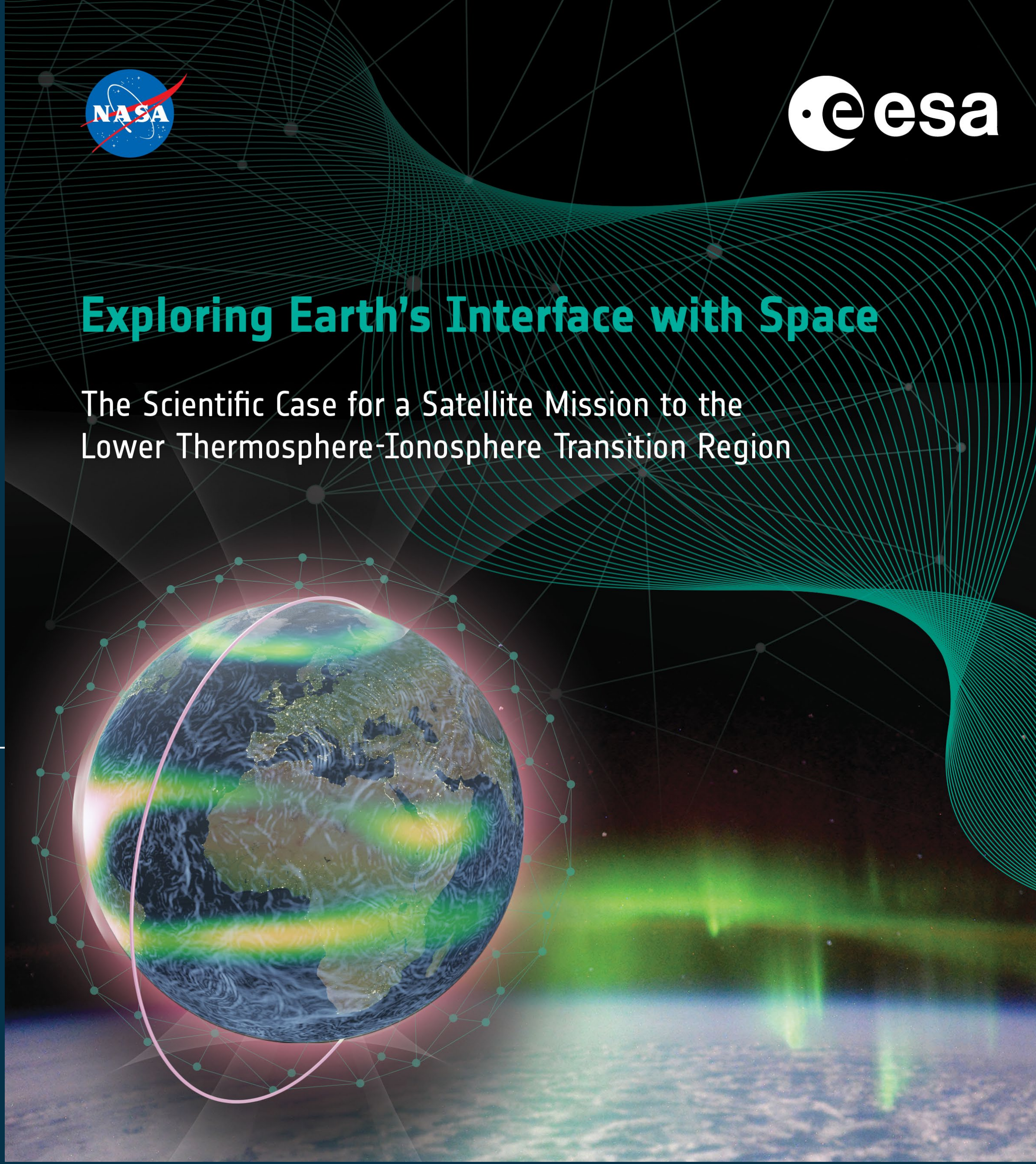
ENLoTIS: ESA-NASA Lower Thermosphere Ionosphere Science Report

Jeff Thayer
University of Colorado

2024-09-24

ESA/NASA (2024). Exploring Earth's Interface with Space – The Scientific Case for a Satellite Mission to the Lower Thermosphere-Ionosphere Transition Region, European Space Agency (ESA), Noordwijk, The Netherlands and National Aeronautics and Space Administration (NASA), Washington DC, United States of America, ESA-EOPSM-ELTI-RP-4592, 128 pp., http://doi.org/10.5270/ESA-NASA.LTI-SC.2024-07-v1.0

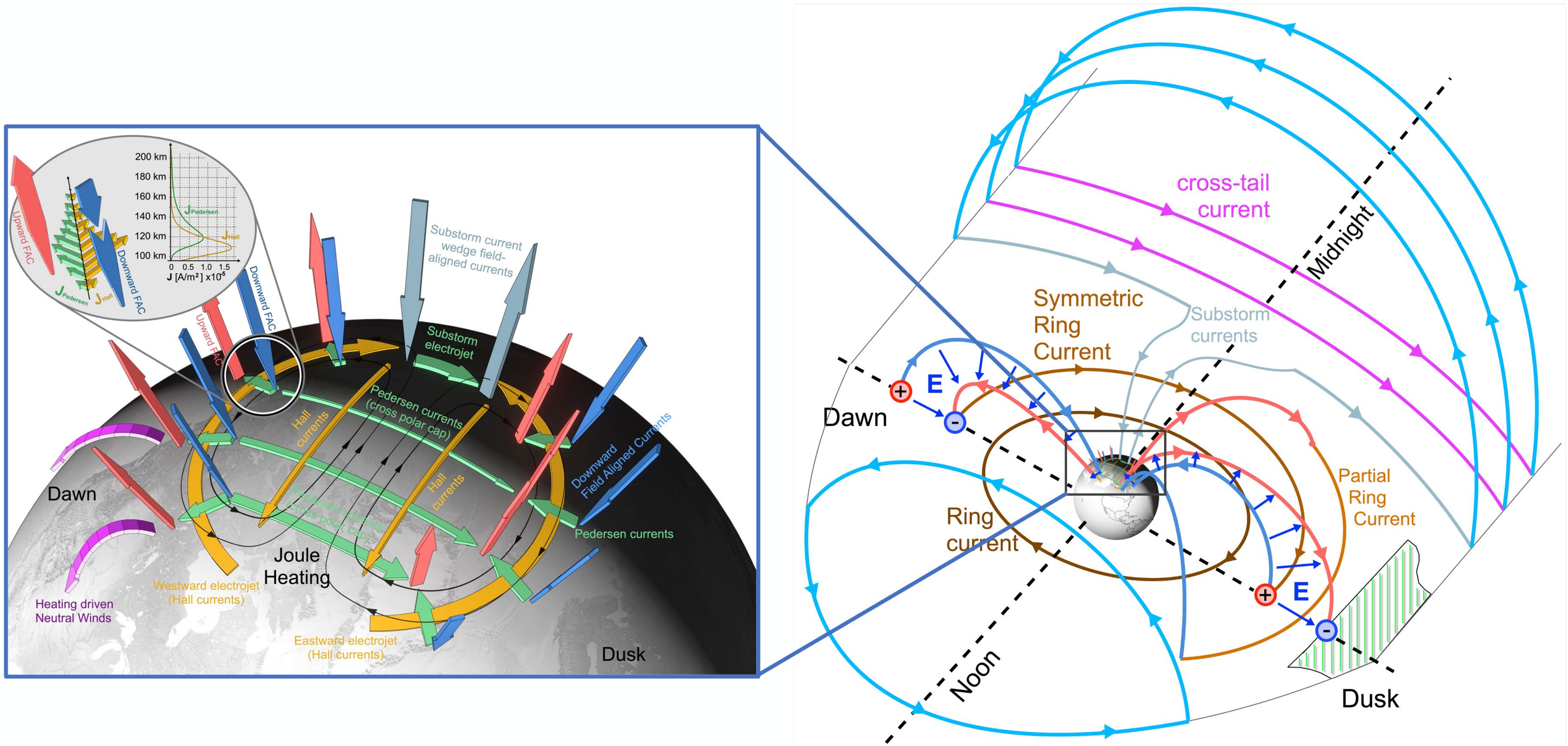


We Live in an Electrified World

Part of a Global Electric Circuit

Part of a Planetary Electric Circuit

Electrified Geospace: A Planetary Electric Circuit



What is ENLoTIS?

https://science.nasa.gov/science-news/NASA_and_ESA_Exploring_New_Joint_Satellite_Mission_Concepts

ENLoTIS Working Group Members	
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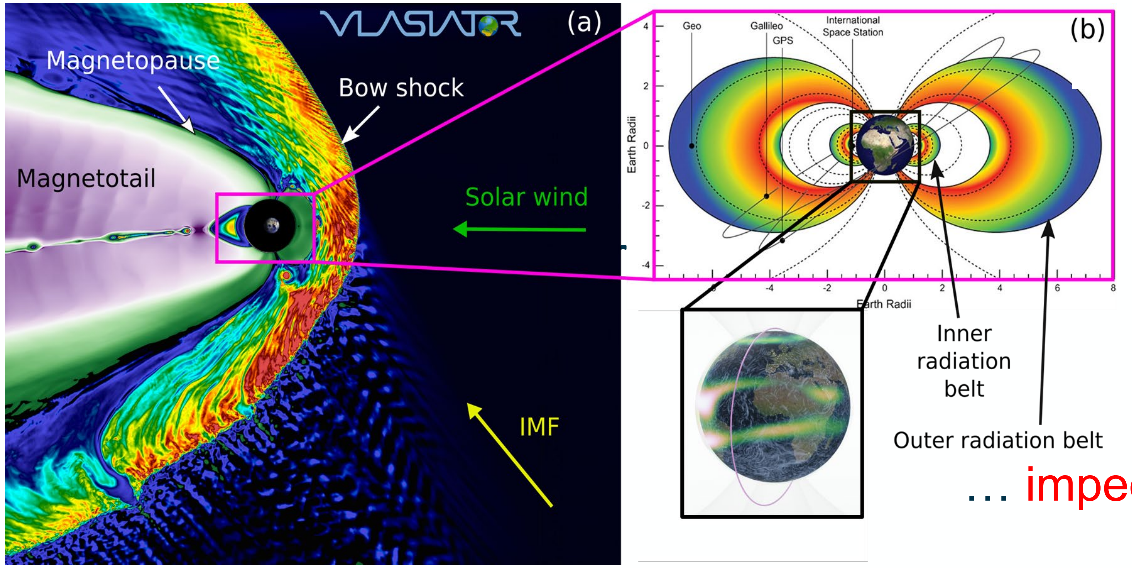
- ❑ EN-LoTIS Working Group explores agency cooperation on future lower thermosphere-ionosphere (LTI) satellite mission concepts, targeting *in situ observations* that advance understanding of neutral-ion interactions from 100 - 200 km altitude and the ionospheric E region.
- ❑ Concept of low-flying LTI mission poses unique scientific & technical challenges. Joint ESA/NASA collaboration proposed to help address these challenges.
- ❑ Initial phase of WG provides information via science study report to help agencies plan possible future joint mission development.
- ❑ **Report now available.**

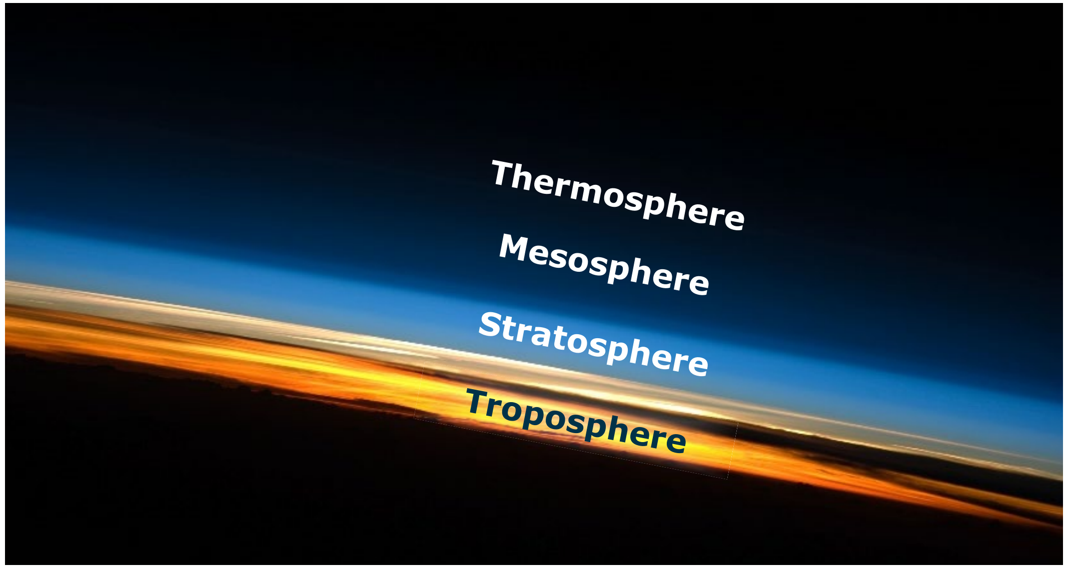
ENLoTIS Steering Committee:
John McCormack, Alex Hoffmann
David Cheney, Larry Kepko, Anja Stromme, Matt Taylor

Why ENLoTIS?

Inadequate knowledge of the transition from atmosphere to space …

… prevents understanding of how Earth's atmosphere and space are linked





… impedes efforts to understand the Sun-Earth system as a whole

… inhibits accurate predictions of the behavior of humanity's space-faring and space-reliant systems

EN-LoTIS WG is studying the first systematic, comprehensive *in situ* exploration of a collision-dominated, neutral-plasma space environment.

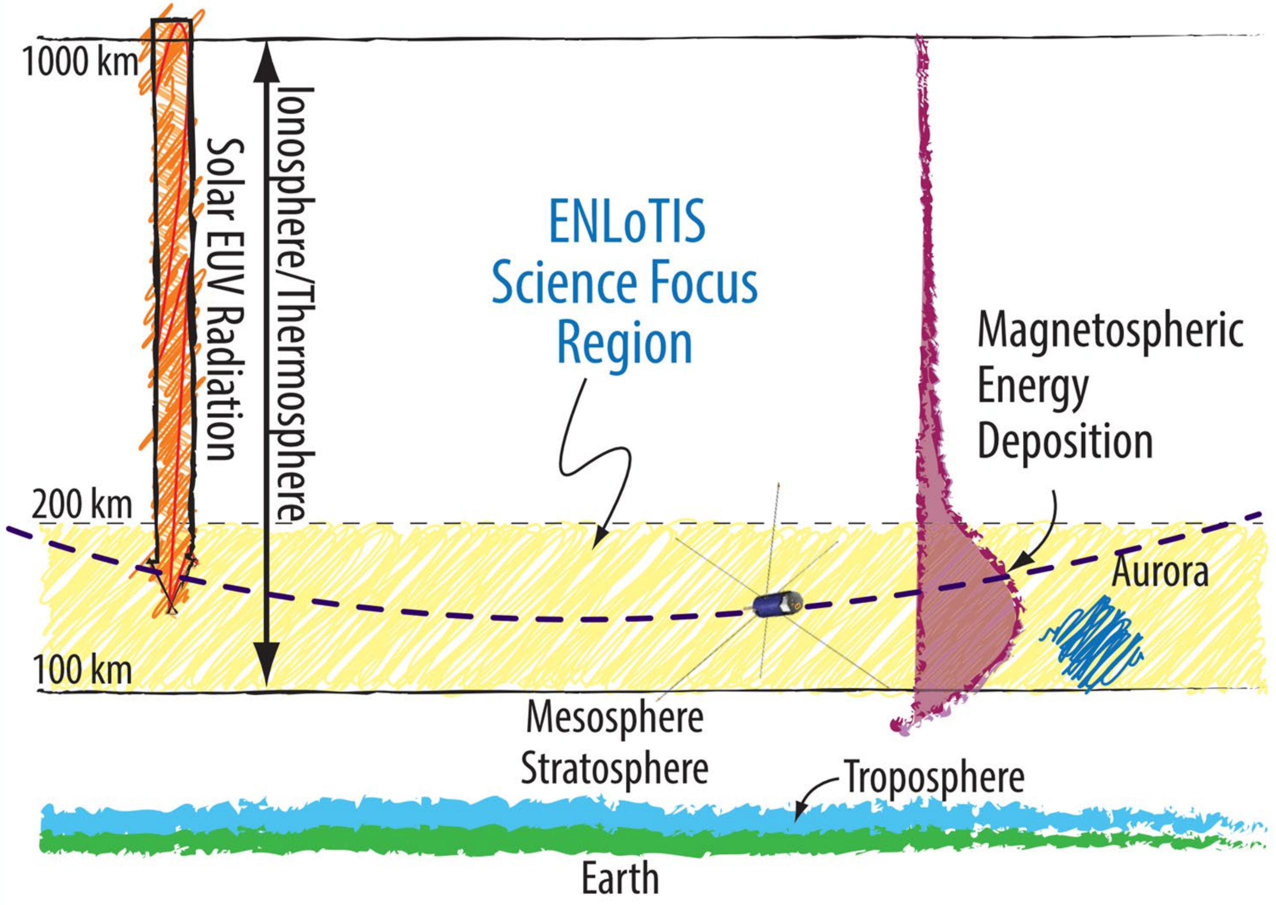
Science of Earth's Lower-Thermosphere-Ionosphere

LTI behavior consists of interactions among commingled matter and fields:

- **Neutral gas (thermosphere)**
- **Plasma (ionosphere)**
- **Electric and magnetic fields**

Frequent collisions between neutral and charged particles results in emergent behavior* not present in simpler systems

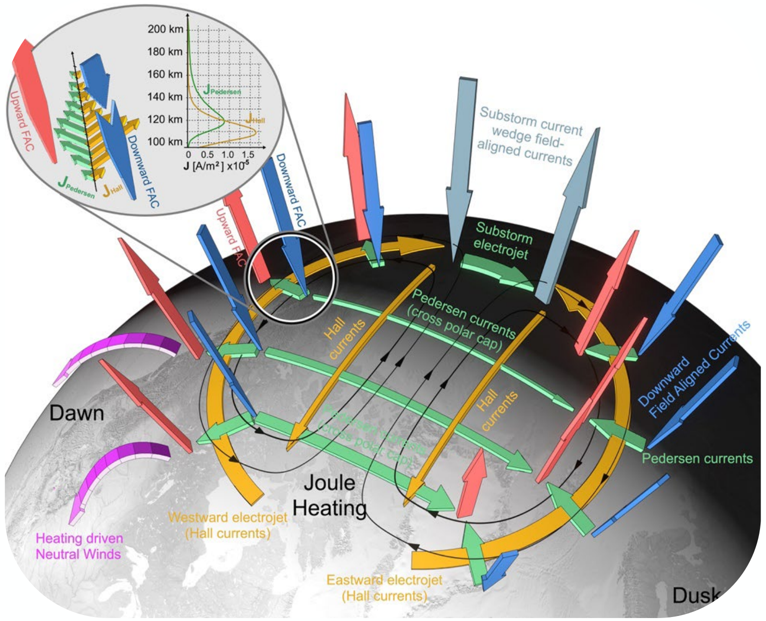
Global **understanding of LTI behavior has been inhibited by lack of *in-situ, multi-property* measurements**



**Emergent behavior*: Behavior that arises out of the interactions between parts of a system and which cannot easily be predicted or extrapolated from the behavior of those individual parts.

The LTI: Where Newton and Maxwell meet

Electric currents close in the LTI, coupling the Earth to magnetospheric electrodynamics



The LTI: Where Newton and Maxwell meet

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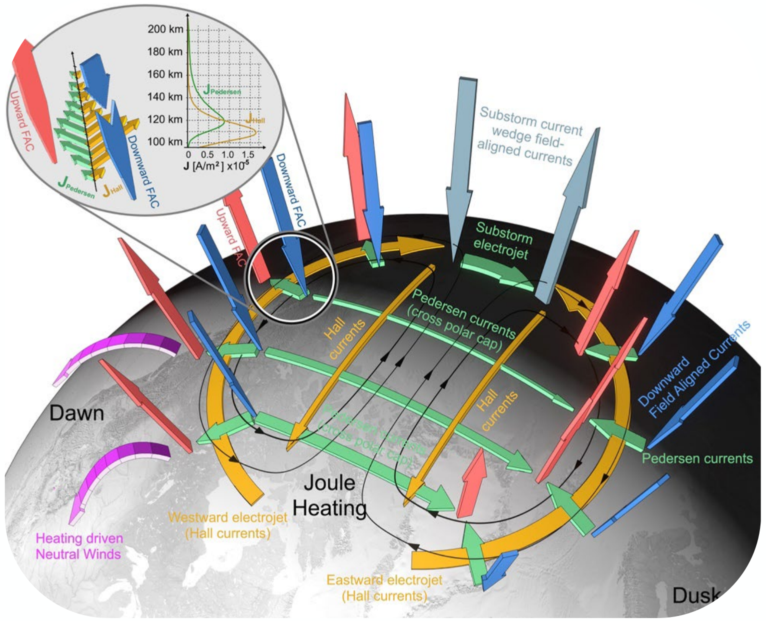
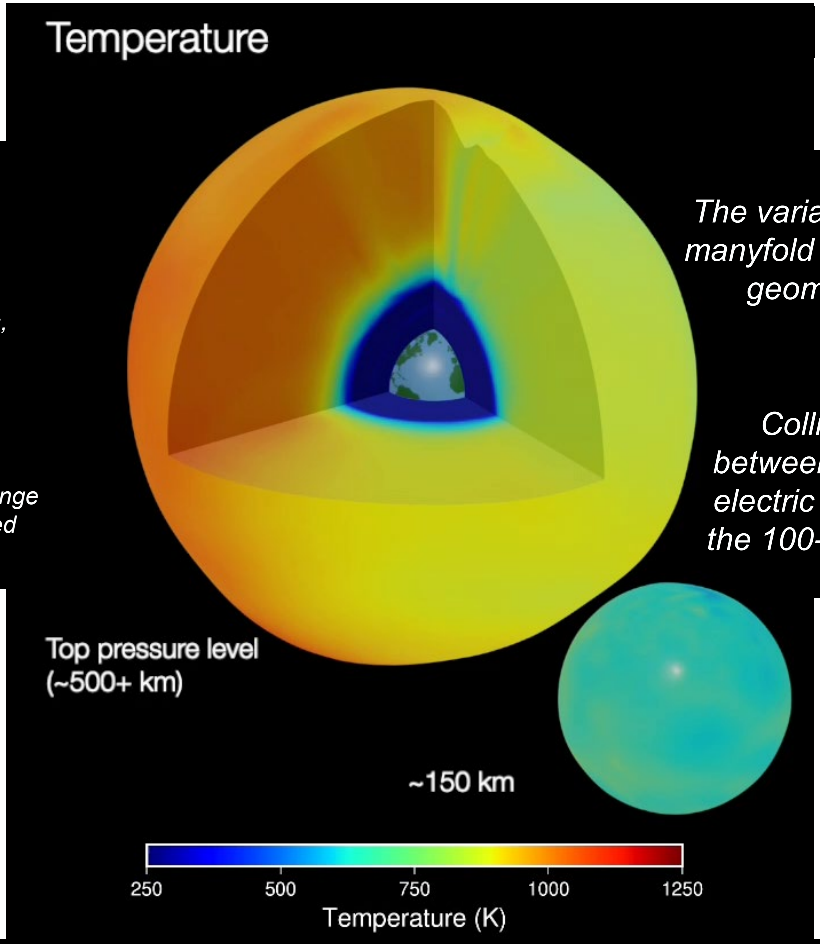


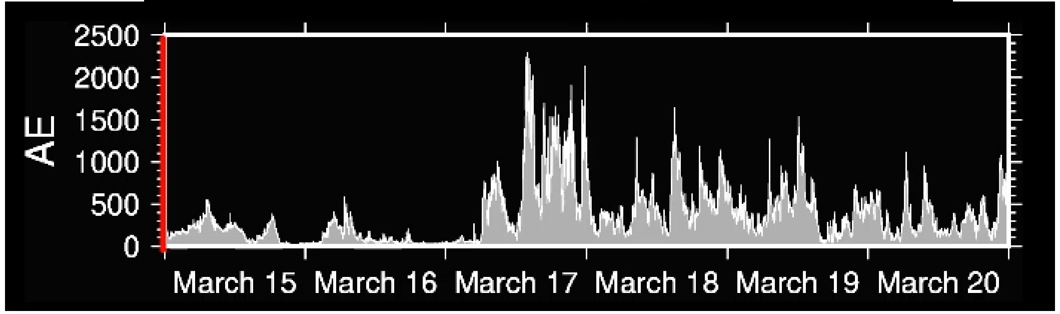
Thermosphere-Ionosphere simulation with TIE-GCM (movie by E. Doornbos, Daedalus Ph0 study, 2020)

100-500 km altitude range vertically exaggerated



The variability of the LTI can be manyfold during active solar and geomagnetic conditions

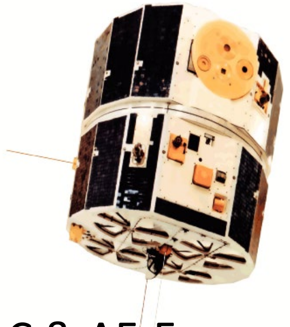
Collisional interactions between ions & neutrals, and electric currents, maximize in the 100-200 km altitude range



Programmatic context

The past, present and future of LTI missions

Flown missions



AE-C & AE-E
(1973-1975)
Handful of orbits, low inclination, limited instruments

200 km

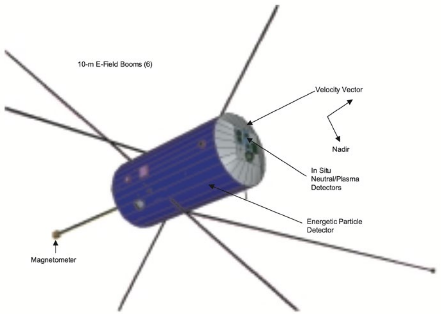
150 km

100 km

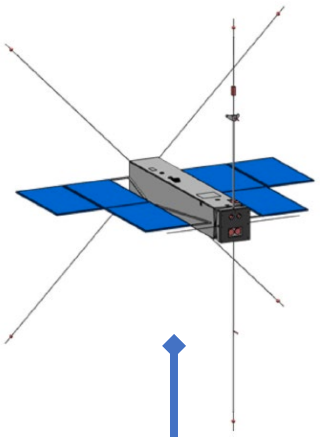
TIMED (1991)
(descoped)

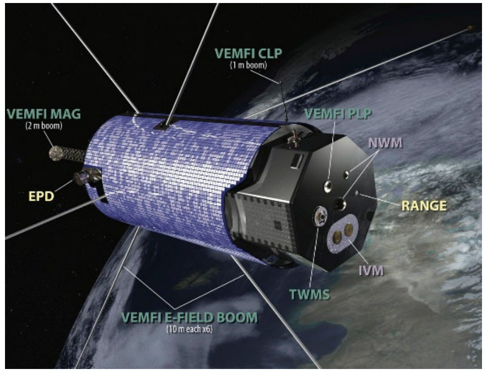
Proposed missions

GEC (2001 STDT)



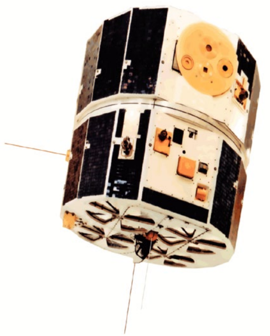
Daedalus (2020)



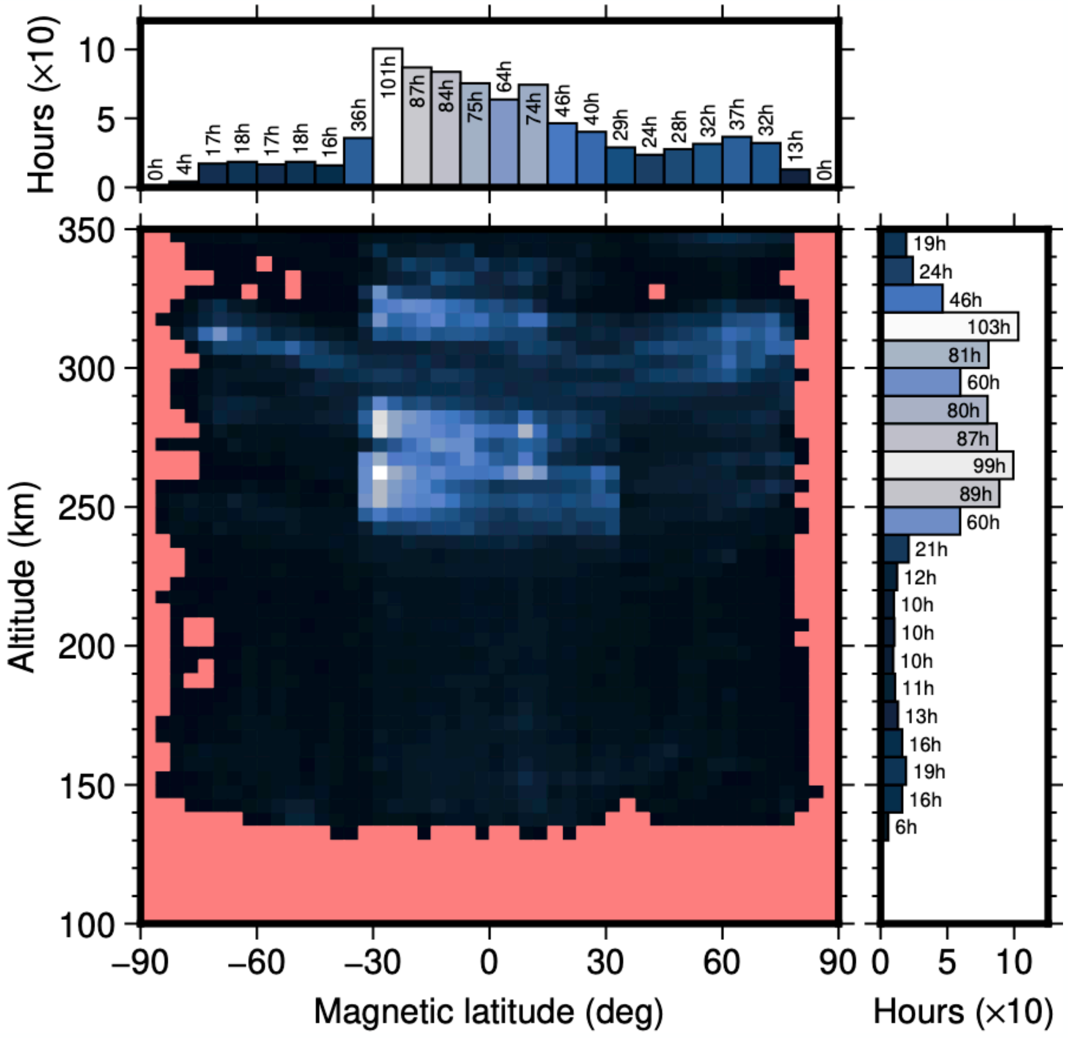


LOPEX, Dipper, MAX, ASTRE, ASTRE2 (1993-2011)

LTI In-Situ Measurements of the Past

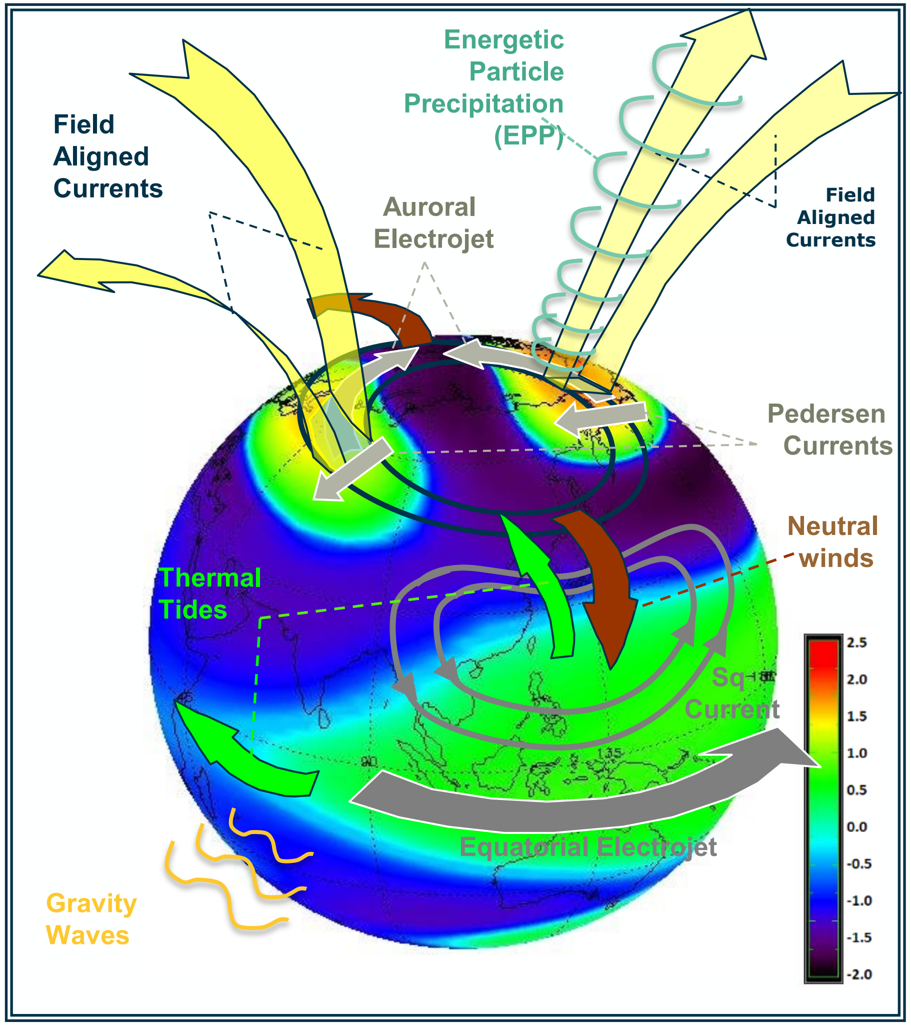


AE-C & AE-E
(1973-1976)



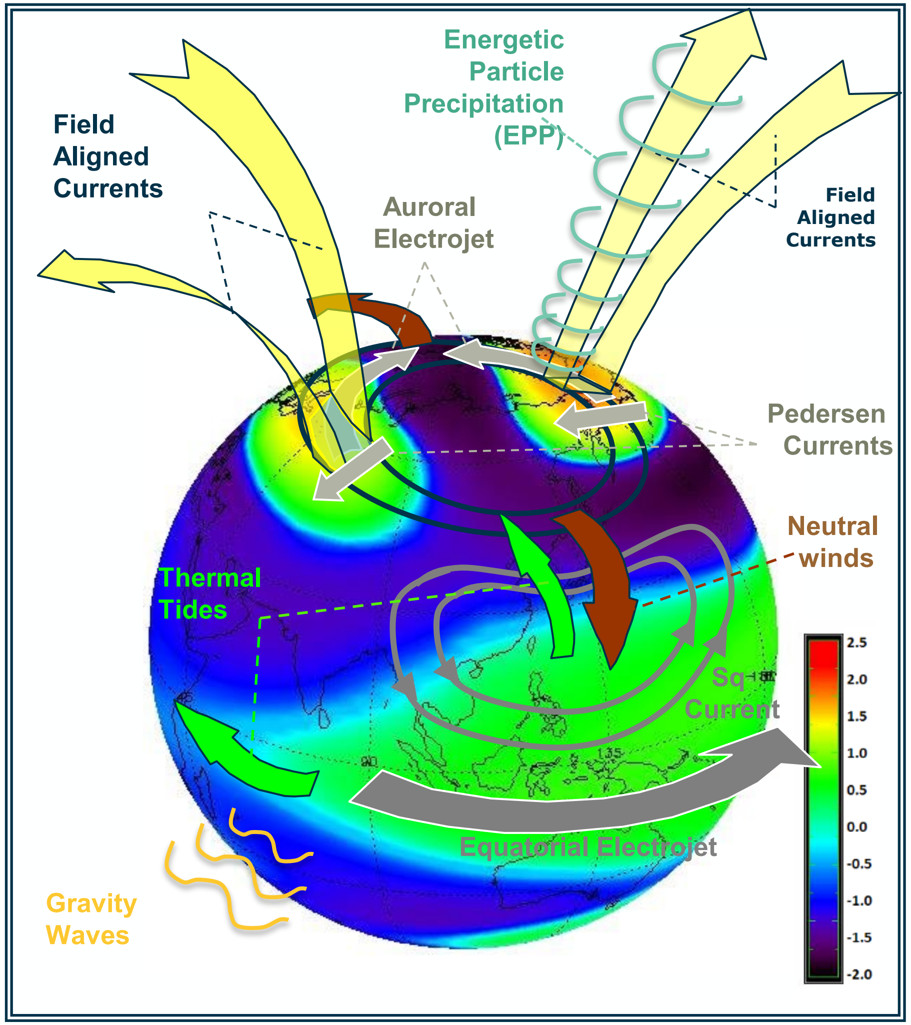
Total observation time < 200 km:
~60 hours

ENLoTIS Report: Scientific Goal & Objectives



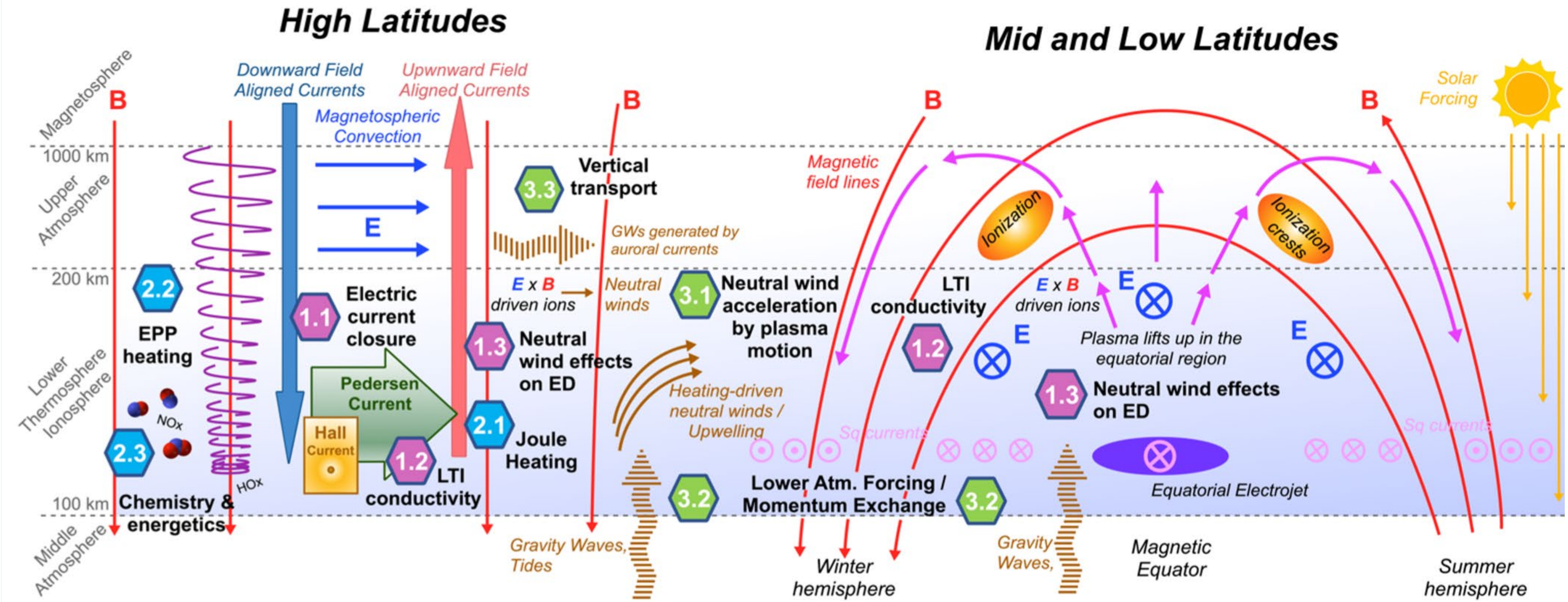
"To understand how the transition from Earth's atmosphere to space is governed by the fundamental plasma-neutral interactions that are intrinsic to the lower thermosphere-ionosphere (LTI) currents."

ENLoTIS Report: Scientific Goal & Objectives

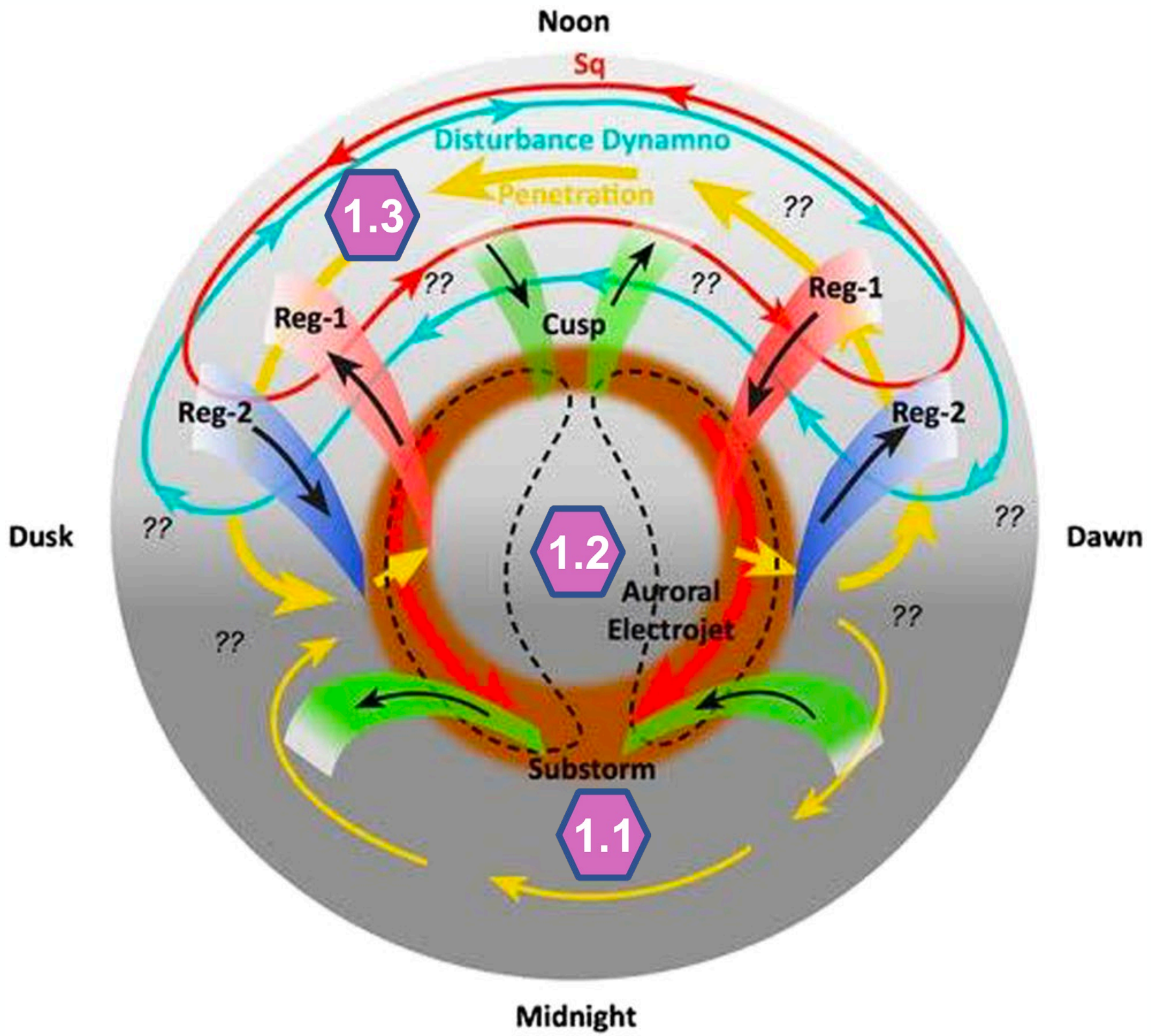


SO1: Collisional Electrodynamics J	SO2: Collisional Energetics J · E	SO3: Collisional Dynamics J × B
1.1 Determine how electric currents flow and close in the LTI, and thereby couple to the mag/spheric electrodynamics	2.1 Determine how Joule (frictional) heating in the LTI depends on scale size, altitude and neutral winds.	3.1 Determine how neutral winds in the LTI are accelerated by plasma motions via ion-neutral collisions
1.2 Understand how the various LTI processes act to determine the Hall & Pedersen conductivity	2.2 Determine how energy from energetic precipitating particles (EPP) directly heats the LTI.	3.2 Discover how the exchange of momentum across scales by means of lower atmospheric forcing manifest in the LTI.
1.3 Determine the effect of the neutral winds on the LTI electrodynamics.	2.3 Determine how plasma-neutral collisions cause chemical changes that affect the energetics of the LTI.	3.3 Determine how collisional processes drive vertical transport & cause composition changes

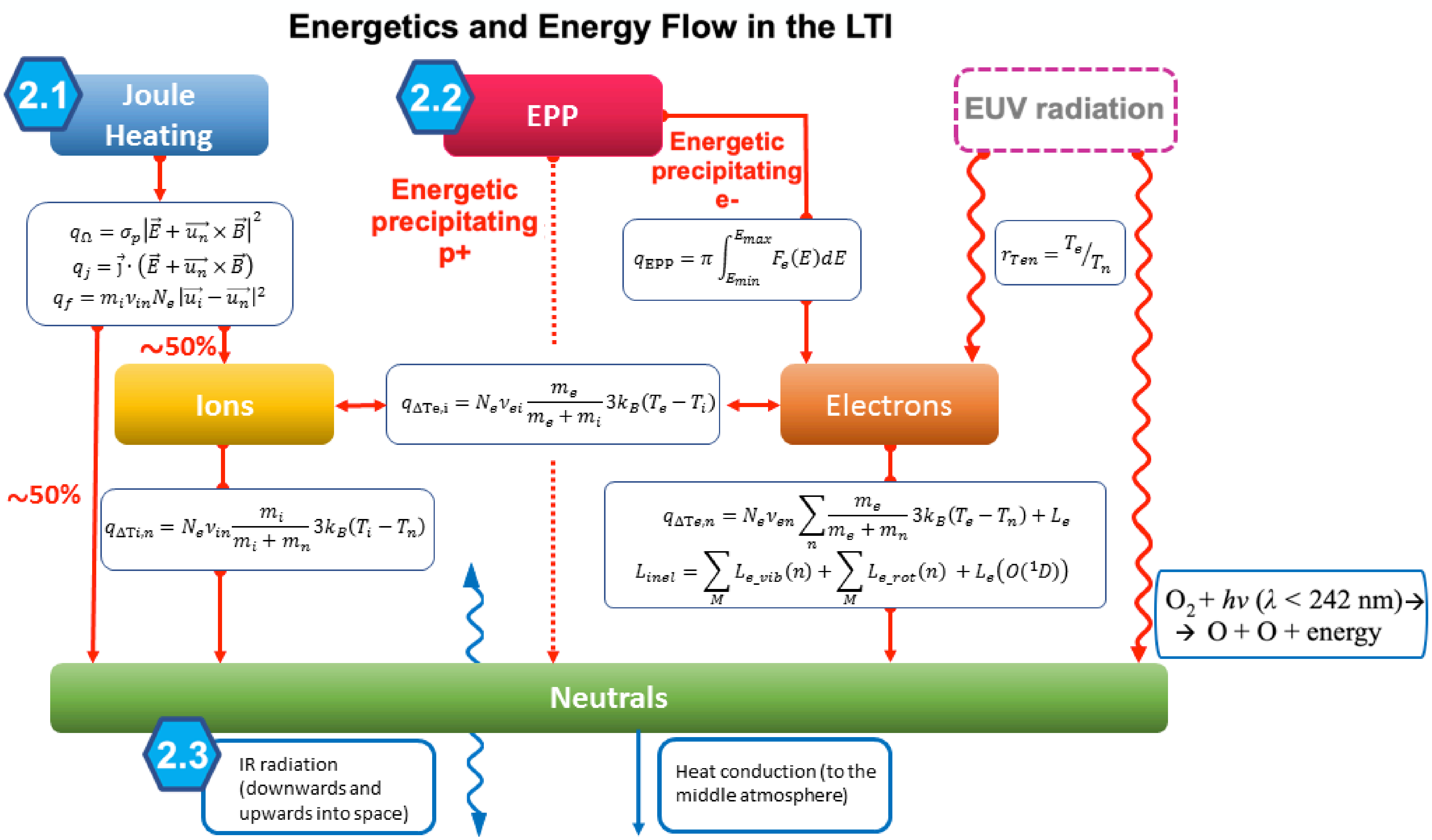
Pictorial Form of SubObjectives



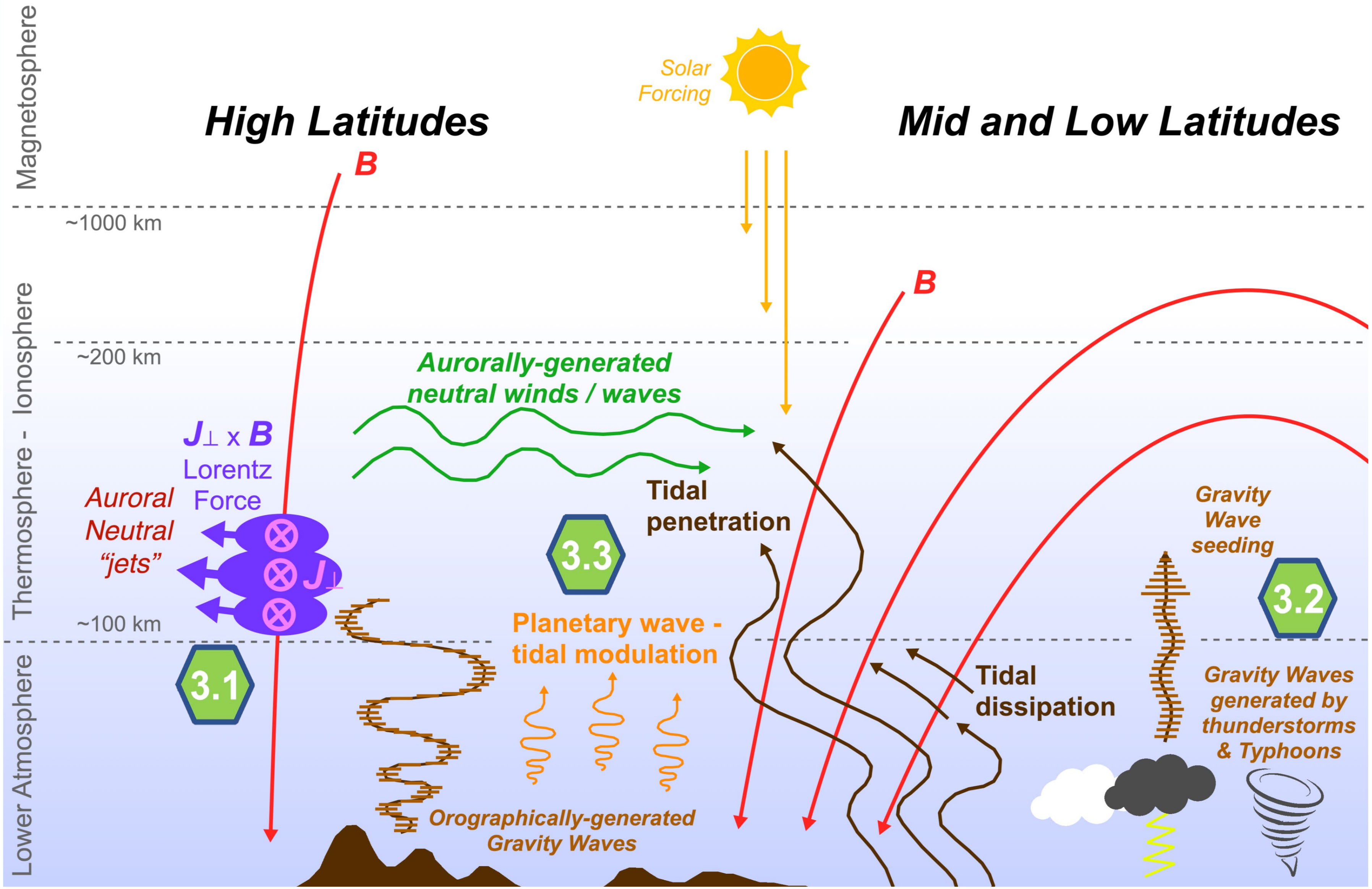
Collisional Electrodynamics



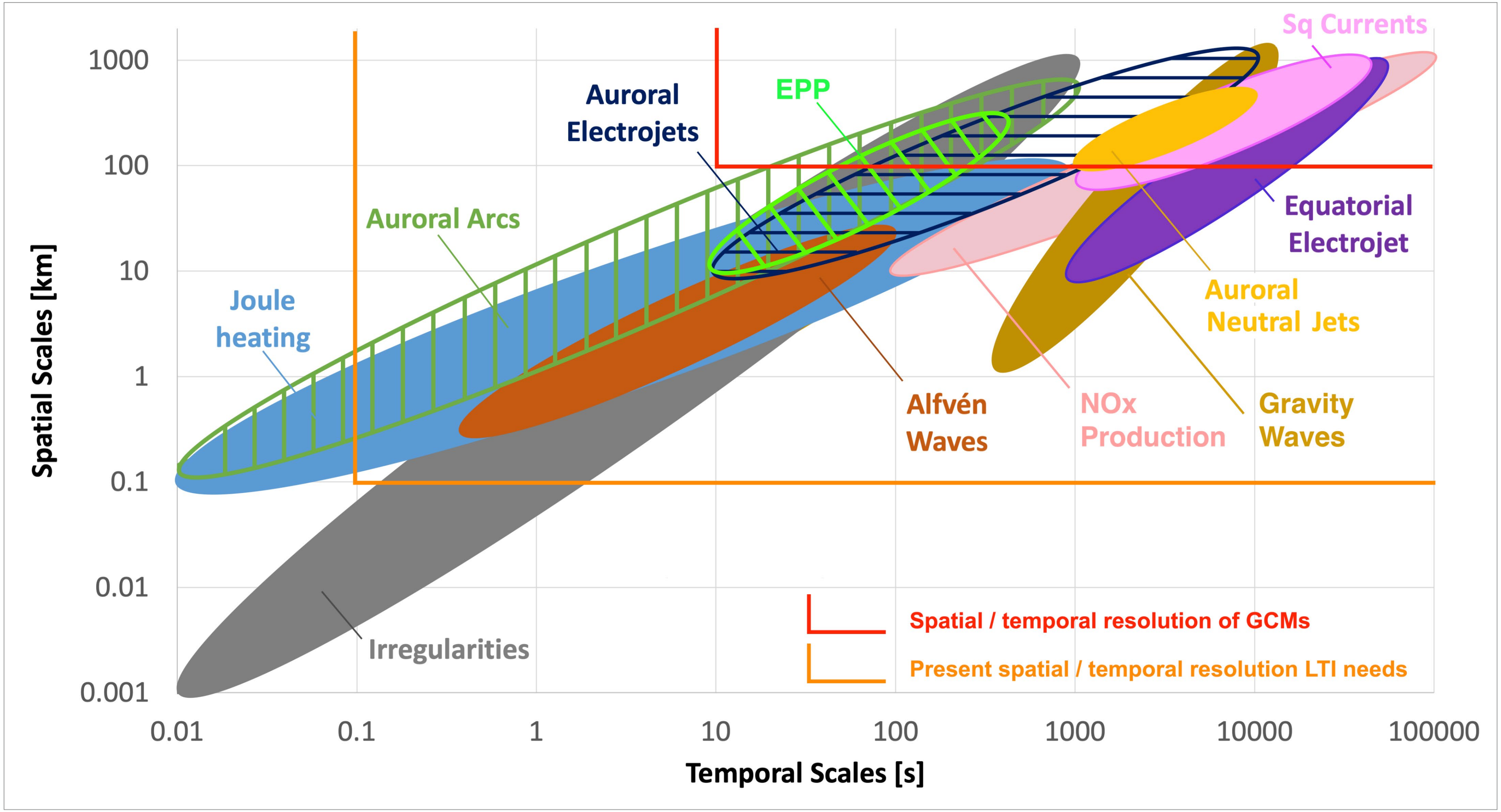
Collisional Energetics



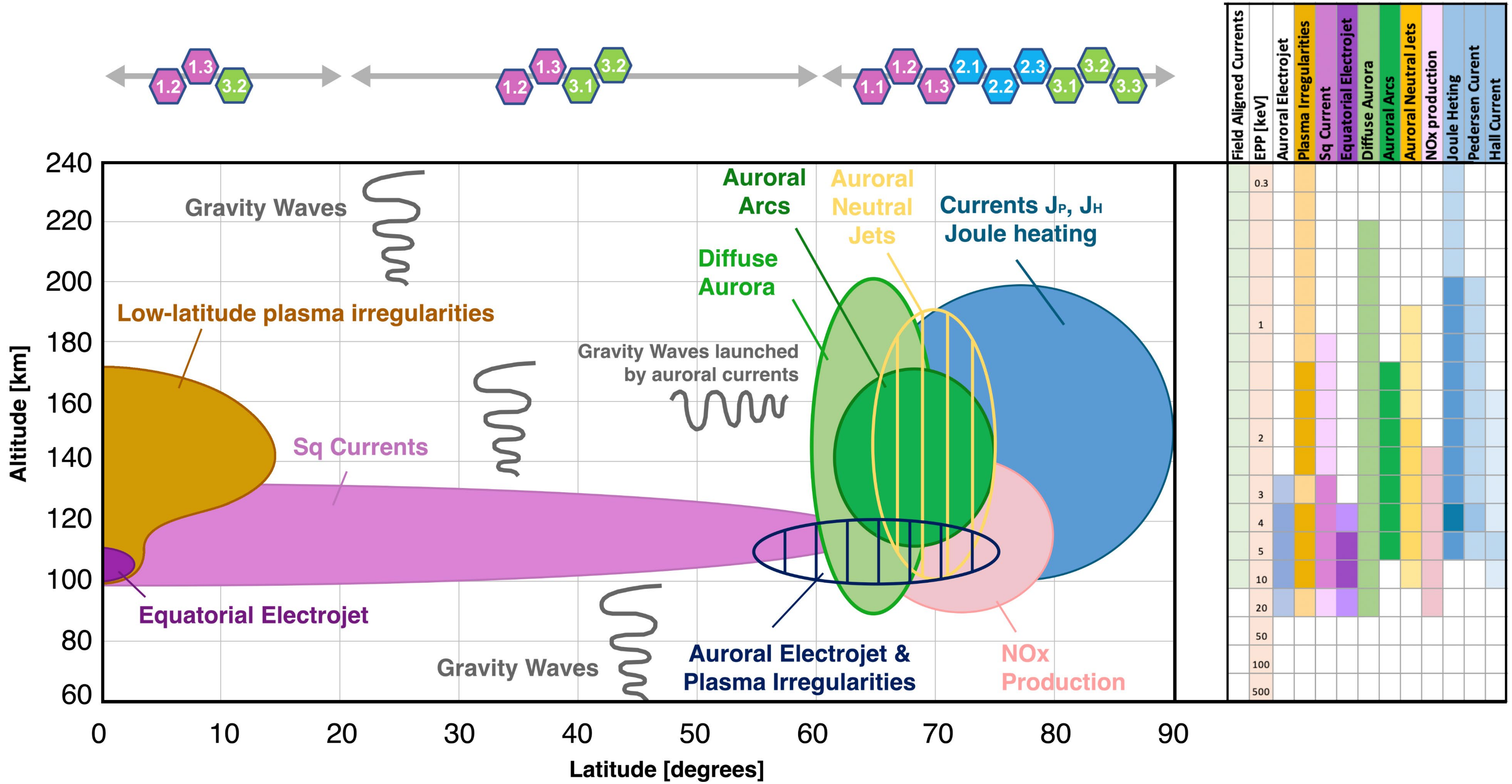
Collisional Dynamics



Spatial and Temporal Scales of LTI Phenomena



Focus Regions of LTI Phenomena



ENLoTIS Report: Measurement Requirements

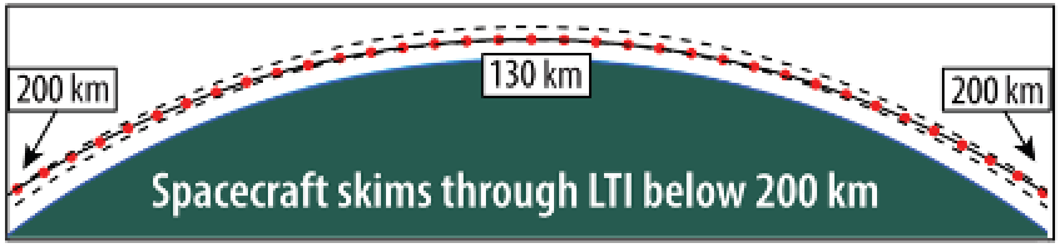
Co-temporal, co-spatial measurements of all parameters involved are needed, in the regions of interest (high and low latitudes, altitudes within 100-200 km)

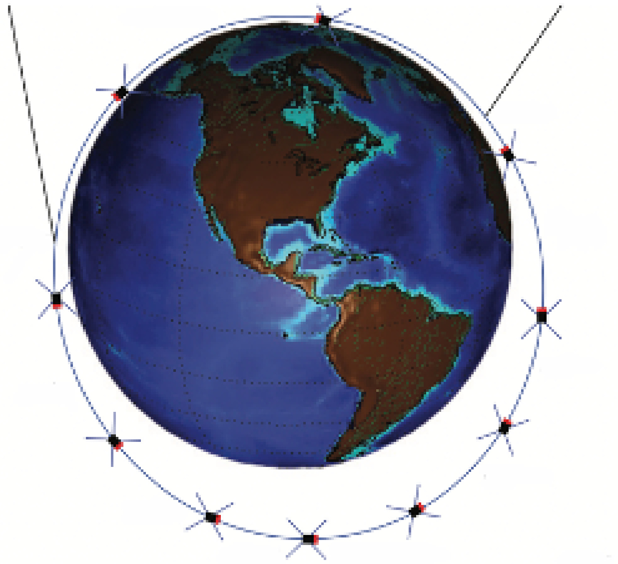
→ In situ mission with comprehensive instrumentation

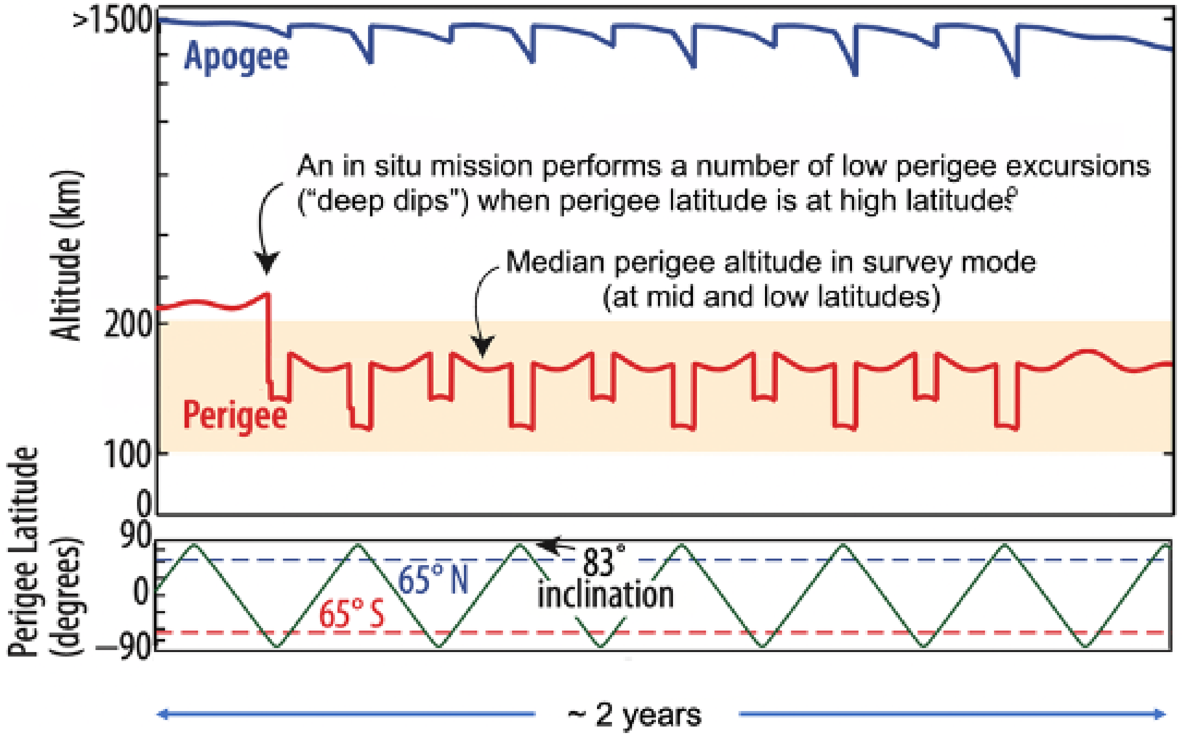
	Abbreviation	Geophysical Observable
ionosphere	$\vec{v}_i$	Ion Drift velocity
	T_i	Ion Temperature
	T_e	Electron Temperature
	N_i	Ion Number Density
	N_e	Electron Number Density
	n_{ix}	Ion Composition
thermosphere	$\vec{u}_n$	Neutral Wind Velocity
	N_n	Neutral Number Density
	ρ	Neutral Mass Density
	α_{ng}	Non-gravitational Acceler.
	T_n	Neutral Temperature
	n_{nx}	Neutral Composition
fields	$\vec{B}$	Magnetic Field
	$\vec{E}$	Electric Field
EPP	F_{le}, F_{he}, F_{li}, F_{le}	Energetic Precipitating Particles (ions, electrons)

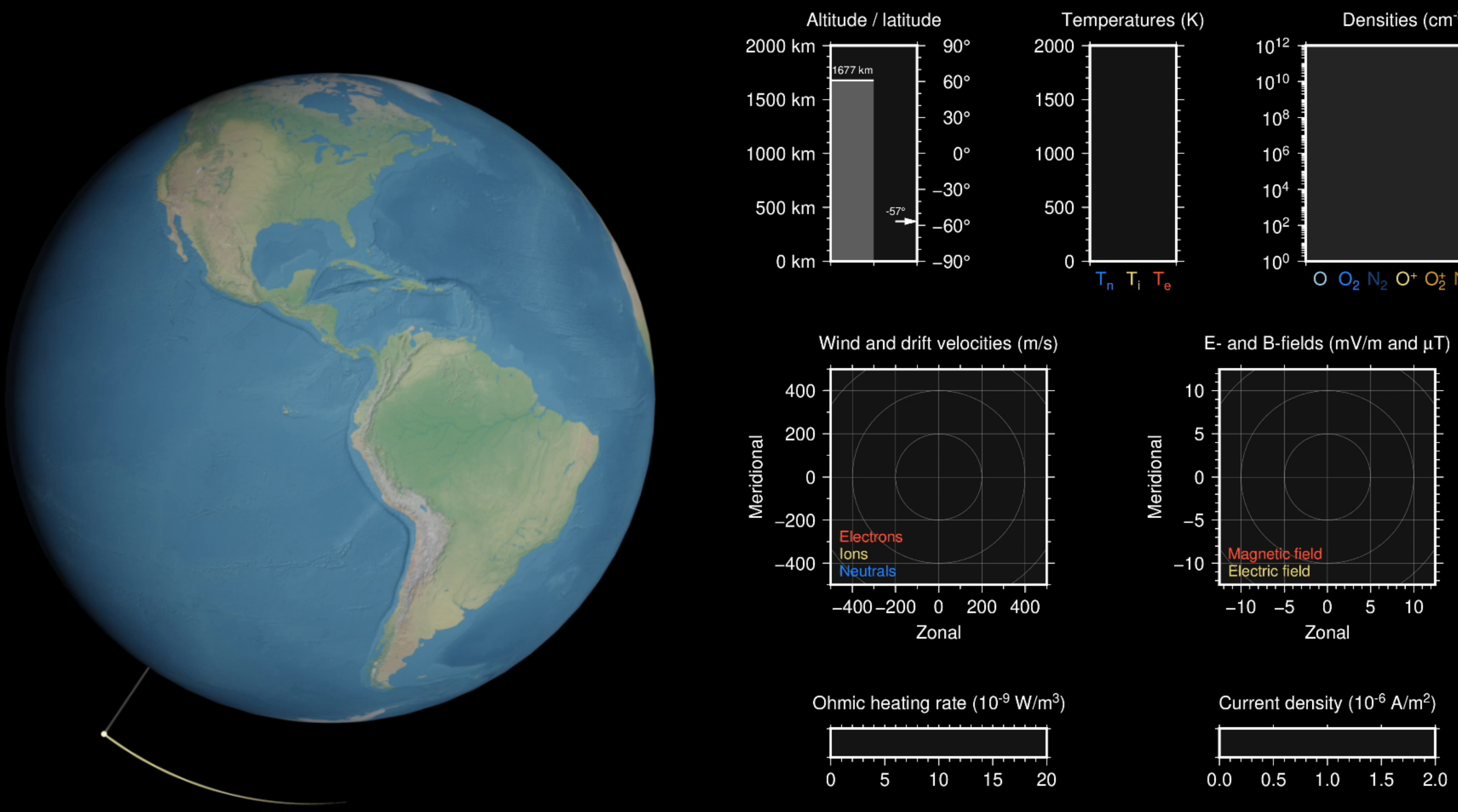
SO	Derived product / reference	Theoretical equation for estimation
SO1: Collisional Electrodynamics	• Perpendicular current (via **u***i*, **u***e*) (Richmond & Thayer 2013, eq. 10)	• $\vec{j}_\perp = eN_e(\vec{v}_{i,\perp} - \vec{E}\times\vec{B}/B^2)$
	• Perpendicular, Pedersen, and Hall currents (Richmond and Thayer 2013, eq. 13)	• $\vec{j}_\perp = \vec{j}_P + \vec{j}_H = \sigma_P(\vec{E} + \vec{u}_n\times\vec{B}) + \sigma_H\hat{b}\times(\vec{E} + \vec{u}_n\times\vec{B})$
	• Field-aligned currents (Ampere's Law, e.g., Lühr et al., 2019, eq. 6.3)	• $\vec{j} = (\vec{\nabla}\times\vec{B})/\mu_0$; $j_{\|\|} = (dB_y/v_{sc,x}dt)/\mu_0$
	• Convective plasma drift	• $\vec{v} = \vec{E}\times\vec{B}/B^2$
	• Pedersen conductivity (Schunk and Nagy 2009, eq. 5.117)	• $\sigma_P = \sum_i \frac{N_i e^2}{m_i\nu_{in}}\frac{{\nu_{in}}^2}{{\nu_{in}}^2+{\Omega_i}^2} + \frac{N_e e^2}{m_e\nu_{en}}\frac{{\nu_{en}}^2}{{\nu_{en}}^2+{\Omega_e}^2}$
	• Hall conductivity (Schunk and Nagy 2009, eq. 5.118)	• $\sigma_H = -\sum_i \frac{N_i e^2}{m_i\nu_{in}}\frac{\nu_{in}\Omega_i}{{\nu_{in}}^2+{\Omega_i}^2} + \frac{N_e e^2}{m_e\nu_{en}}\frac{\nu_{en}\Omega_e}{{\nu_{en}}^2+{\Omega_e}^2}$
	• Parallel conductivity (Schunk and Nagy 2009, eq. 5.125a)	• $\sigma_{\|\|} = \frac{N_e e^2}{m_e(\nu_{en}+\nu_{ei})}$
SO2: Collisional Energetics	• Poynting Flux (e.g., Richmond and Thayer 2013, eq. 23)	• $\vec{S} = (\vec{E}\times\delta\vec{B})/\mu_0$
	• Joule heating (Strangeway 2012, eq. 38)	• $q_j = eN_e(\vec{v}_{i,\perp} - \vec{u}_{n,\perp})\cdot(\vec{E} + \vec{u}_n\times\vec{B})$
	• Ohmic heating (Lu et al. 1995, eq. 3)	• $q_\Omega = \sigma_p\left\|\vec{E} + \vec{u}_n\times\vec{B}\right\|^2$
	• Frictional heating (Strangeway 2012, eq. 28)	• $q_f = m_i\nu_{in}N_e$
	• Energetic precipitating particle-associated heating	• $q_{EPP} = \sum_{n,s}\sigma_n(E)N_nF_{EPP,s}(E)$
SO3: Collisional Dynamics	• Magnetic forcing (Richmond and Thayer 2013, eq. 20)	• $J \, x \, B$
	• Gravity Wave Forcing - Momentum and Heat Flux	• $F_M = ½ \langle u' w' \rangle$
	• Vertical Transport	• $F_H = ½ \langle w' T' \rangle$

Skeleton Mission Concept



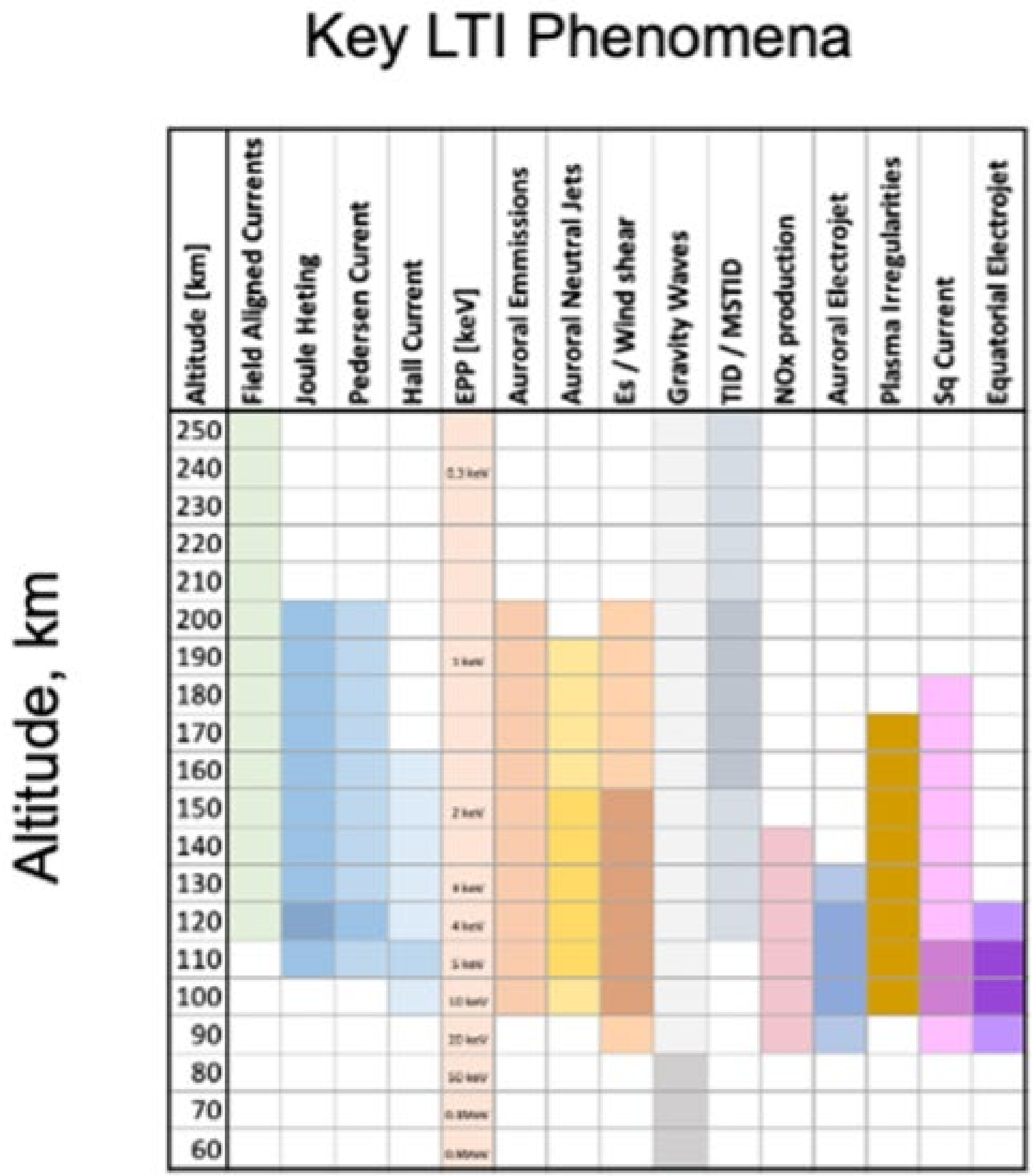


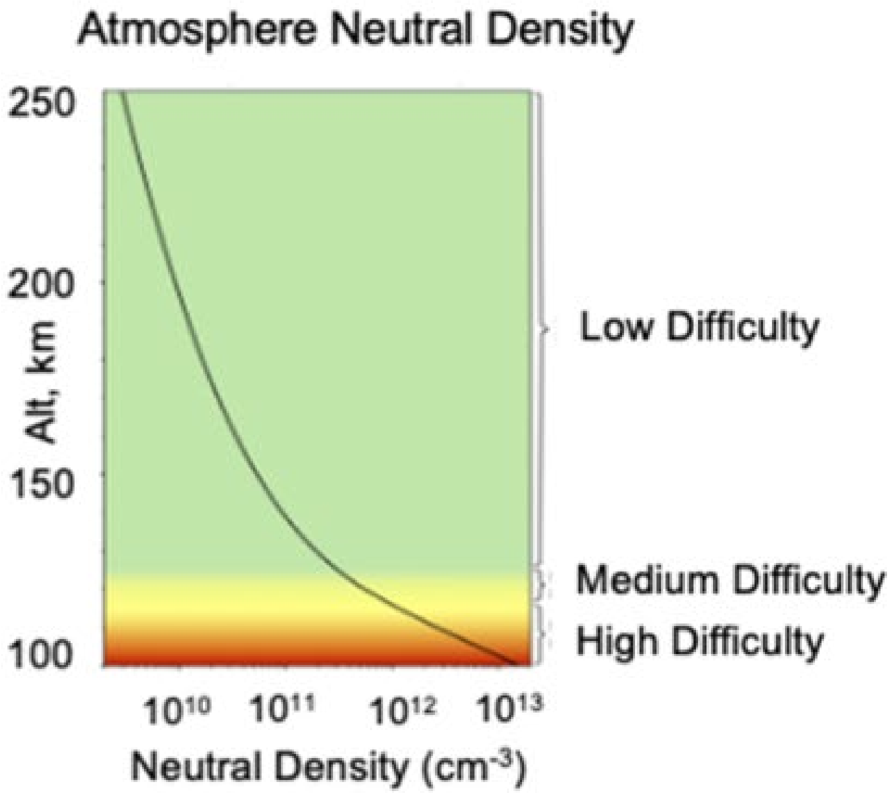




Altitude / latitude
2000 km
1500 km
1000 km
500 km
0 km
1677 km
-57°
90°
60°
30°
0°
−30°
−60°
−90°
Temperatures (K)
2000
1500
1000
500
0
T_n T_i T_e
Densities (cm^{-3})
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
10^{0}
O O_2 N_2 O^+ O_2^+ N^+ e
Wind and drift velocities (m/s)
Meridional
400
200
0
−200
−400
Electrons
Ions
Neutrals
−400 −200 0 200 400
Zonal
E- and B-fields (mV/m and µT)
Meridional
10
5
0
−5
−10
Magnetic field
Electric field
−10 −5 0 5 10
Zonal
Ohmic heating rate (10^{-9} W/m^3)
0 5 10 15 20
Current density (10^{-6} A/m^2)
0.0 0.5 1.0 1.5 2.0

Science Return as a Function of Altitude





Challenges

Likely Instrument Performance on Low Perigee Satellite

(Oribital Velocity ~8 km/s)

Geophysical Observable

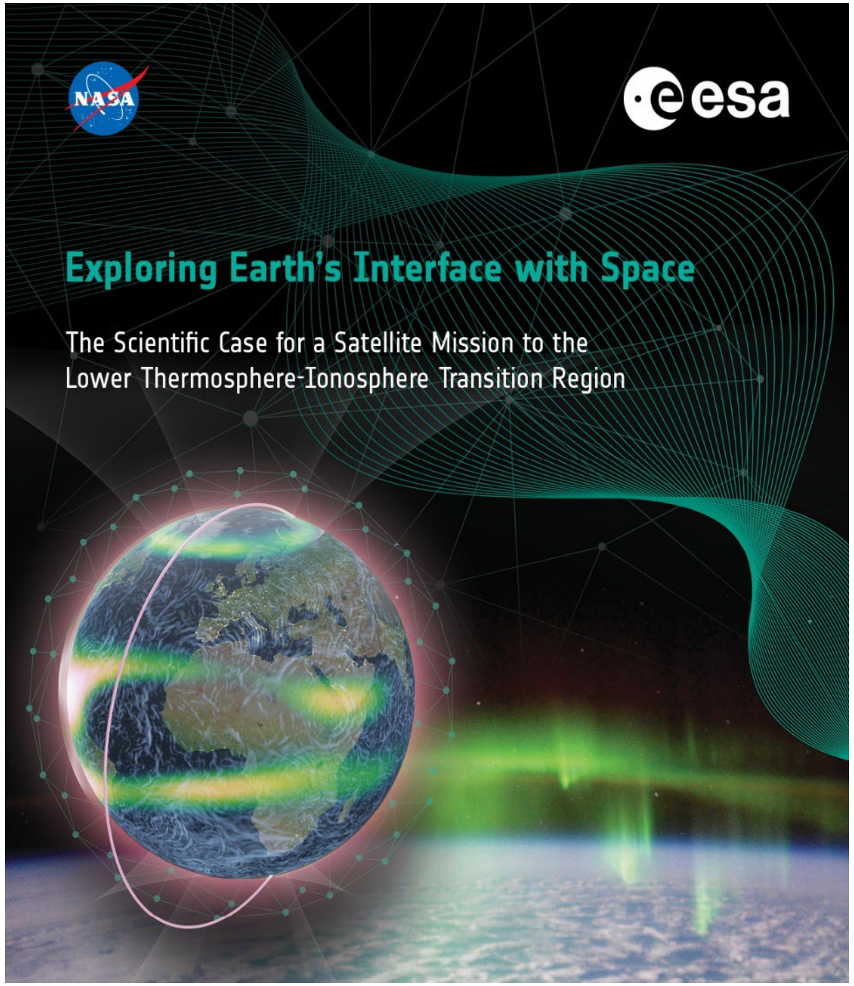
Altitude	N_i	V_i	T_i	N_{ix}	N_e	T_e	N_n	$\mathbf{U}_n$	T_n	N_{nx}	ρ_n	$\mathbf{E}$	$\mathbf{B}$
>200 km	green	green	green	green	green	green	green	green	green	green	green	green	green
150 km	green	green	green	green	green	green	green	green	green	green	green	green	green
130 km	green	green	green	green	green	green	green	green	green	green	green	green	green
125 km	green	green	green	green	green	green	green	green	green	green	green	green	green
120 km	green	green	green	green	green	green	green	green	green	green	green	green	green
115 km	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	green
110 km	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	green
105 km	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	green
100 km	red	red	red	red	red	red	red	red	red	red	red	red	green

ENLoTIS Report: Summary and Next Steps

- In situ measurements in the 100-200 km altitude range with a comprehensive instrument suite will provide, for the first time, all geophysical observables needed for the unambiguous quantification of key processes in the LTI
- These processes need to be quantified in-situ, with statistically representative sampling over the mission lifetime.

Next steps:

1. Flow-down of the scientific needs expressed in this report into firm mission requirements supported by analyses, tools and capabilities to justify and verify these requirements;
2. Assessment of instrumental capabilities needed to meet measurement requirements;
3. Study of orbits, propulsion, as well as mission and science operational concepts capable of meeting sampling requirements;
4. Further study on mitigation approaches to the special environmental challenges listed above that affect the measurement techniques, data processing, spacecraft design choices and concepts of operations.



http://doi.org/10.5270/ESA-NASA.LTI-SC.2024-07-v1.0

Questions?

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ESA POC: Alex.Hoffmann@esa.int

The WG enables ESA-NASA cooperation on future LTI satellite mission concepts by:

a) Reviewing and consolidating **consensus science questions or goals, mission objectives, and high-level mission requirements** that would inform the eventual definition and design of (a) future mission concept(s)

→ Not starting from "blank slate" – leverage knowledge from past and current mission studies

→ Input/feedback from research community throughout initial phase will be key

→ From Heliophysics perspective, initial phase of ENLoTIS WG would resemble an "SDT" or Science Definition Team.

b) Identifying **scientific and technical challenges and constraints** associated with these high-level requirements from *(a)* in view of facilitating trade-offs and identifying candidate measurements.

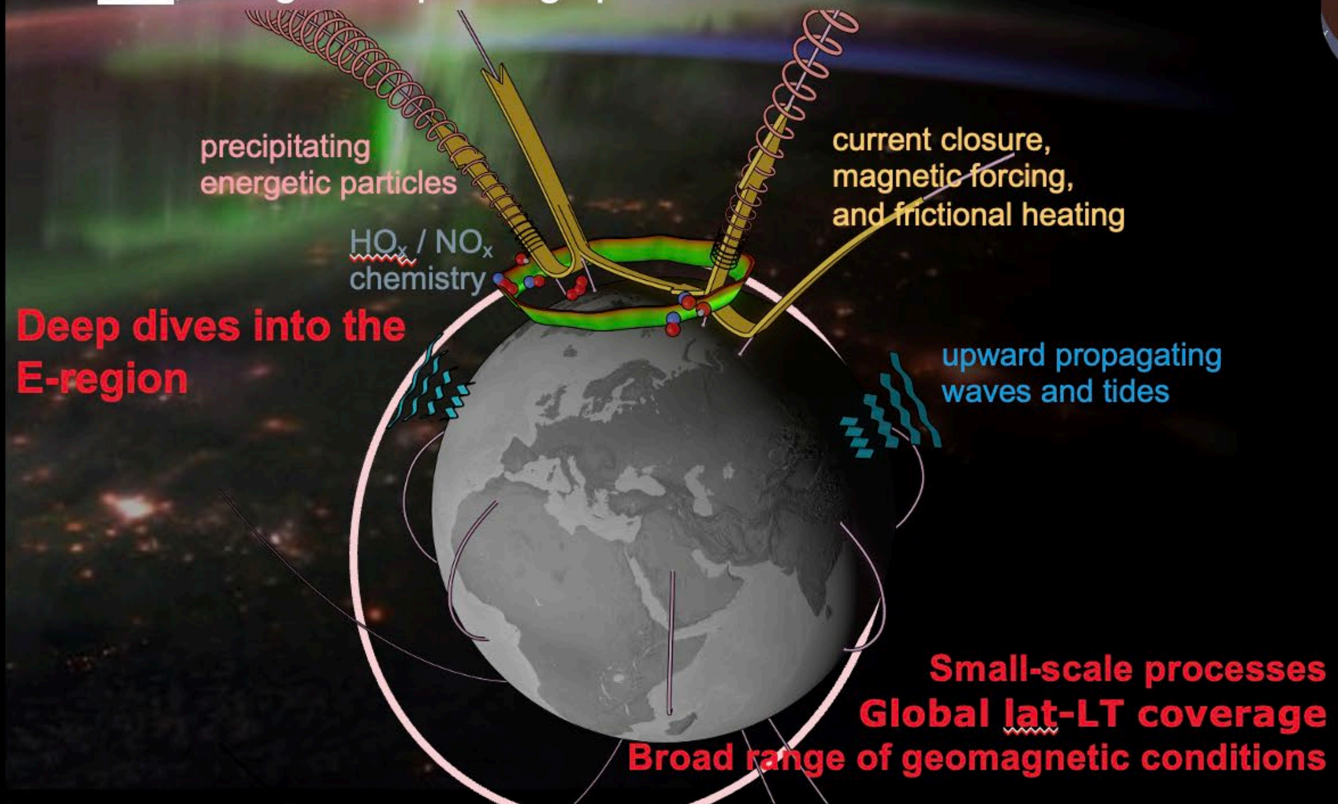
→ Balancing science and feasibility – how low should we go vs. how low can we go?

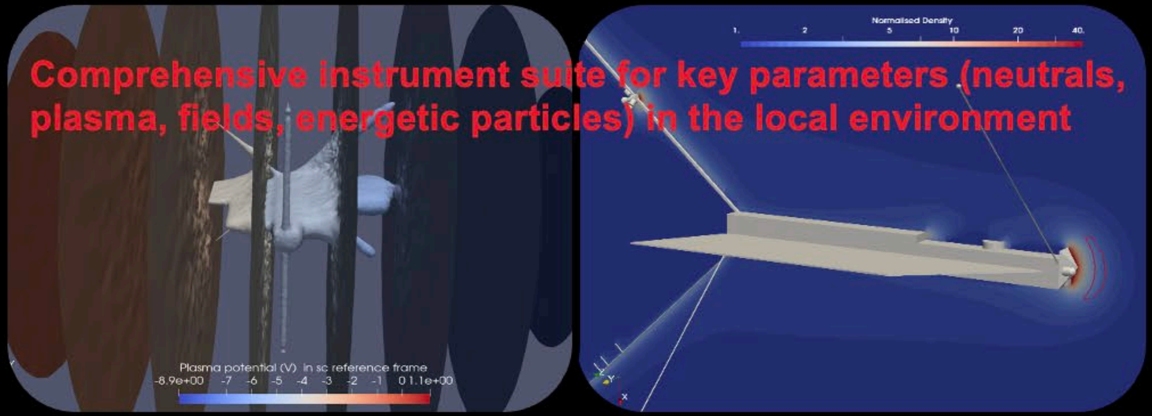
c) Coordinating with **on-going and planned activities** between NASA & ESA supporting (a) and (b)

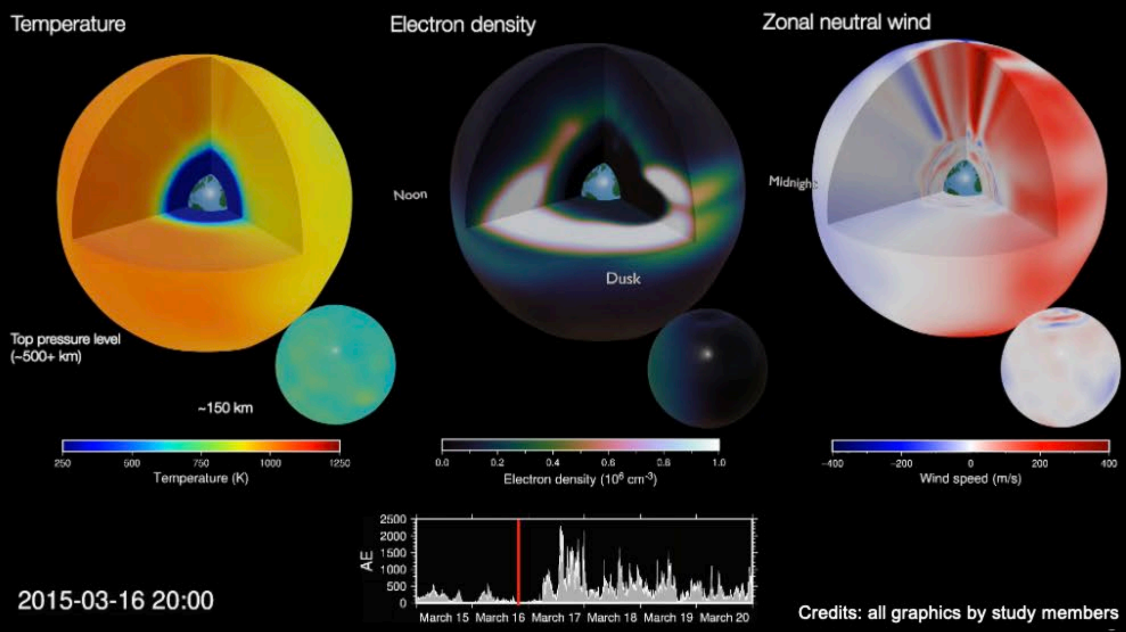
Programmatic context (ESA)

The Daedalus concept, an ESA Earth Observation Programme Earth Explorer 10 mission candidate (Phase 0)

- Targets a better understanding of the ***atmosphere-space*** (thermosphere-ionosphere) ***coupling***, to shed light on key ion-neutral interaction processes affecting structure, energetics, composition and dynamics of the upper atmosphere, by
- Exploring the ***transition region*** (~120 to 200 km altitude) ***<u>in situ</u>***, using a deep diving spacecraft.







Credits: all graphics by study members