A new outlook at Uranus' and Neptune's 10 keV-5 MeV energy electron distributions from data analyses and physics-based models

Daniel Santos-Costa[1]

[1]Southwest Research Institute

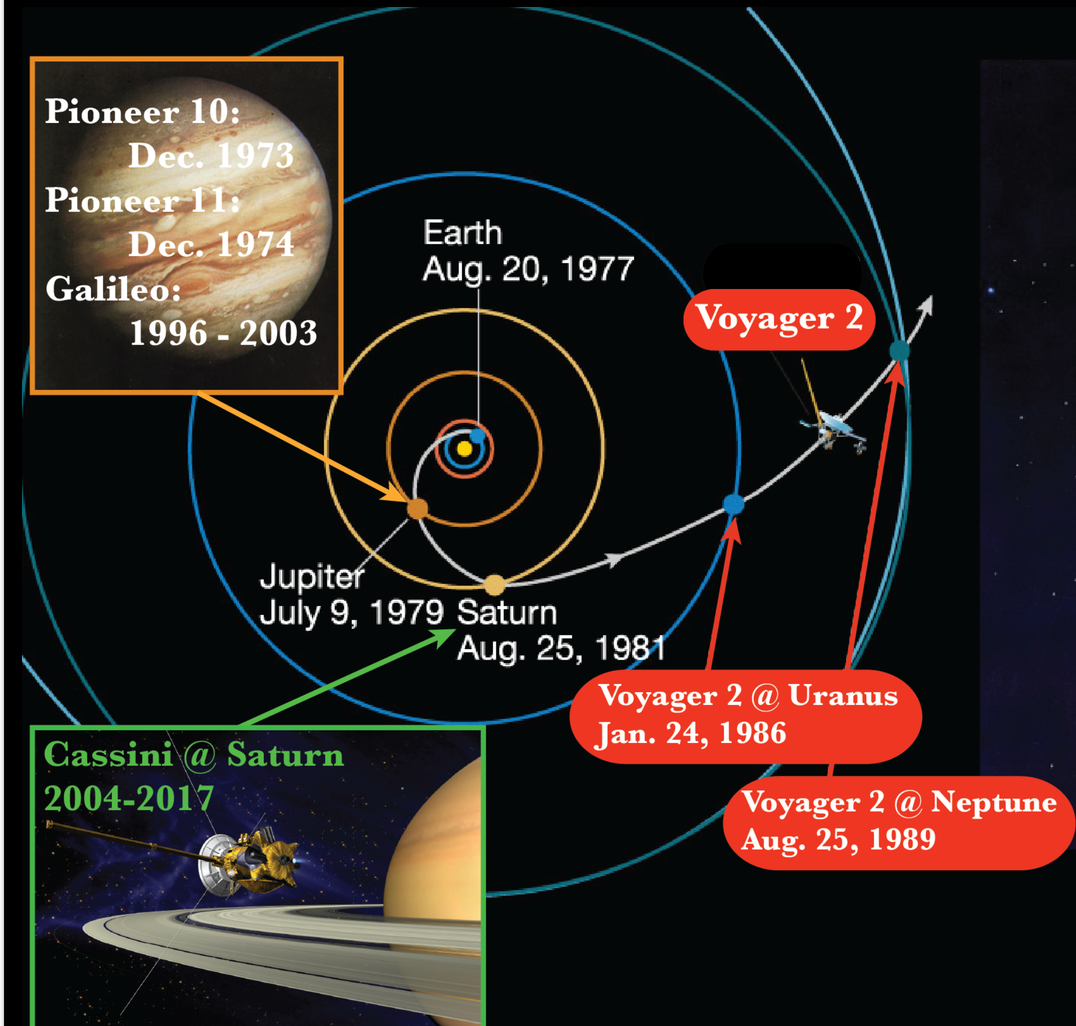
November 21, 2022

Abstract

We present our latest understanding of the processes that shape the spatial distributions of energetic electrons trapped in the magnetospheres of Uranus (L $<$ 15) and Neptune (L $<$ 25). To determine what controls the energy and spatial distributions throughout the different magnetospheres, we compute the time evolution of particle distributions with the help of a diffusion theory particle transport code that solves the governing 3-D Fokker-Planck equation. Different mechanisms of particle loss, source and transport are numerically examined. Our theoretical modeling is guided by the analysis of particle, field and wave data collected during Voyager 2's flyby of Uranus in January 1986 and at Neptune in August 1989. Our preliminary data-model comparison results at Uranus show that adiabatic transport cannot explain the radial and angular features of warm to ultra-relativistic electron populations within the ˜1-15 L region. Our simulation results also suggest that, with absence of loss mechanisms inside L = 15, energetic and radiation-belt electron populations would be higher by 1-3 orders of magnitude in intensity close to the planet (L ˜ 1-8). Particularly, our results confirm that moon sweeping effect is a significant loss mechanism at Uranus. Nonetheless, other radial, energy and pitch-angle dependent mechanisms seem to be missing to explain the in-situ data. We will thus present our ongoing effort to examine the role of - for instance, Uranus' rings system, atomic hydrogen corona and wave activity inward of L ˜ 8-10 to improve our modeling of Uranus' electron populations between L values of 1 and 15. Our first physics-based model of energetic electrons at Neptune will be presented, emphasizing first the role of radial transport and moon sweeping effect for the 1-25 L region before investigating new processes. Our models developed for Uranus and Neptune are based on the theoretical modeling of electron distributions at Saturn, which included the modeling of radial transport and interactions of electrons with Saturn's dust/neutral/plasma environments and waves, as well as particle sources from high-latitudes, interchange injections, and outer magnetospheric region. Comparisons between the distributions of electron populations at Gas and Ice Giant systems will be discussed. Data analysis, theoretical modeling, and numerical computations for Uranus and Neptune are carried out by adapting the Kronian modeling tools developed at Southwest Research Institute to the Ice Giants environment. Key data analysis, theoretical modeling, and numerical computational tasks for Saturn were carried out at Southwest Research Institute under NASA GSFC grant 80NSSC18K1100.

A new outlook at Uranus' and Neptune's 10 keV - 5 MeV energy electron distributions from data analyses and physics-based models

Daniel Santos-Costa, Southwest Research Institute, TX USA (dsantoscosta@swri.edu)

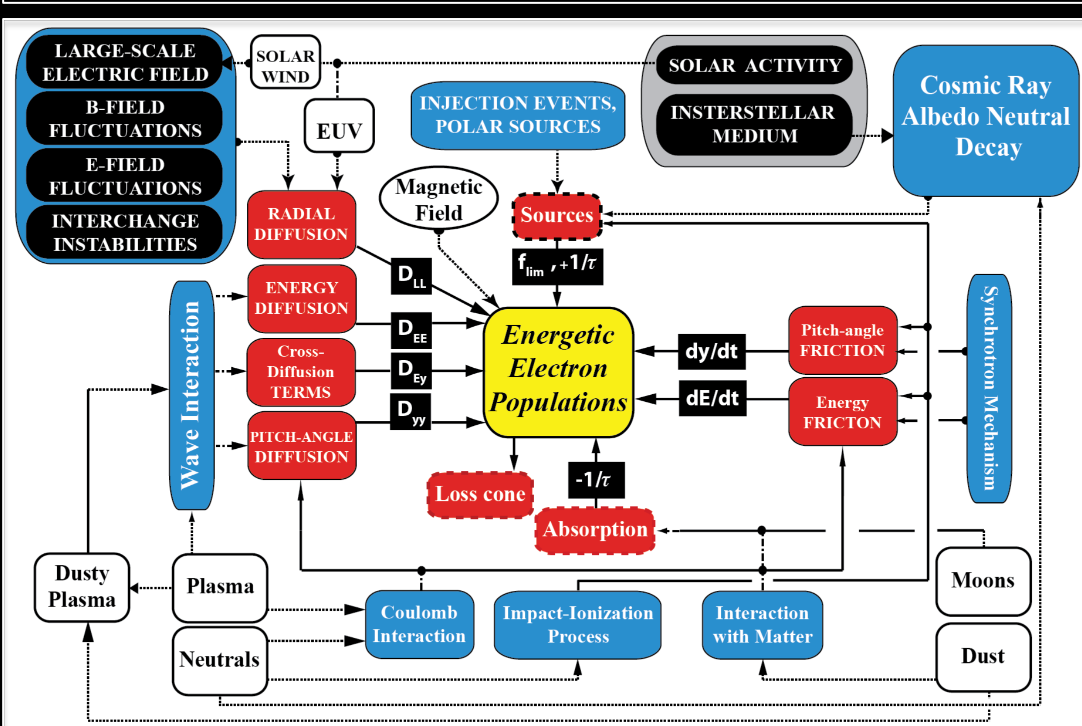


- Discuss the role of different mechanisms within the magnetospheres of Uranus and Neptune.
- Data analysis and interpretation of Voyager 2's in-situ data are guided by a theoretical modeling of the energetic electron populations.
- We compare our preliminary results at Ice Giants with our current understanding of processes at play at Saturn.

MODELING APPROACH AND DATA SETS

We model the energy and spatial distributions of electrons in the different magnetospheres with the help of a diffusion theory particle transport code that solves the governing three-dimensional Fokker-Planck equation:

$$\begin{aligned}\frac{\partial f(J_1,J_2,J_3,t)}{\partial t} &= (S)+(L)+\frac{1}{G}\frac{\partial}{\partial L}\left[GD_{LL}\frac{\partial f(M,J,L,t)}{\partial L}\right]_{M,J}\\ &- \frac{1}{G'}\sum_{i=1,2}\frac{\partial}{\partial Q_i}\left[G'\left(\frac{dQ_i}{dt}\right)f(E,y,L,t)\right]\\ &+ \frac{1}{G'}\sum_{i,j=1,2}\frac{\partial}{\partial Q_i}\left[G'D_{ij}\frac{\partial f(E,y,L,t)}{\partial Q_j}\right] \qquad (1)\end{aligned}$$



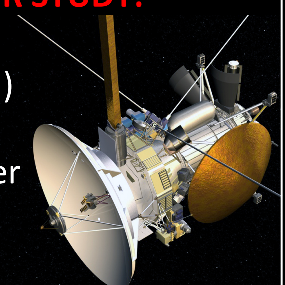
Theoretical approach for our three-dimensional modeling of electron populations at outer planets.

VOYAGER 2 DATA SETS FOR OUR STUDY:

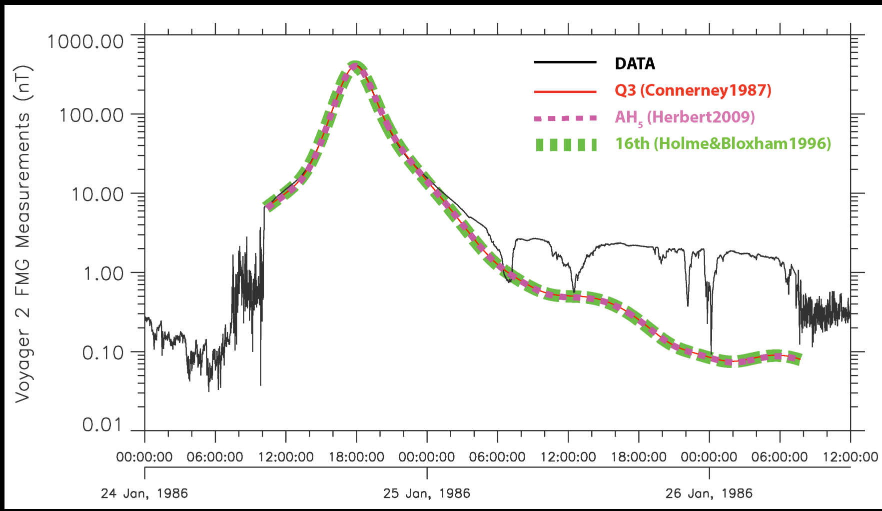
- from magnetometer (MAG)
- from Low Energy Charged Particle instrument (LECP)
- from Cosmic Ray System (CRS)
- from Plasma Wave Subsystem (PWS)

CASSINI DATA SETS FOR OUR STUDY:

- from magnetometer (MAG)
- from Electron Spectrometer (CAPS/ELS)
- from Low-Energy Magnetospheric Measurements System (MIMI/LEMMS)
- from Radio & Plasma Wave Science instrument (RPWS)

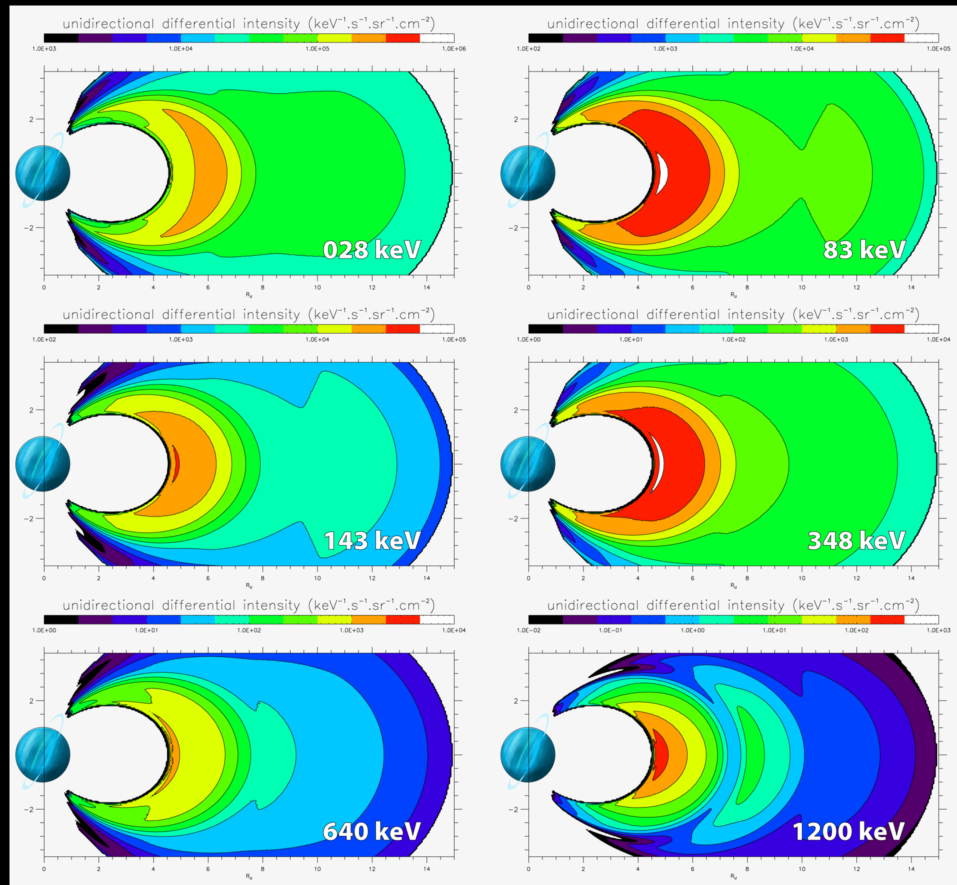


INVESTIGATING URANUS ENERGETIC ELECTRON POPULATIONS (1/2)



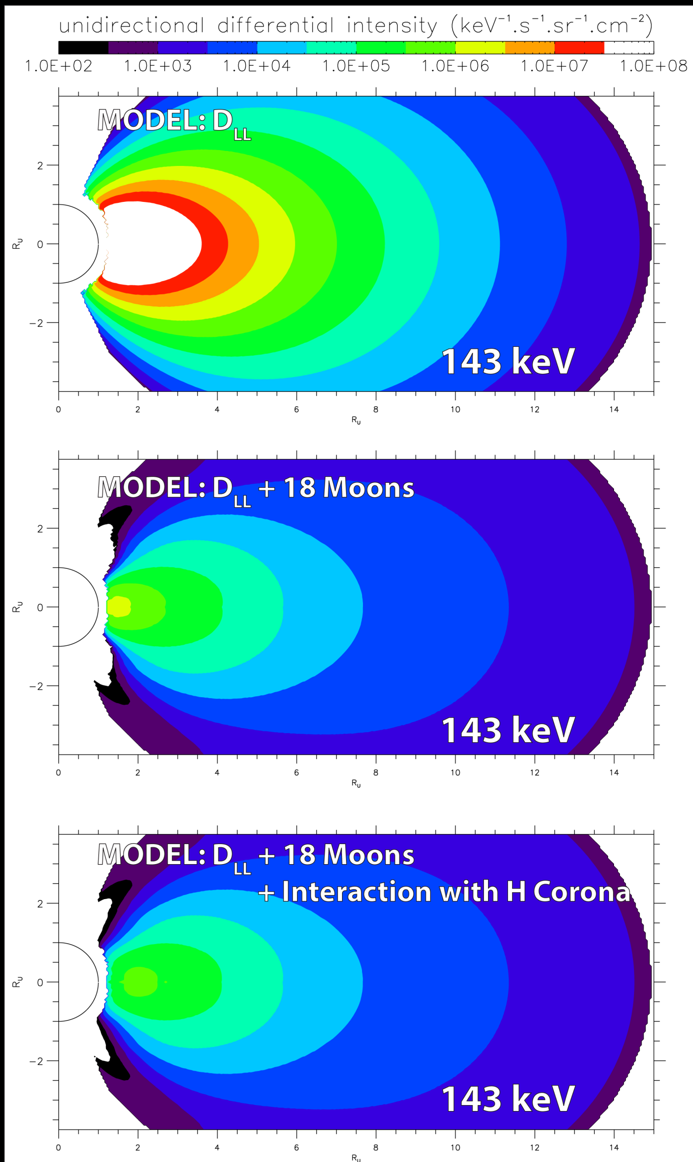
Left-hand panel: Magnitude of magnetic field (48-s averages) and comparisons with magnetic field models. The Q3 model is used in the present work.

after *Santos-Costa, "Reappraising the Distributions of Energetic Electrons at Jupiter, Saturn and Uranus from Data Analyses and Physics-based Models", Earth and Space Science Open Archive, doi: 10.1002/essoar.10505829.1, 2021*



Right set of panels: Meridian profiles of the Uranian energetic electron population inferred from in-situ data (after Mauk et al., 1987; Selesnick and Stone, 1991; Garrett et al., 2015). Note that there is an absence of data inside ~4.2 R_U that prevents to empirically model the charged particle environment close to the planet.

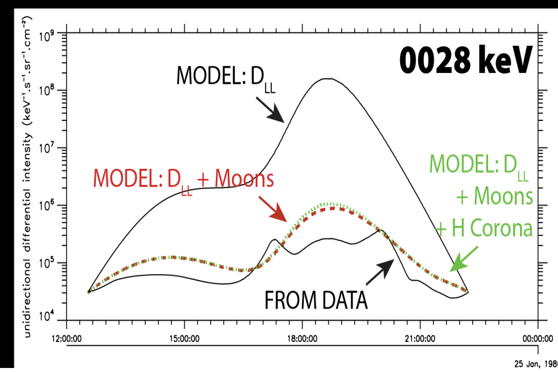
INVESTIGATING URANUS ENERGETIC ELECTRON POPULATIONS (2/2)

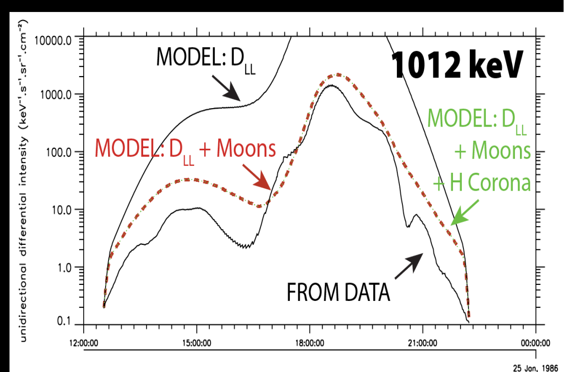


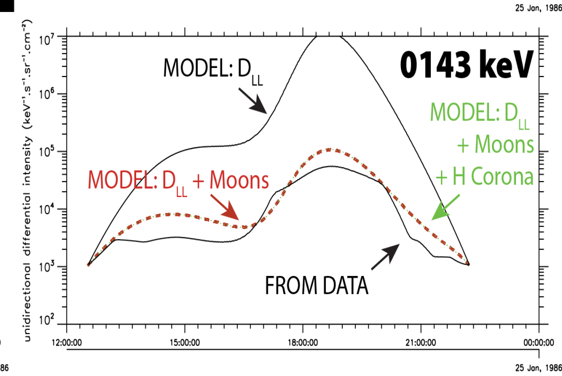
Left set of panels: Simulated meridian profiles of the Uranian energetic electron population when model accounts only for radial diffusion (top), radial diffusion and sweeping effect by 18 moons (middle), and all previous processes + interaction with H corona (bottom).

Bottom right panels: Comparisons between data and simulations along Voyager 2's trajectory for different LECP energy channels. Three sets of model results are discussed for each energy:

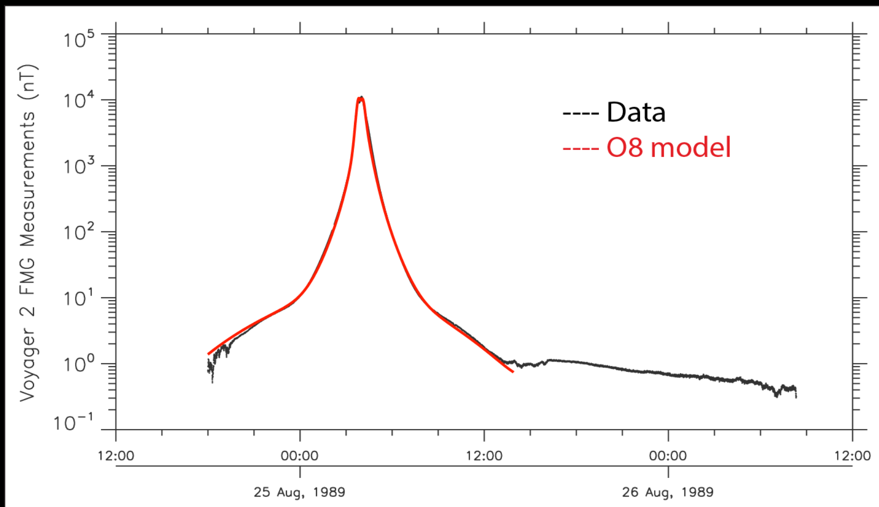
1. Radial diffusion D_{LL}
2. D_{LL} + sweeping effect by 18 moons
3. D_{LL} + sweeping effect by 18 moons + interaction with H corona



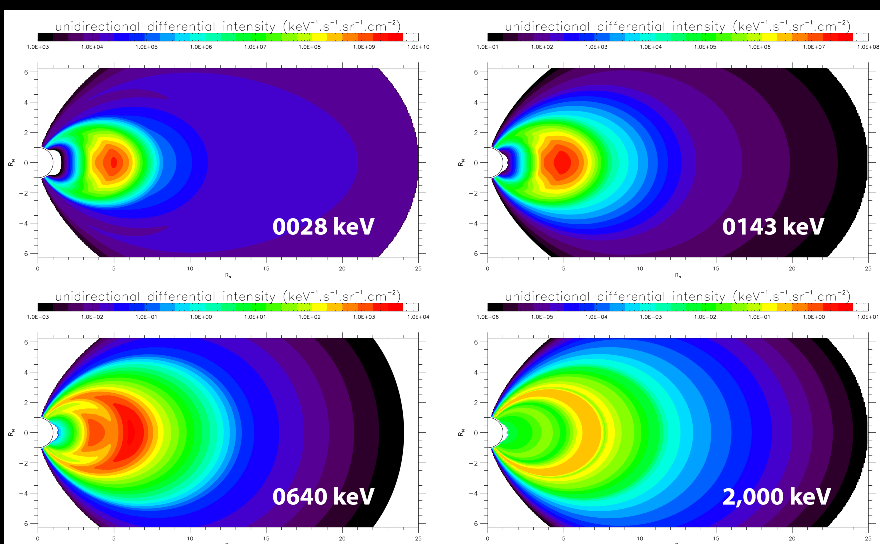


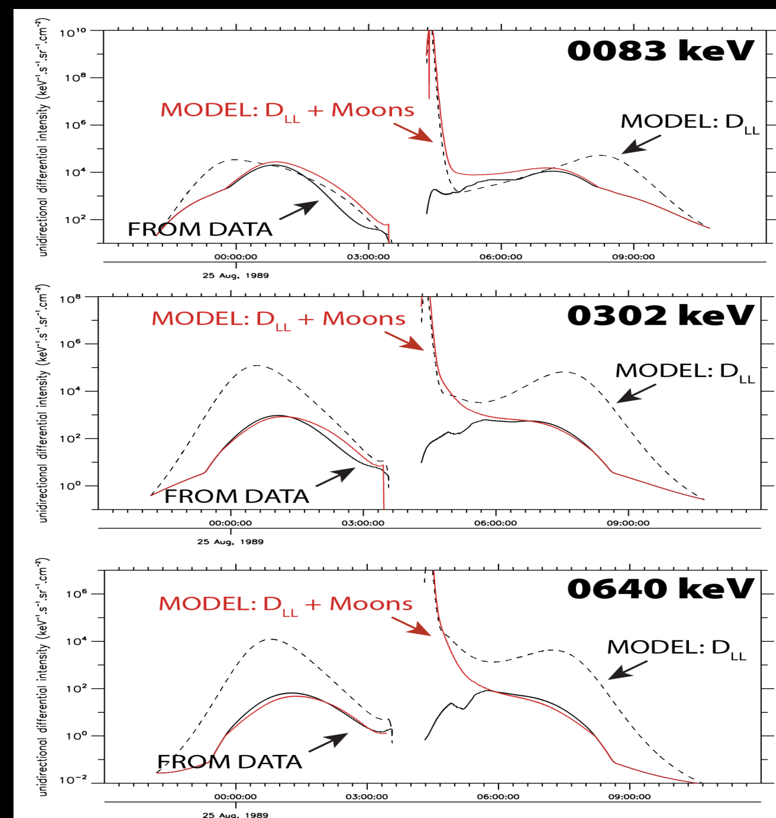


INVESTIGATING NEPTUNE'S ENERGETIC ELECTRON POPULATIONS (1/1)



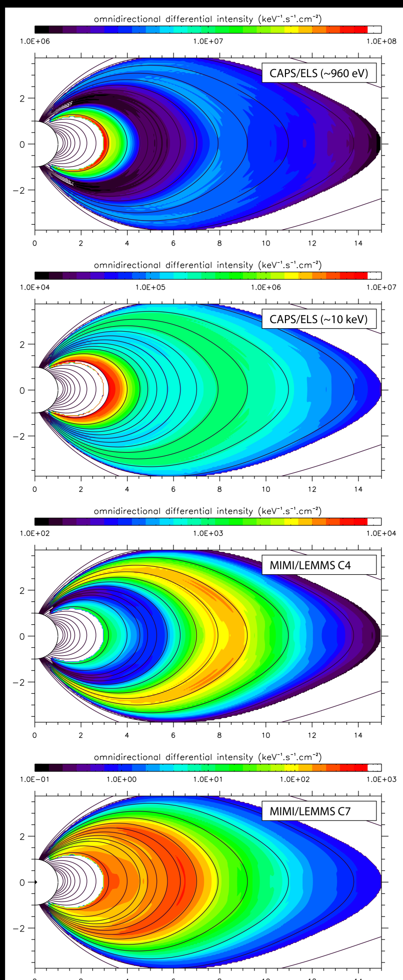
Left-hand panel: Magnitude of magnetic field (48-s averages) and comparison with magnetic field model. The O8 model is used in the present work (Connerney et al., 1991). **Lower left panels:** Meridian profiles of Neptune's energetic electron population inferred from in-situ data (after Mauk et al., 1991; Stone et al., 1989; Garrett & Evans, 2017). **Below panels:** Samples of simulation results demonstrating the coupled role of radial transport and moon sweeping effect.

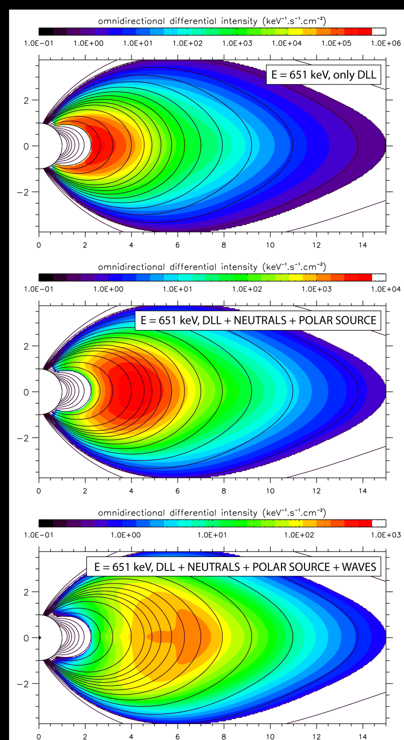


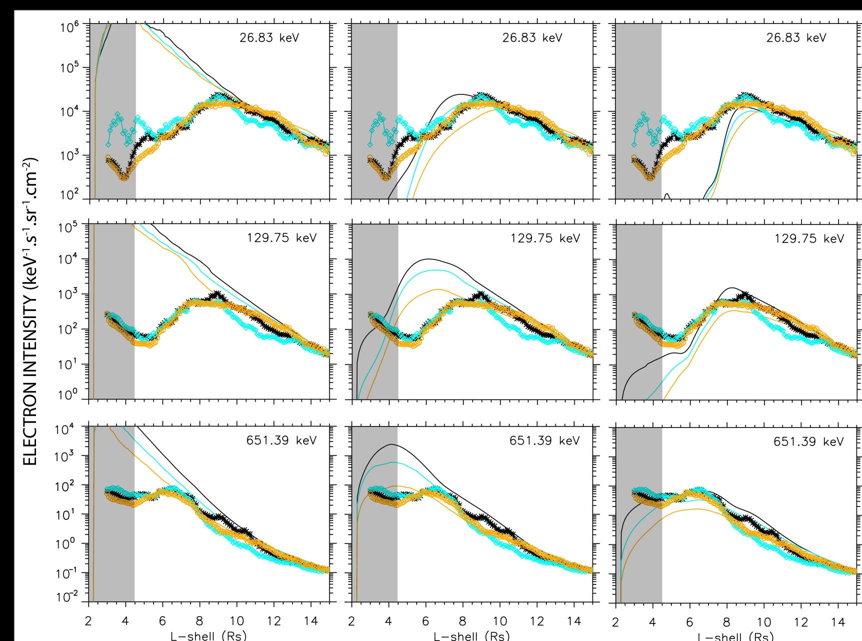


INVESTIGATING SATURN'S ENERGETIC ELECTRON POPULATIONS (1/1)

Left set of panels: Samples of mission-averaged data for different energy channels of CAPS/ELS and MIMI/LEMMS instruments. **Middle set of panels:** Samples of simulations results with different processes taken into account. **Right set of panels:** Samples of comparisons between MIMI/LEMMS data and models when simulations included only radial transport (left-hand panels), combined radial diffusion with interaction with neutrals and a polar source (middle panels), and accounted for all previous mechanisms + wave interaction (right-hand panels). Symbols are used to display the data. Black color is used to display radial profiles for 80^0, cyan for 40^0, and orange for 20^0 pitch-angle.







after *Santos-Costa, "Reappraising the Distributions of Energetic Electrons at Jupiter, Saturn and Uranus from Data Analyses and Physics-based Models", Earth and Space Science Open Archive, doi: 10.1002/essoar.10505829.1, 2021*