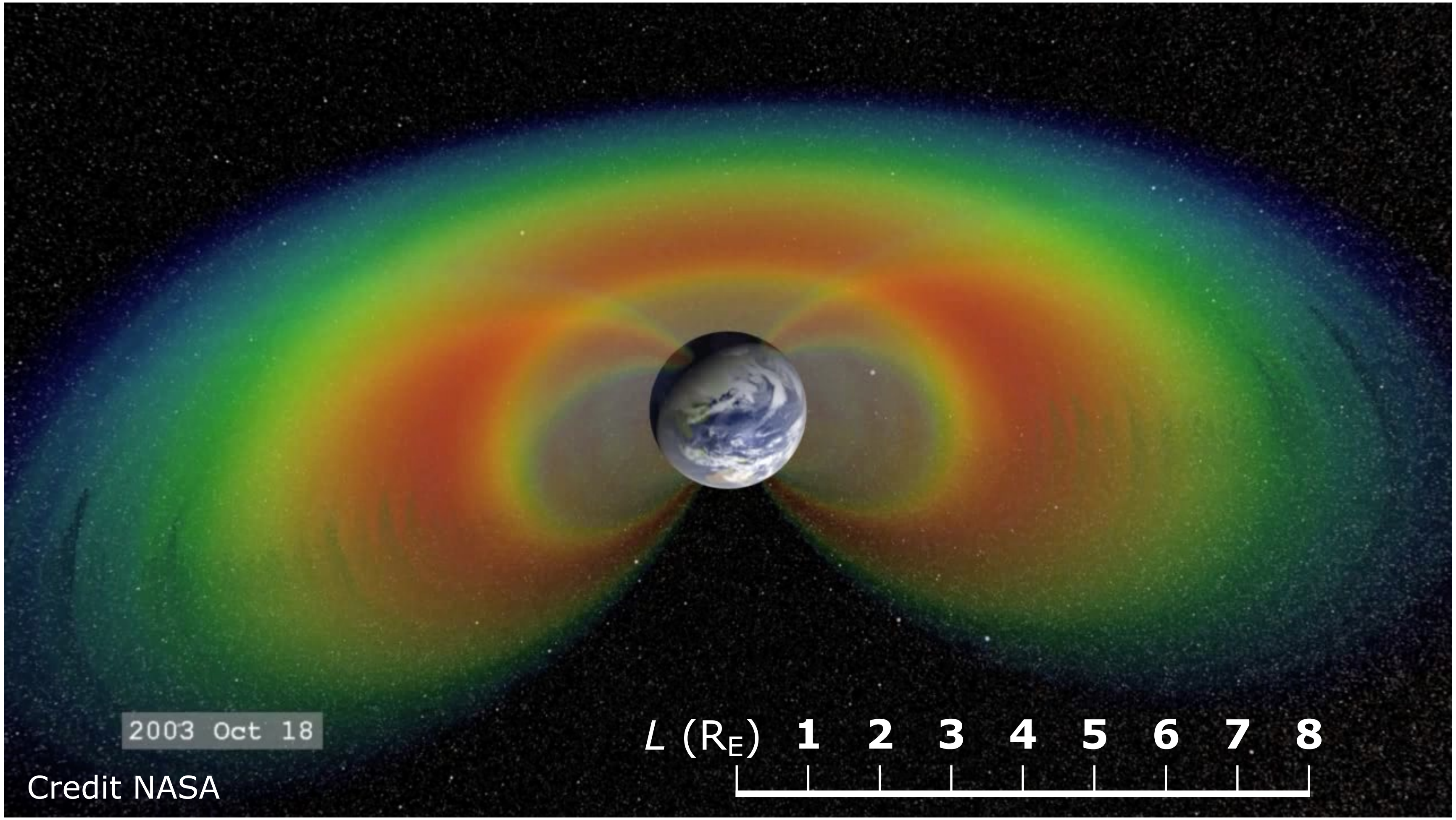
Particle energies > 500 kilo-electron volts (keV)
Inner belt: fairly stable | Outer belt: very dynamic

The Earth's Radiation belts



[Baker and Panasyuk, 2017]

"My God, space is radioactive!"
---Ernie Ray, 1958



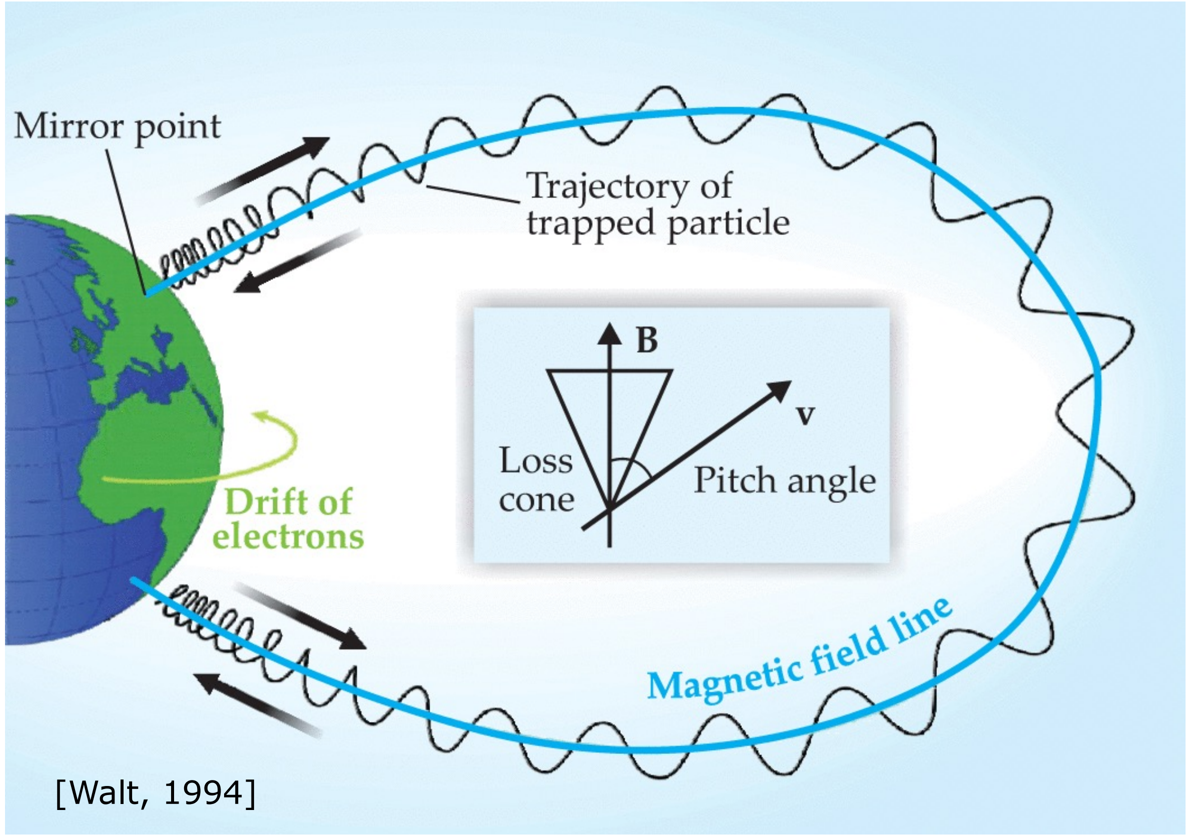
Which energy range are you talking about?

How do these particles move in the magnetosphere?

$\beta = \frac{v}{c}$	$\gamma = \frac{1}{\sqrt{1-\beta^2}}$	$E_k = (\gamma - 1) m_0 c^2$
0.997	**13**	**6.15 MeV**
0.98	**5**	**2.05 MeV**
0.87	**2**	**512 keV**
0.75	**1.5**	**256 keV**
0.41	**1.1**	**51.2 keV**
0.30	**1.05**	**25.6 keV**

Radiation belt

Ring current



Characteristic time scales for
1 MeV electrons

[Zong, 2020]

- Gyro: ~ millisecond
- Bounce: ~ 0.1-1.0 s
- Drift: ~ 1-10 minutes

Do they influence the Earth's magnetic field?

Where are these particles from?

Alexander von Humboldt

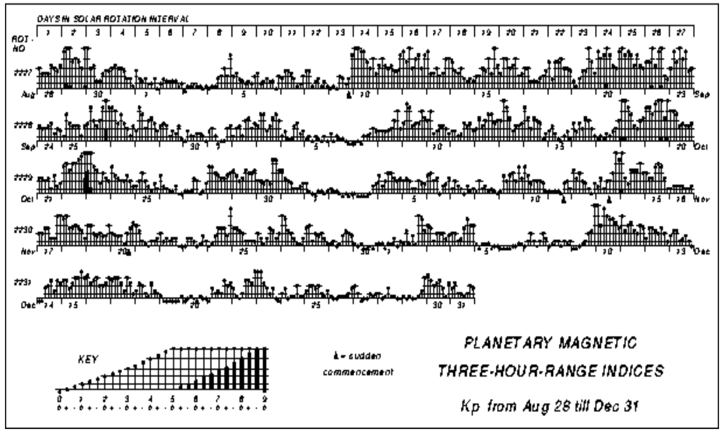
"Magnetisches Ungewitter"

Magnetic storm

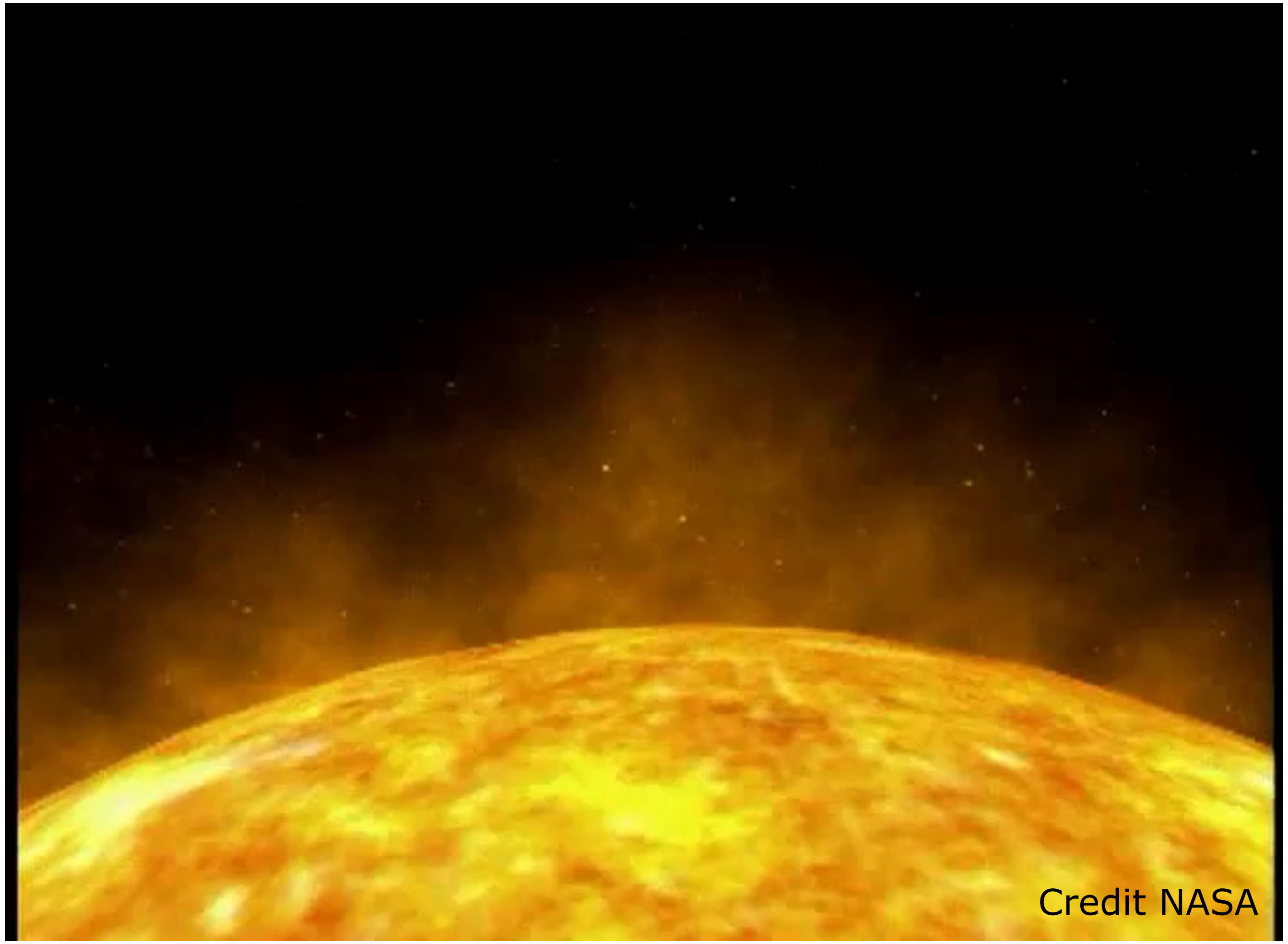
Magnetic needle deflections observed at his home in Berlin on 21 December 1806

Annalen der Physik (1808)

J. Bartels Director of Geophysical Institute Potsdam since 1936



Kp (Planetarische Kennziffern) index
Now Kp is provided by GFZ Section 2.3



Credit NASA

Do they influence the Earth’s magnetic field?

Ring current and geomagnetic storms

$\beta = \frac{v}{c}$	$\gamma = \frac{1}{\sqrt{1-\beta^2}}$	$E_k = (\gamma - 1)m_0c^2$
0.997	**13**	**6.15 MeV**
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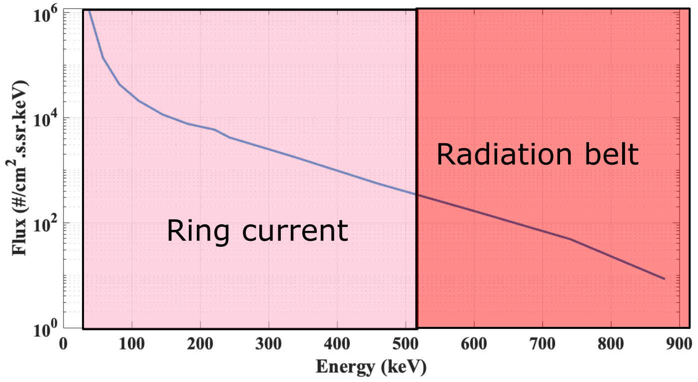
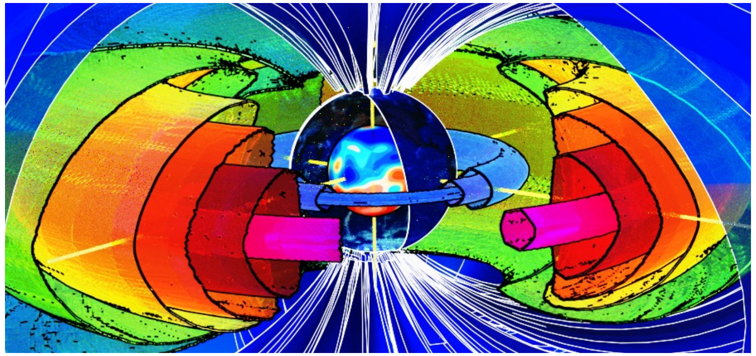
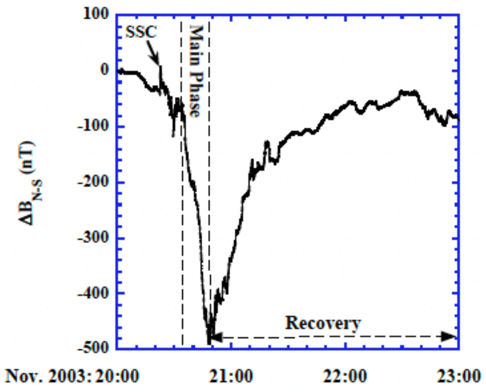
Radiation belt

Ring current

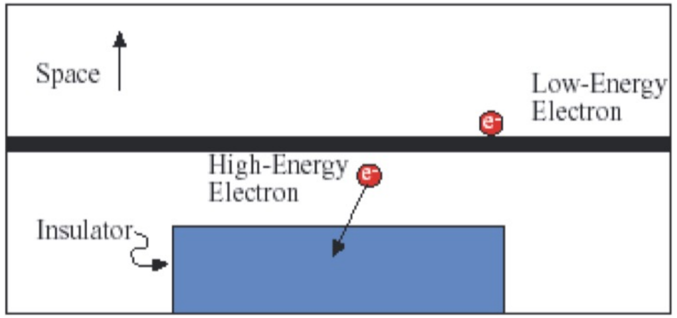




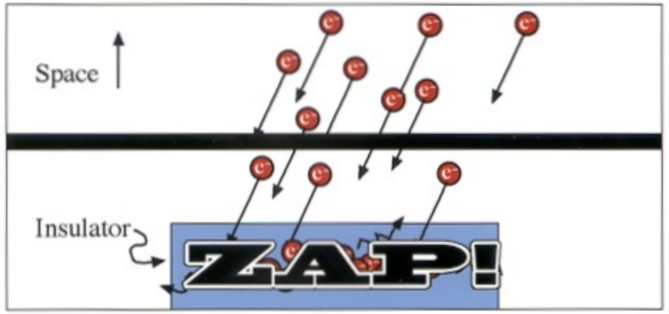


Impact of High Energy Particles on Satellites

High-energy electrons cause deep-dielectric charging



1. High-energy electrons can penetrate the shielding's of the satellite



2. Discharge (electrical spark) that damages or destroys the material

[*Baker et al., 2018*, Space Science Review]

Image Credit: L. J. Lanzerotti, Bell Laboratories, Lucent Terchnologies, Inc.

- ➢ Over 1,000 active satellites; Supporting €125B/yr industry
- ➢ Satellite navigation essential for modern life

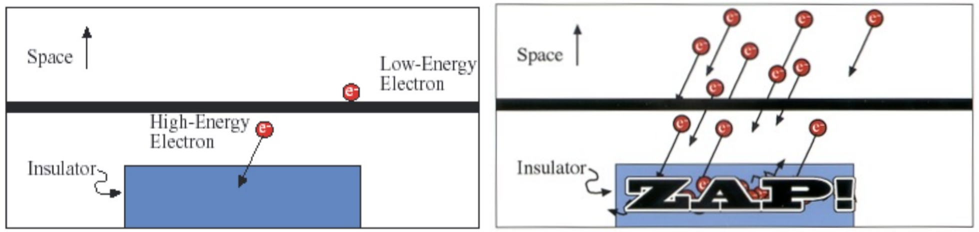
Avg. total satellite costs ~500 M€

Why Do We Care about Geomagnetic Storms?

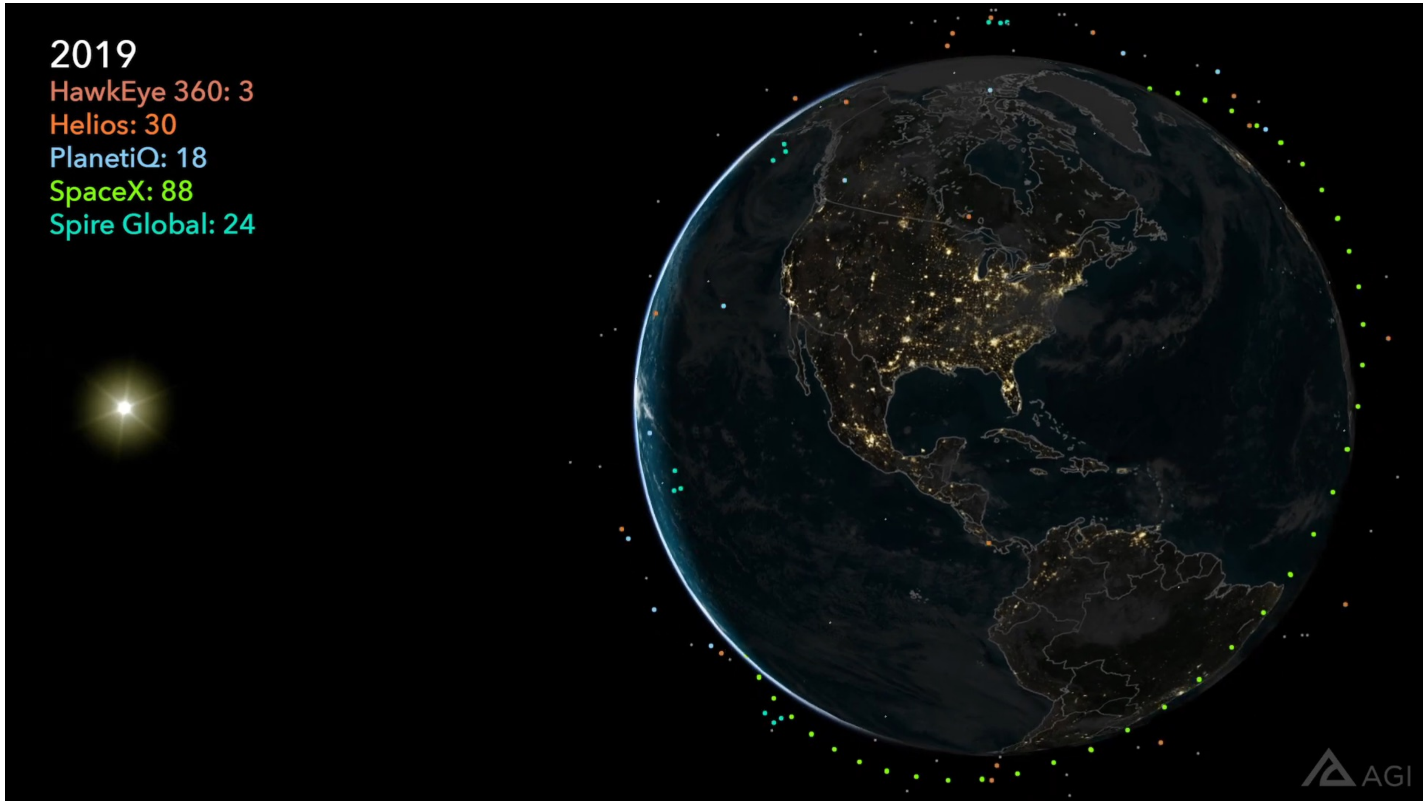
They influence technology in space and life on the ground - space weather

It has been estimated that a Carrington-type storm, the strongest solar storm ever observed at Earth which occurred in 1859, today may cause more than a trillion Euros in global damage [*Lloyd’s of London*, 2013]

- Vulnerability of power grids, blackouts
- **March 13, 1989:** Quebec, Canada
- Over 1,000 active satellites; Supporting €125B/yr industry
- **February 4, 2022:** 40 of 49 Starlink satellites
- Satellite navigation essential for modern life

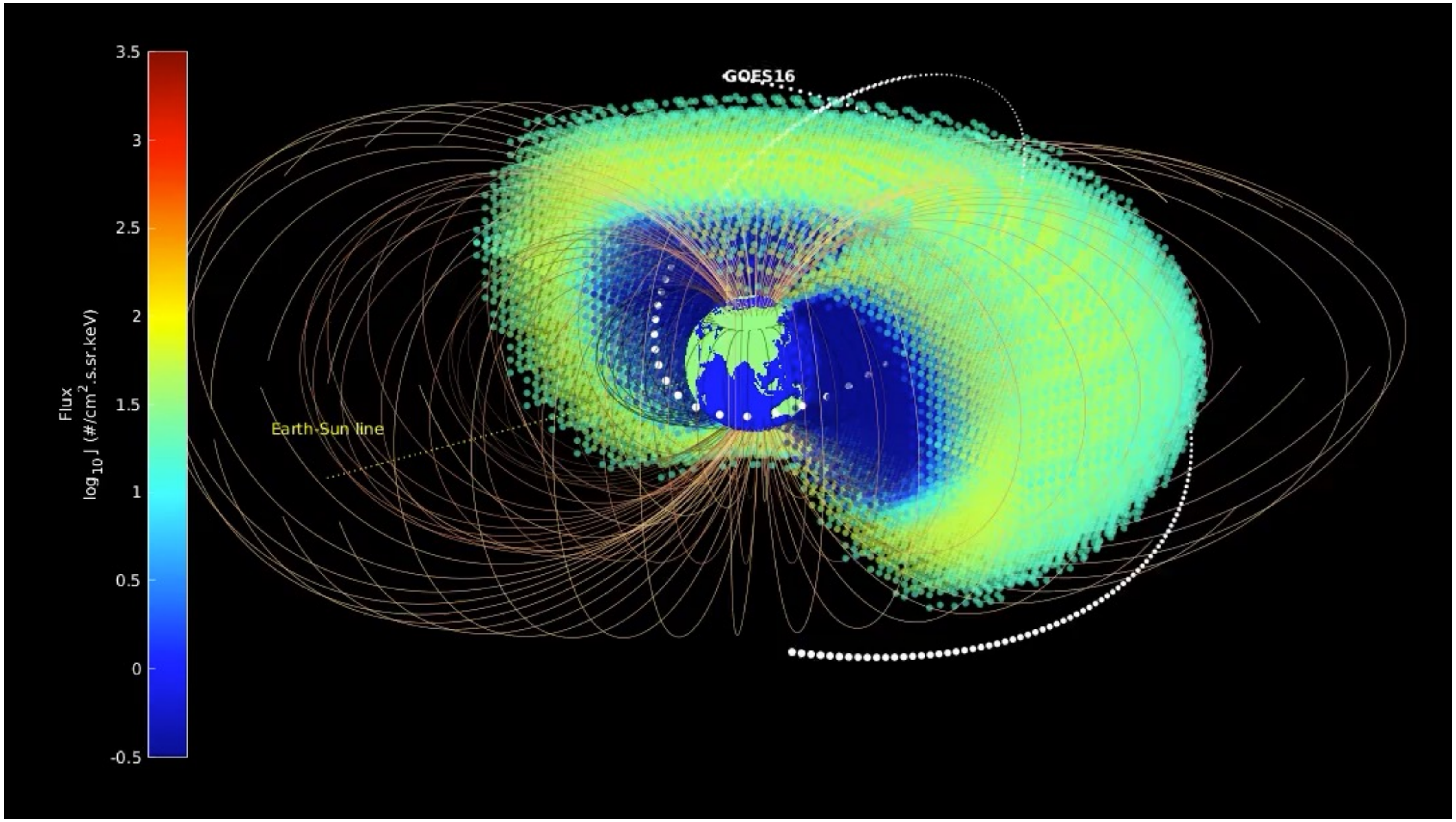


[*Baker et al., 2018*]



PoF IV: Changing Earth – Sustaining our Future

Topic 3: Living on a Restless Earth: Towards Forecasting Geohazards



"Ionizing radiation from geomagnetic storms can harm satellite performance, e.g., reduce GNSS location and communication services. We will make significant improvements to **forecasting the near-Earth space weather** by developing forecasting tools for the near-Earth radiation environment."
– POF IV Topic 3

Milestone M3.7-4 (2026): Implement a new model to **forecast the magnetospheric ring current, radiation belts** and the Kp-index.

An Overarching, Compelling and Unanswered Question

Scientists are still finding mysterious features about the high energy particles

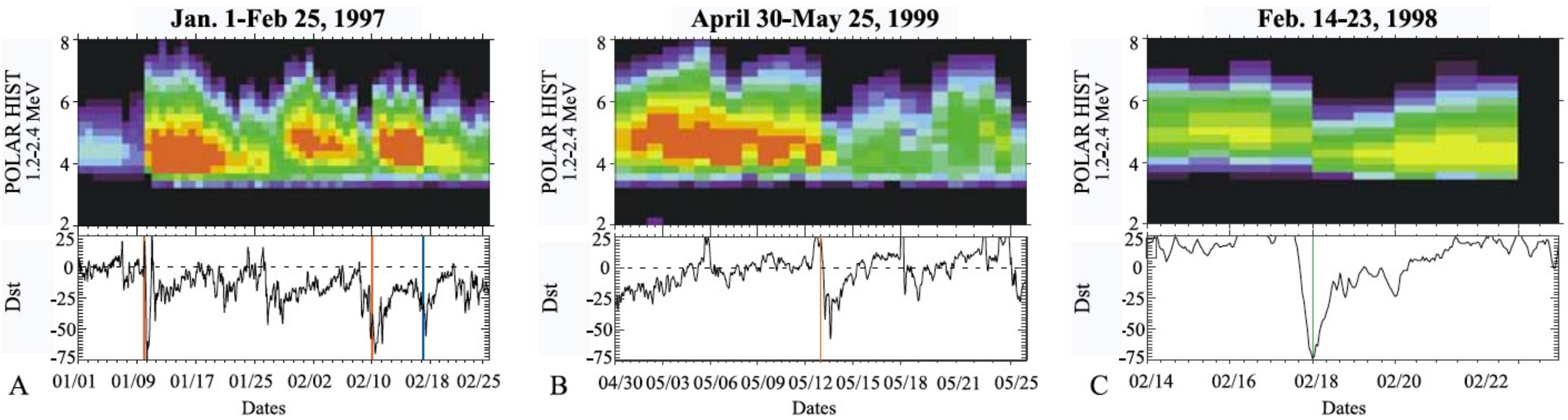
Why do the high energy particles respond so differently to similar geomagnetic storms?

[*Reeves et al.*, 2003]

Enhancement

Depletion

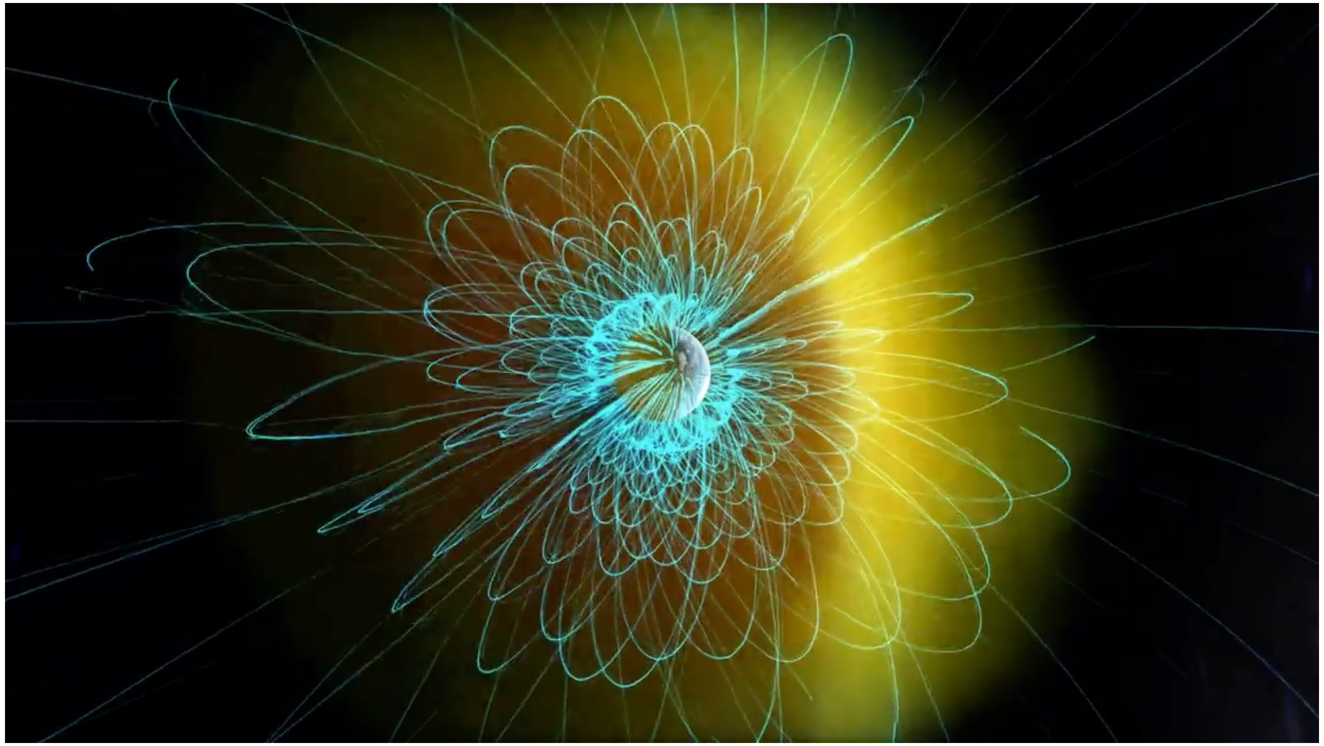
No change

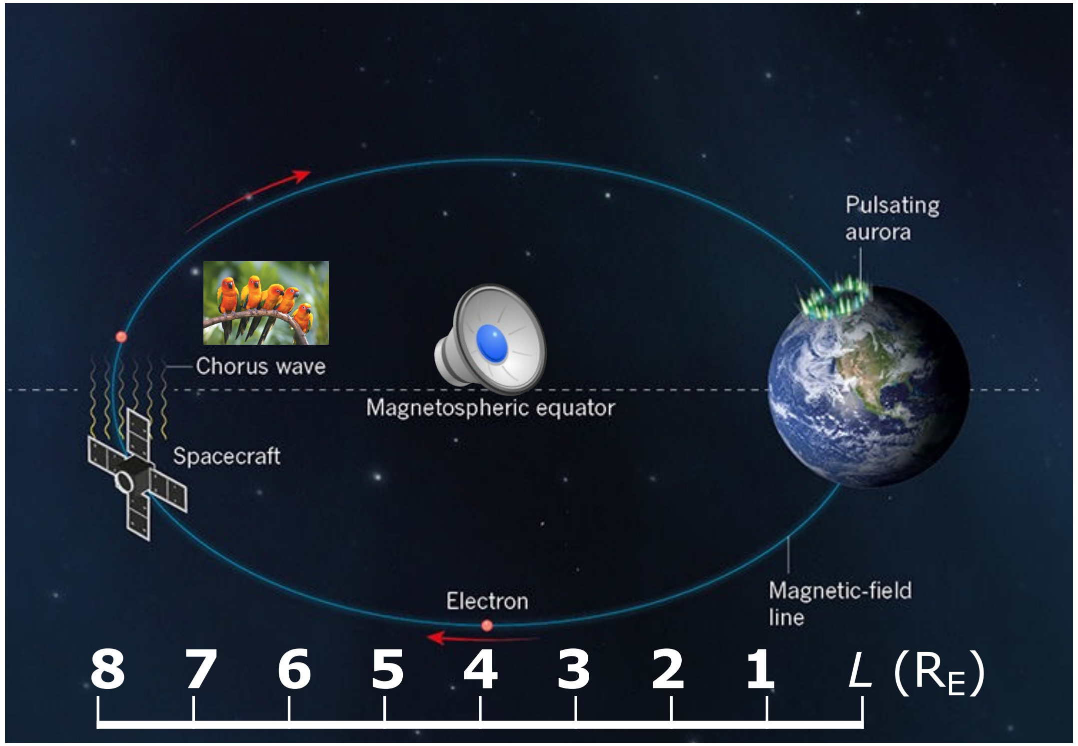


Dst: Disturbance Storm Time index

How Are These Particles Accelerated and Lost?

Most Important Mechanism: Wave-Particle Interactions



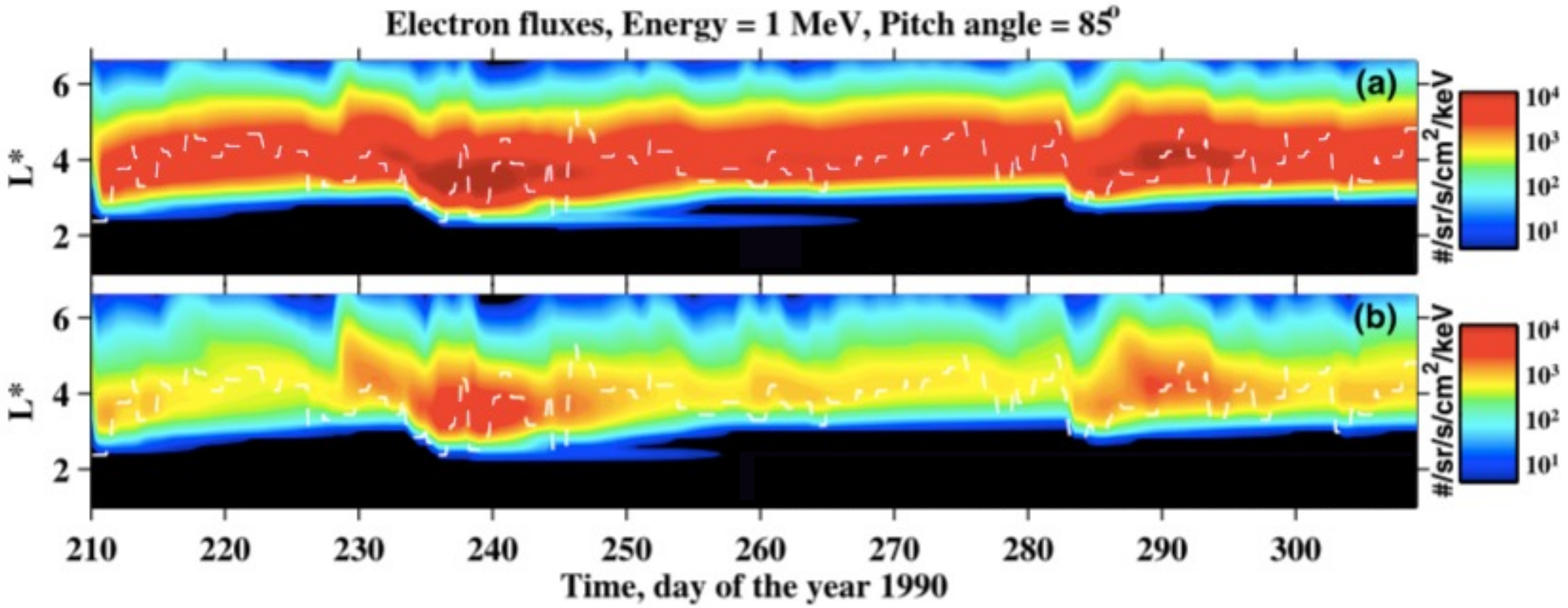


Credit: JAXA

[Kasahara et al, 2018, *Nature*]

The frequencies of these waves range from mHz to kHz!
At least we need the wave information in 8 dimensions of variables: wave type, frequency, intensity, propagation direction, local time, latitude, L, geomagnetic activity level dependence.

Accurate Wave Model is very important



A sensitivity test. Comparing with the first panel, chorus waves power used in the simulation for the second panel is twice as high on the dayside and twice as low on the nightside.

[*Subbotin et al., JGR, 2011*]

PoF IV: Changing Earth – Sustaining our Future

Topic 1: The Atmosphere in Global Change

"Energetic particles that precipitate from the magnetosphere can have a profound effect on nitric oxide, with consequences for ozone and climate. To quantify the **effects of particle precipitation**, we will need to understand and quantify the dynamic evolution of energetic particles and their effect on upper-atmospheric chemistry." – POF IV Topic 1

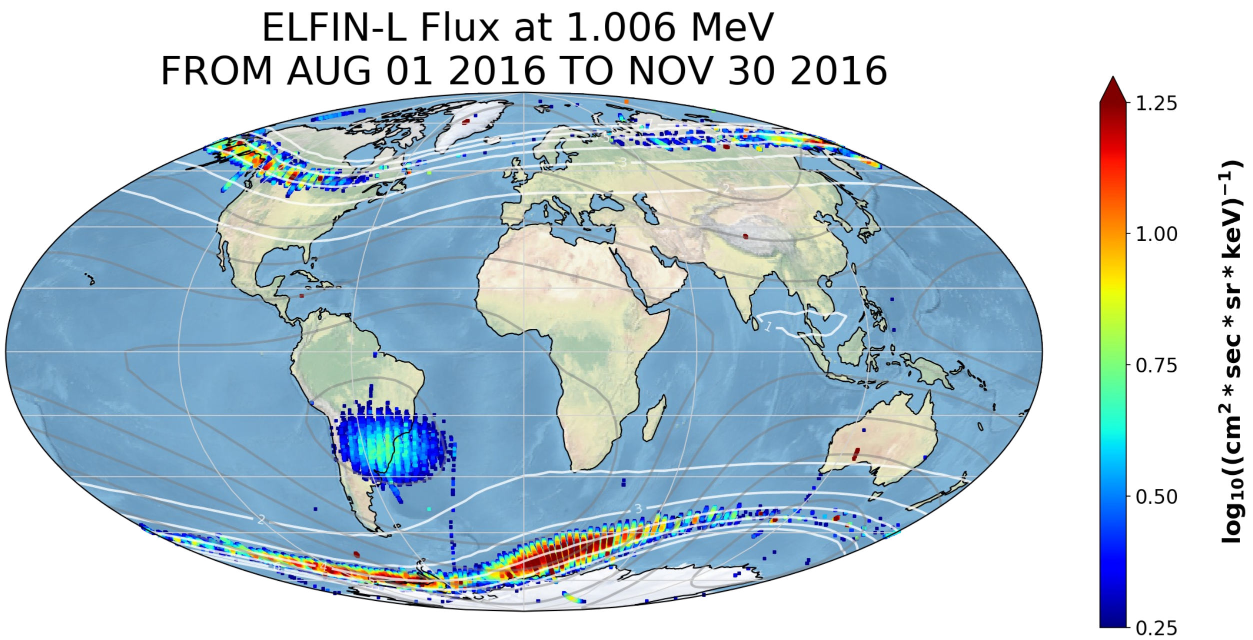
Energetic Particle Precipitation

↓↓↓

Ionization

↓↓↓

NOx and HOx



Deliverable D1.5 (2027): Assessment of solar-terrestrial processes taking place in the near Earth's space, and of its possible feedback mechanisms on lower atmosphere dynamics.

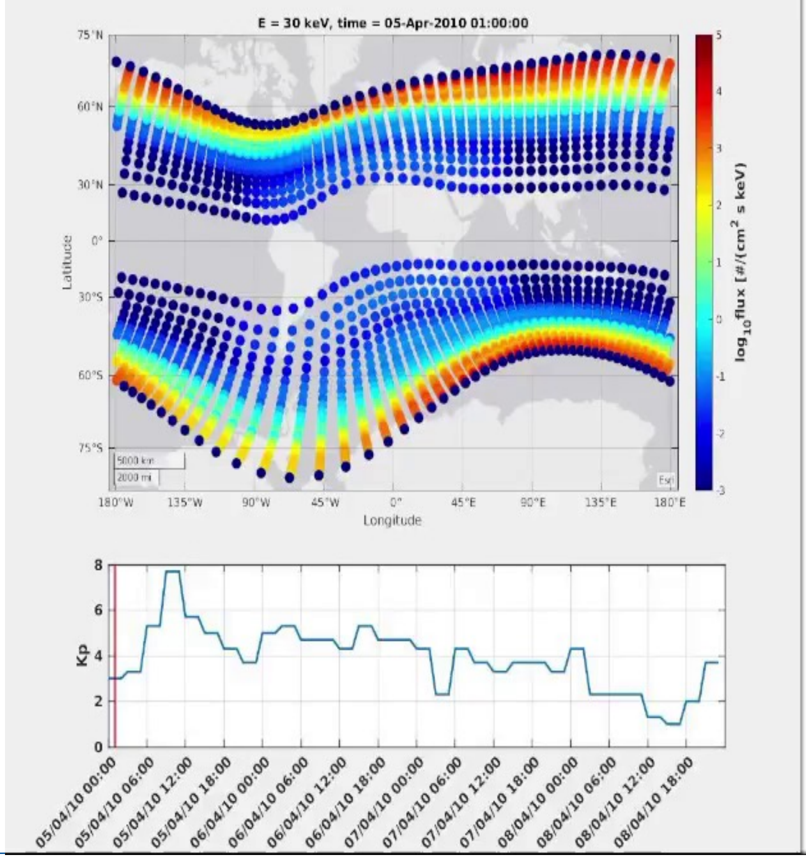
Geomagnetic activity is recommended as part of the solar forcing of the climate system for the upcoming CMIP-6 (IPCC) model experiments.
CMIP: Coupled Model Intercomparison Project
IPCC: the Intergovernmental Panel on Climate Change

DFG Project Collaborating with Dr. Miriam Sinnhuber at KIT

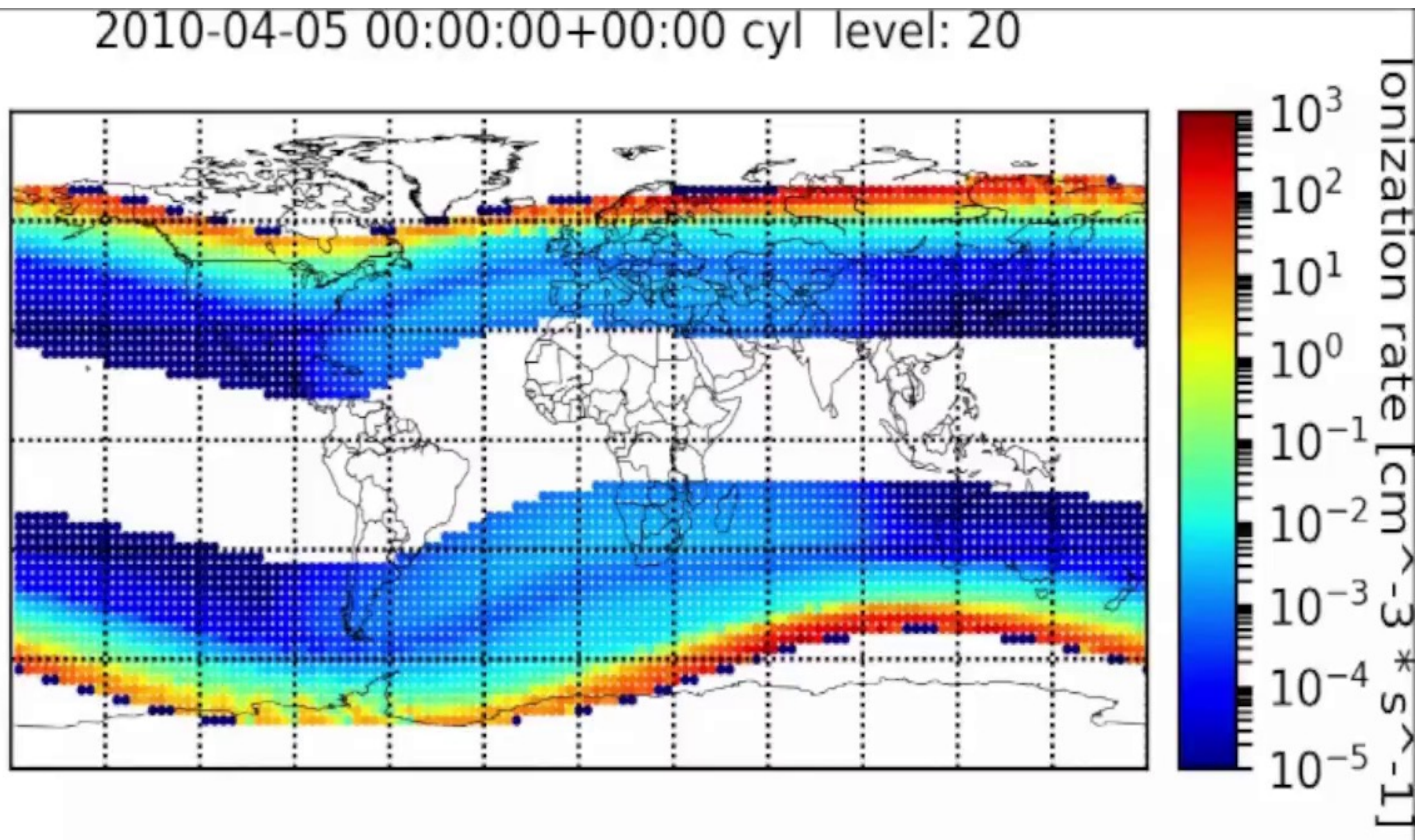
Precipitation of Ring Current Electrons and Their Effect

We are extending our model to ring current and inner radiation belt

Precipitation of ring current electrons



Ionization rates



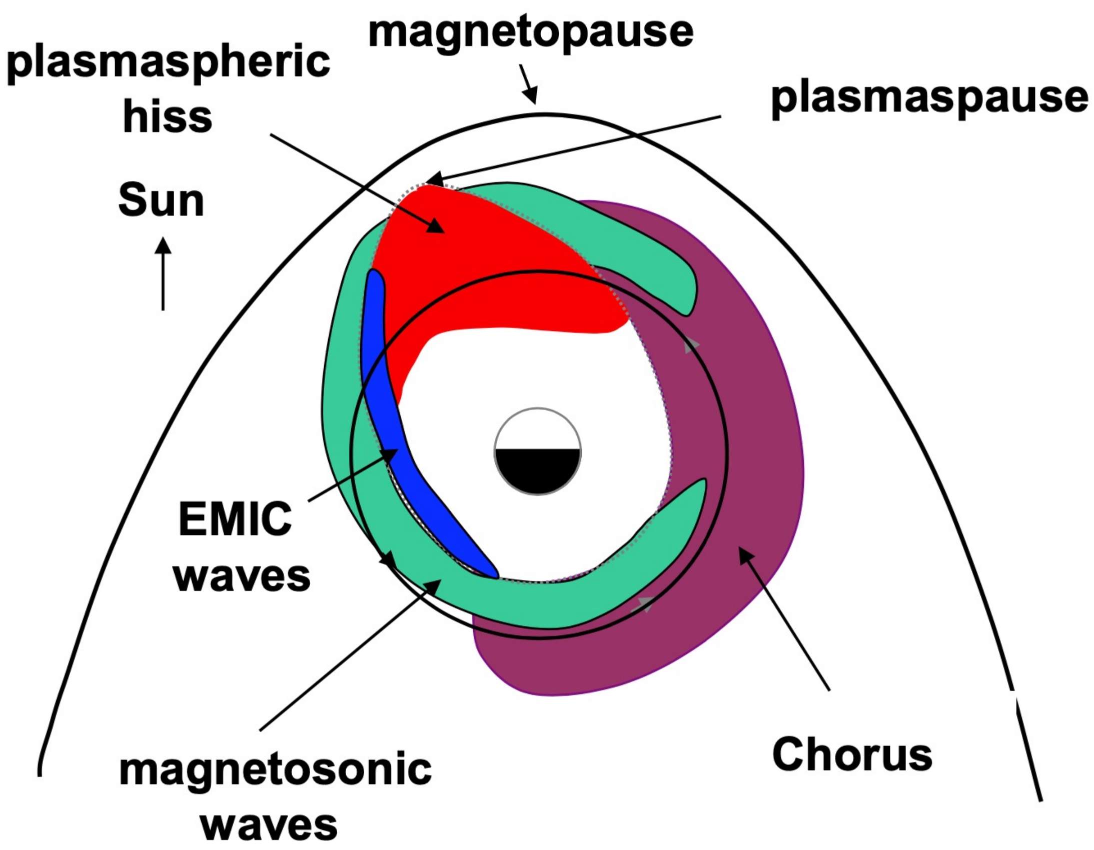
[*Grishina et al*, 2024, ASR]

GFZ Helmholtz Centre Potsdam

Different Important Waves

Zoo of Waves

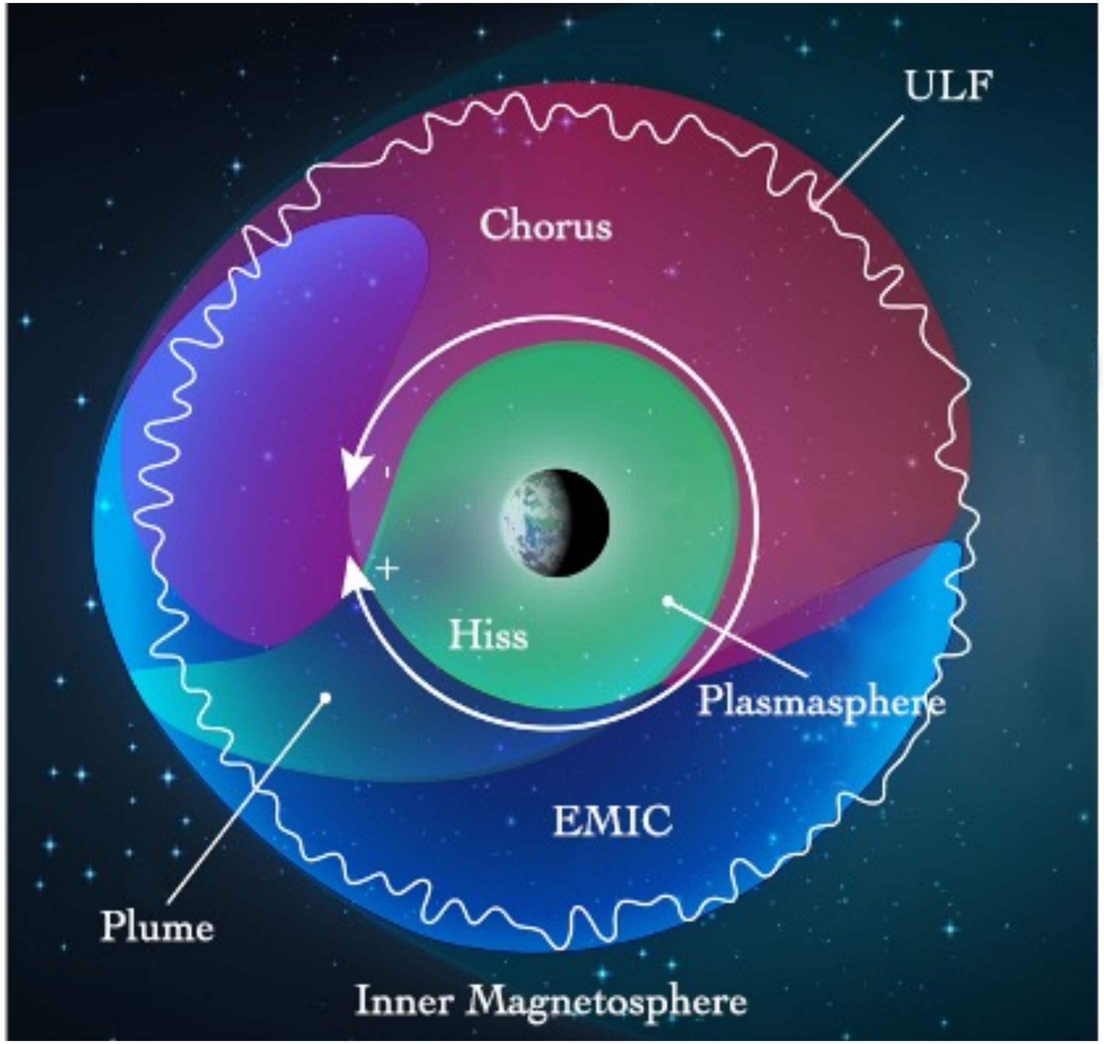
- ***Chorus waves*** are an important acceleration and loss mechanism for radiation belt electrons.
- ***Magnetosonic waves*** may be an important acceleration mechanism.
- ***Plasmaspheric hiss*** is a major loss process for radiation belt electrons
- ***EMIC waves*** may be an important loss mechanism for electrons with energies > ~ 1 MeV



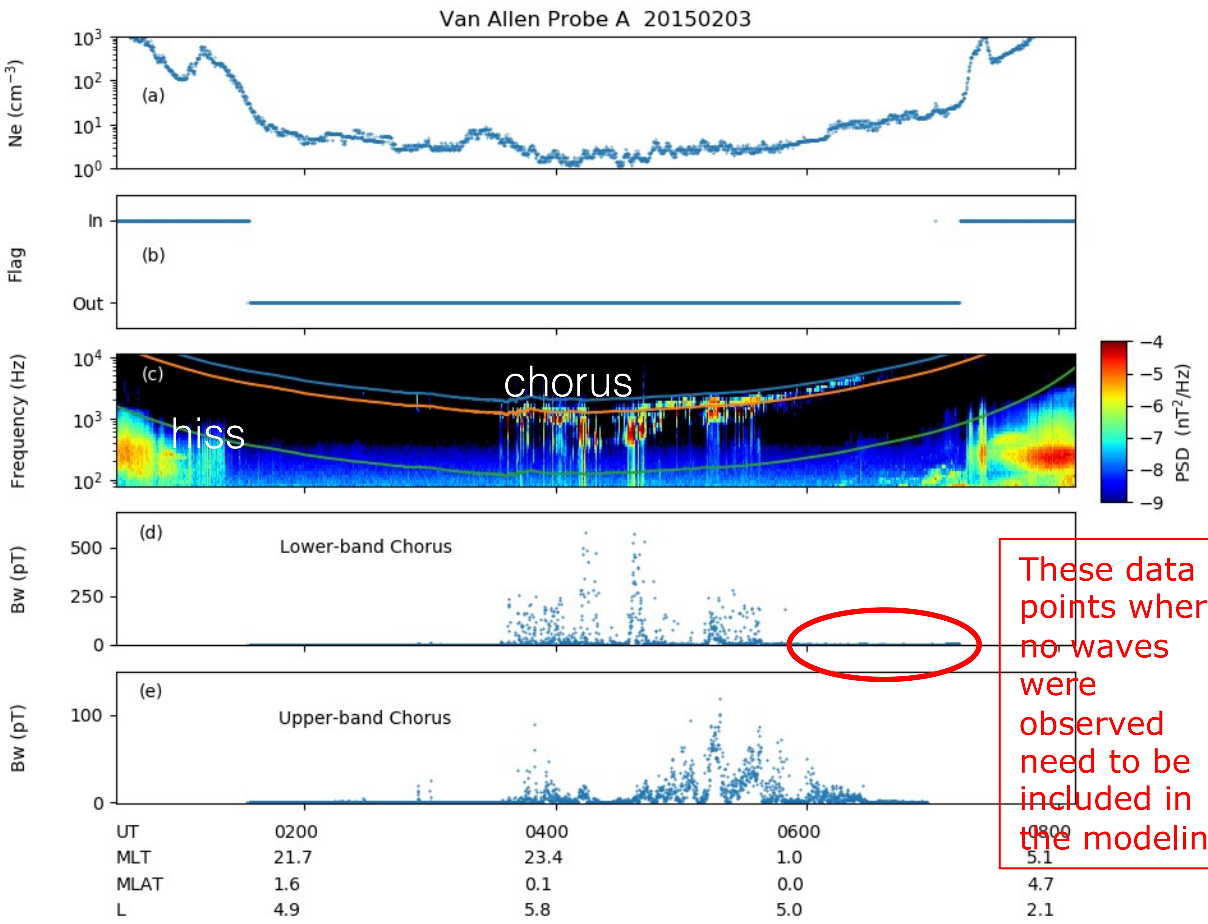
Credit: N. Meredith, BAS

Important Waves in the Earth's Inner Magnetosphere

Chorus, hiss, EMIC, and ultra-low frequency (ULF)



[Courtesy of M. Usanova]



These data points where no waves were observed need to be included in the modeling!

[*Wang et al.*, 2019, JGR]

Our Approach to Understand Wave Particle Interactions

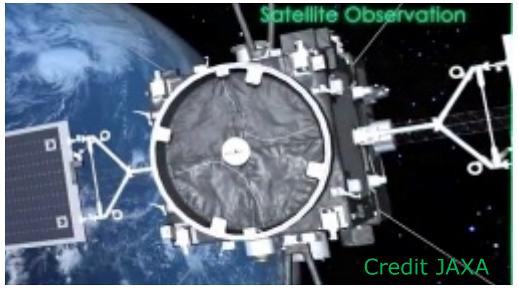
3 steps

Satellite data

Step 1: Global empirical wave models

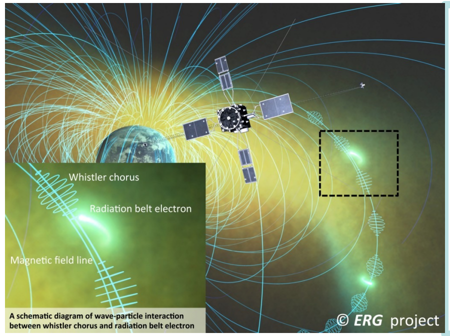
Parameters

Wave observation



Particle observation

Answer: can these processes account for the dramatic dynamics, or do we need to include other processes?



Step 2: How fast are the acceleration and loss caused by waves?

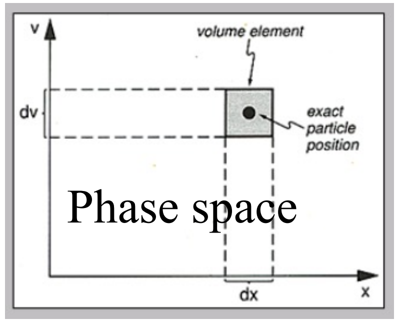
Coefficients

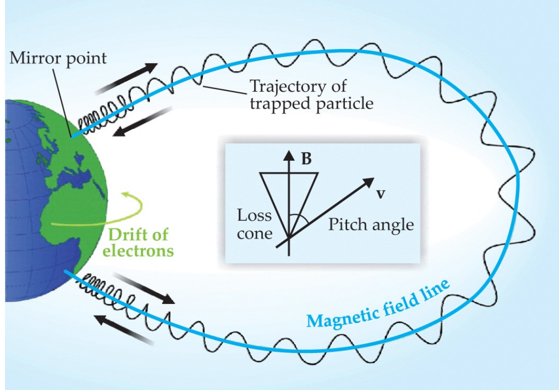
Step 3: Numerical Simulations

Simulation results

Three dimensional Fokker Planck Equation

Used in the three dimensional Versatile Electron Radiation Belt Code





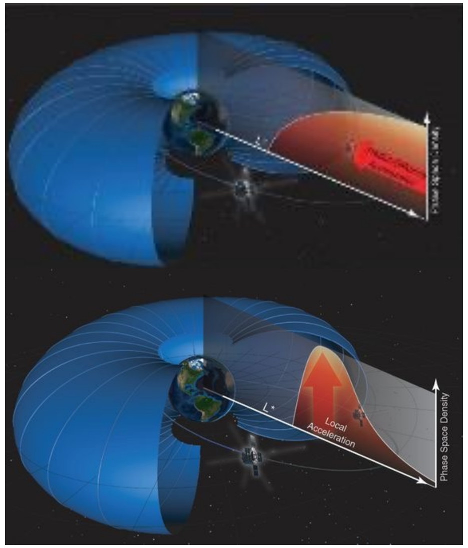
approximate L^*

L^* is the distance in Earth radii at which a magnetic field line crosses the magnetic equatorial plane

Radial Diffusion

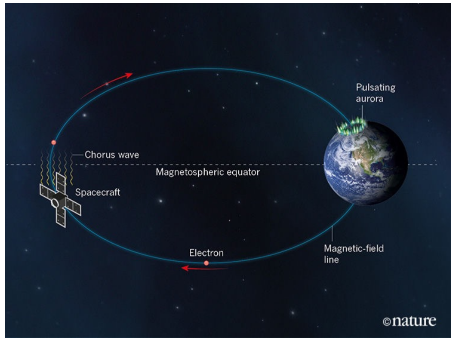
$$\frac{\partial f}{\partial t} = L^{*2}\frac{\partial}{\partial L^*}\bigg|_{J_1,J_2}\frac{1}{L^{*2}}D_{L^*L^*}\frac{\partial f}{\partial L^*}\bigg|_{J_1,J_2} + \frac{1}{p^2}\frac{\partial}{\partial p}\bigg|_{L,\alpha_0} p^2\left(D_{pp}\frac{\partial f}{\partial p}\bigg|_{L,\alpha_0} + D_{p\alpha_0}\frac{\partial f}{\partial \alpha_0}\bigg|_{L,p}\right) + \frac{1}{T(\alpha_0)\sin(2\alpha_0)}\frac{\partial}{\partial \alpha_0}\bigg|_{L,p} T(\alpha_0)\sin(2\alpha_0)\left(D_{\alpha_0 p}\frac{\partial f}{\partial p}\bigg|_{L,\alpha_0} + D_{\alpha_0\alpha_0}\frac{\partial f}{\partial \alpha_0}\bigg|_{L,p}\right) + Sources - Losses$$

Energy Diffusion Results in the local ACCELERATION



[Reeves et al., 2013, Science]

[e.g., Haerendel, G. 1968; Schulz and Lanzerotti., 1974; Shprits et al., 2008]



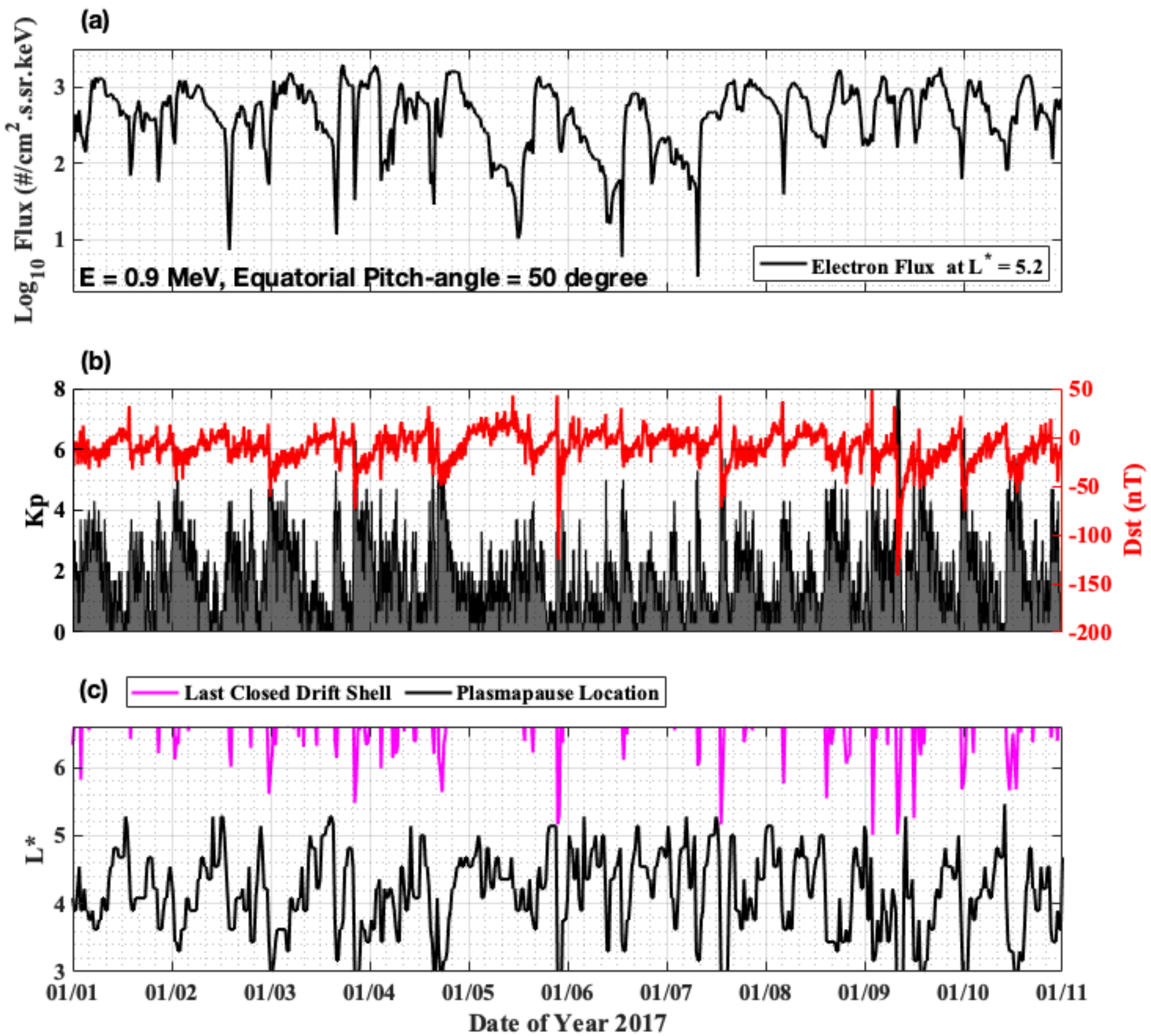
Pitch Angle Diffusion Results in the LOSS INTO THE ATMOSPHERE

[Kasahara et al., 2018, Nature]

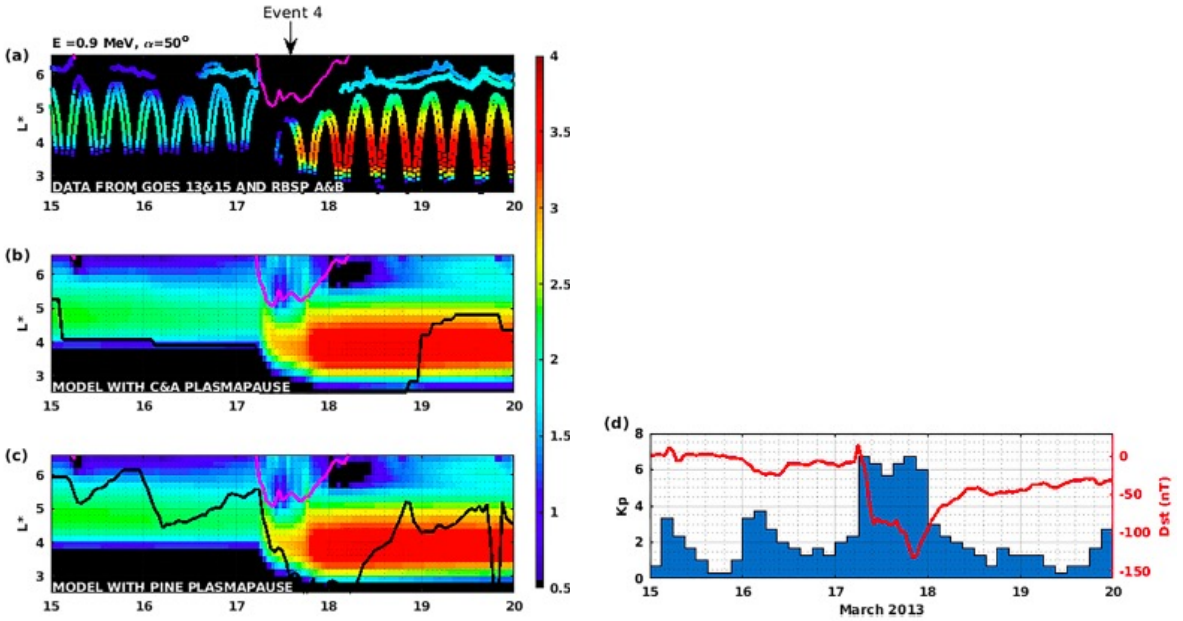
To calculate diffusion coefficients, we need to know the global distribution of waves!

Loss of Energetic Electrons in the Earth's Outer Radiation Belts

What are the mechanisms driving these losses?



- ➢ Adiabatic change
- ➢ Magnetopause shadowing
- ➢ Wave-particle interactions



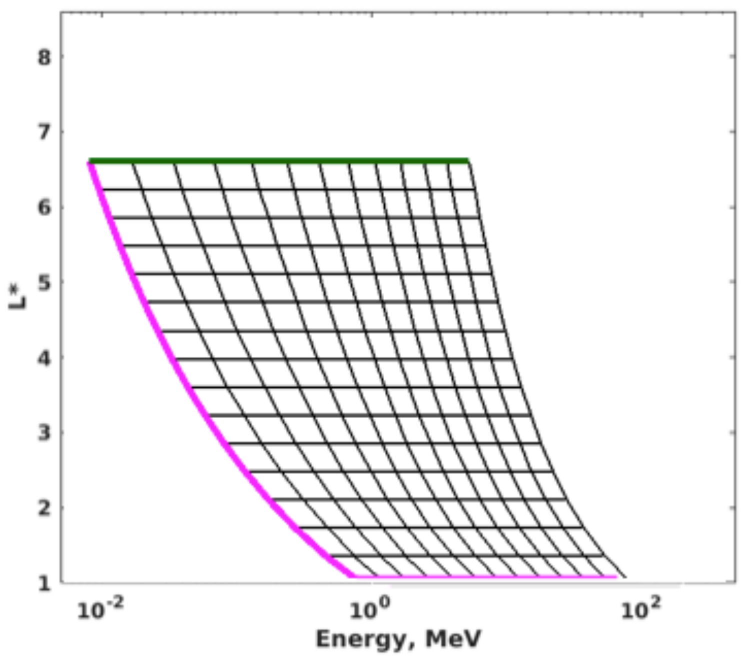
[*Wang et al*, 2020, JGR]

The Boundary Condition Setup of VERB-3D Simulations

No data from Van Allen Probes is used in the boundary conditions to drive the simulation.
We validate our results against observations from Van Allen Probe and GOES measurements.

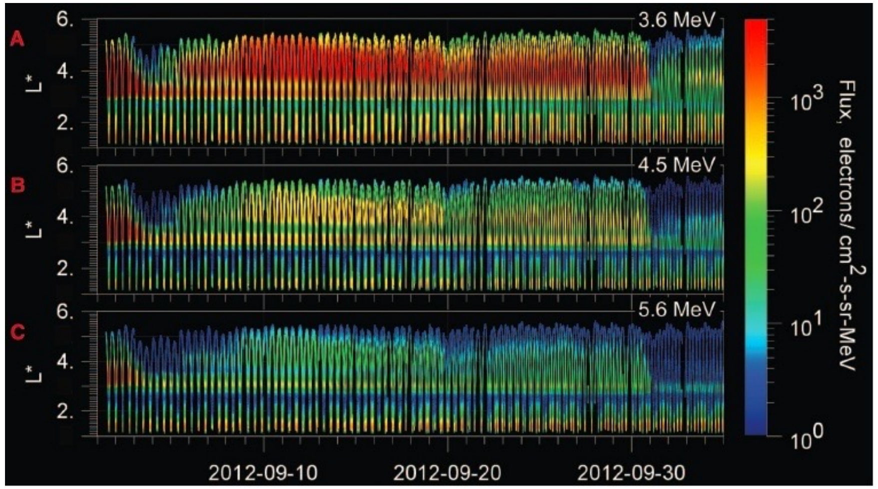
Boundary	Condition	Physics
$\alpha = 0.7^{\circ}$	$\partial f / \partial \alpha = 0$	Strong diffusion regime
$\alpha = 89.3^{\circ}$	$\partial f / \partial \alpha = 0$	Flat-top distribution
$E_{min} = 10\ \mathrm{keV}$	$\partial f / \partial t = 0$	Balance convection and loss
$E_{max} = 10\ MeV$	$f = 0$	Absence of such electrons
$L^{*} = 1$	$f = 0$	Losses to the Atmosphere
$L^{*} = 6.6$	Scaling	Using GOES Measurements

Simulation Grids in L* and Energy

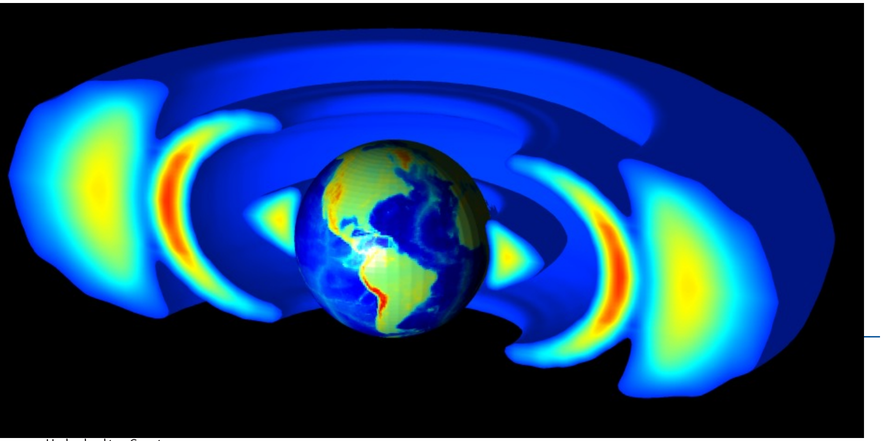


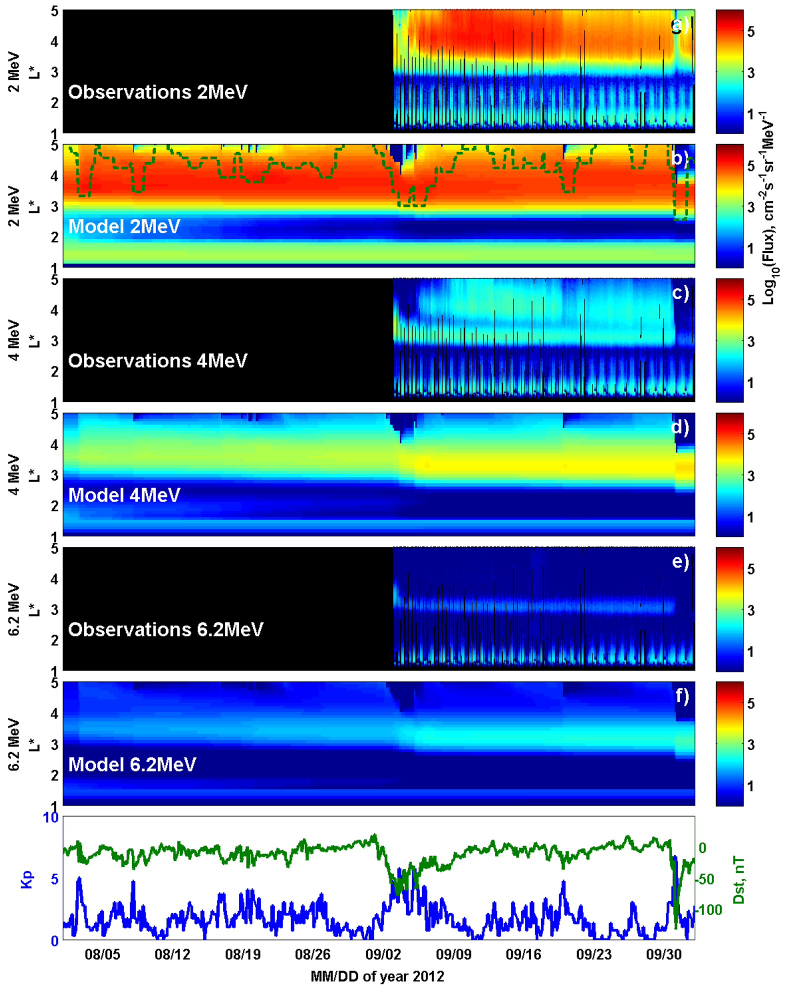
Magnetopause shadowing are included in the simulation using **Last Closed Drift Shell (using IRBEM)**.
Diffusion coefficients are based on our most recent wave models (Wang et al., 2019; Orlova et al., 2016; Abel and Thorne, 1998)

Simulations of Loss to MP and 3 Diffusive Processes



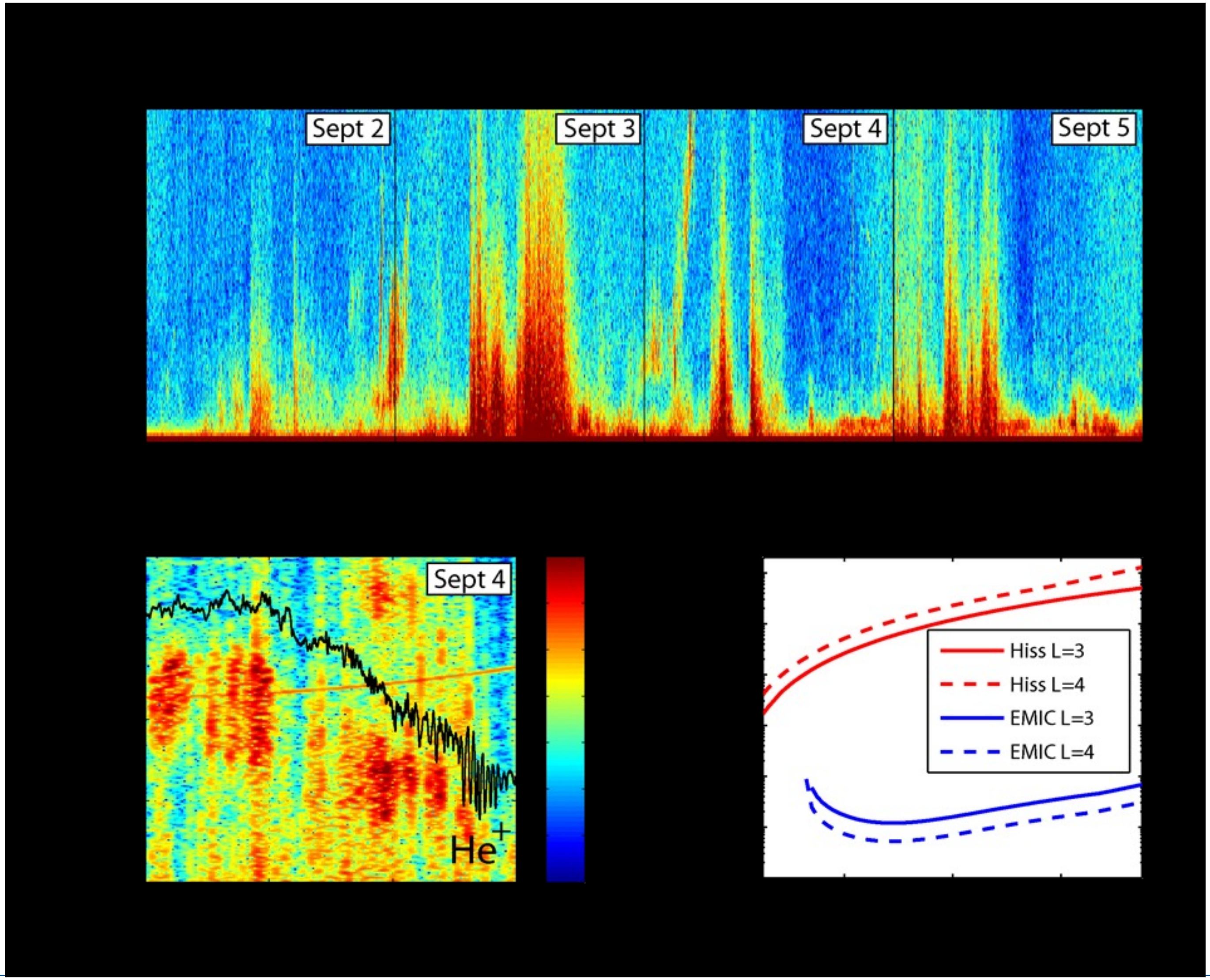
Baker et al., 2013 *Science*





- Magnetopause loss that can explain for the loss of particles at relativistic energies cannot explain losses at ultra-relativistic energies.
- Narrow belt at 6.2 MeV can not be explained by the model.
- Additional loss is required to produce a narrow ring of radiation observed by Baker et al. (2012).

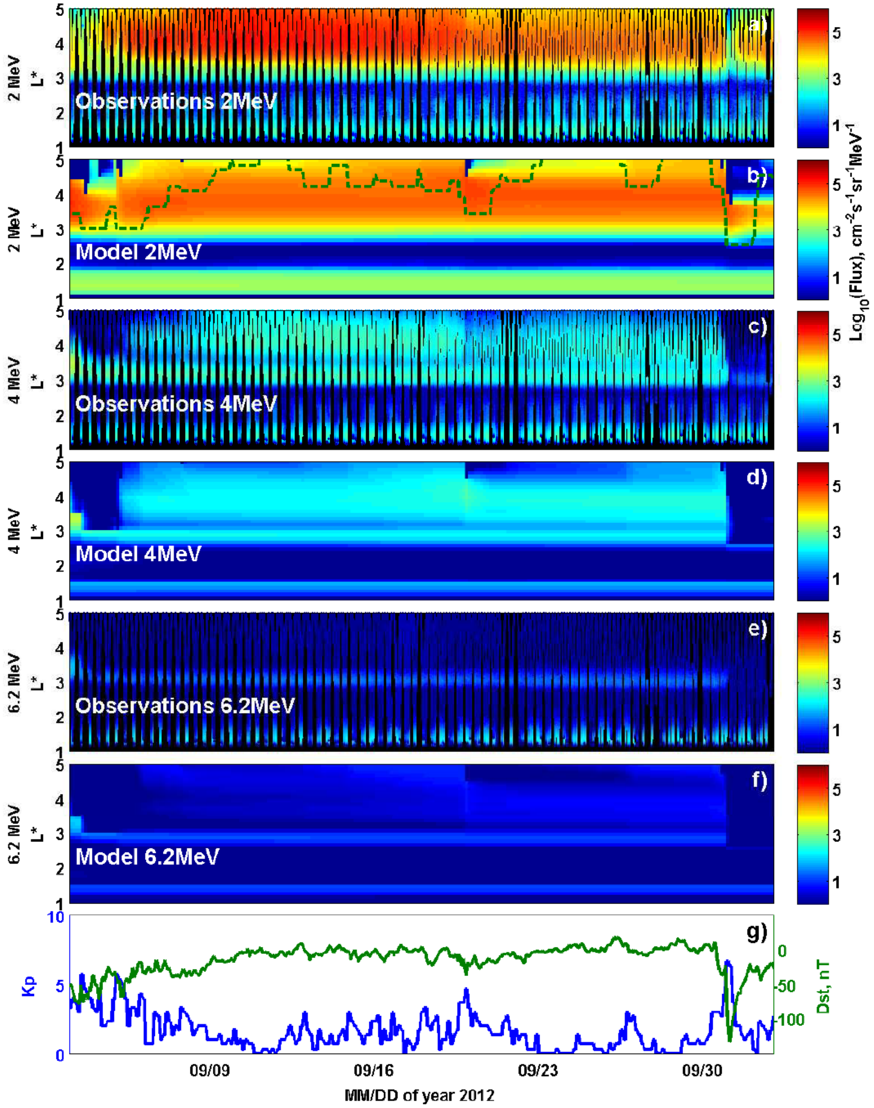
EMIC Wave Observations



- ElectroMagnetic Ion Cyclotron (EMIC) waves are observed on the ground during the main phase of the storms.
- *In situ* observations of waves

[Shprits et al., 2013 *Nature Physics*]

Difference in Behavior of Ultra-relativistic and Relativistic Electron Fluxes



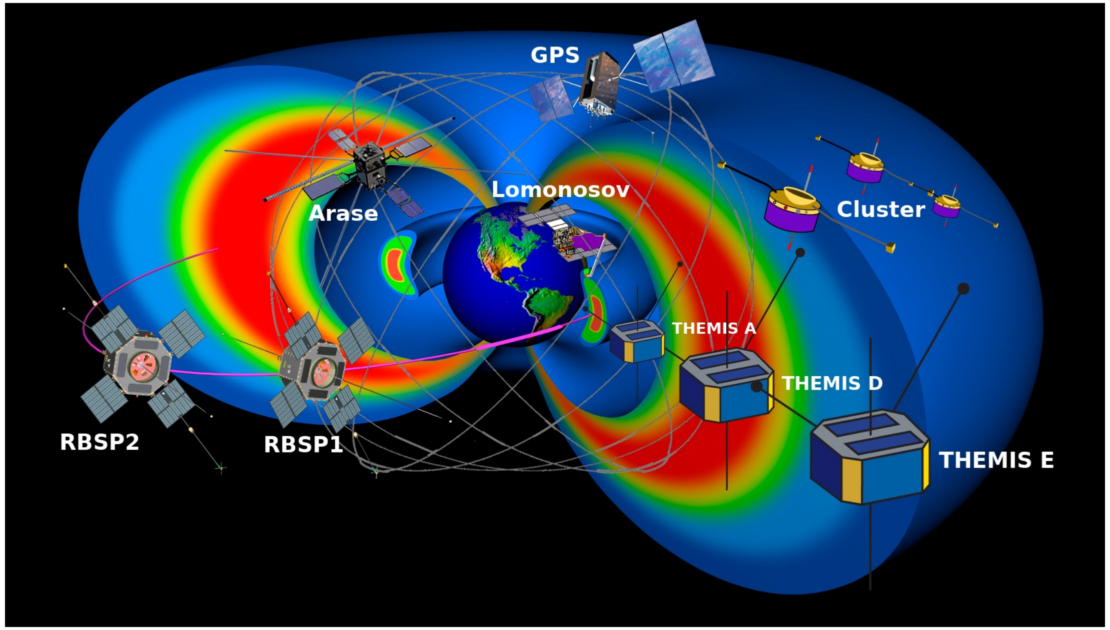
- Simulations with EMIC wave scattering can reproduce unusual behavior of the radiation belts.
- Simulations with EMIC scattering reproduces 3 zone structure at 4MeV and a very narrow remnant belt at 6.2 MeV.
- Simulations without EMIC waves can not reproduce such narrow remnant belts.

•[Shprits et al., 2013, *Nature Physics*]

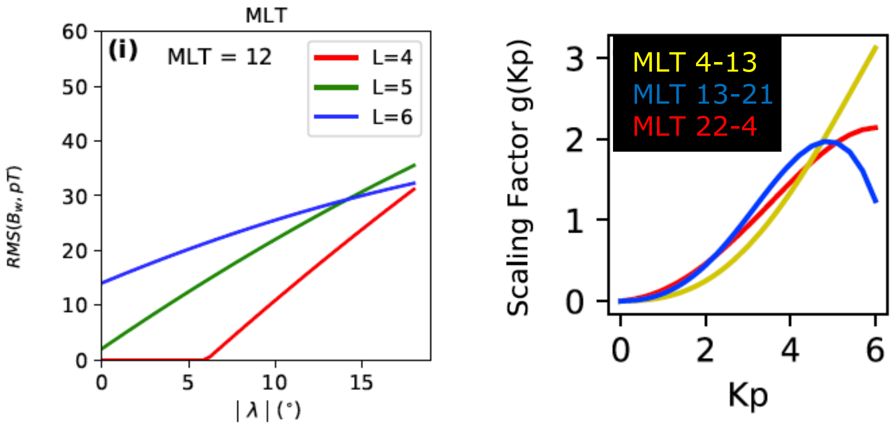
HELMHOLTZ

Global Distribution of Chorus Waves

Using Satellite Data to Develop Empirical Models for Waves

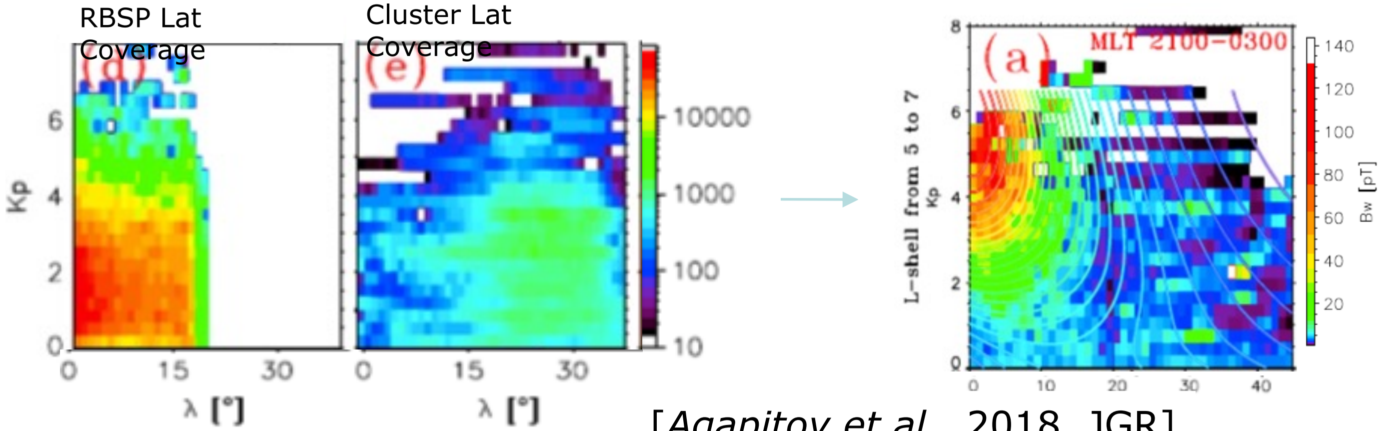


5 years of RBSP data → Analytical chorus wave model



[*Wang et al.*, 2019]

$$\sqrt{\langle B_w^2(\mathrm{MLT}, L, |\lambda|, \mathrm{Kp})\rangle} = f(\mathrm{MLT}, L, |\lambda|)g(\mathrm{Kp})$$

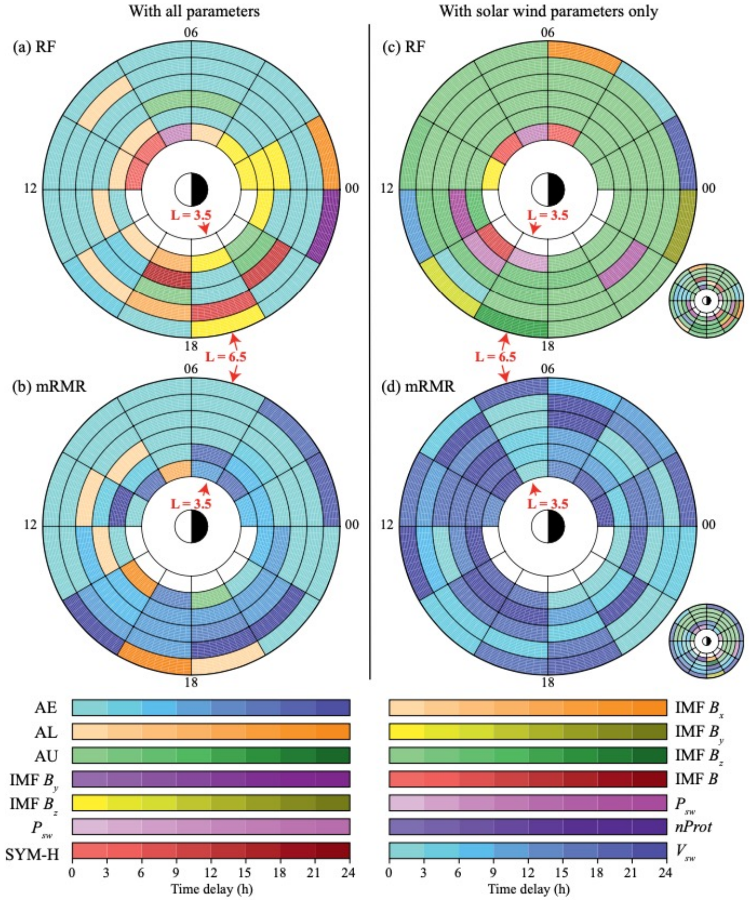


[*Agapitov et al.*, 2018, JGR]

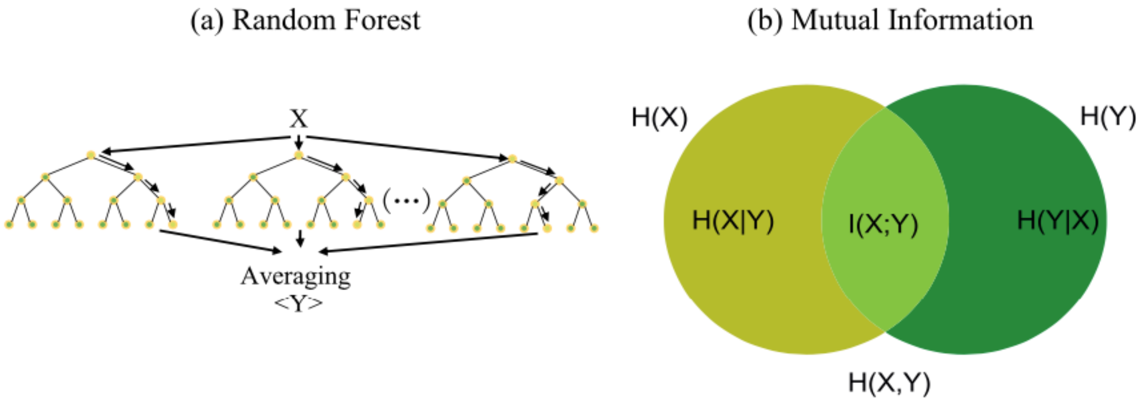
Careful inter-calibration between measurements from different satellites is needed!

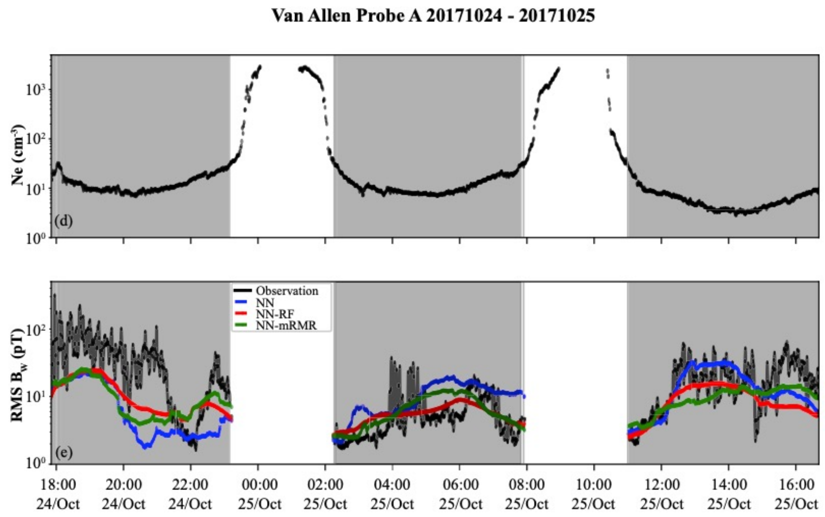
Machine Learning in Wave Model Development

Find which parameters are most important



[*Guo et al*, 2021, JGR]





A set of important features are automatically determined by feature selection techniques, namely, Random Forest and Maximum Relevancy Minimum Redundancy.

Using the combination of all these important features, a predictive neural network model of chorus wave intensity is established to reconstruct the temporal variations of chorus wave intensity.

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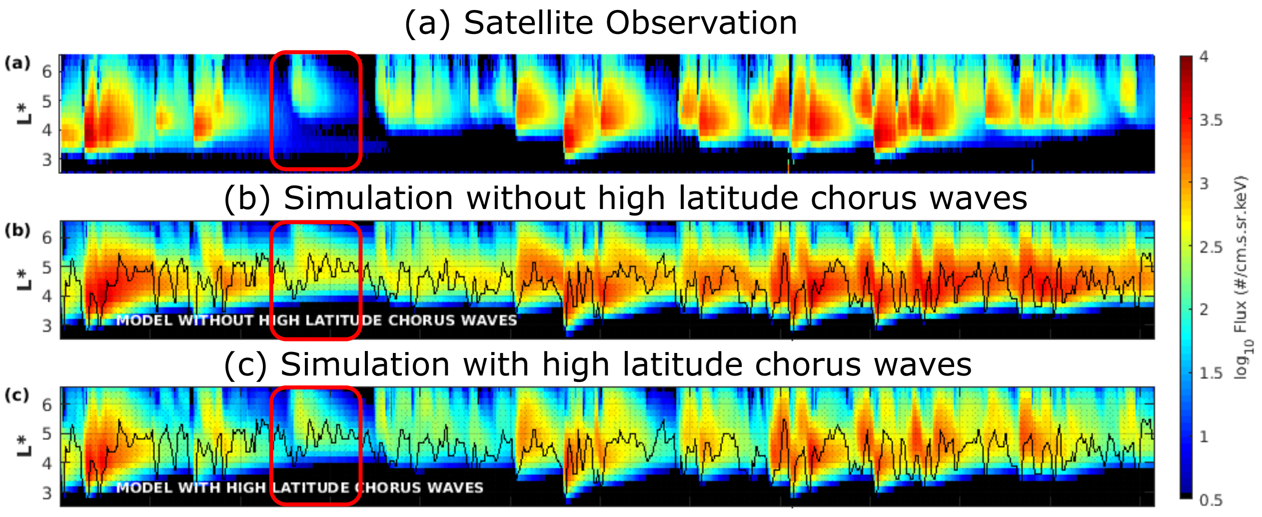
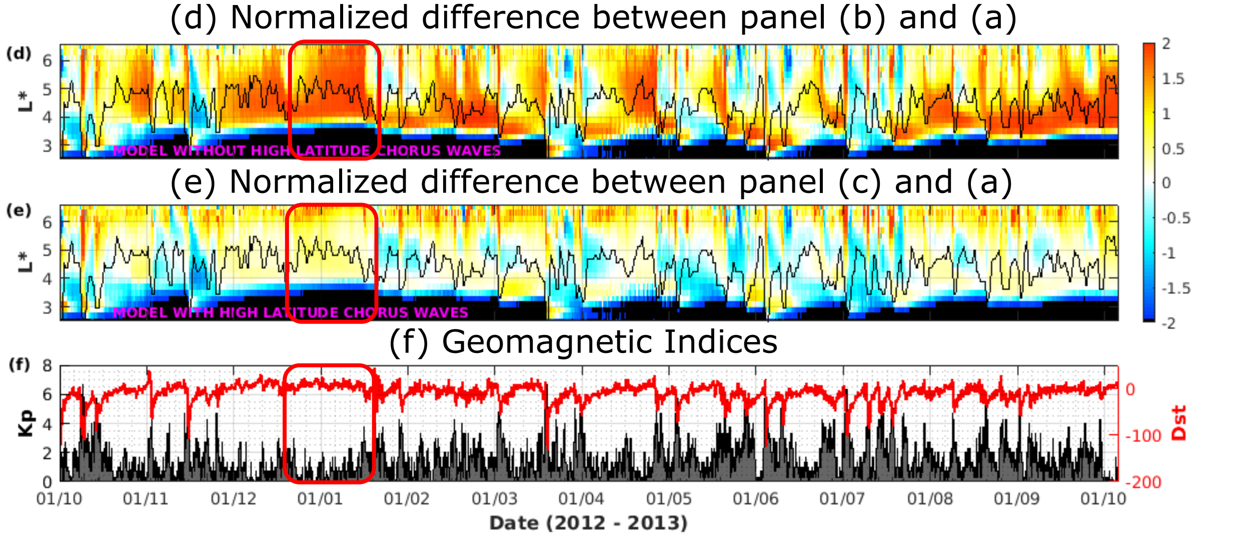
Importance of Waves at High Latitude

Using Chorus Wave Models Based on Van Allen Probe and Cluster Observations



$$ND_{max}(L^*,t) = \frac{J_S(L^*,t) - J_O(L^*,t)}{\max|_{\text{over } L^* \text{ every 8 hours}} \frac{J_S(L^*,t)+J_O(L^*,t)}{2}}$$

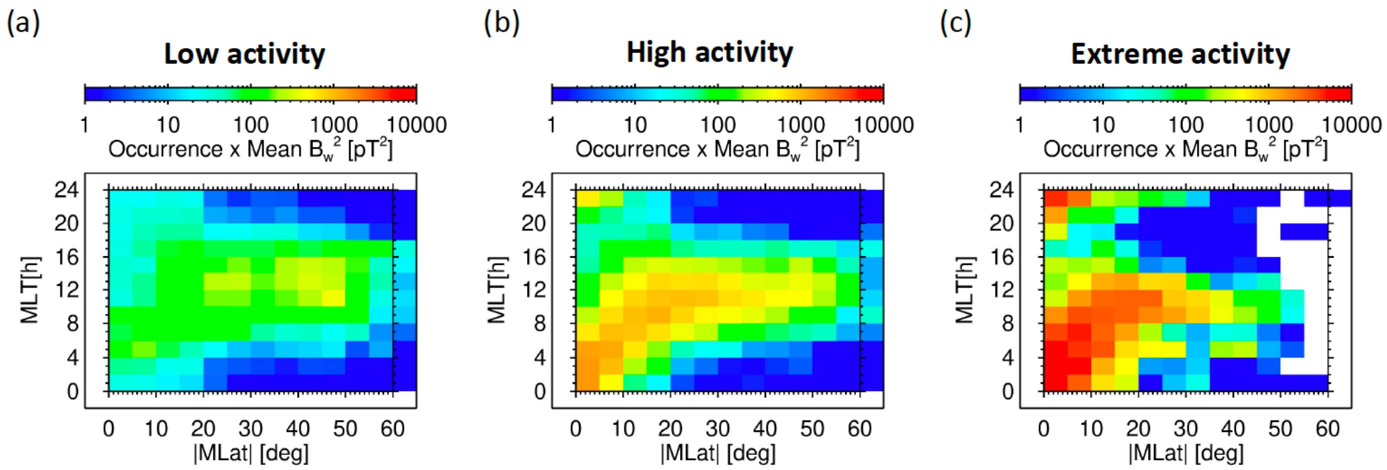


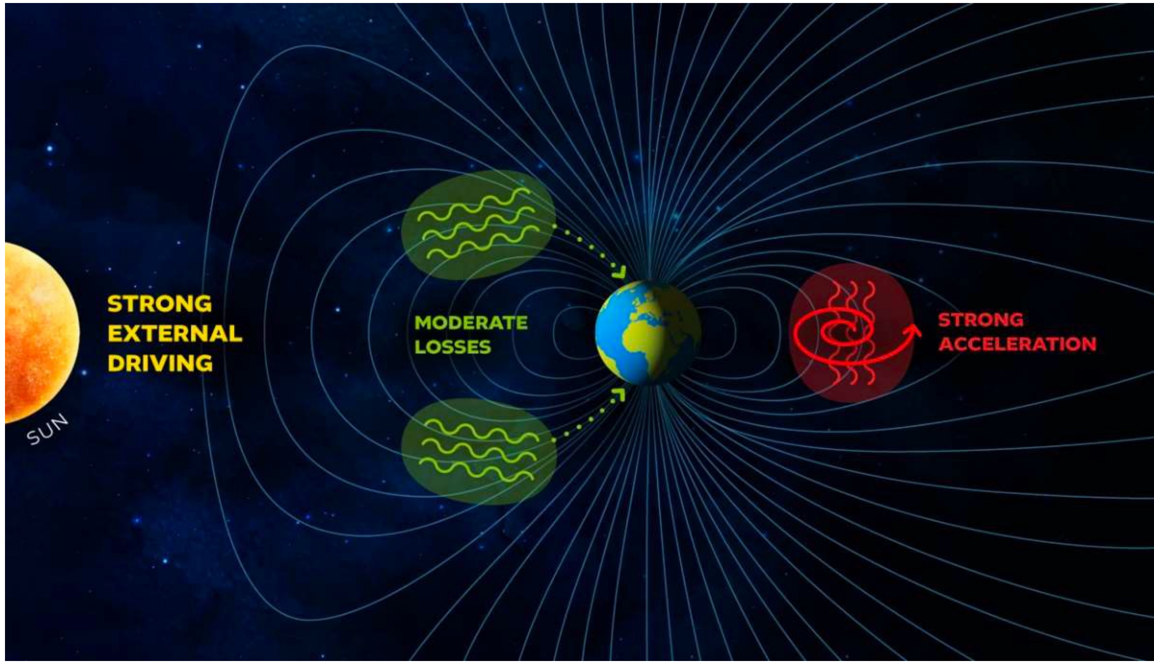
[*Wang and Shprits*, 2019, GRL]

- Chorus waves at high latitude can tip the balance between the effect of acceleration and loss on MeV electrons.
- During storm times, the net effect of chorus waves on MeV electrons can be acceleration.
- However, during quiet times, when chorus waves can propagate to high latitude, their net effect on MeV electrons can be loss.

Assumption Proved by Recent Study

Combining 6 years of Van Allen Probe data and 20 years of Cluster data





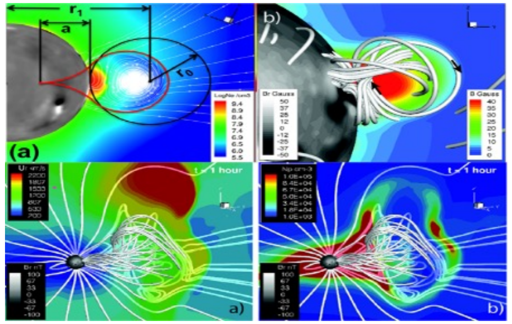
[*Santolik, Shprits.. Wang et al*, AGU Advances, in revision]

Prediction of Adverse effects of Geomagnetic storms and Energetic Radiation (PAGER) – EU Horizon 2020

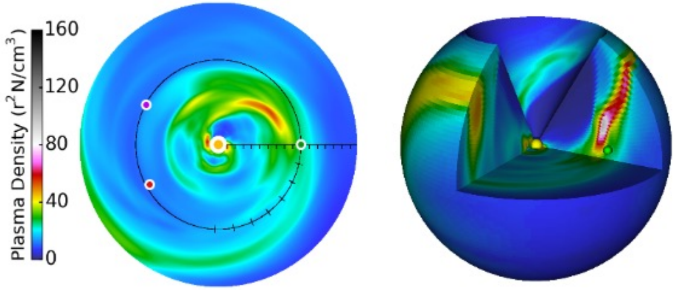
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 870452

Ensemble forecast from the Sun will allow a long-term probabilistic prediction.

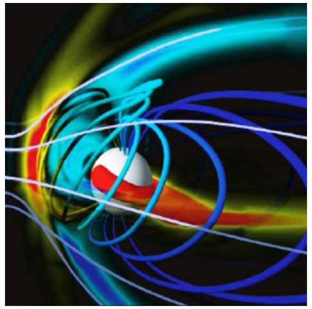
Predictions at 20 R☼

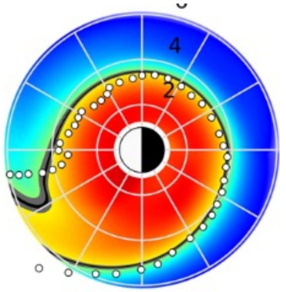


Ensemble predictions of the heliosphere

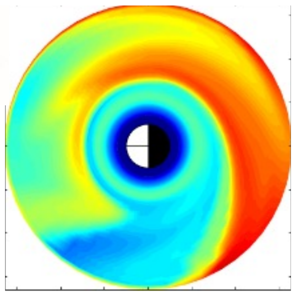


Global modelling of the magnetosphere dynamics

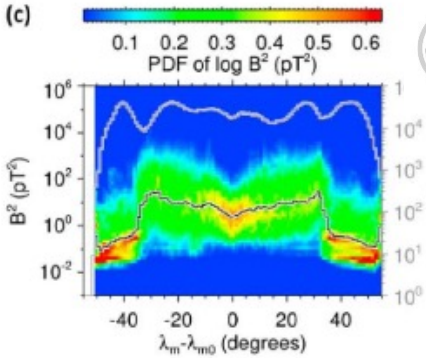




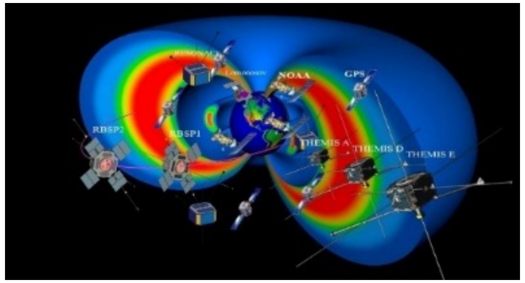
Ensemble predictions of the Plasmasphere and Kp



Ensemble predictions of the Ring Current

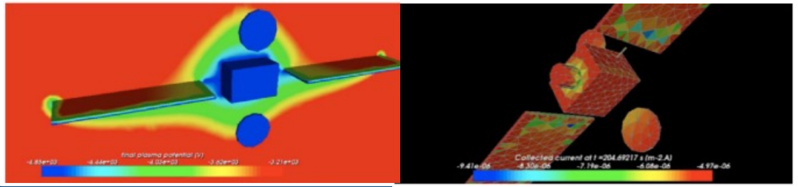


Statistical models of waves from multiple spacecraft



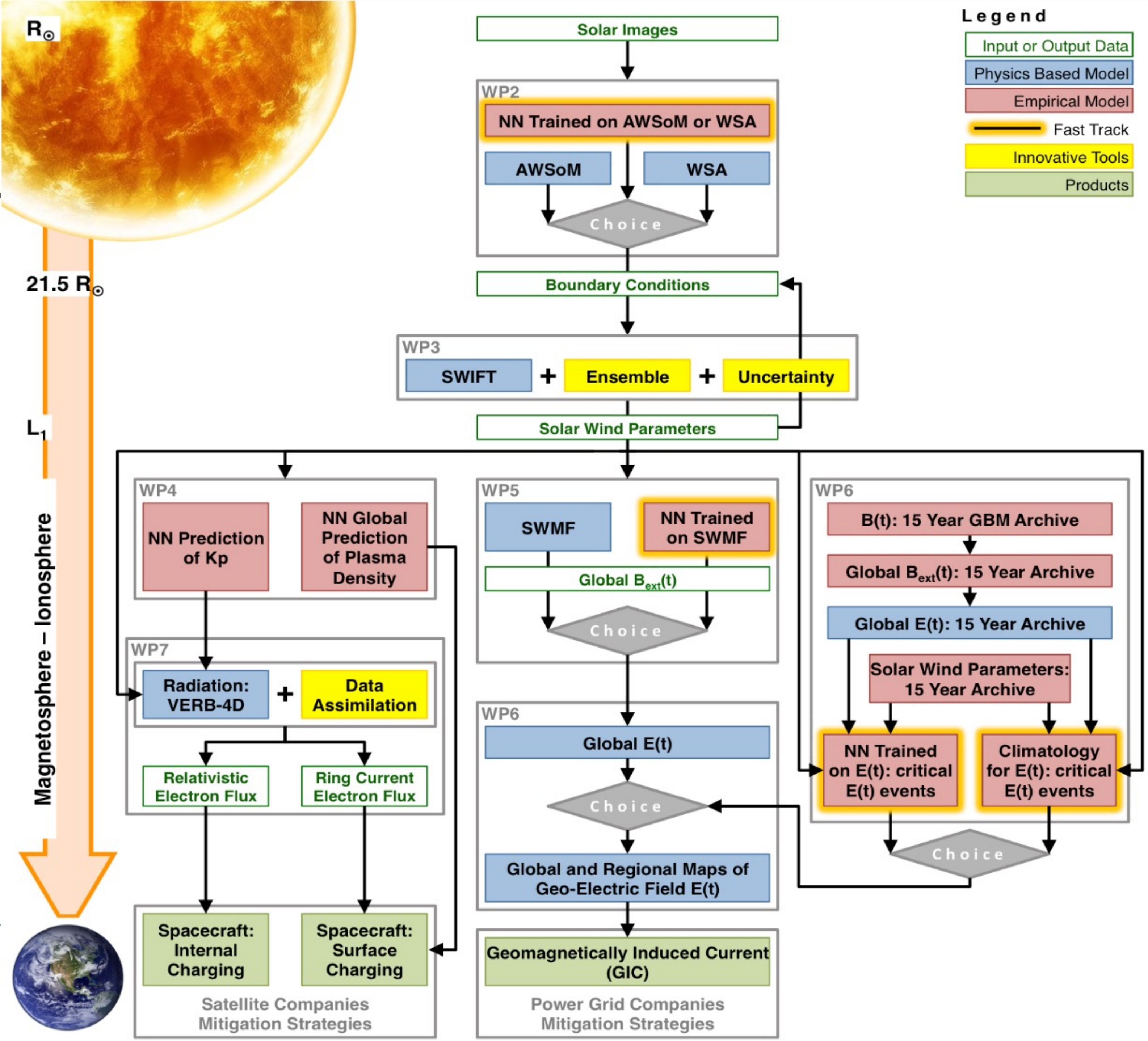
Ensemble predictions of the Radiation Belts

3D engineering analysis of spacecraft charging



Various Space Weather applications (e.g. GIC, TEC, Kp prediction, etc.)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 870452



PAGER

Prediction of Adverse effects of Geomagnetically-induced currents and Energetic Radiation

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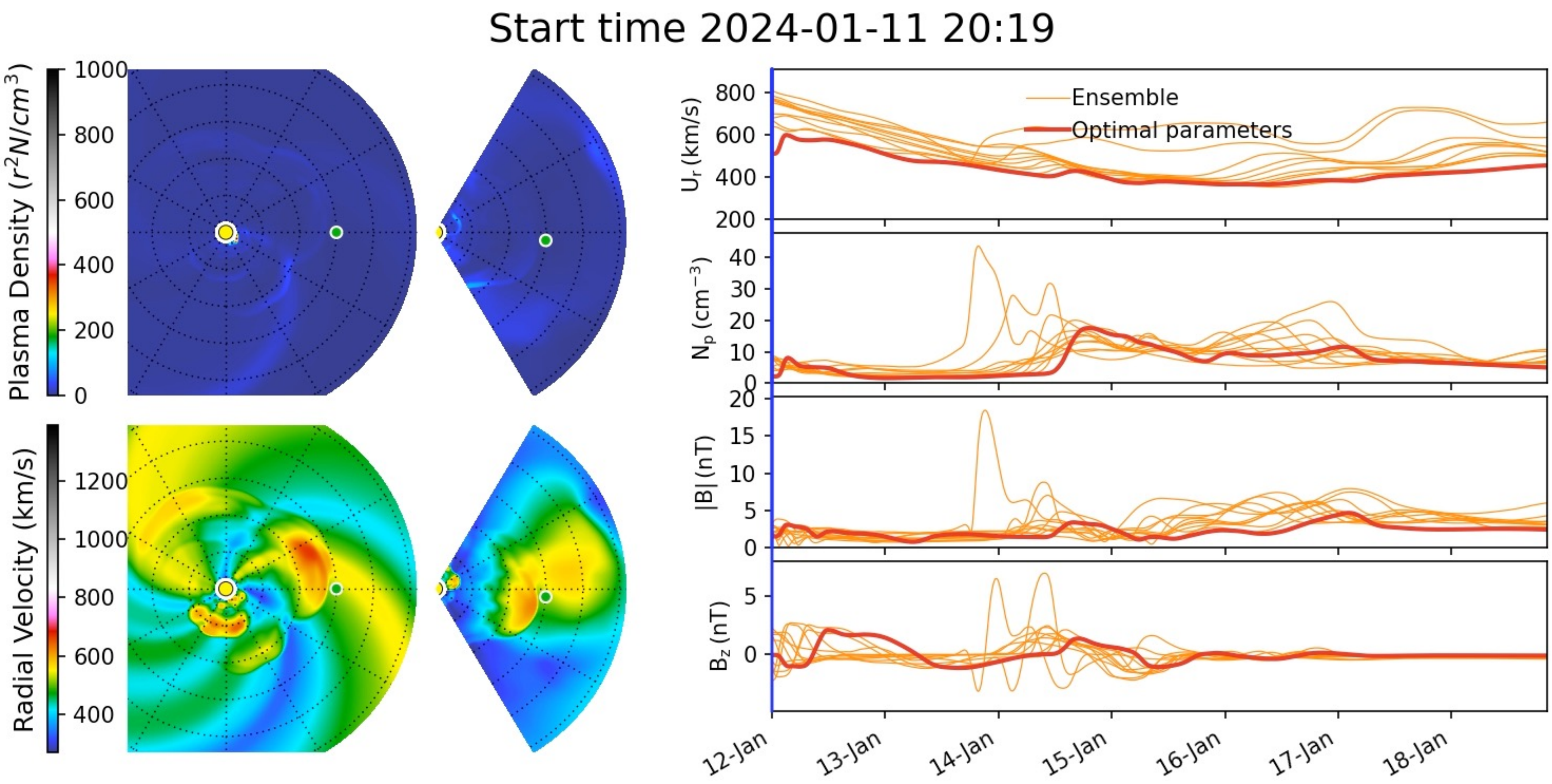
Data Products of the PAGER Project

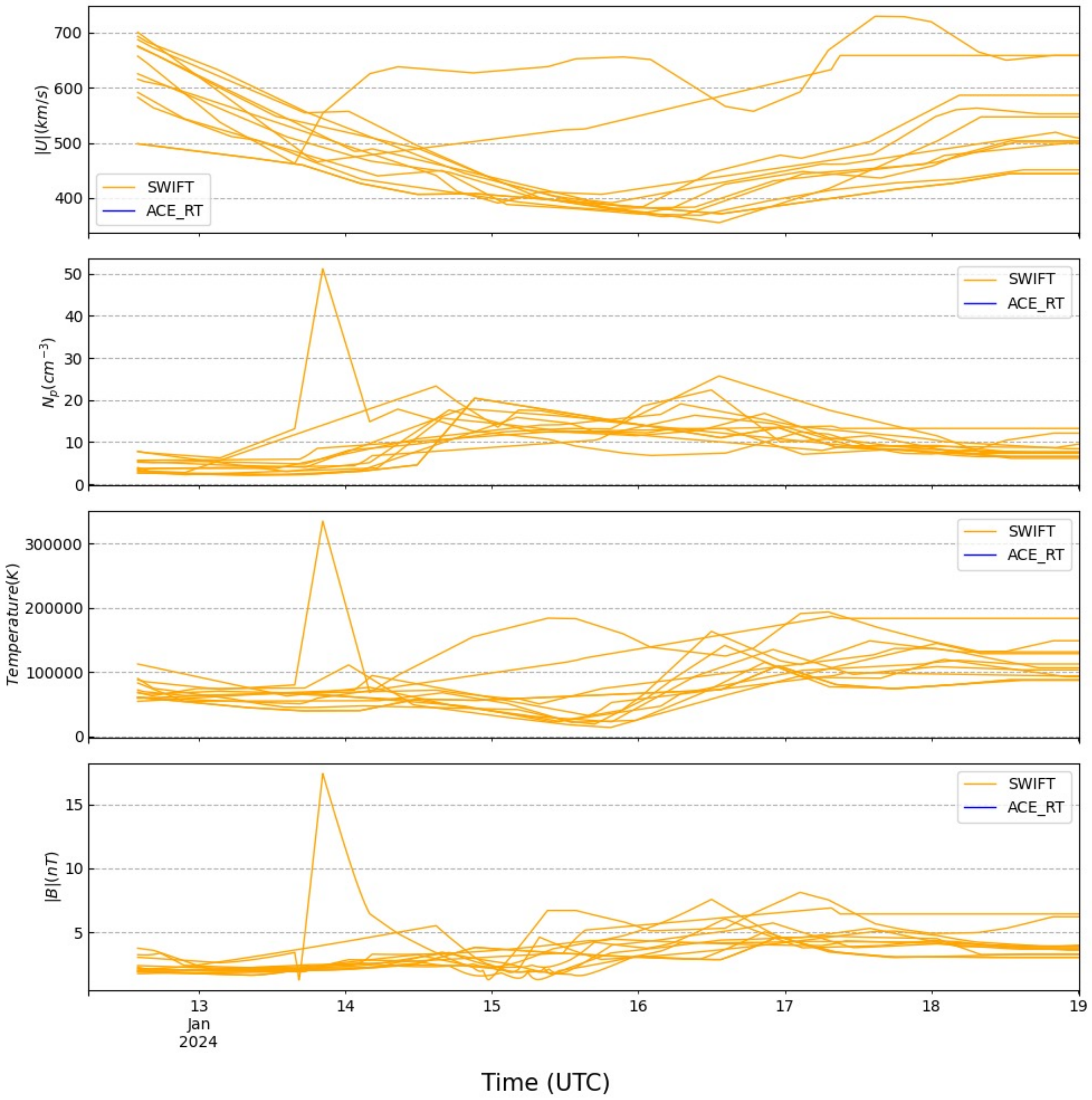
Ensemble Solar Wind Forecast using real-time CME Alerts

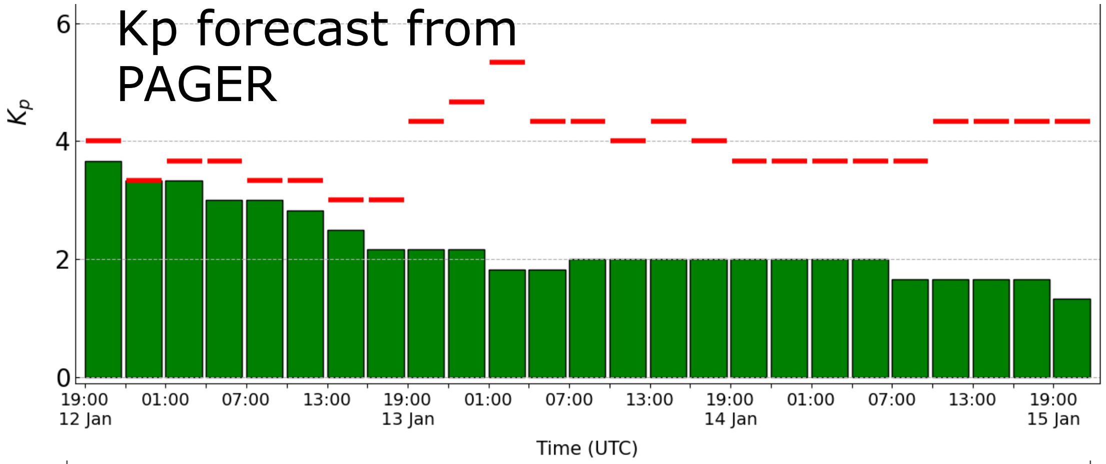


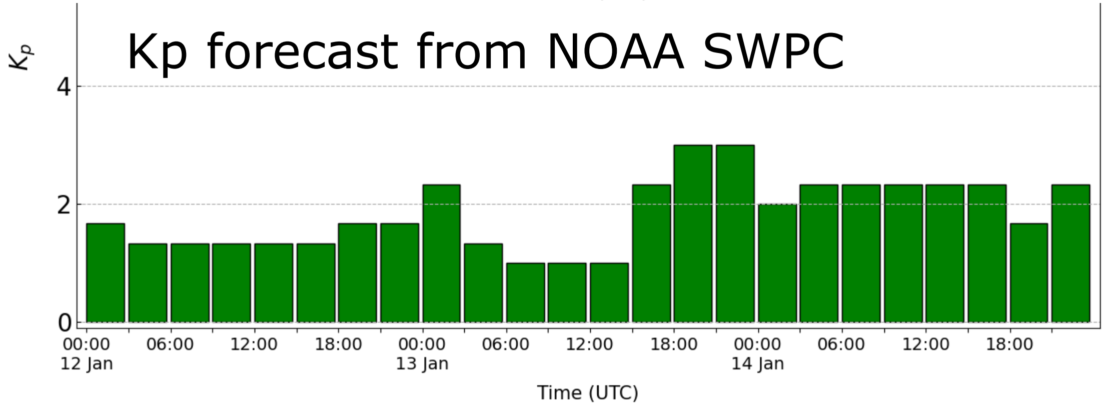
https://www.spacepager.eu/data-products/

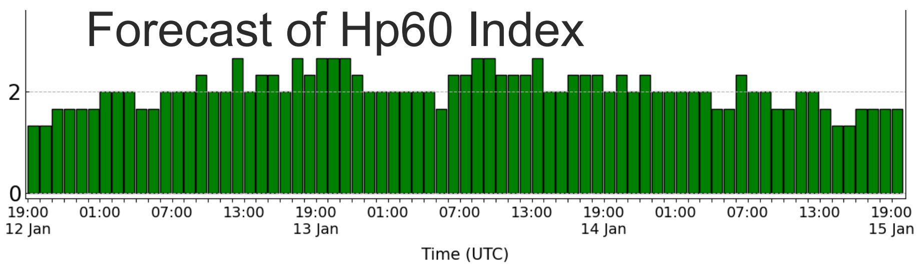
Ensemble Prediction of the Solar Wind with Bias Correction

Ensemble Kp forecast based on PAGER ensemble solar wind predictions









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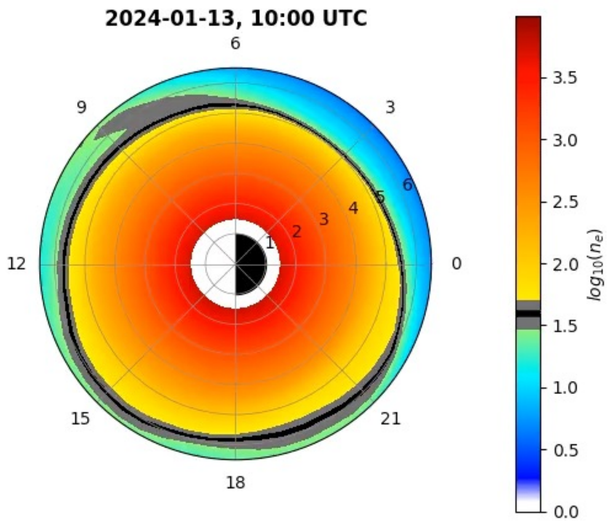
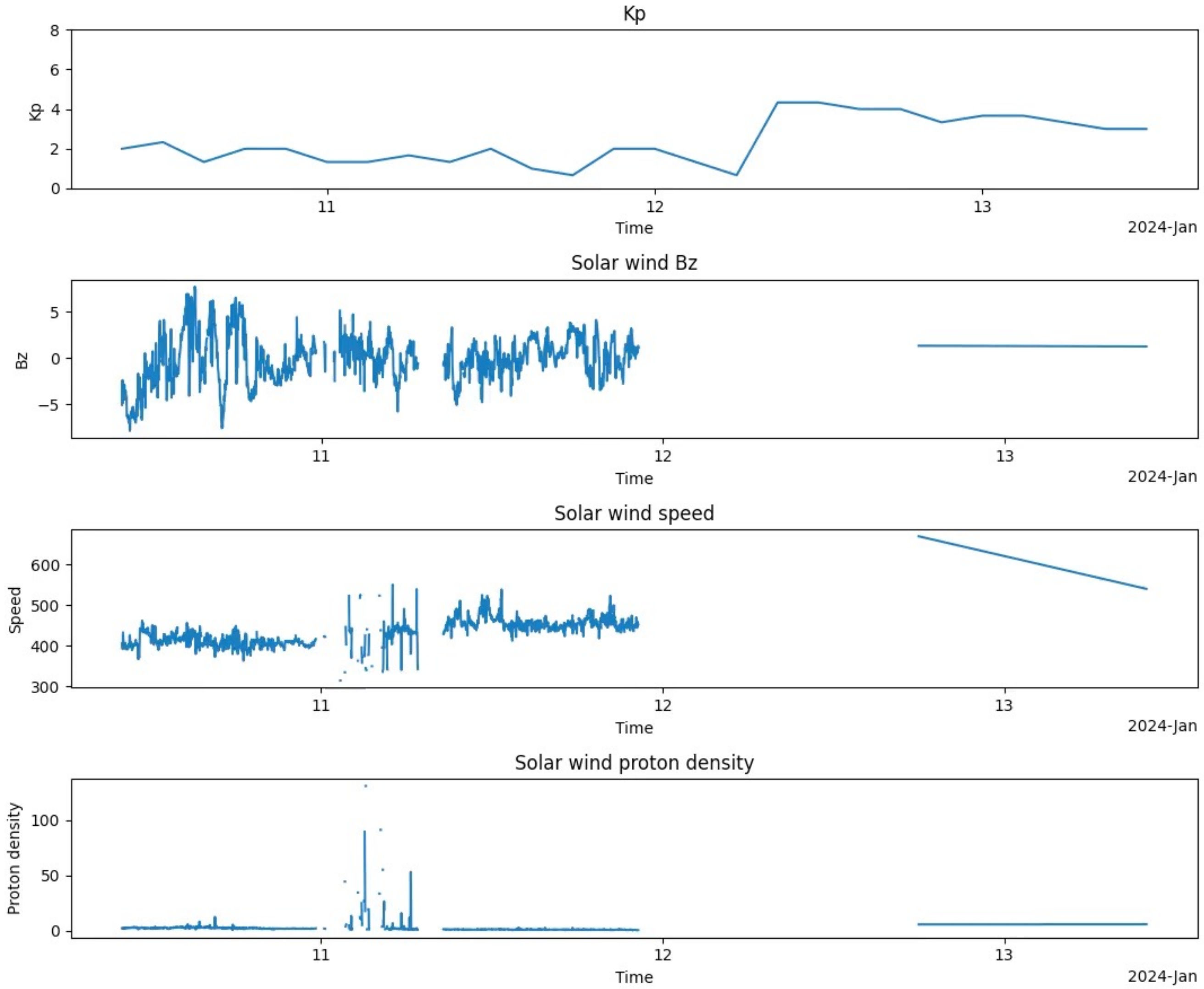
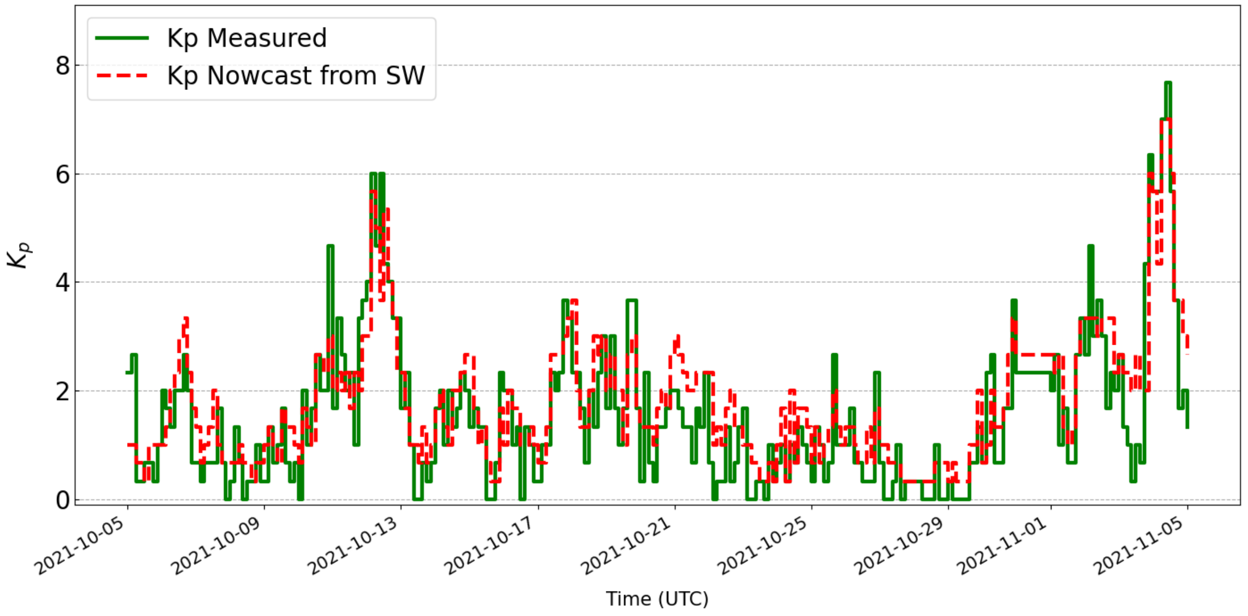
Data Products of the PAGER Project

Forecast of the Plasma Density in the Plasmasphere

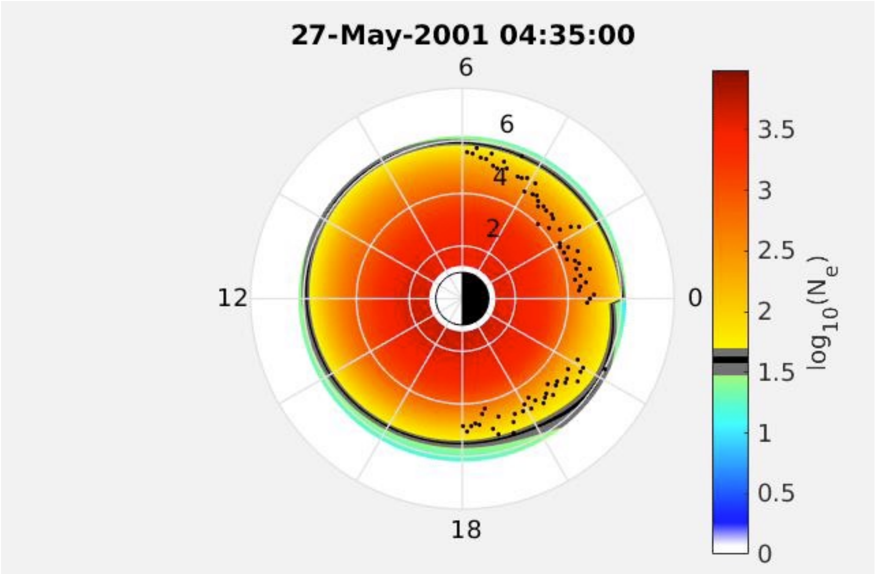




Machine Learning Model of Kp and Plasma Density



Example output



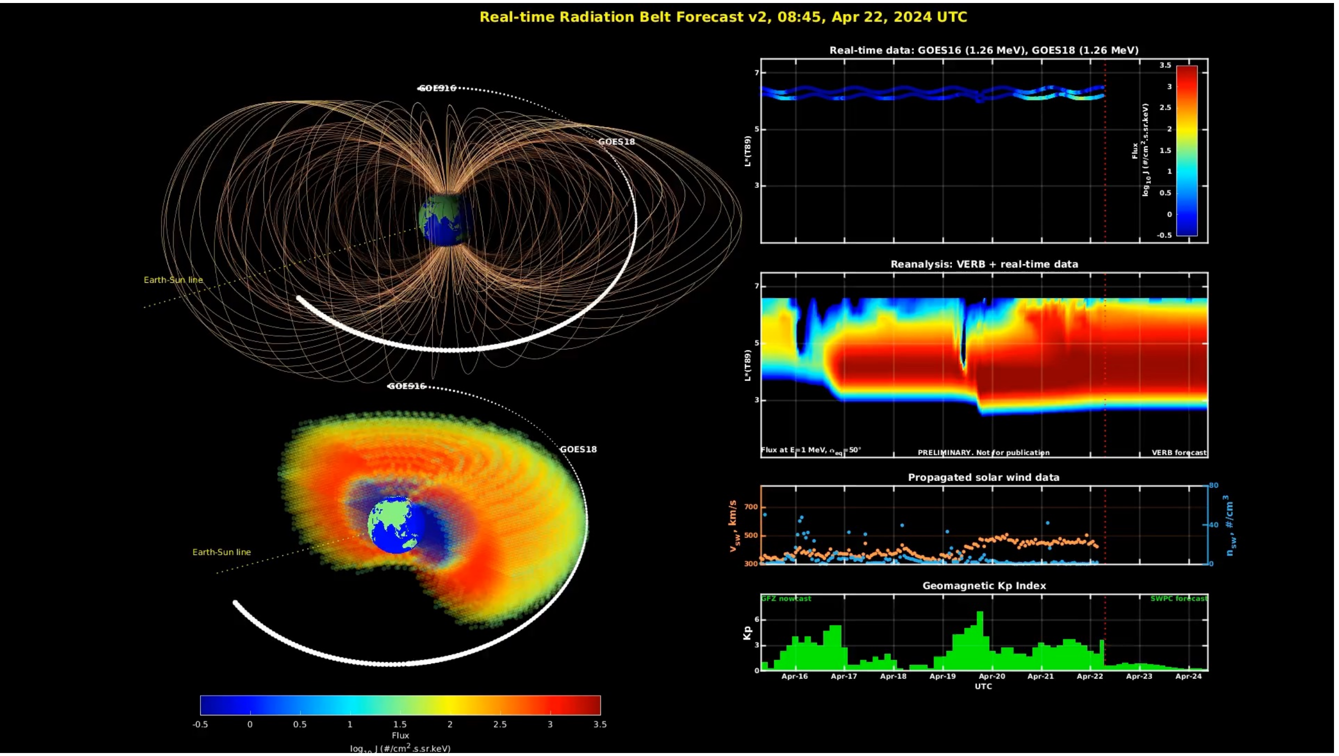
Zhelavskaya et al., 2017

The model trained on single point measurements from 2012 to 2016 reproduces the global dynamics observed in 2001

The Forecasting that We Currently Have in Our Section

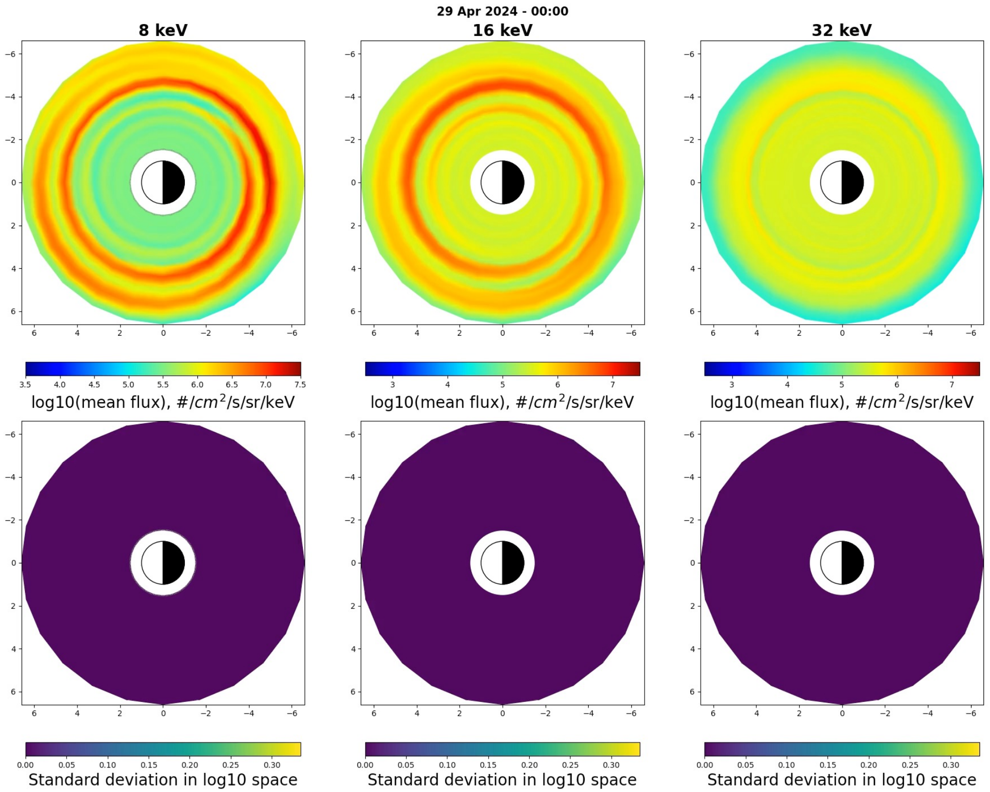
We are improving the forecast

Radiation Belt Electron Forecast



https://www.gfz-potsdam.de/en/section/space-physics-and-space-weather/data-products-and-services

Ring Current Electron Forecast



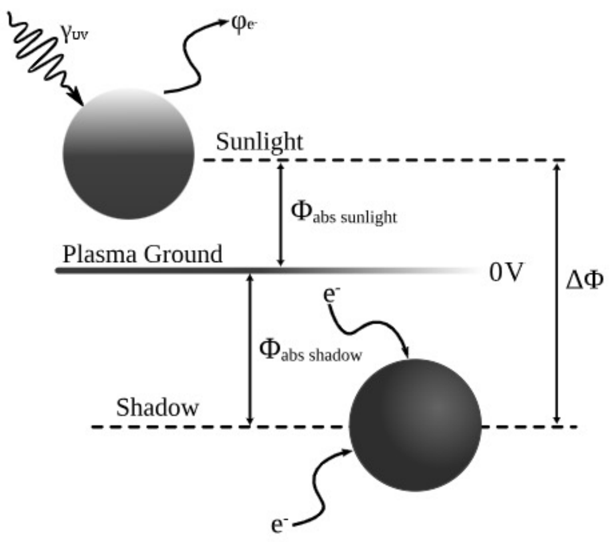
https://www.spacepager.eu/data-products/

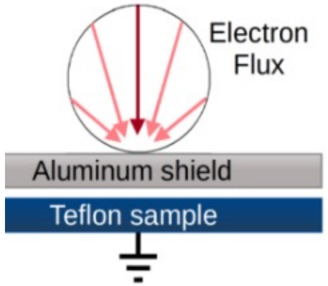
Data Products of the PAGER Project

Surface Charging Indicators and Internal Charging Indicators

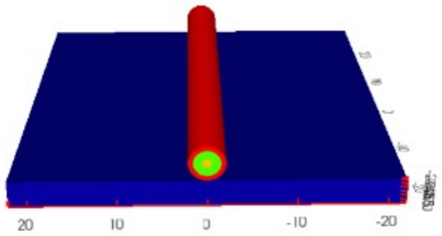
Surface Charging results

Orbit	Mission	Platform	2024-01-12 0000	0600	1200	1800	2024-01-13 0000	0600	1200	1800	2024-01-14 0000	0600	1200	1800
GEO	GOES16	SC1: Double Sphere	🟢	🟢	🟢	🟠	🟢	🟢	🟢	🟠	🟢	🟢	🟢	🟢
	GOES18	SC1: Double Sphere	🟢	🟢	🟢	🟠	🟠	🟢	🟢	🟢	🟢	🟢	🟢	🟢





DEVICE ID	THICKNESS
IC1	0.50 mm
IC2	0.75 mm
IC3	1.00 mm
IC4	1.25 mm
IC5	1.50 mm
IC6	1.75 mm
IC7	2.00 mm



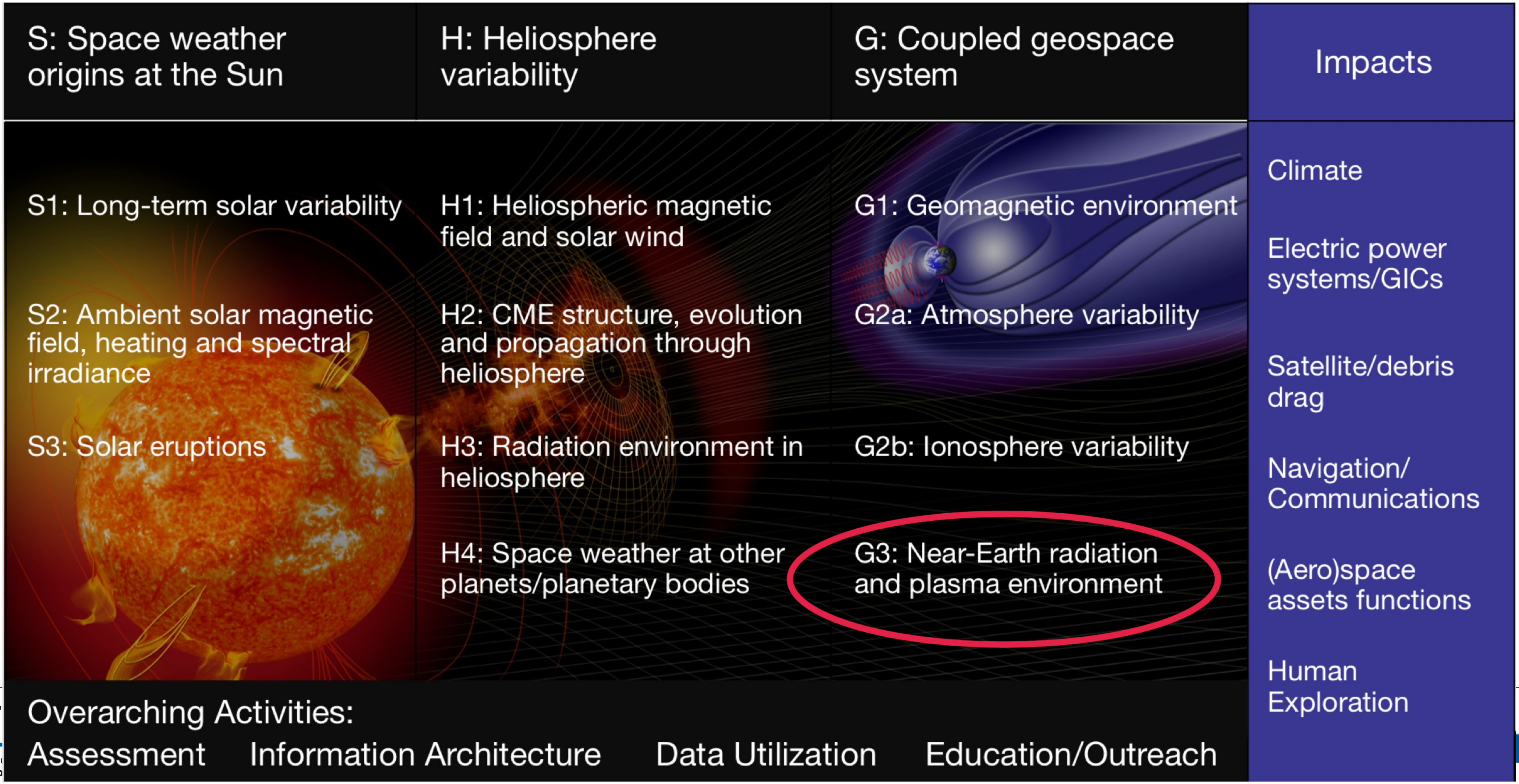
https://www.spacepager.eu/data-products/

Internal Charging results

Orbit	Mission	Platform	2024-01-12 0000	0600	1200	1800	2024-01-13 0000	0600	1200	1800	2024-01-14 0000	0600	1200	1800	2024-01-15 0000
MEO	ARASE	IC1:0.50mm Shield Detector	🟠	🟠	🟠	🟠	🟠	🟠	🟠	🟠	🟠	🟠	🟠	🟠	🟠
		IC2:0.75mm Shield Detector	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟠	🟠	🟠	🟠
		IC3:1.00mm Shield Detector	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢
		IC4:1.25mm Shield Detector	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢
		IC5:1.50mm Shield Detector	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢
		IC6:1.75mm Shield Detector	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢
		IC7:2.00mm Shield Detector	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢
		IC10: No Shield Cable	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟠	🟠	🟠	🟠
		IC1:0.50mm Shield Detector	🟠	🟠	🟠	🟠	🟠	🟠	🟠	🟠	🟠	🟠	🟠	🟠	🟠
		IC2:0.75mm Shield Detector	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟠	🟠	🟠
		IC3:1.00mm Shield Detector	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢

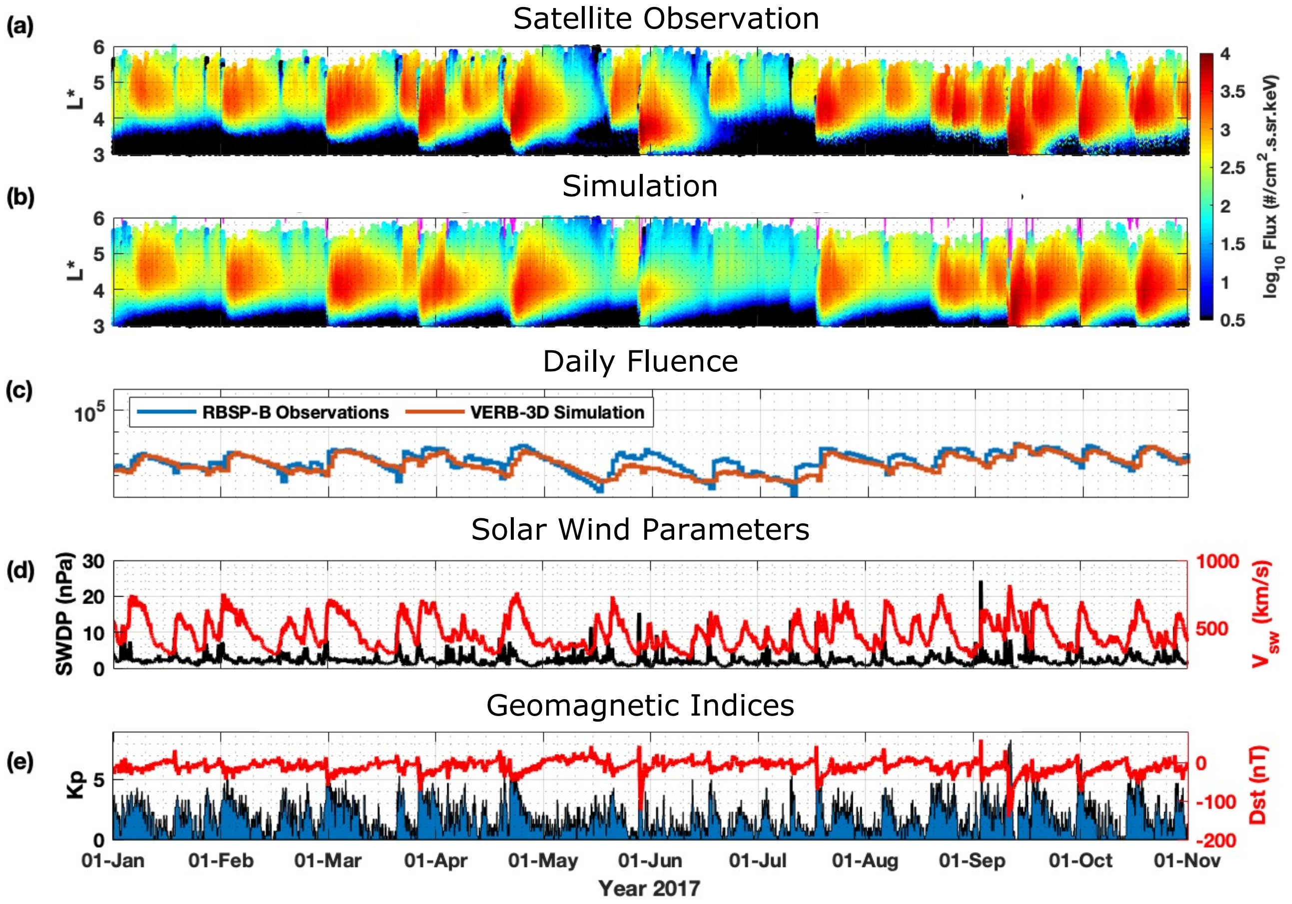
How reliable are these forecasting and models?

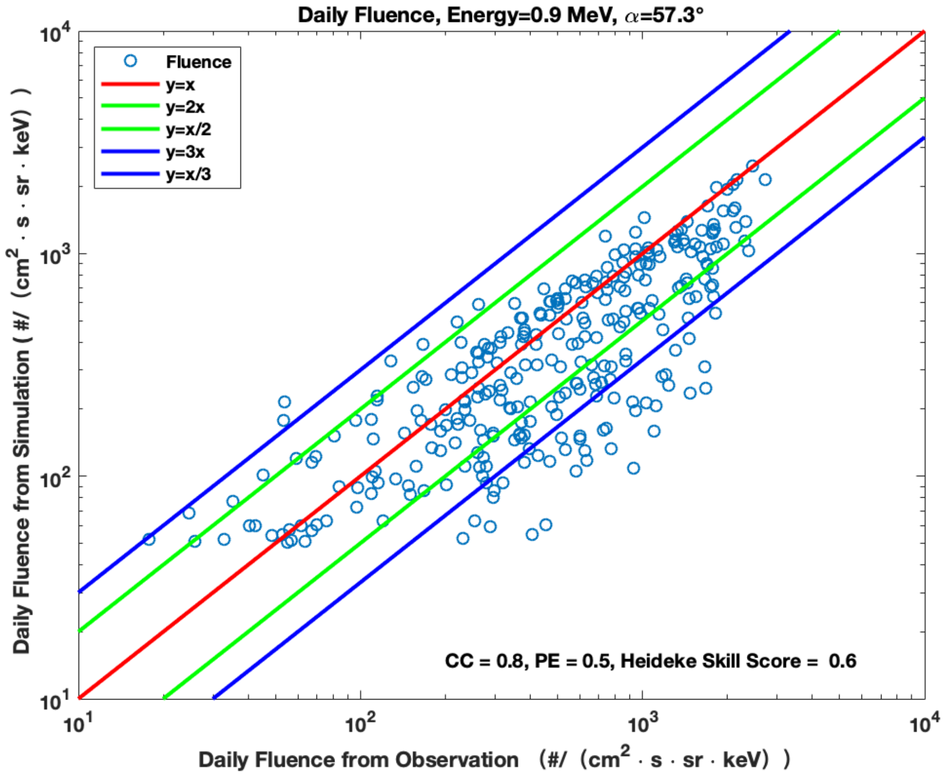
Validation Challenge: COSPAR International Space Weather Action Team (ISWAT)



International Space Weather Action Team Challenge

Validate Different Radiation Belt Models Against Van Allen Probe Observations





[*Wang, Shprits et al*, 2022, in prep.]

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Compare Daily Fluence from Observation and Simulation

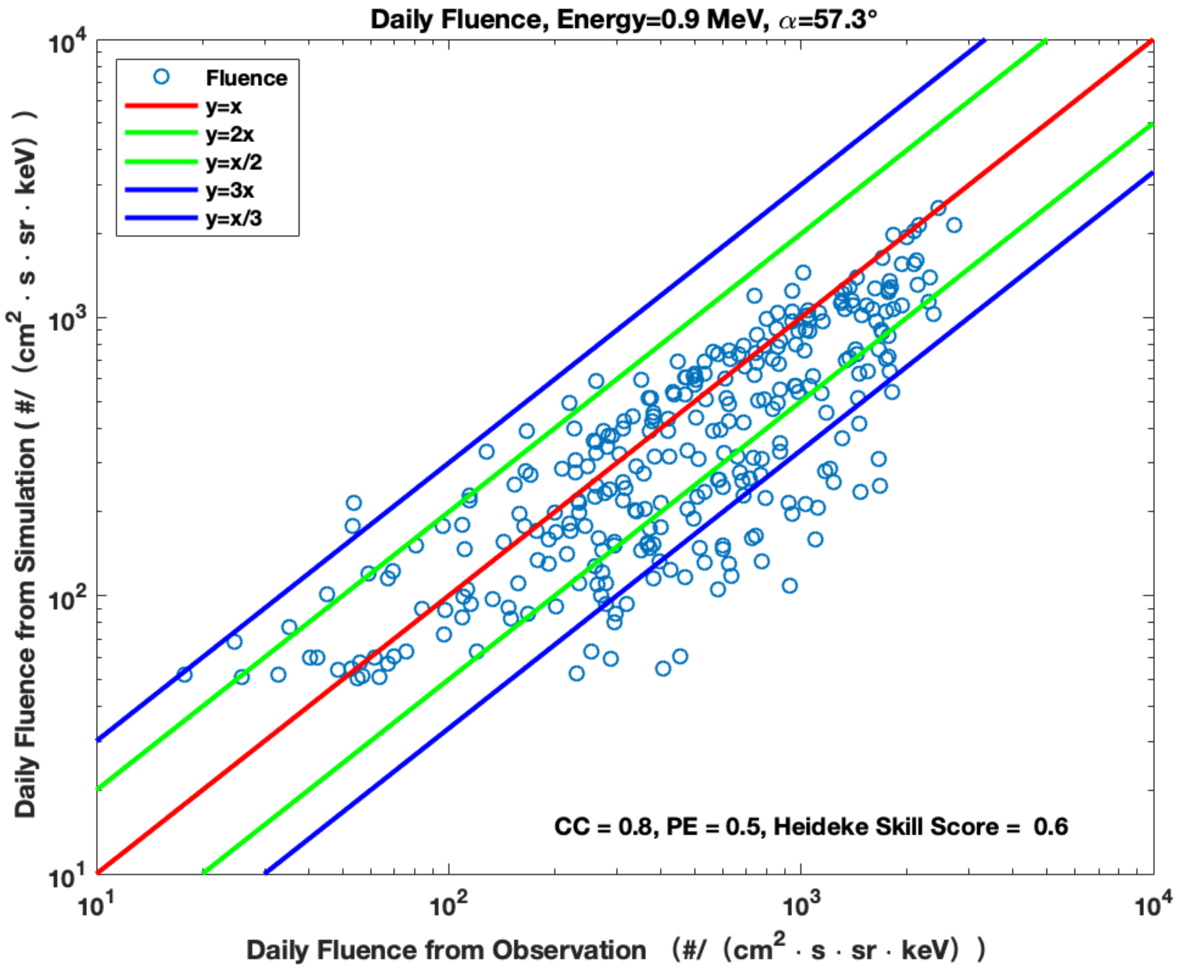
In general, daily fluence from simulation agrees well with observations

Correlation Coefficient = 0.8
Prediction Efficiency (PE) = 0.5

$PE = 1 - \frac{1}{N}\sum\frac{(X_i - Y_i)^2}{\mathrm{Var}(X)}$, (Y-simulation, X-Observation)

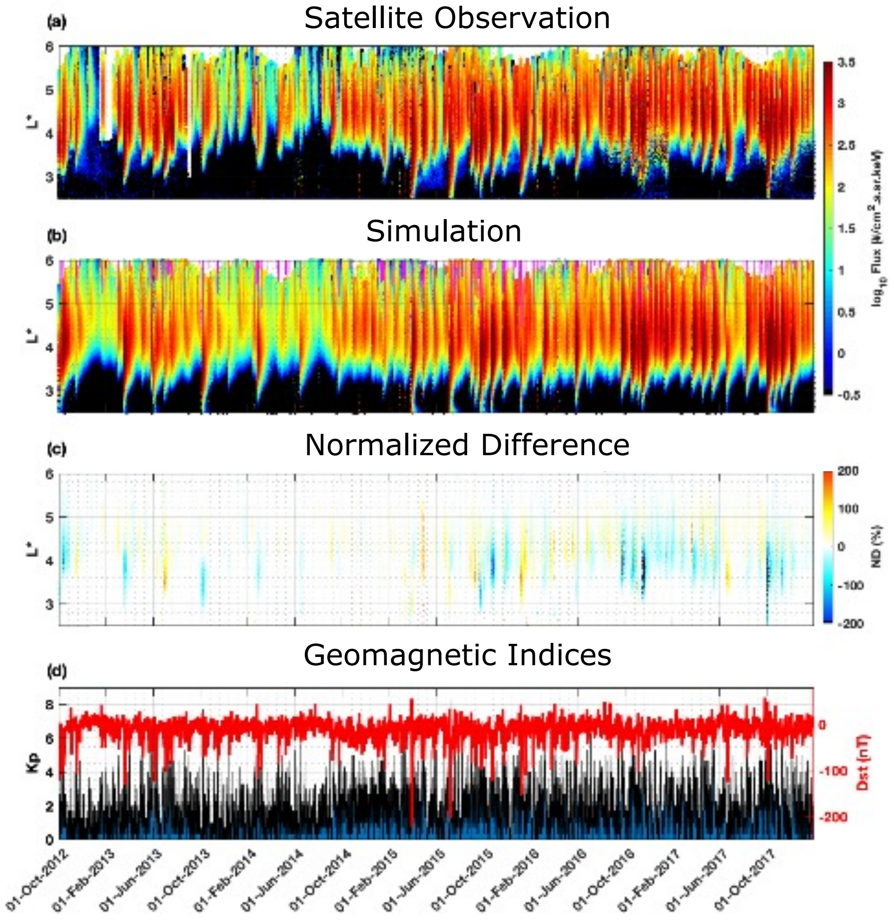
where $\mathrm{Var}(X) = \frac{1}{N}\sum(X_i - \langle X_i\rangle)^2$, and $\langle \ldots \rangle$ is the ensemble average of the parameters.

Threshold for 'Positive Event' Daily Fluence: 10^3			
Number of Daily Fluence Exceeding the Threshold: 74 (of 300 in total)			
Overall **Heideke Skill Score** (S): 0.6187 $S = \frac{2(xw-yz)}{y^2+z^2+2xw+(y+z)(x+w)}$			
Successful Negative Predictions (w)	Successful Positive Predictions (x)	False Negative Predictions (y)	False Positive Predictions (z)
222	41	33	4

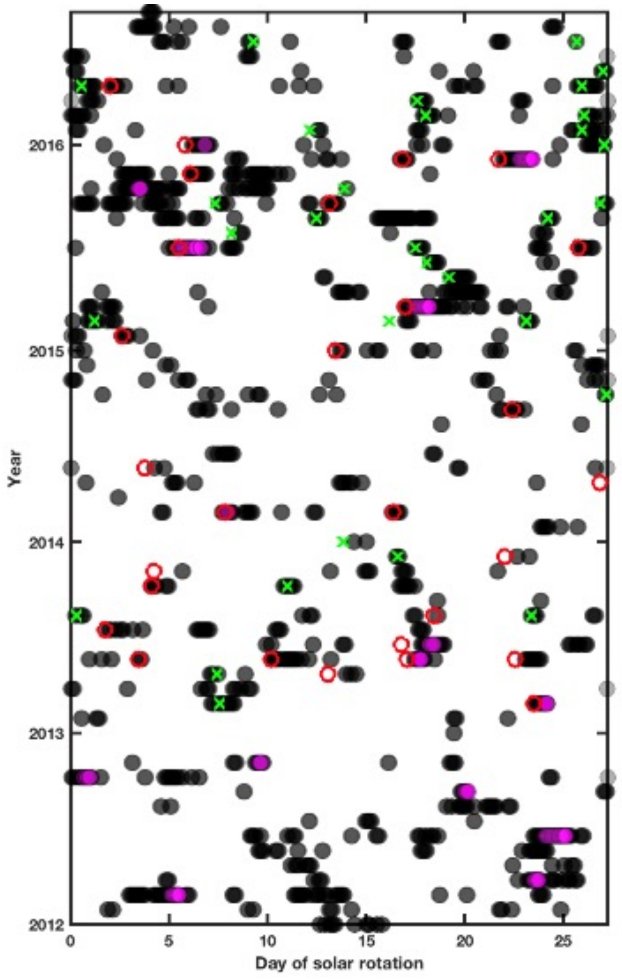


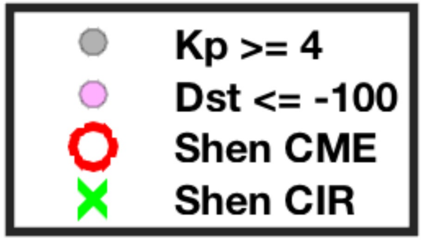
Long-term Simulation for Van Allen Probe Era

Long-term Comparison and Zoom Into Different Storms



[*Shprits, Allison and Wang et al*, 2022, JGR]





CME: Coronal Mass Ejection
CIR: Corotating Interaction Regions

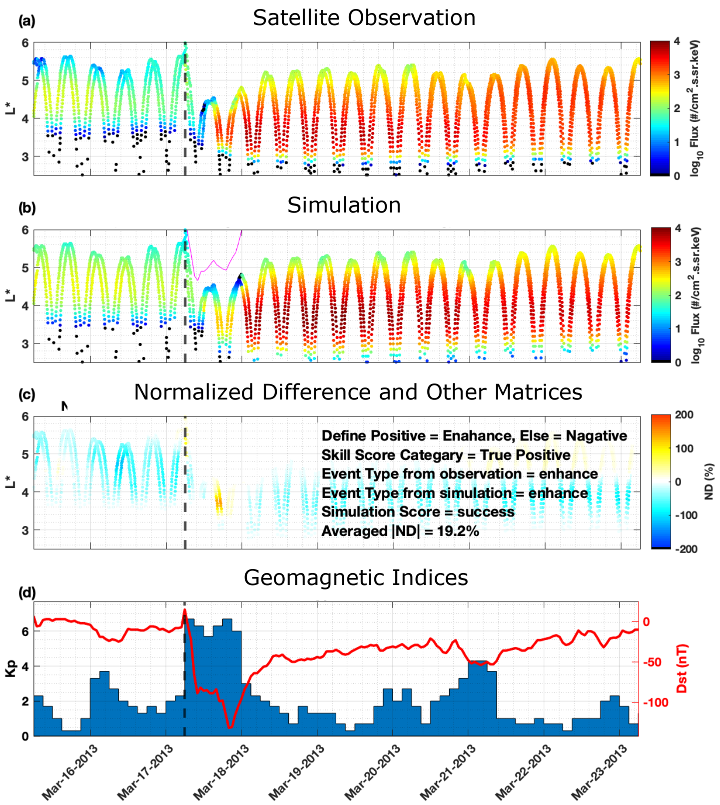
CME and CIR Event List from *Shen, Hudson, Jaynes et al.*, 2017

[*Wang, Shprits, … Effenberger et al*, 2024, in prep]

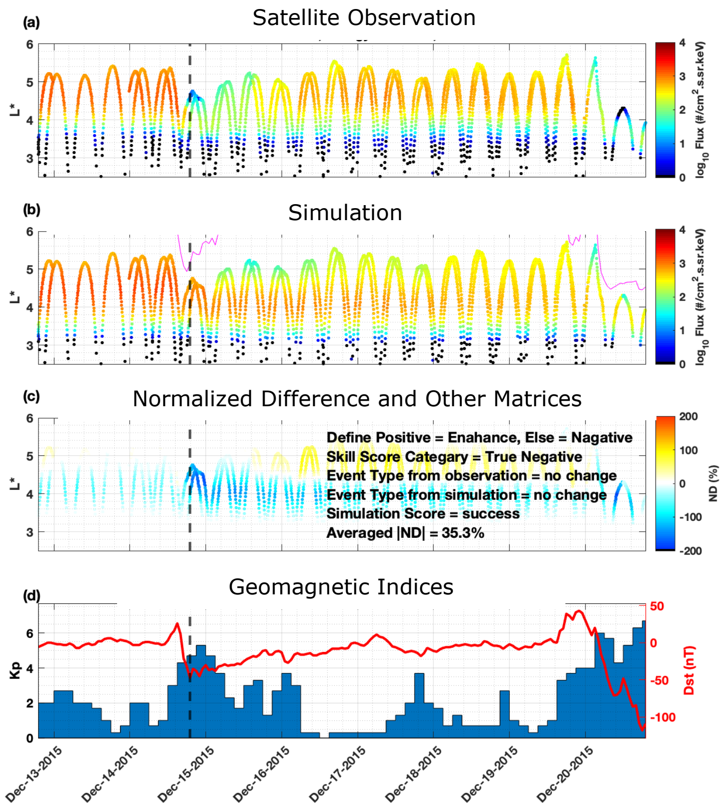
Answer the Long-standing and Compelling Question

Reproduce the Dynamics in Different Geomagnetic Storms

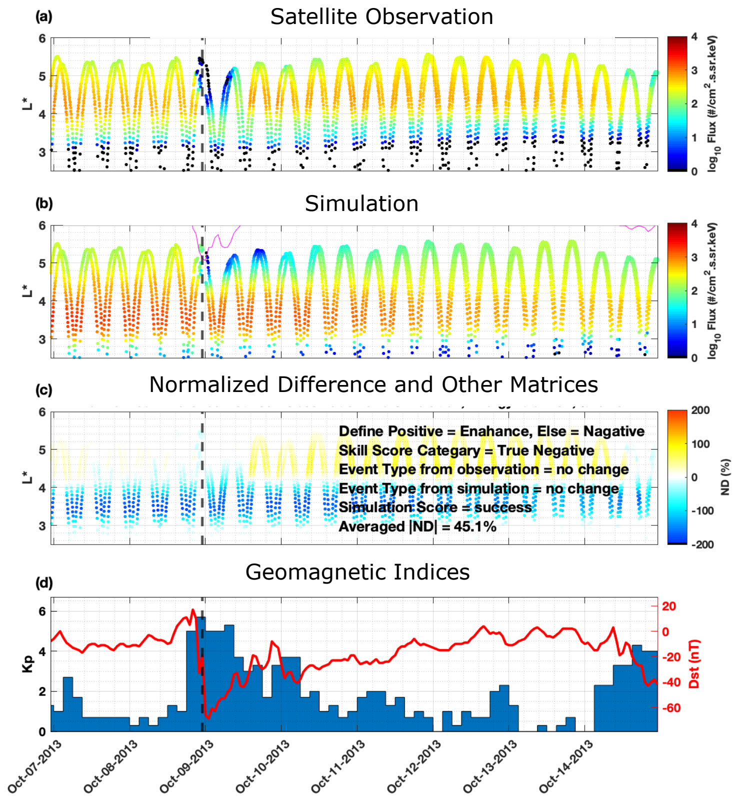
Enhancement



Depletion



No change



More systematic analysis is still going on… [*Wang, Shprits et al*, 2024, in prep]

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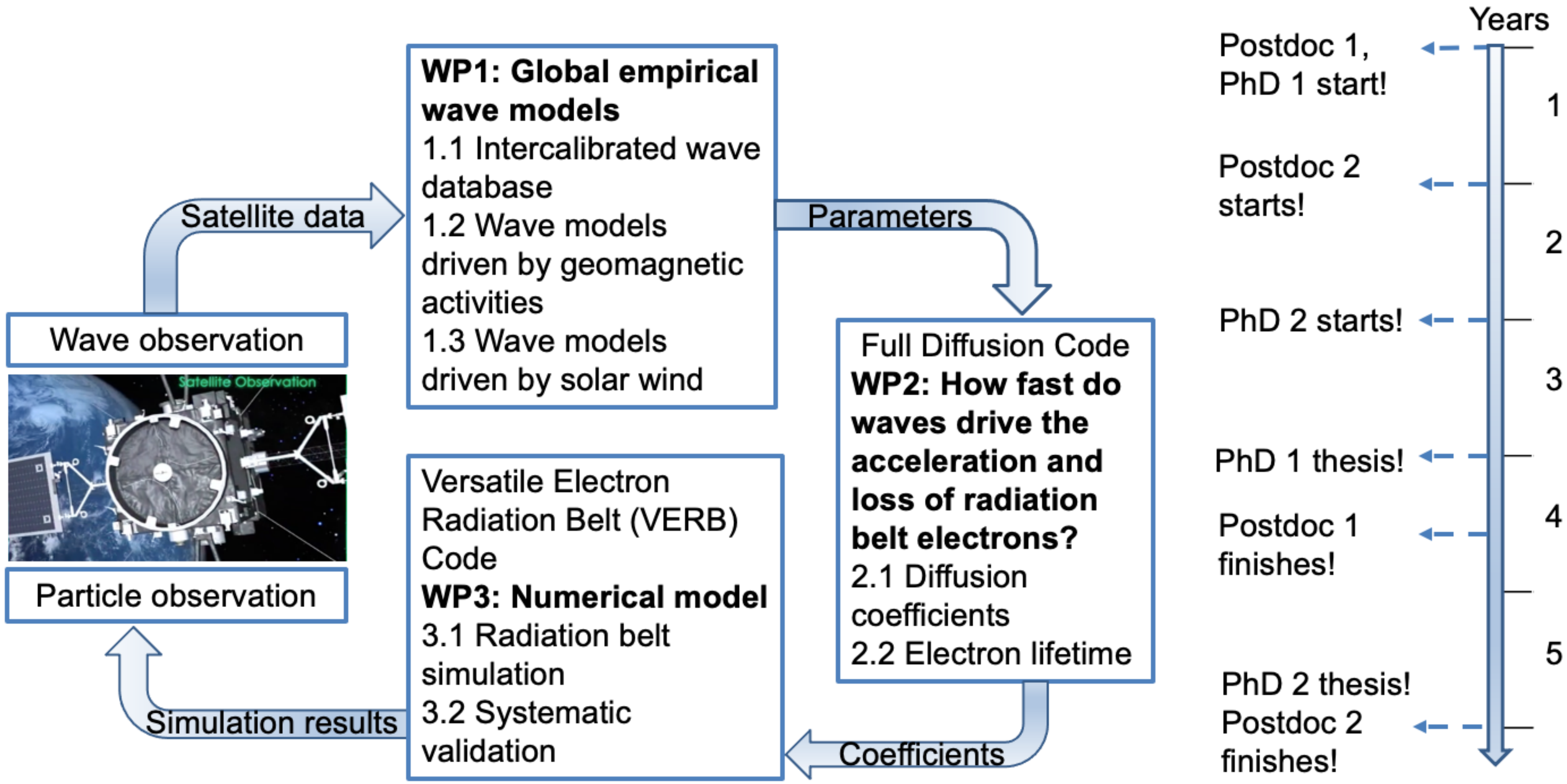
Extend Our Study to All Important Waves

Recently Funded ERC Consolidator Grant (WIRE)

Budget: € 2 Million
Duration: 5 years

Collaborations:
KIT, Uni Potsdam, LMU
DLR, Japan, France,
South Korea,
China, UK,
Czech Republic, USA

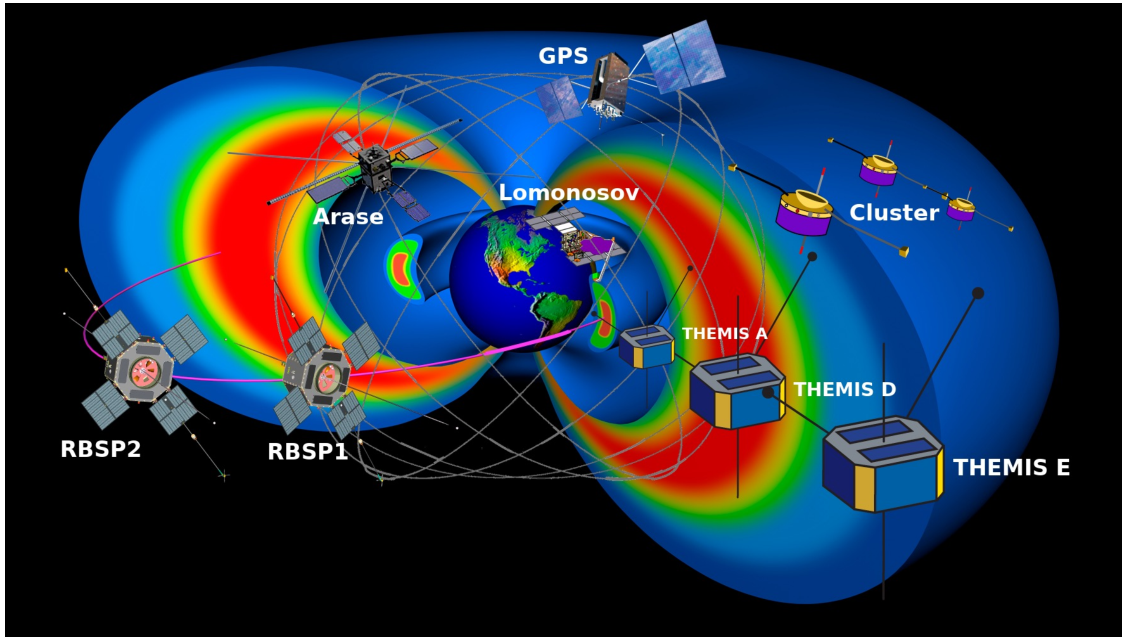


Can these processes account for the dramatic dynamics, or do we need to include other processes?

Timeliness of the Proposed Research Activities

State of the art and beyond

- ➢ Increasing space weather awareness
- ➢ Multi-satellite measurements
- ➢ New data released
- ➢ Currently no wave model driven by solar wind using multiple satellite data
- ➢ Preliminary work and preparations



[Adapted from NASA]

Satellite mission	Launch time - End time	Data can be used in this study	Orbit coverage
RBSP	2012 - 2019	Wave & Particle	Inner-magnetosphere, latitude < 20
Arase	2016 -	Wave & Particle	Inner-magnetosphere, latitude < 45
Cluster II	2000 -	Wave & Particle	magnetopshere
THEMIS	2007 -	Wave & Particle	magnetosphere
Lomonosov	2016 - 2017	Particle	Low Earth Orbit
GPS	1978 -	Particle	Medium Earth Orbit

Chorus Wave Observation from Arase Satellite

a) PWE HFA L3 Data

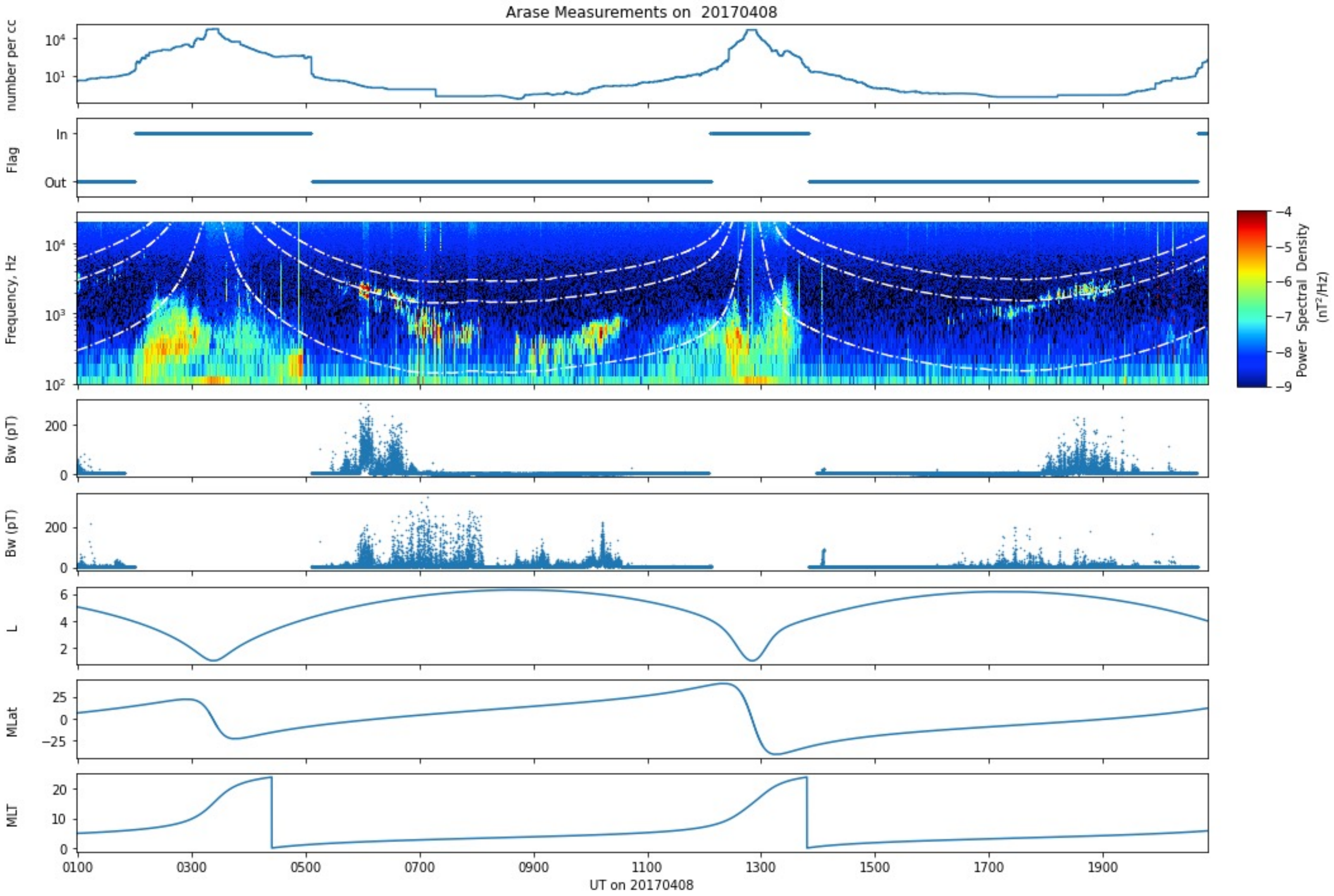
b) Inside/outside plasmapause

c) PWE OFA L2 Spectrum Data

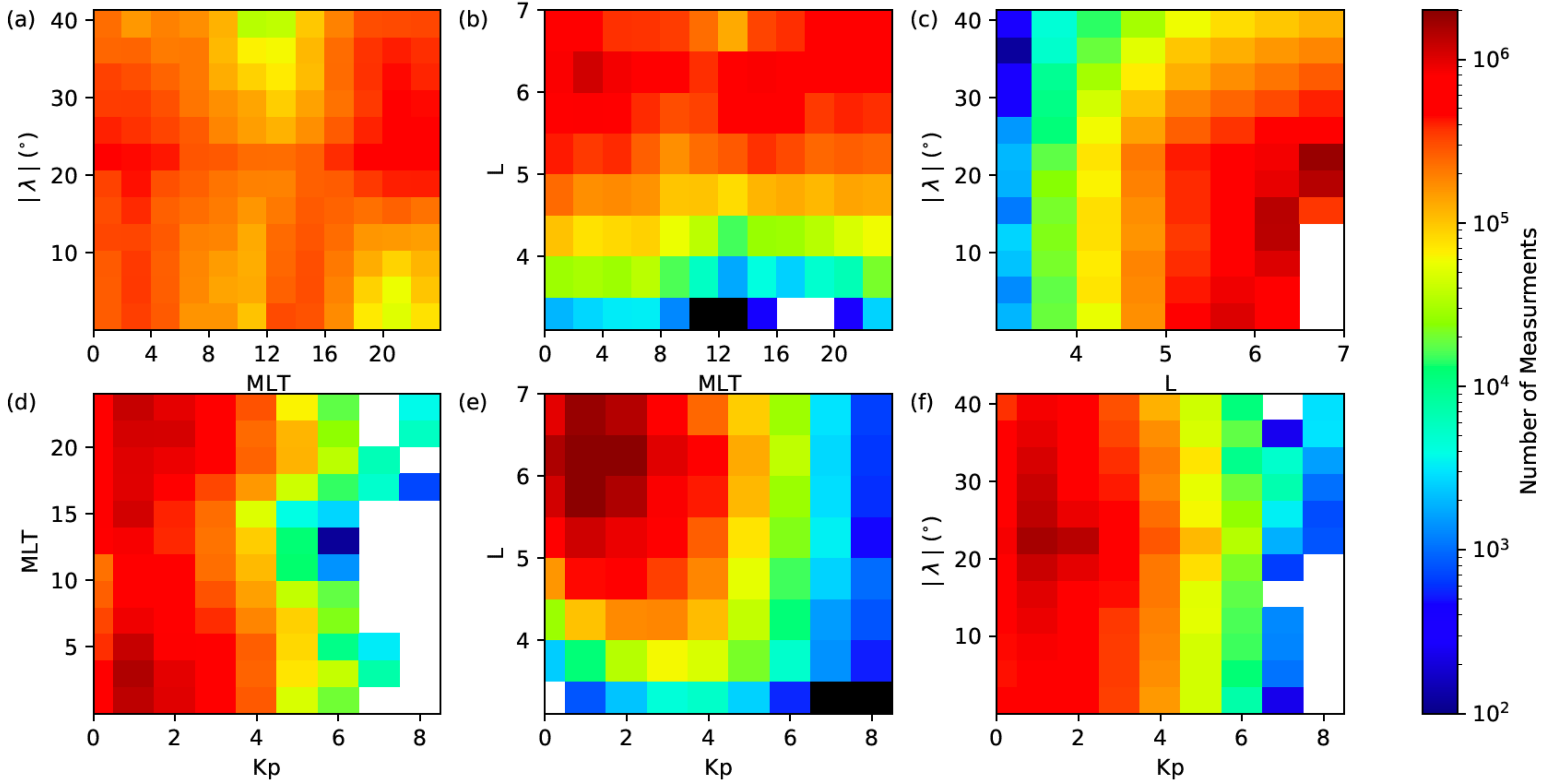
d) Amplitudes of Upper-band chorus

e) Amplitudes of lower-band chorus

f) Orbit level 2 data



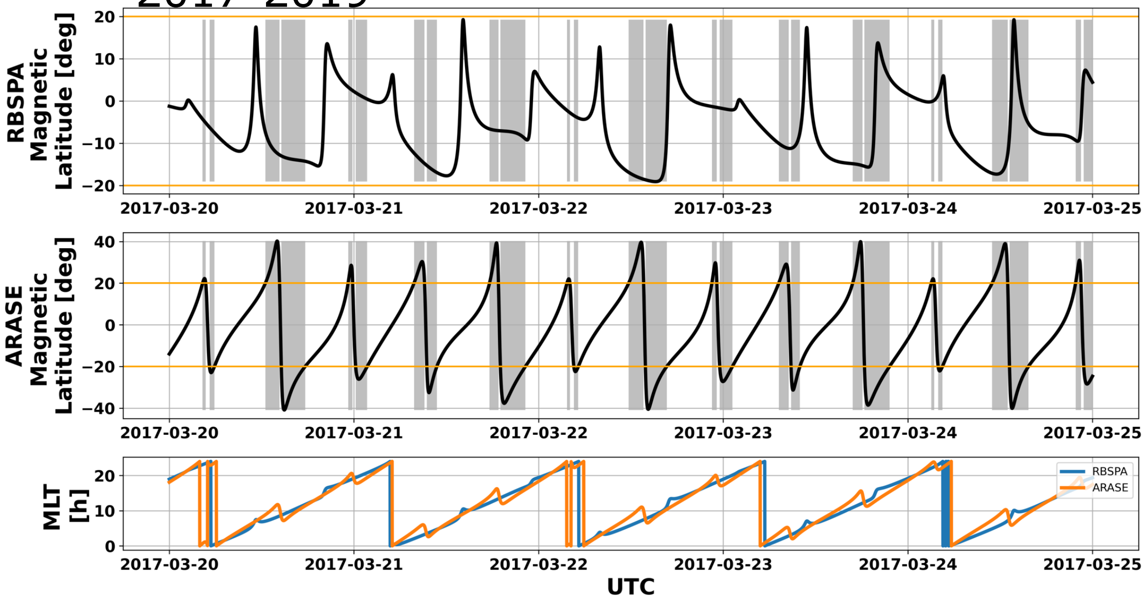
Distribution of Arase Measurements Outside the Plasmapause



Inter-calibrate Wave Measurements

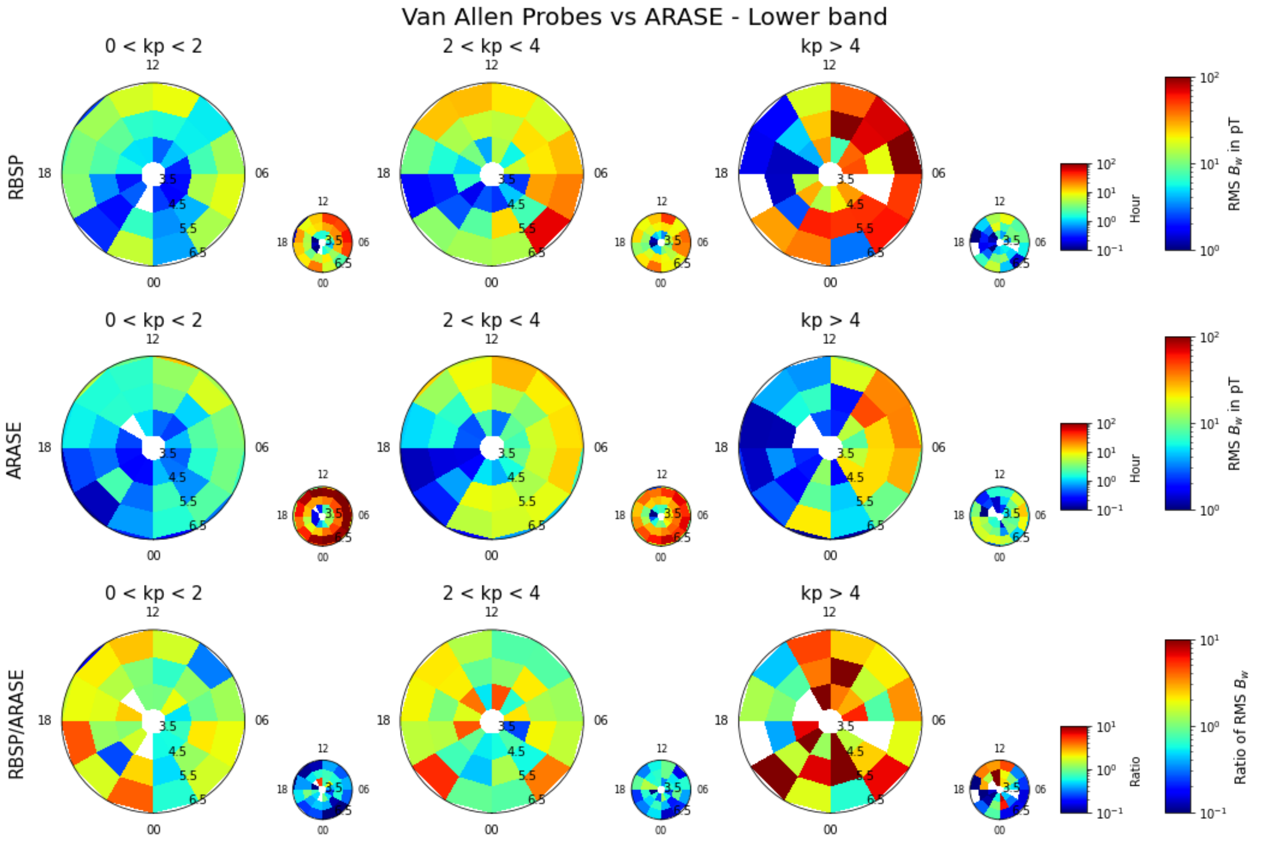
Waves from RBSP are Systematically Stronger than Those from Arase

First we choose time interval when latitude of Arase satellite is lower than 20 degree from 2017-2019



An **Example** Showing How We Choose Time Intervals
Data in the intervals with grey color shaded are removed

Then we compare root mean square of Bw (pT)

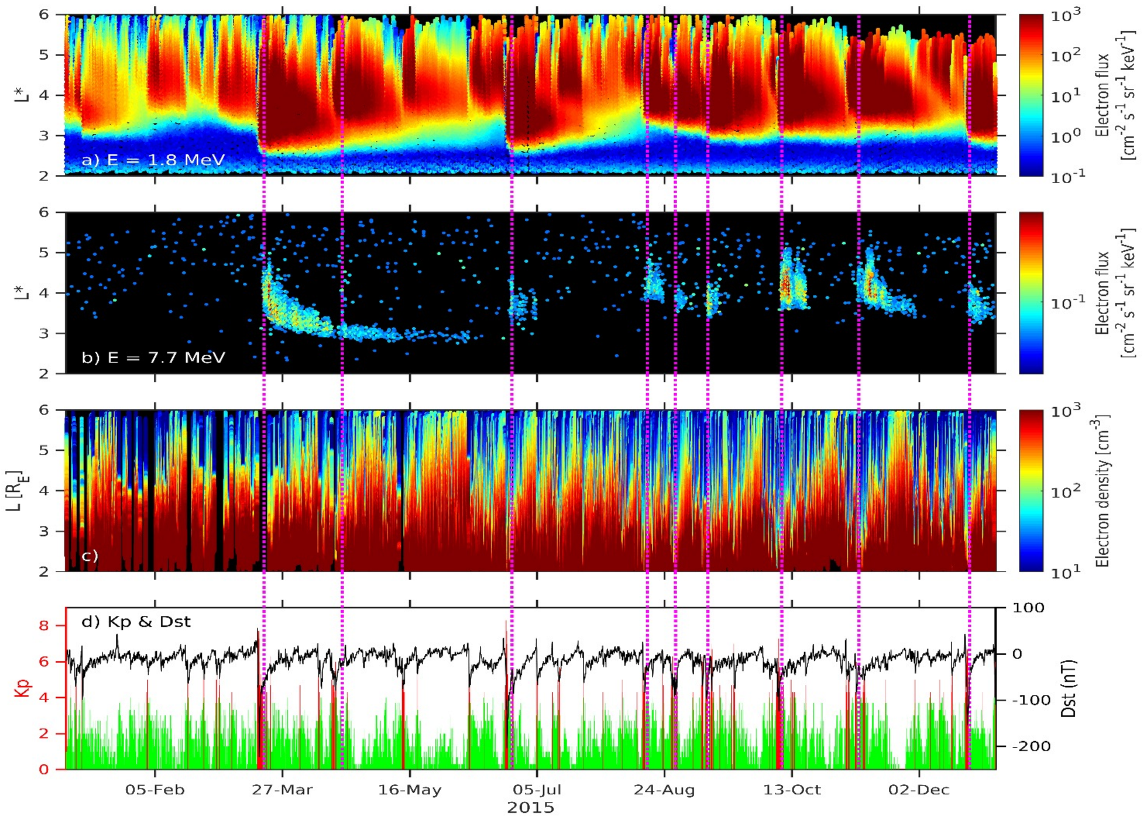


Work on this slide was carried out by the joint research program of the Institute for Space-Earth Environmental Research, Nagoya University.

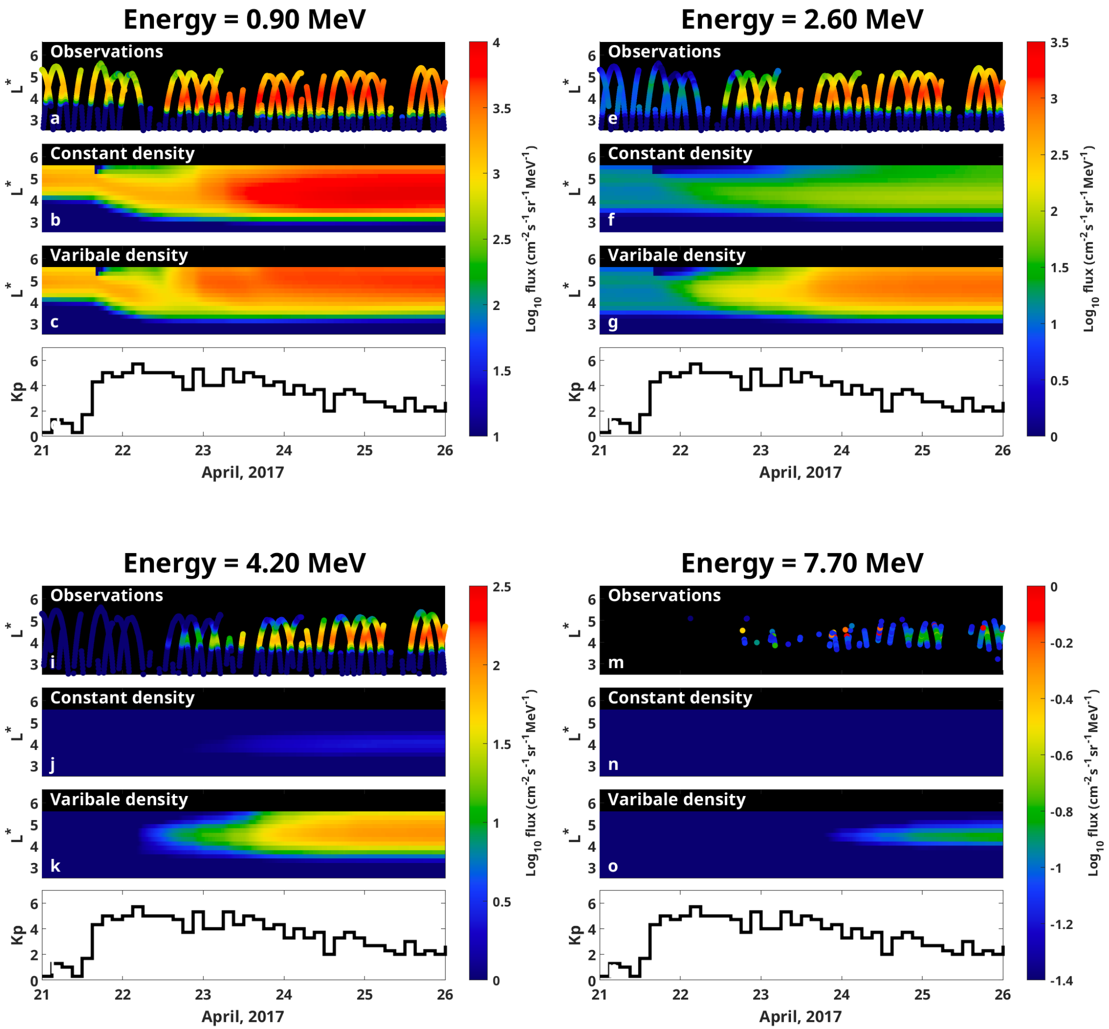
Acknowledge to Arase and RBSP Team
Credit Ting Feng

Amplitude is not the only factor controlling wave-particle interactions

Cold plasma density is also very important



[Allison, Shprits, Zhelavskaya, Wang et al., Science Advances, 2021]



[*Shprits, Haas, Wang et al*, to be submitted to Nature]

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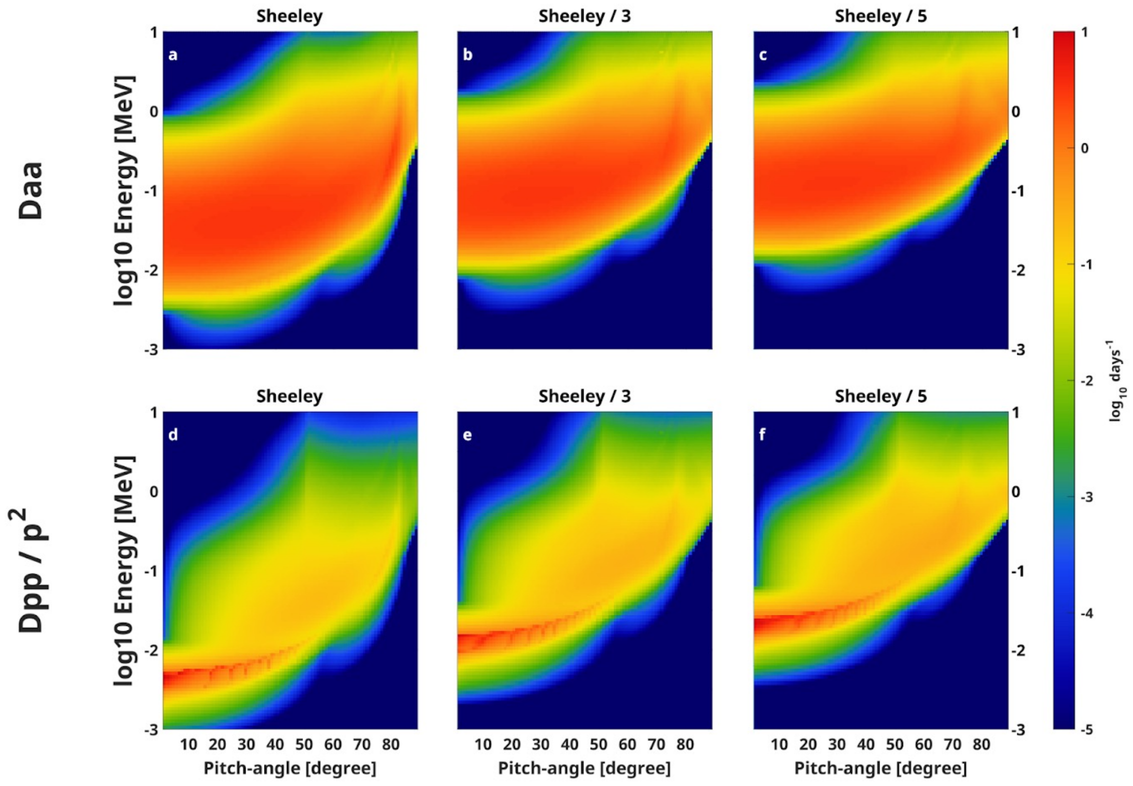
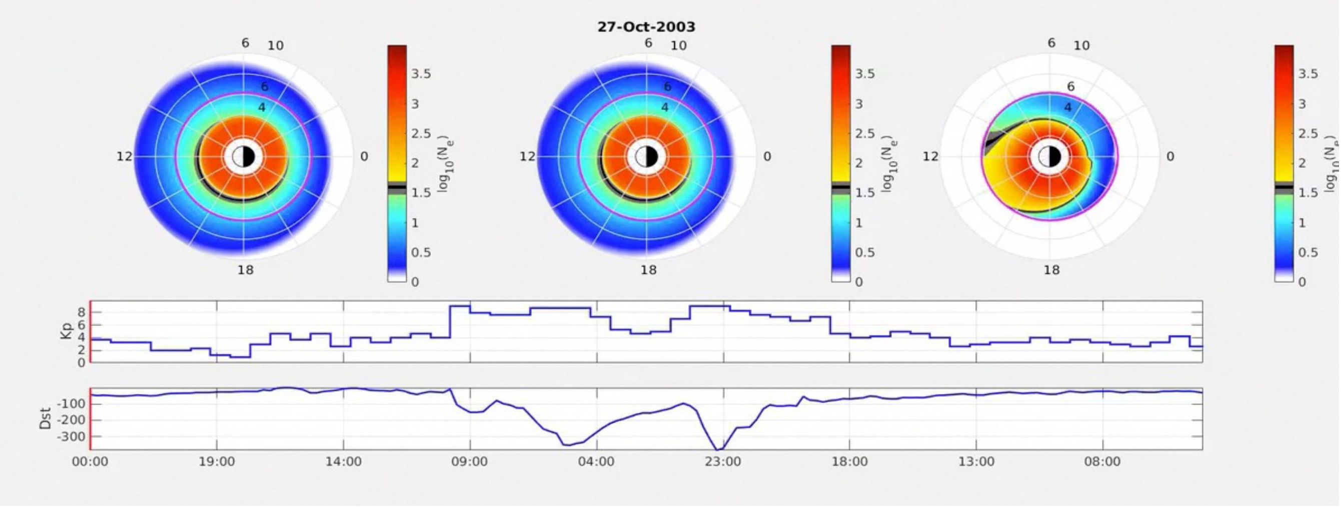
Besides wave models, we need accurate global plasma

Resonance energy varies with plasma density



Combine machine learning model and Physics-based model

Assimilative code   Physics-based model   ML model



Summary

- Accurate plasmasphere model is important
- Wave models are very important
- In general, our simulations reproduce the observations in both long-term and different storm periods well
- We have our real time forecasting models in running in real time at GFZ
- We provide our models to our community

Next steps:

- Empirical models using machine learning techniques for different important waves
- Long-term simulations and systematic validations
- Improve the forecasting by using more advanced wave models
- Further communication with end users, stake holders
- Propose a new satellite mission

Thank you!

Looking forward to your questions, sugestions, comments and our collaboration :)

We are hiring!

dedong@gfz-Potsdam.de

Backup Slides

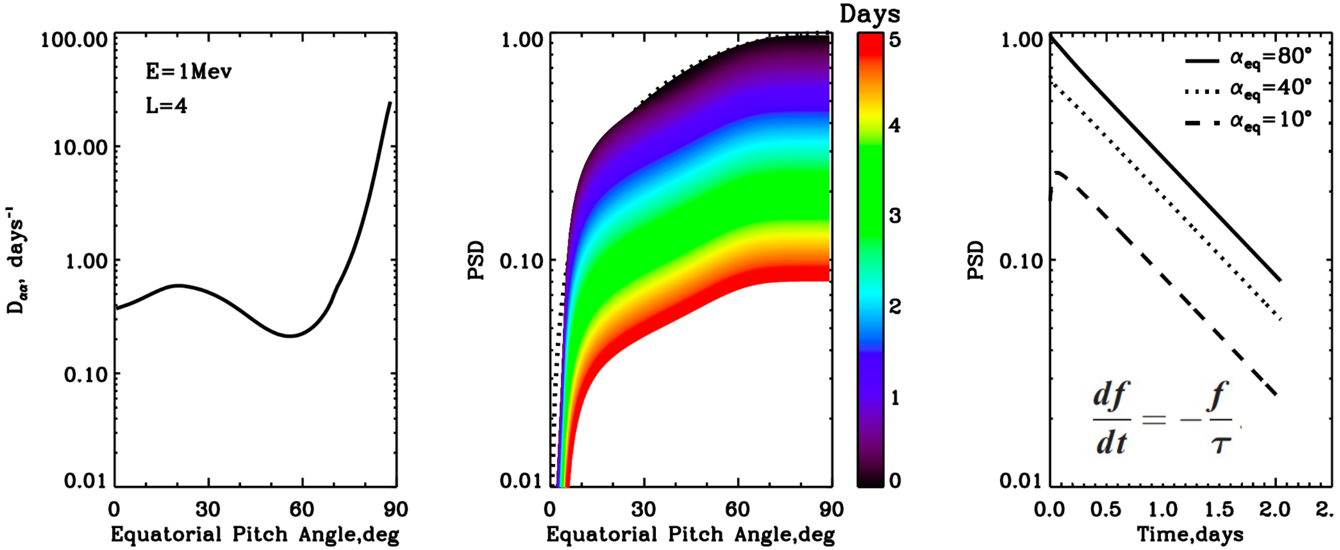
Why Can We Infer Electron Lifetime from Diffusion Coefficients?

From diffusion coefficients with pitch-angle dependence to lifetime without that dependence

The evolution of the electron pitch-angle distribution

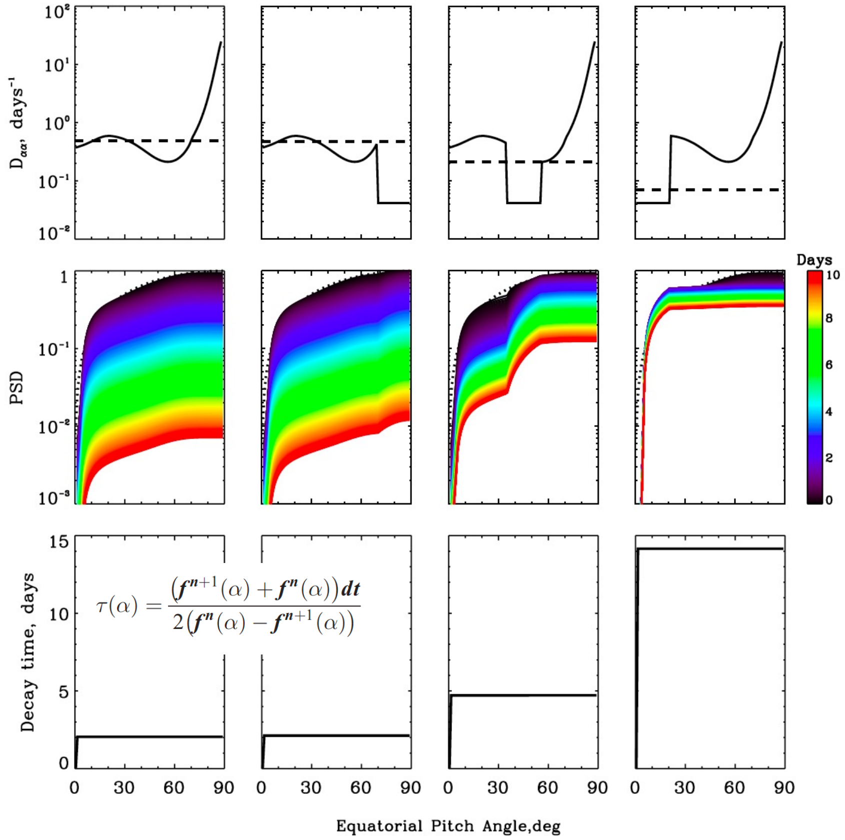
$$\frac{\partial f}{\partial t} = \frac{1}{T(y)y}\frac{\partial}{\partial y}T(y)yD_{yy}\frac{\partial f}{\partial y} - \frac{f}{\tilde{\tau}}$$

$$y = \sin(\alpha),\ T(y) = 1.3802 - 0.3198 \times (y + y^{1/2})$$



Wave properties refered to Summers et al [2002], Meredith et al [2003], Horne et al [2005], assuming parallel propagation.

[*Shprits, Li and Thorne*, 2006, JGR]



Sensitivity tests show that lifetimes are most sensitive to the pitch-angle diffusion coefficients near the edge of the loss cone.

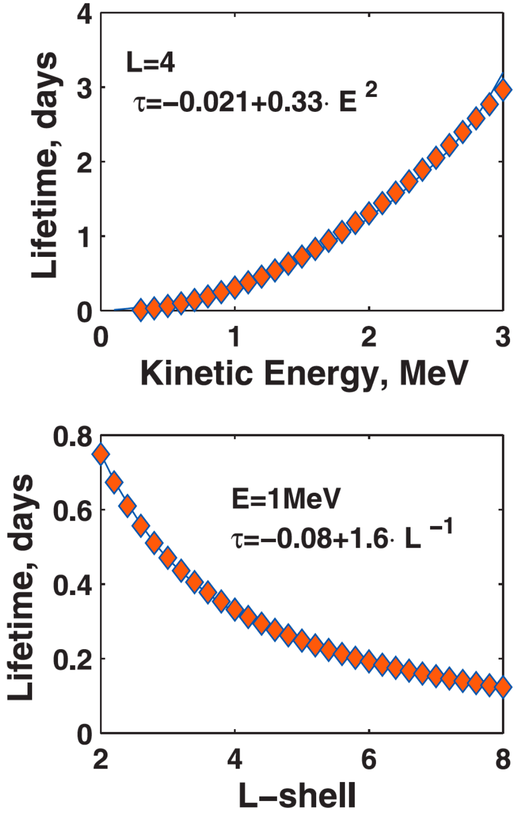
What Do We Know Now and Where Can We Improve?

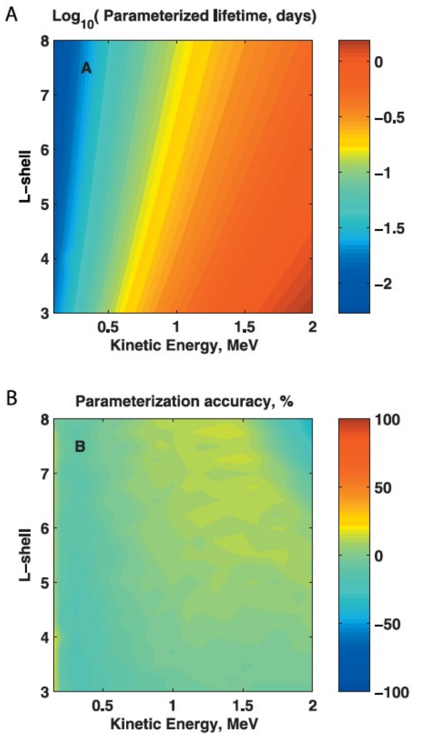
Start from simple wave models

Chorus waves: fixed amplitude, parallel propagation

$$\tau = 1/ < D_{\alpha\alpha} > |_{\alpha_0=\alpha_{lc}}$$

$$\tau = a_1 E^2 + a_2 L^{-1} + a_3 E^2 L^{-1}$$

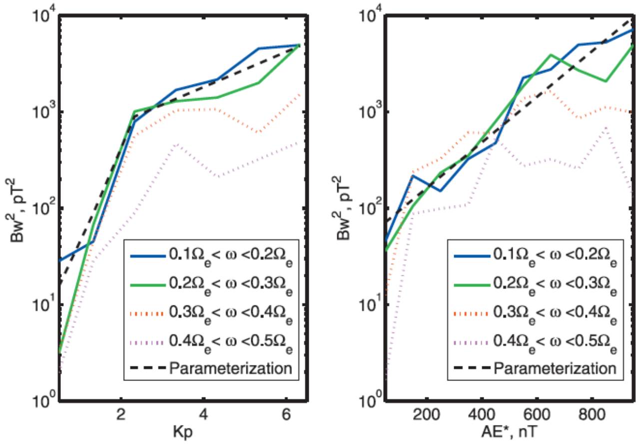




[*Shprits, Meredith and Thorne*, 2007, GRL]

Scale with wave amplitude at different geomagnetic condition

$$\tau = 4*1.2*\left(10^4 B_w^{-2}\right) \cdot \left(L^{-1}E^2\right)$$

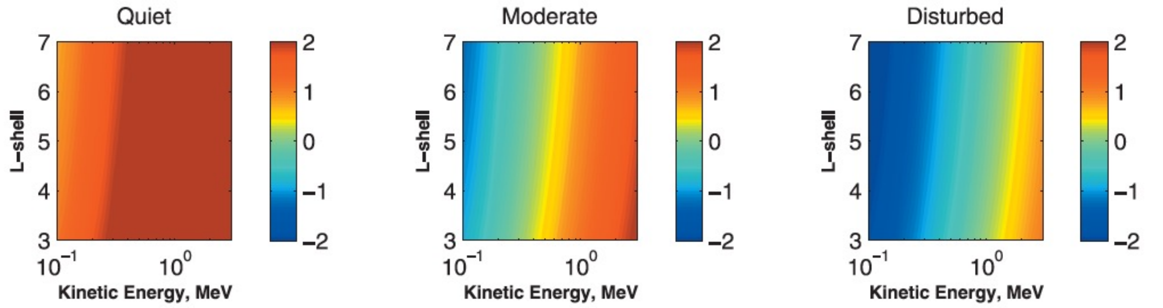


From CRRES satellite

$$B_w^2 = 2 \cdot 10^{0.73+0.91Kp}\ pT^2,\ Kp \le 2+$$

$$B_w^2 = 2 \cdot 10^{2.5+0.18Kp}\ pT^2,\quad Kp > 2+ \le 6$$

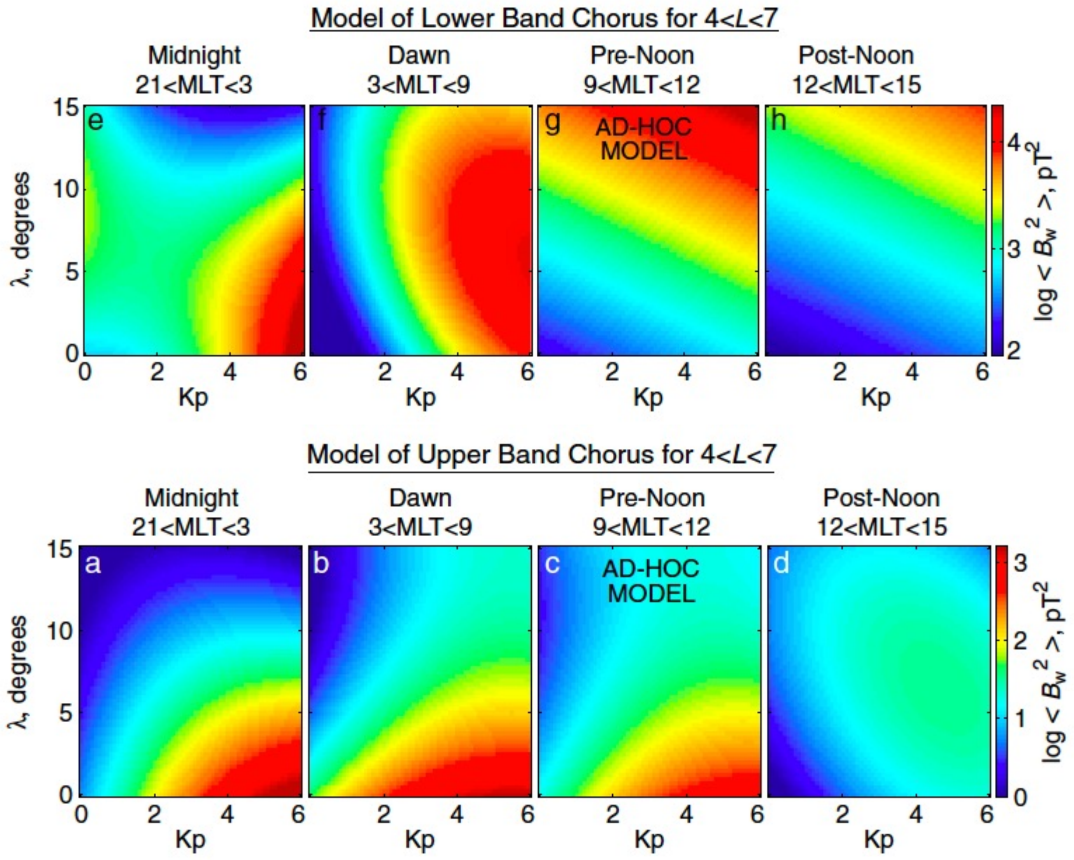
$$B_w^2 = 2 \cdot 10^{1.7+2.3\cdot 10^{-3}AE^*}\ pT^2,\ AE^* < 900\ \text{nT}$$



What Do We Know Now and Where Can We Improve?

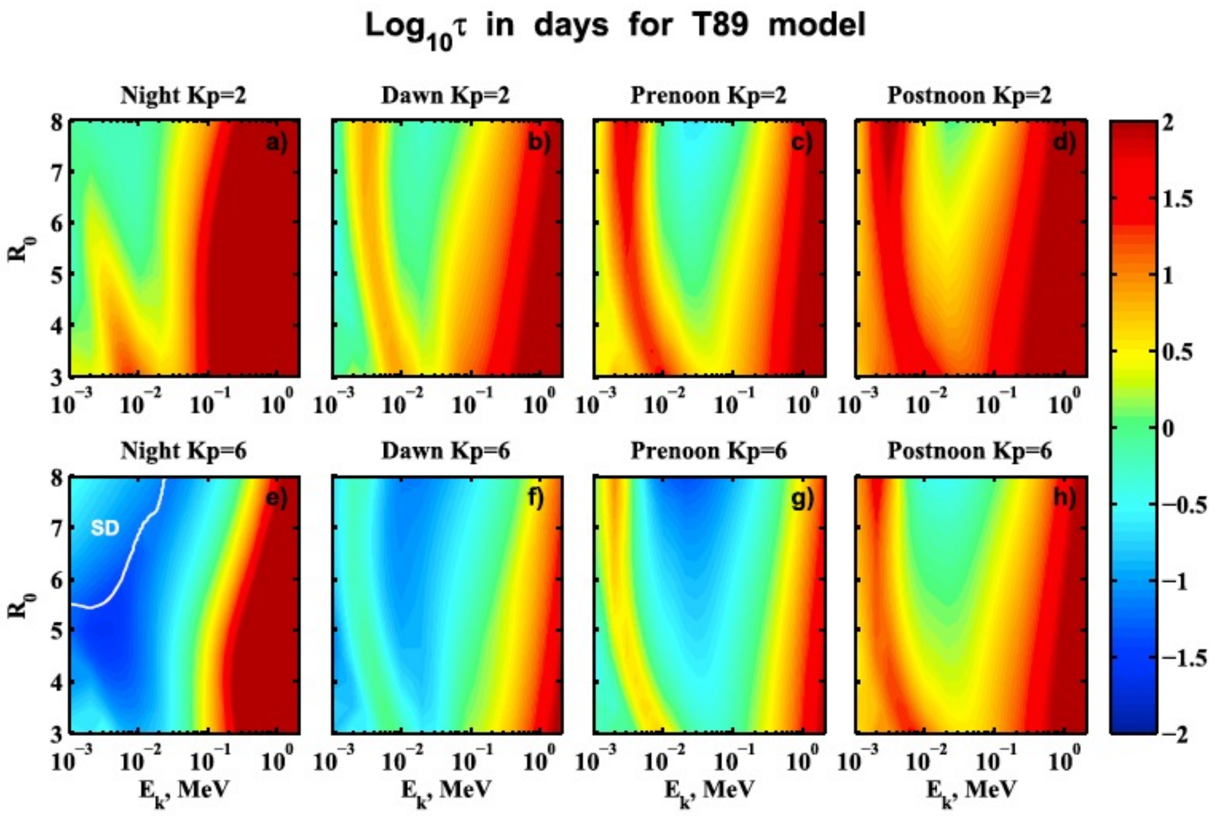
Previous Chorus Wave Models and Related Lifetime Parameterization

Derived from CRRES data



[*Spasojevic and Shprits*, 2013]

Parameterized Electron Lifetime in days



[*Orlova and Shprits*, 2014]

Estimate Electron Lifetime

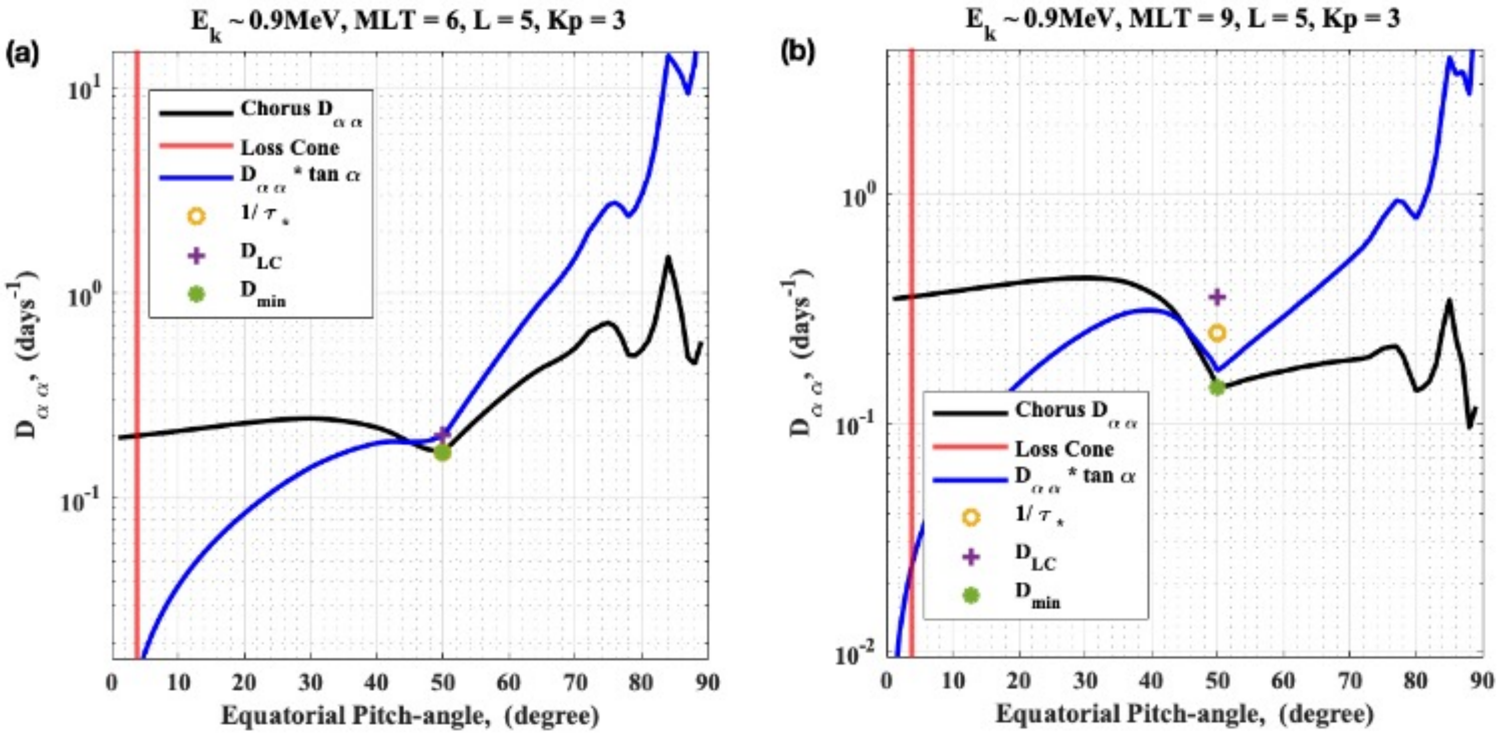
Using Chorus Wave Models Based on Van Allen Probe and Cluster Observations

- Full energy, MLT, L, Kp dependence

- Method 1: inverse of diffusion coefficients near the loss cone (e.g., Shprits et al., 2007)

- Method 2: equation from Albert and Shprits (2009, JASTP)

$$\tau_* \equiv \int_{\alpha_L}^{\pi/2} d\alpha \frac{\cos\alpha}{2D\sin\alpha}$$



[*Wang, Shprits, Haas and Drozdov*, 2024, GRL, under review]

Parameterization of Electron Lifetime

Polynomial fitting is used as a first step

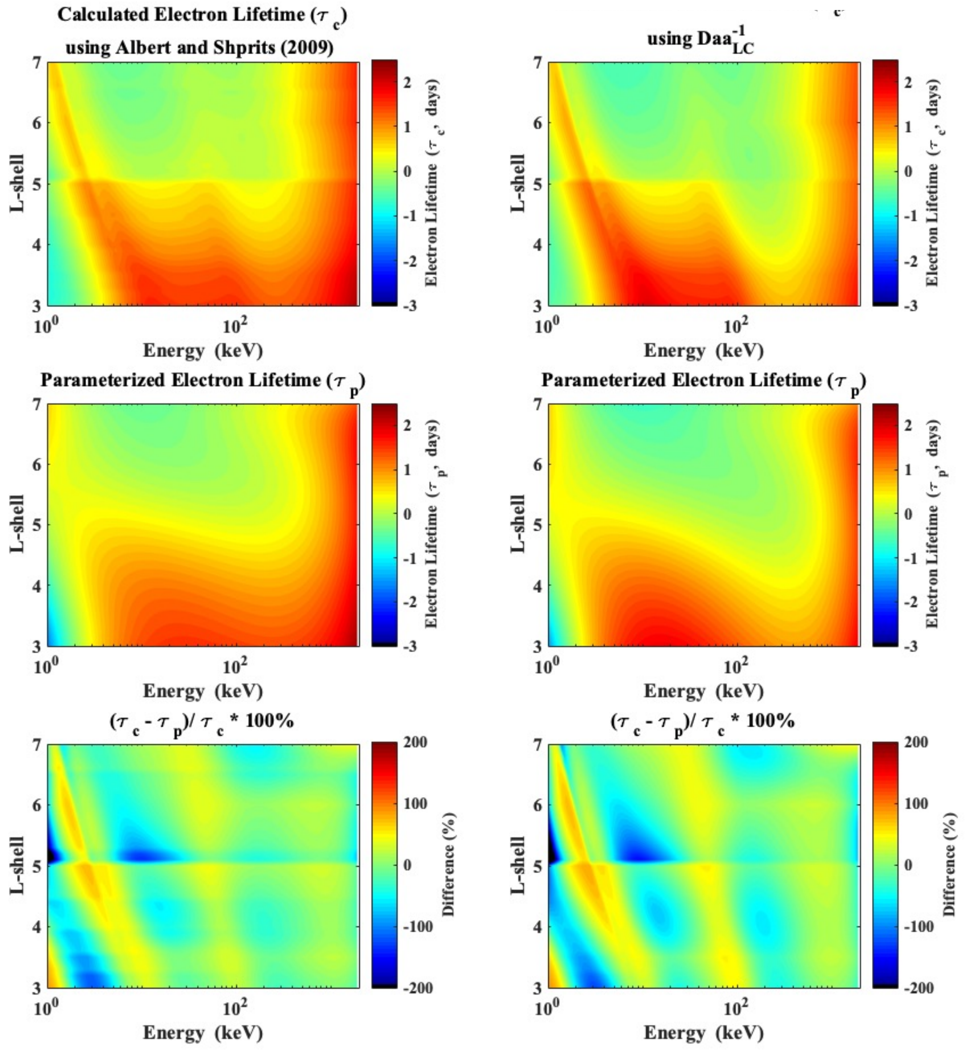
A lifetime data base [1067640x8 double] is created

X: Variables						y: Lifetimes	
1.	2.	3.	4.	5.	6.	7.	8.
Kp index	MLT	cos(MLT/ 12*pi)	sin(MLT/ 12*pi)	L	Energy (MeV)	Electron lifetime (days)	Electron lifetime (days)
[1 to 7]	[0 to 23]	[-1 to 1]	[-1 to 1]	[3 to 7]	[0.001 to 2]	[~0 to ~2e+17]	[~0 to ~1600]

Col 7.: Calculated using the equation from Albert and Shprits (2008).
Col 8.: Calculated using pitch-angle diffusion coefficients near the loss cone.

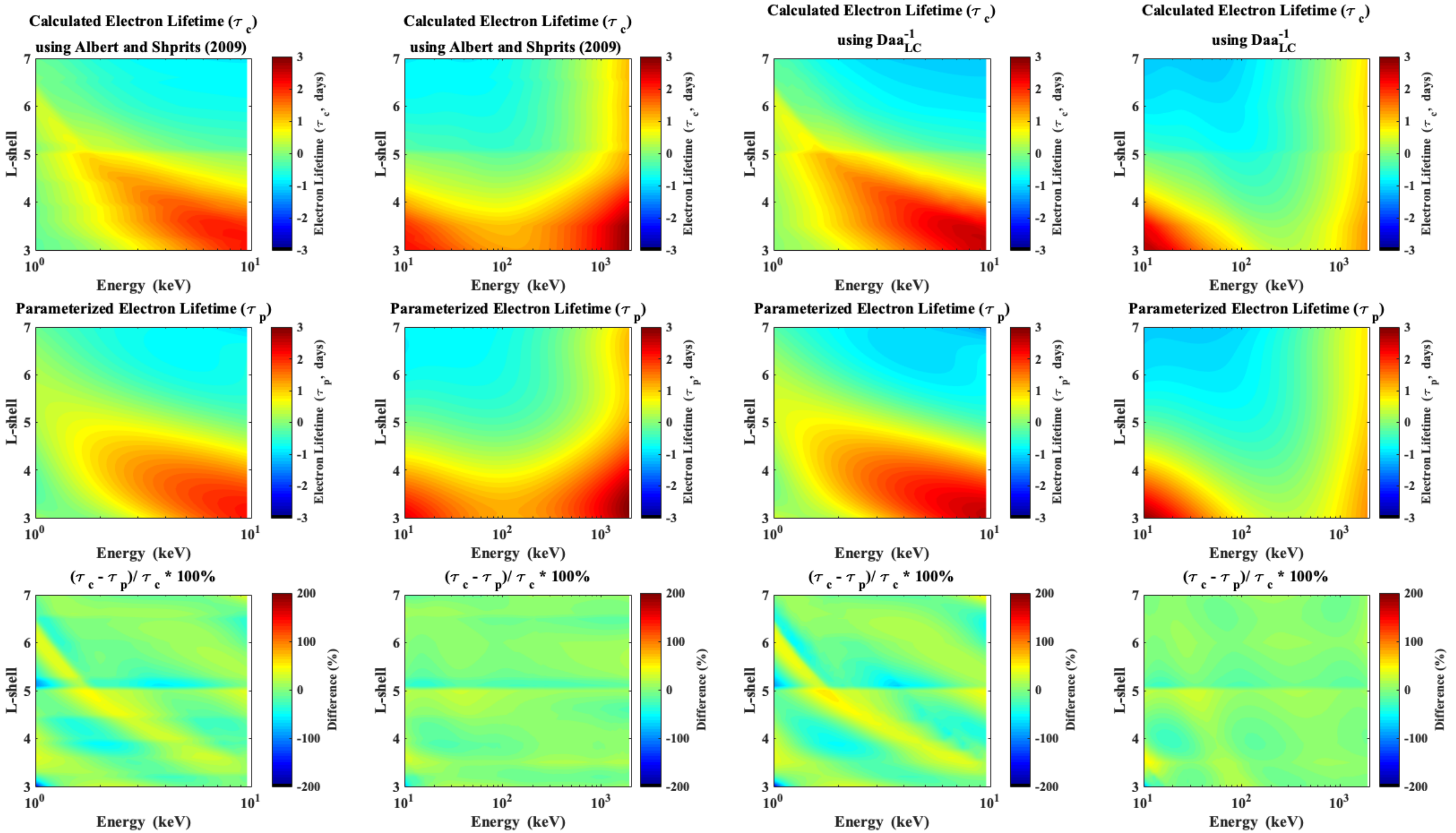
[*Wang, Shprits, Haas and Drozdov*, 2024, GRL, under review]

MLT 6, Kp 2



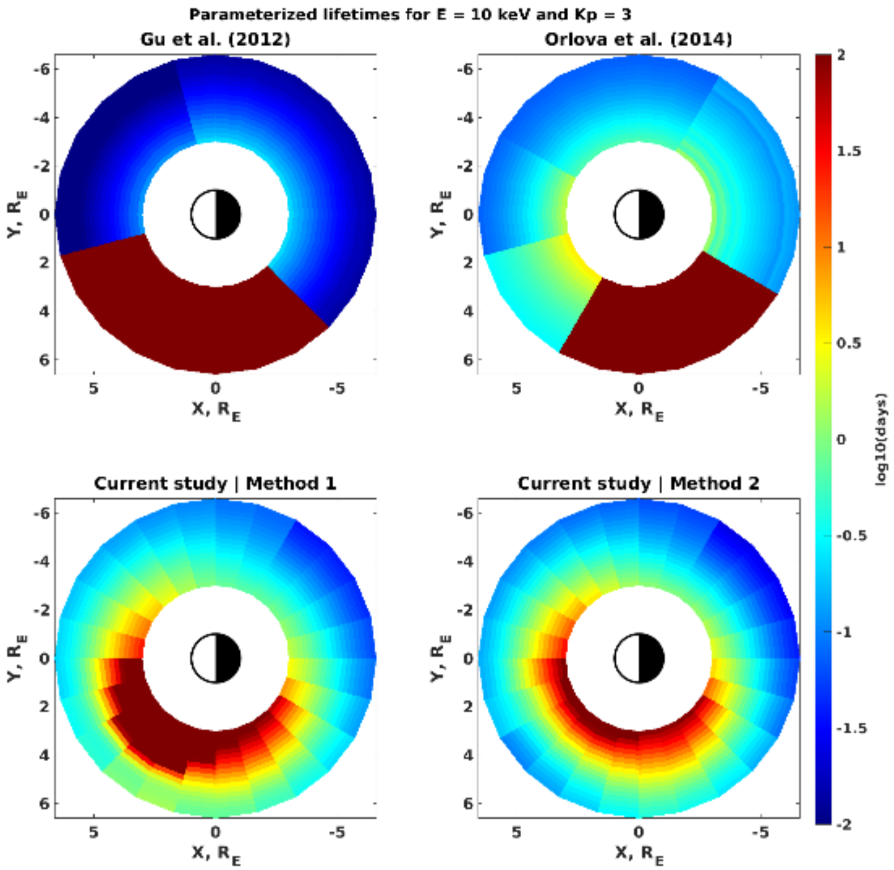
Parameterization of Electron Lifetime

Separate Energy Ranges



Improve Electron Lifetime Models Due To Chorus Waves

Two Methods, Better MLT Coverage Due to Satellite Data



- ➢ Two methods are used to estimate electron lifetime using diffusion coefficients
- ➢ New lifetime parameterization is developed and is dependent on MLT, L, energy and geomagnetic activity
- ➢ MLT coverage is better due to satellite data coverage
- ➢ Test new parameterization in inner magnetosphere codes

[*Wang, Shprits, Haas and Drozdov*, 2024, GRL, under review]

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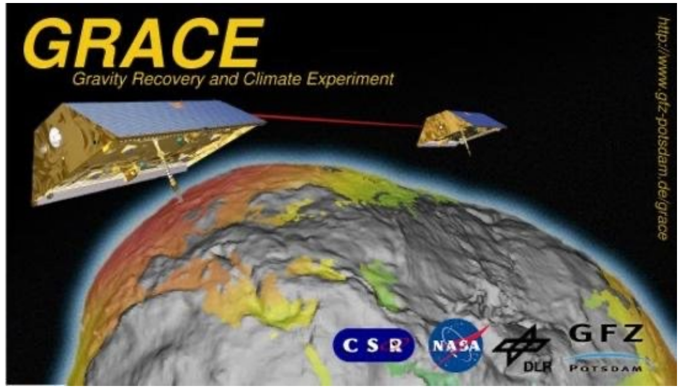
Form New Satellite Mission Concept

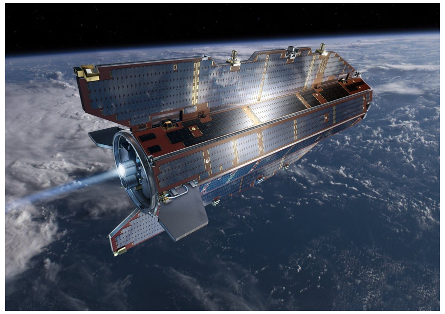
Benefit from the GFZ expertise, experiences and infrastructure

The existing GFZ infrastructure is able to help develop new missions focusing on the space environment and space weather, and a continuous monitoring of the geomagnetic field. Such initiatives are facilitated by GFZ's history of collaboration with national space agencies and satellite companies.

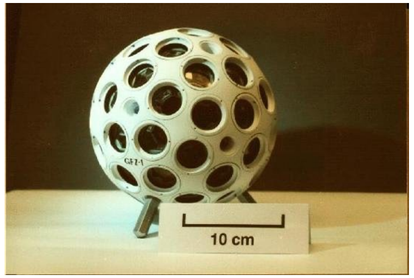


Swarm

CHAMP



GOCE



GFZ-1

Satellite Receiving Station Ny-Ålesund

Satellite Laser Ranging Station Potsdam

GFZ was and is involved in the development, manufacturing, operation, and analysis of various geoscientific satellite missions and systems. Further, a Satellite Receiving Station and a Satellite Laser Ranging Station are operated at the GFZ.

Wave Particle Interactions

Most important mechanism of driving radiation belt dynamics

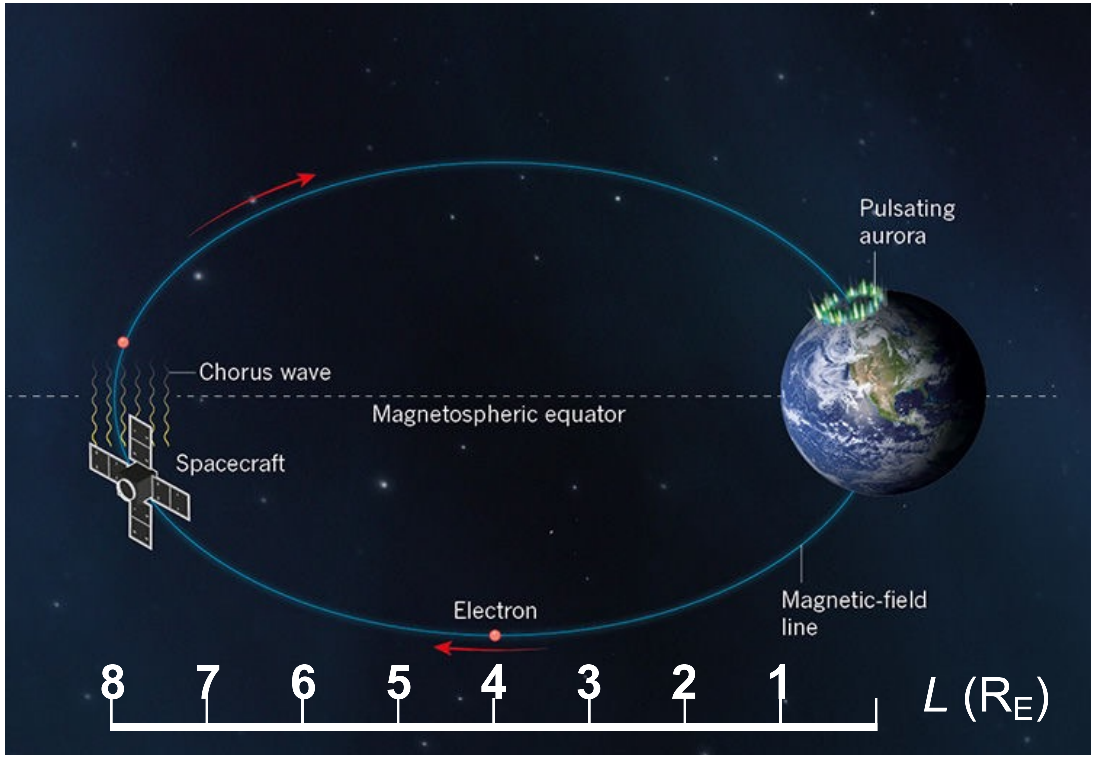
Chorus waves can cause both the acceleration and loss of energetic particles in the Earth's radiation belts.

Here we focus on the effect of loss.

How can we quantify these processes?

- ➢ Nonlinear Approach
- ➢ Quasi-linear Approach

$$\omega - k_{||} v_{||} = n\Omega_e/\gamma$$



[Kasahara et al, 2018, *Nature*]

At least we need the chorus wave information in 7 dimensions of variables: frequency, intensity, propagation direction, local time, latitude, *L*, geomagnetic activity level dependence.