Unique and Unpredictable 1-100 keV Electrons in the Earth's Magnetosphere

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1. Motivation

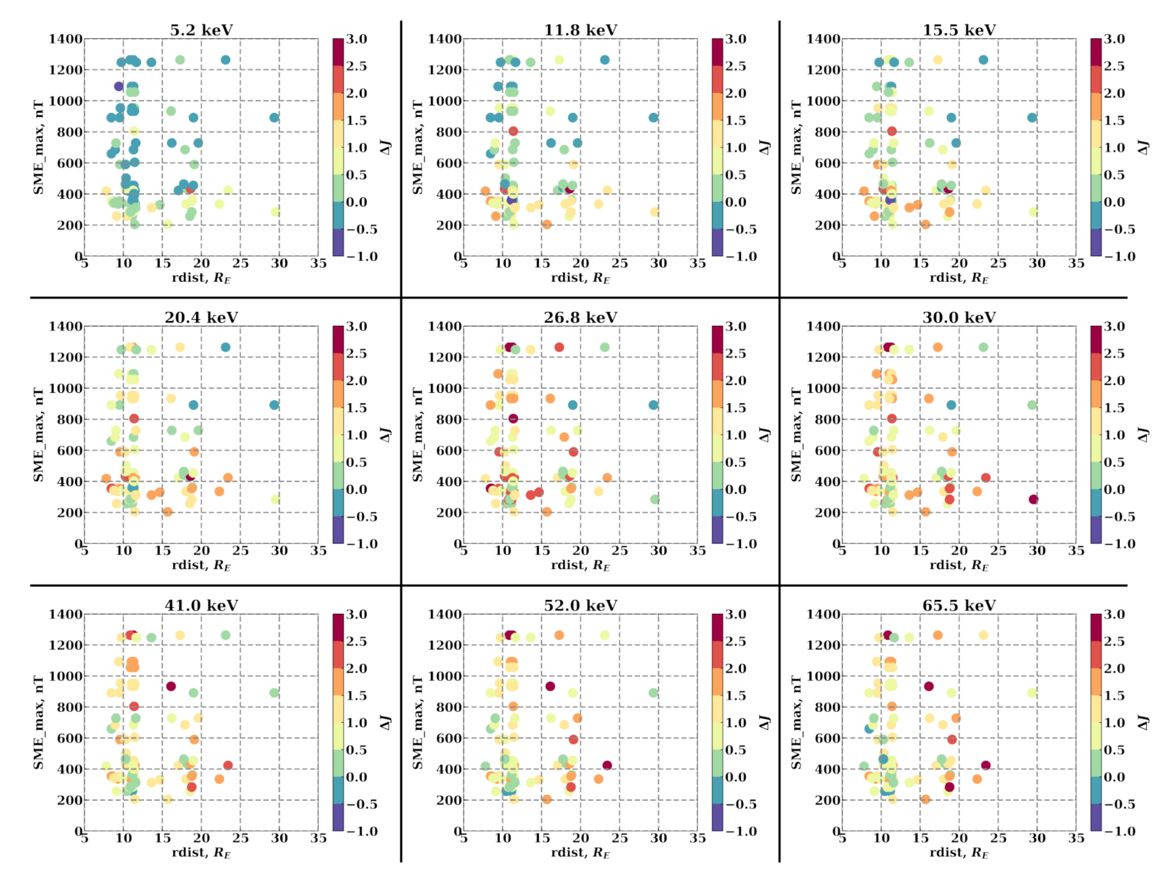
- Low energy electrons (1 to few hundreds of keV) are the "seed population" for further **acceleration to MeV energies**, critically important for **radiation belts**
- **Surface charging due to < 100 keV electrons** can cause significant damage and anomalies on satellites

KeV electrons exhibit rather complicated behavior:

- Fluxes vary on time scales of minutes and strongly depend on local time, so no averaging them over a satellite orbit as done for MeV radiation
- It is **not necessary to have even a moderate storm for significant surface charging** event to happen
- Fluxes will not be higher and surface charging will not be stronger for more intense geomagnetic storms
- Significant surface charging can occur during substorms without any clear dependence on the substorm strength
- Specification of 1-100 keV electrons at different orbits can be provided by the **operational Inner Magnetosphere Particle Transport and Acceleration model (IMPTAM, imptam.engin.umich.edu)**.
- No direct driver: no simple dependencies between flux increase and surface charging occurrences and solar wind driving parameters and geomagnetic indices
- Determine the possible drivers analyzing available datasets by statistical and ML methods

2. KeV electrons fluxes do not depend on substorm strength

45 substorms during the 2008 and 2009 THEMIS tail seasons, onset times identified by isolated substorm list by *Ohtani and Gjerloev* (2020)
Electron flux data are from the **THEMIS ESA and SST**.
We define the change in flux, ΔJ, as the log10 post-onset flux minus the log10 pre-onset flux. We looked for patterns of correlation between ΔJ and substorm strength as well as locations

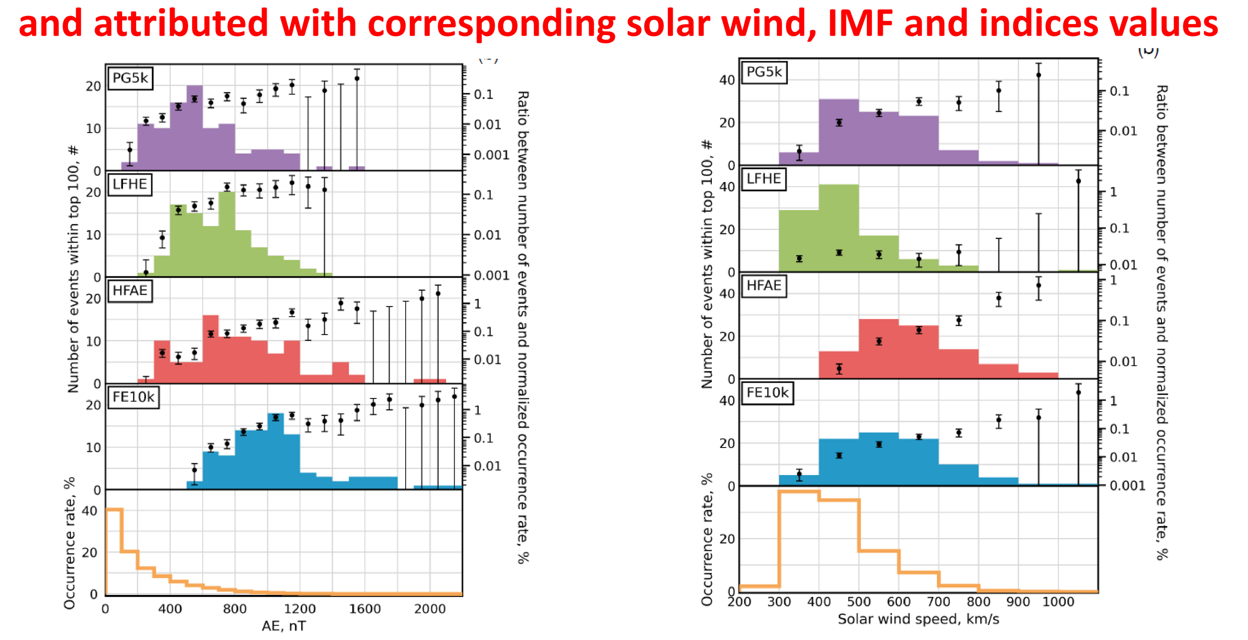


3. Surface Charging vs. Activity

Matéo-Vélez et al., Sp. W., 2018, *Ganushkina et al.*, Sp. W., 2021

- **1989- 2005 years of LANL data (MPA, SOPA, ESP) at GEO**

Best correlation with potentials is for 10-50 keV electrons
Criteria for severe conditions (15-min averaged fluxes):
(**FE10k**): highest Fluxes of electrons at Energies above 10 keV
(**HFAE**): highest Fluxes at All Energies (high fluxes at <50 keV, > 200 keV);
(**LFHE**) : high fluxes at low energies together with a Low Flux at High Energy (high fluxes at <50 keV and low fluxes at >200 keV);
(**PG5k**) : longest events with a Potential Greater than 5 kV (in absolute).
400 events with worst-case environments were identified and attributed with corresponding solar wind, IMF and indices values



It is not necessary to have extreme conditions for severe spacecraft surface charging to occur, **AE index** defines and V_{SW} is related to the highest risk. A disturbance in the magnetosphere is necessary.

4. Drivers for plasma sheet keV electrons

- Empirical models of the plasma sheet electron temperature and number density on the nightside for $6\,R_E < r < 11\,R_E$ constructed using THEMIS SST and ESA data during storms.

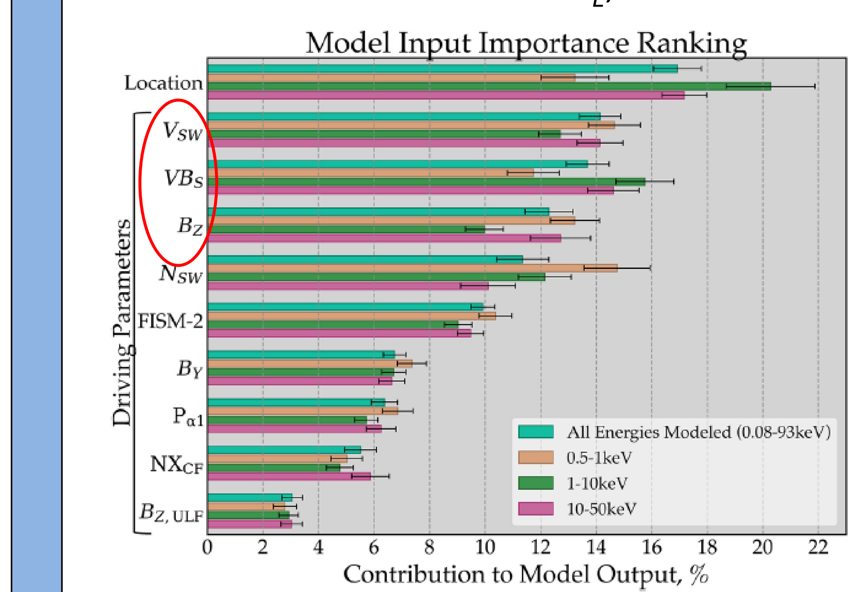
$$N_{ps} = A_1 + A_2R^* + A_3\phi^{*2}R^* + A_4\phi^{*2} + A_5N^*_{sw} + (A_6 + A_7R^*)B^*_S,$$

$$T_{ps} = \left[A_1 + A_2\phi^* + A_3V^*_{sw} + (A_4 + A_5\phi^{*2}R^*)B_S^{*A_7} + A_6R^*(B_N^*)^{A_8}\right]^{A_9},$$

Dubyagin et al., J. Geophys., 2016

Driving parameters: solar wind density N_{sw}, southward and northward IMF components, and solar wind velocity V_{sw}

- Based on 12 years of THEMIS ESA and SST data, SWPSNN (Solar Wind Plasma Sheet Neural Network) to predict differential 0.08-93 keV electron flux in the plasma sheet, at distances from 6 to 12 R_E, at 18-06 MLT.



Most important drivers: IMF B_Z-component, solar wind velocity V_{SW}, and $V_{SW}B_S$

Swiger et al., Space Weather, 2022

5. Drivers of 40-150 keV electrons at GEO

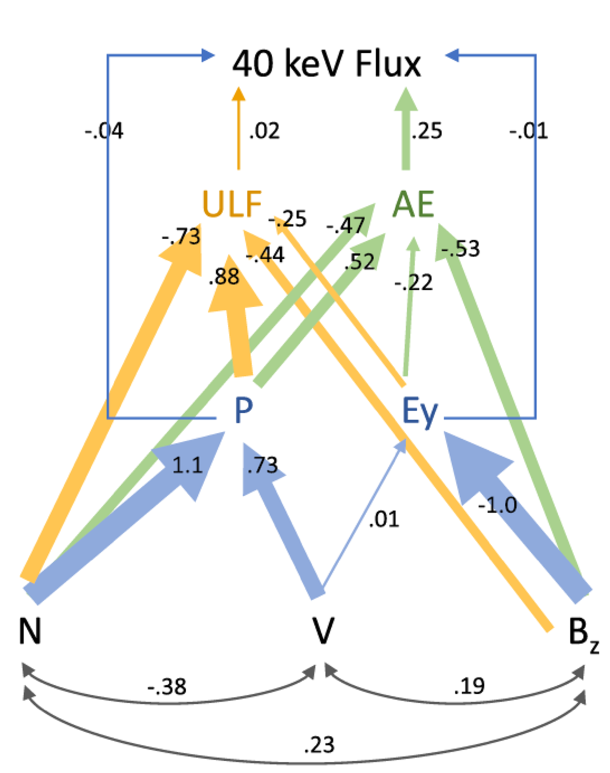
- Empirical model for flight direction integrated differential electron fluxes f_{EMP} (in 1/(cm² s sr keV)) at GEO based on GOES 13-15 MAGED data

$$f_{EMP} = a1 \cdot 10^{V_{SW}(a2 \cdot sMLT + a3 \cdot cMLT + a4)} + b1 \cdot \exp\left[-\frac{12 - ||MLT - b2| - 12|}{b3} - \left(\frac{B_z + 11}{8}\right)^3\right] + c1,$$

Sillanpää et al., Space Weather, 2017

Driving parameters: solar wind velocity V_{SW} and IMF B_Z

- Hourly electron flux at GEO (GOES 13), ARMAX help to remove the confounding effect of diurnal cyclicity and allow assessment of each parameter independently. ARMAX models show substorms (AE index) are the dominant influence at 40–75 keV and over 20–12 MLT, with little difference between disturbed and quiet periods.



Causal model with the standardized regression coefficients obtained by predicting 40 keV flux from *AE*, *ULF*, *P*, and *Ey*.

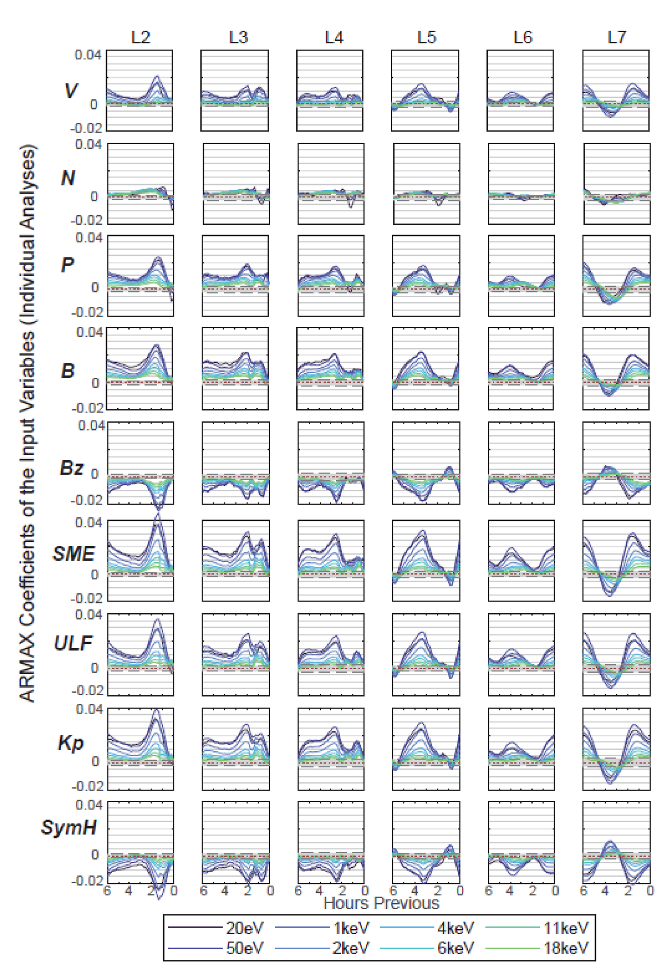
Indirect Drivers (*N*, *V*, and *Bz*)

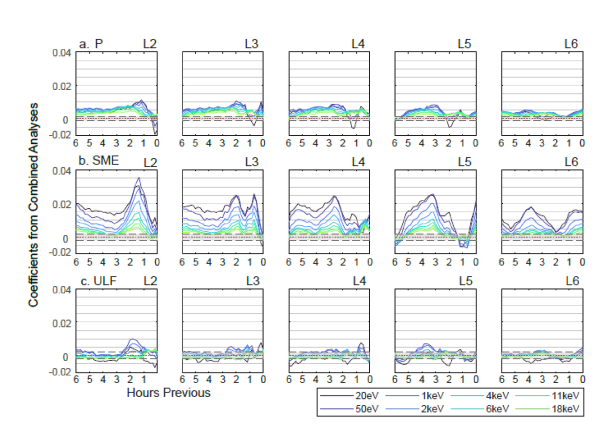
Although *Kp*, *SymH*, and *AE* show high simple (single variable) correlations with electron flux, the influences of *Kp* and *SymH* disappear in a full regression model with other variables included.

Simms et al., J. Geophys. Res., 2022; *Space Weather*, 2023

6. Drivers for keV electrons inside GEO

3 min averaged, unidirectional electron flux data (20 eV- 2 MeV) from the RBSP-A satellite over Feb 2013-Dec 2018 over L= 2-7 from REPT, HOPE and MagEIS instruments.





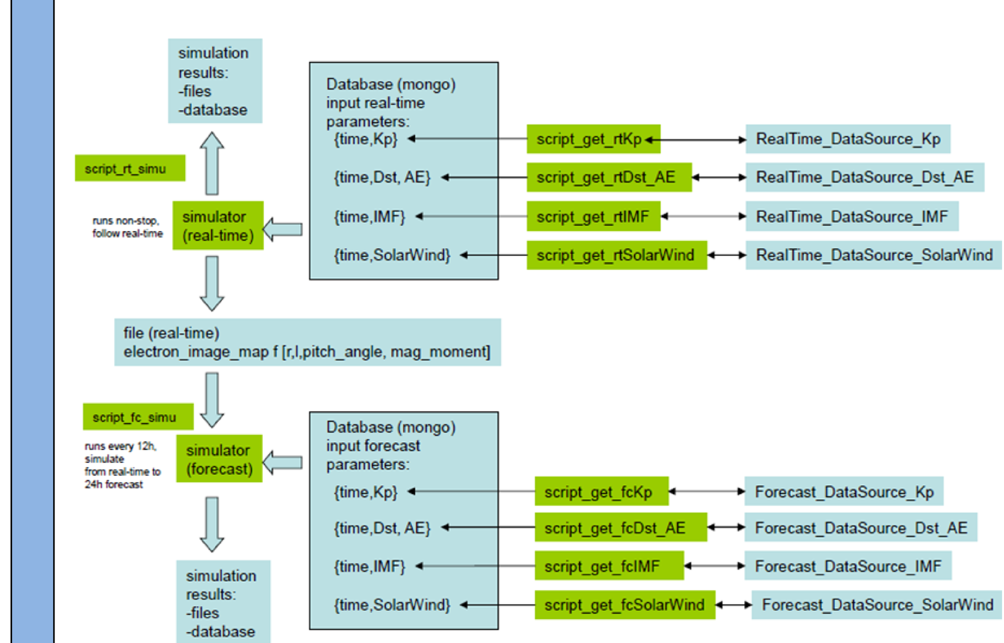
Simms et al., J. Geophys. Res., 2024

Solar wind velocity and pressure (but not number density), IMF magnitude (with lower influence of Bz), SME (a substorm measure), a ULF wave index, and geomagnetic indices Kp and SymH show associations with electron flux in the ARMAX individual analyses.

Only substorms (electron injection), ULF waves (radial diffusion), and pressure (magnetosphere compression) are direct drivers of electron flux.
In a combined analysis, SME is the strongest influence. ULF waves are most influential at the 1-2 MeV energies. Pressure is less associated with flux.

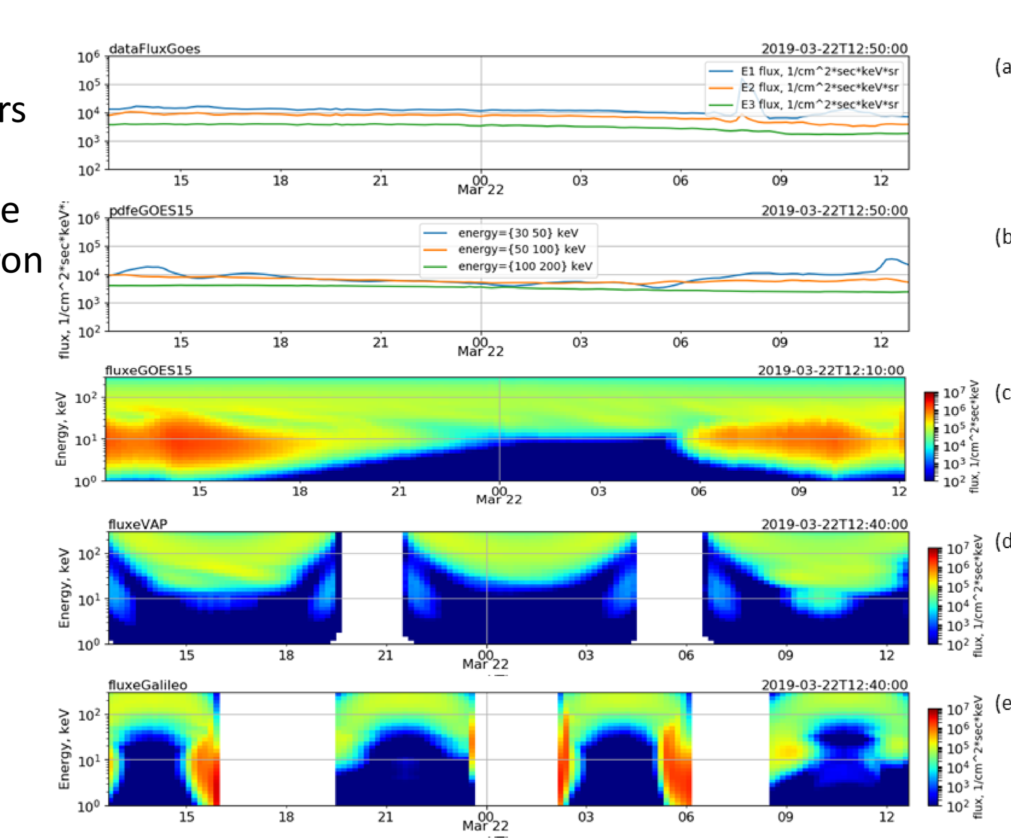
7. Operational imptam.engin.umich.edu

Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
(*Ganushkina et al., JGR, 2013, 2014, Space Weather, 2015, 2019*)



The IMPTAM is driven by
(1) Solar wind number density,
(2) Solar wind dynamic pressure,
(3) Solar wind velocity,
(4) IMF B_Y, B_Z, and B_{IMF},
(5) Dst index,
(6) Kp index.

If these driving parameters are available in near real time, IMPTAM can provide the nowcast of keV electron fluxes in the inner magnetosphere.
If the parameters can be forecasted some time in advance, then IMPTAM can forecast these keV electrons.



8. Summary

✓ KeV electrons constitute radiation environment which contributes to surface charging effect on satellite

✓ They vary in time and location in the Earth's magnetosphere, so that a satellite can experience surface charging at one part and nothing at all at the other part of its orbit

✓ No simple, direct dependencies between keV electron flux increases/surface charging occurrences and solar wind driving parameters

✓ Data analysis tells us that we need to monitor solar wind velocity, Bz-component of IMF and substorm index AE (SME): they might work as possible proxies for keV electron fluxes

✓ Substorms are the most dominant factor

✓ **It is not necessary to have extreme conditions** (storms) for severe spacecraft surface

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