NATIONAL CENTER OF GIS & SPACE APPLICATIONS

Seventh International Conference on Aerospace Science & Engineering

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December 14-16, 2021

Build Geodetic Space Weather Research: Coupling Processes Between Magnetosphere, Thermosphere and Ionosphere

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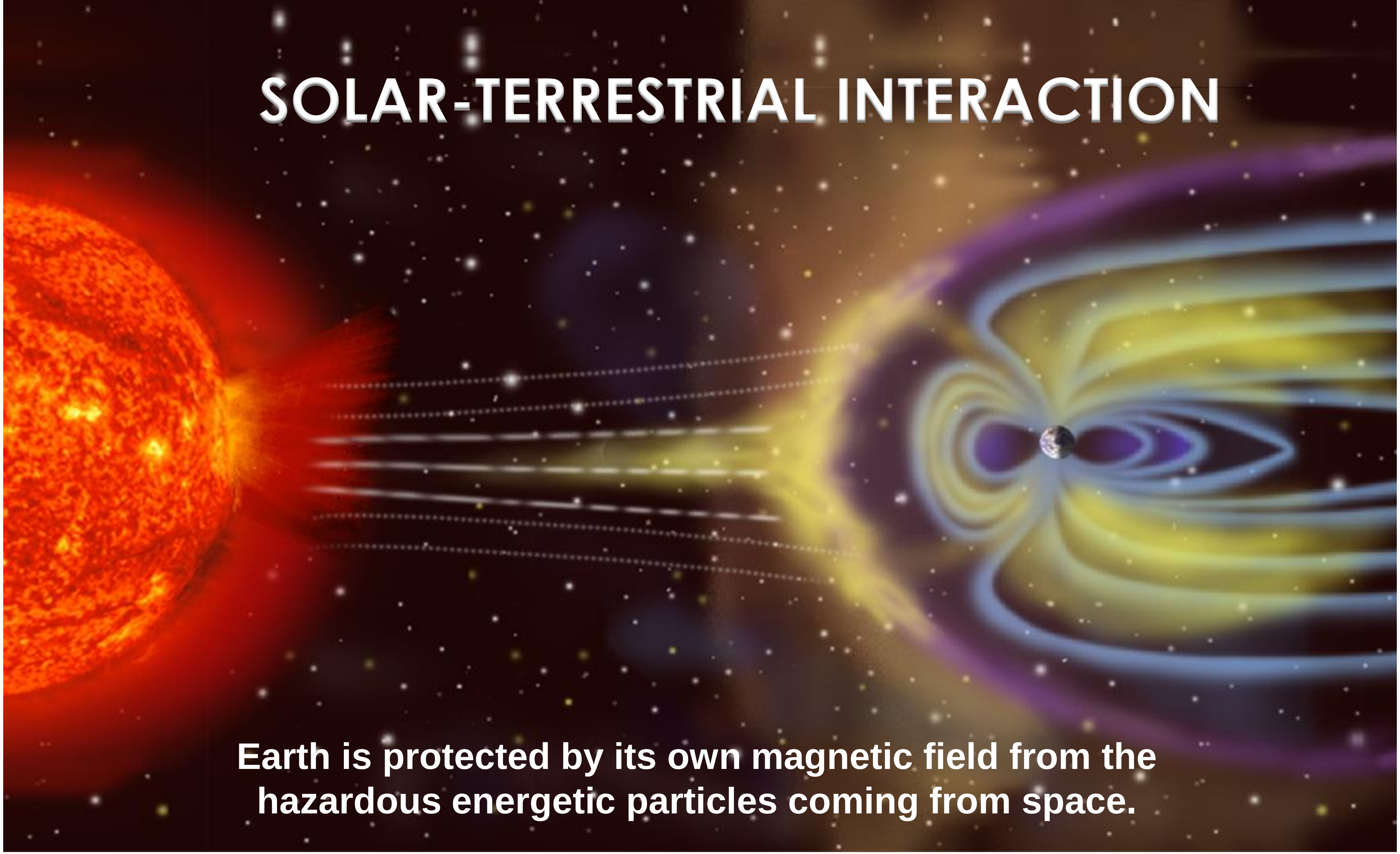
ICASE 2021, December 14-16, 2021, Islamabad, Pakistan

OUTLINE

NATIONAL CENTER OF GIS & SPACE APPLICATIONS

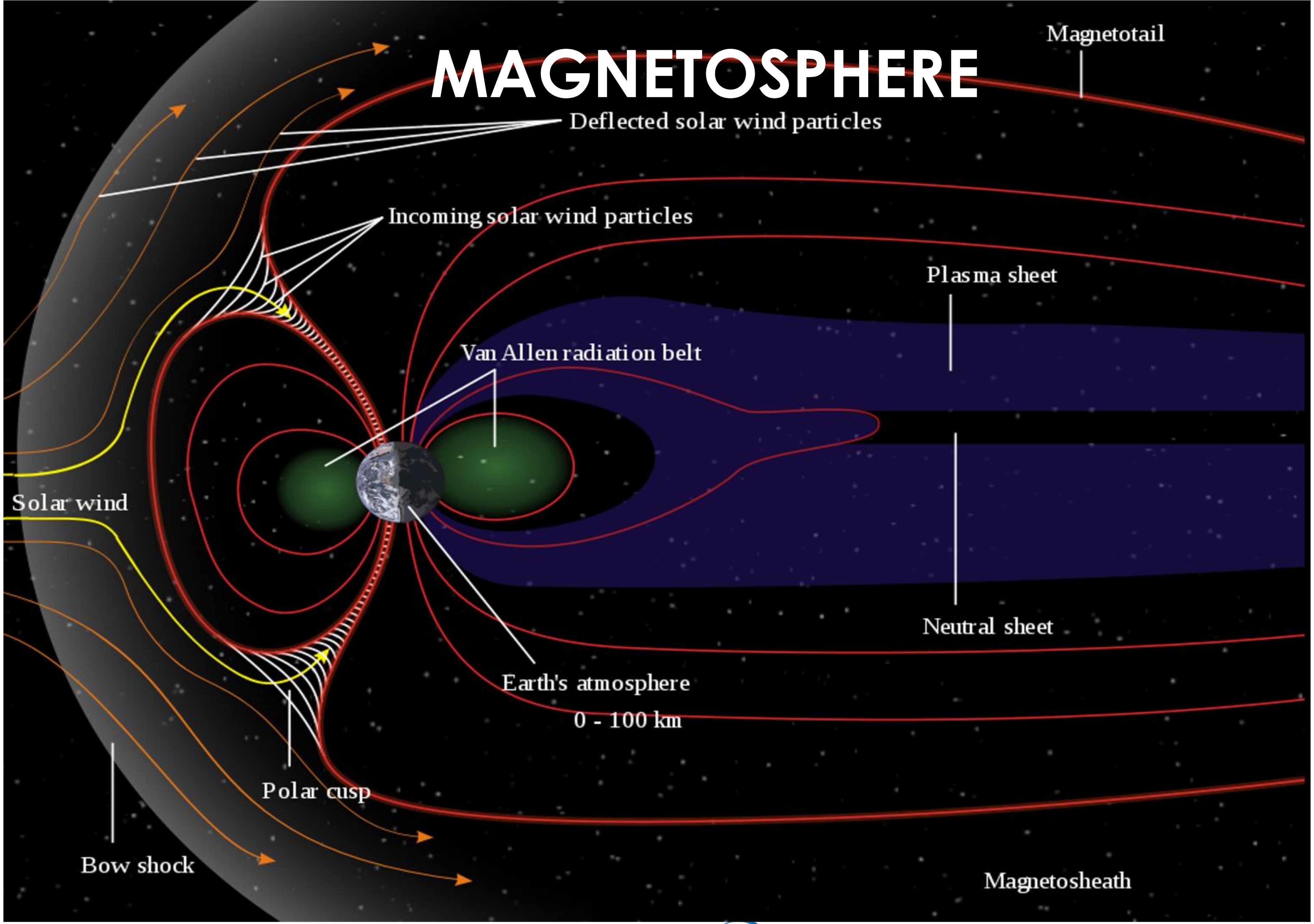
SOLAR-TERRESTRIAL INTERACTION



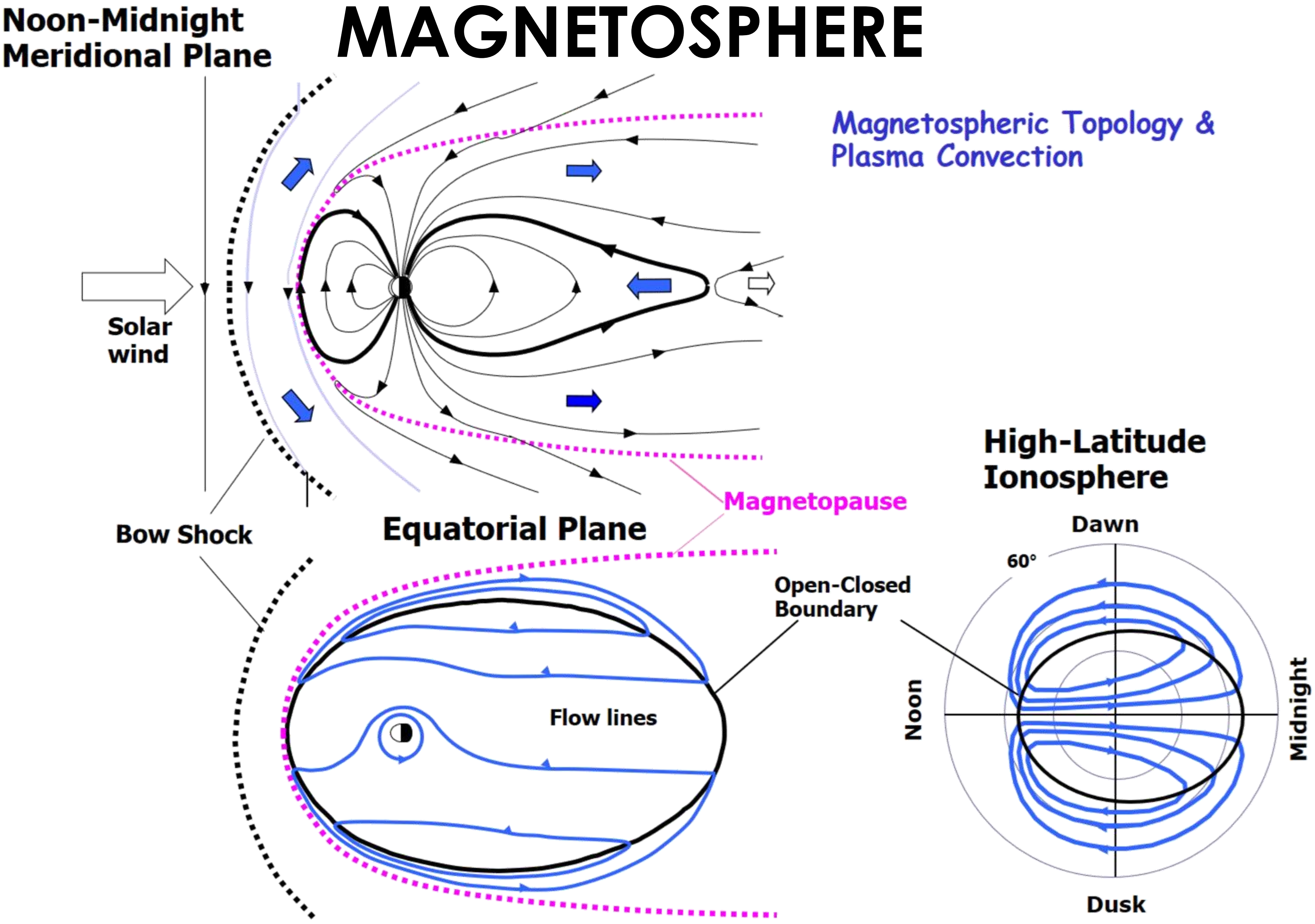
Earth is protected by its own magnetic field from the hazardous energetic particles coming from space.

http://sec.gsfc.nasa.gov/popscise.jpg

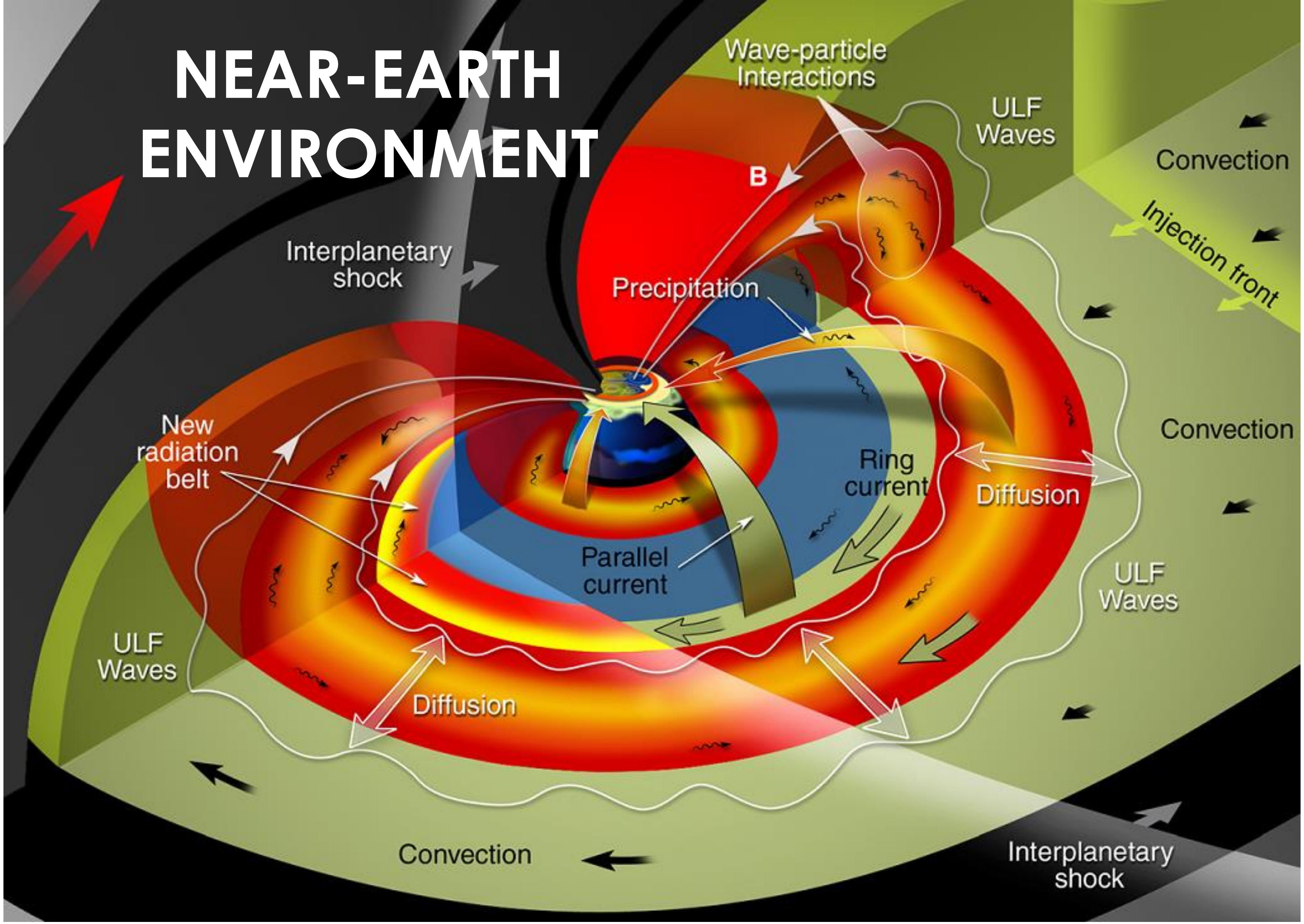
MAGNETOSPHERE



MAGNETOSPHERE



NEAR-EARTH ENVIRONMENT

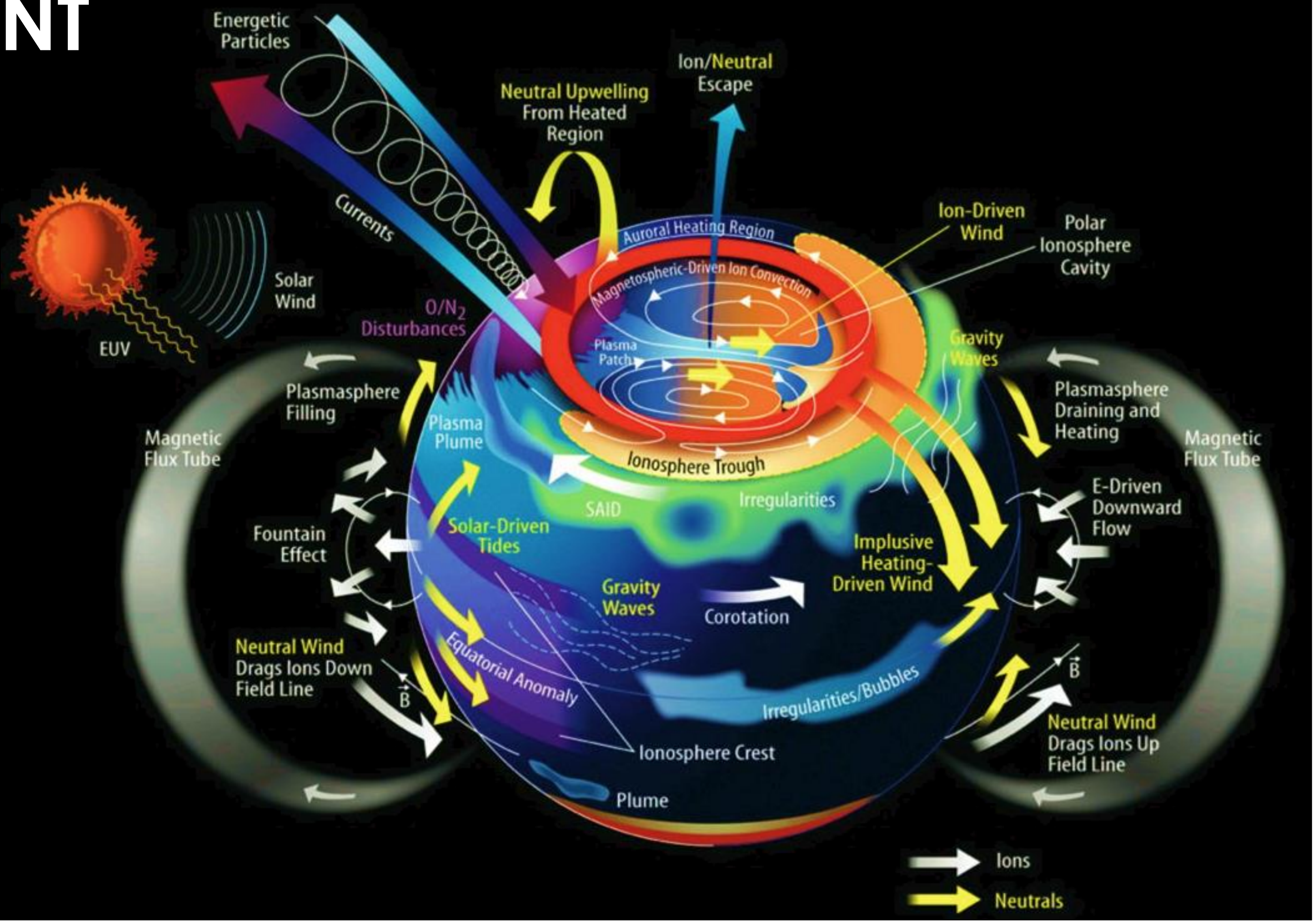


Mauk et al. (2013)

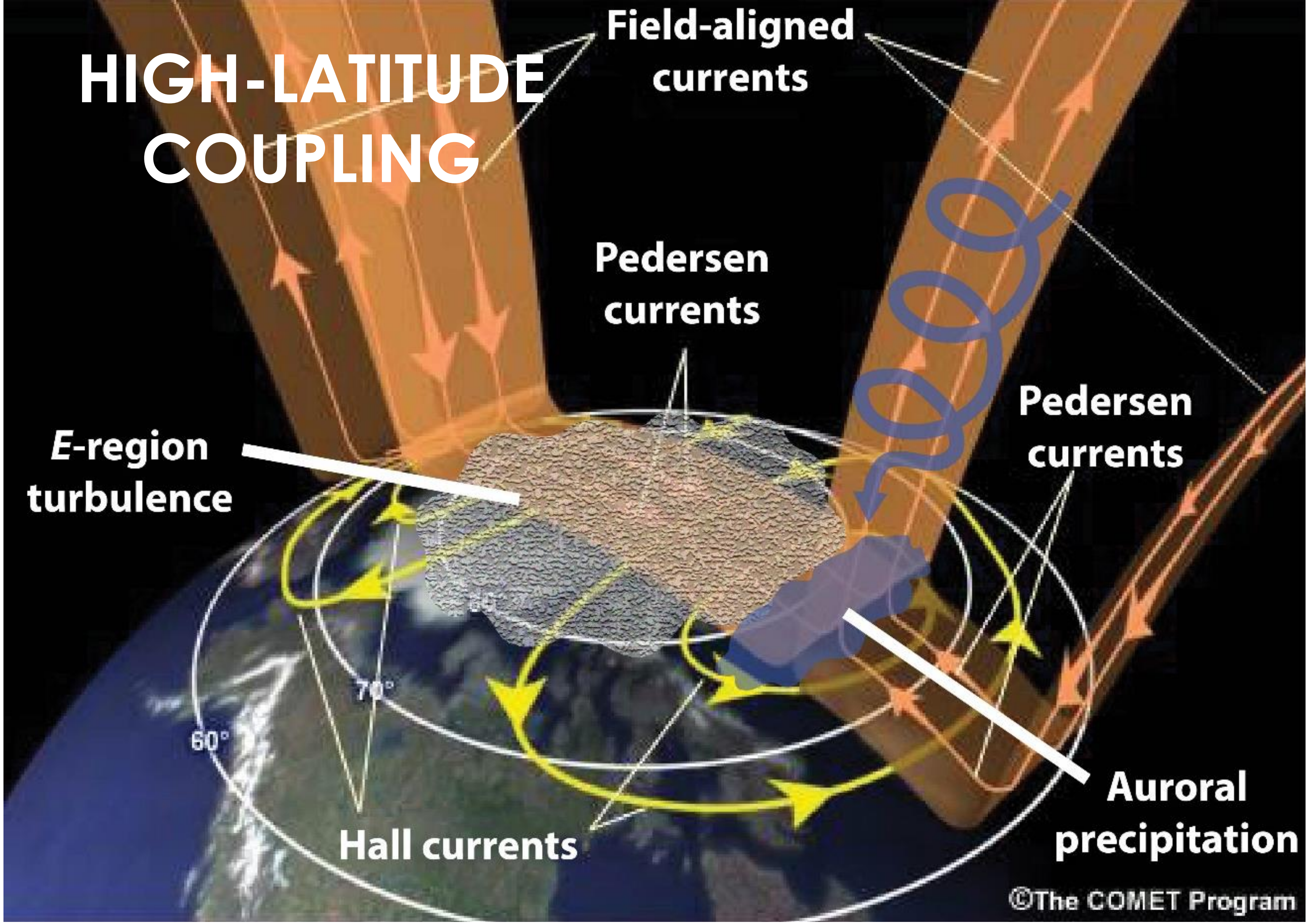
NEAR-EARTH ENVIRONMENT

The understanding of coupled processes in the Magnetosphere-Thermosphere-Ionosphere (**MTI**) is still a <u>challenge</u>.

Variations in the upper atmosphere are strongly influenced by <u>solar and magnetospheric forcing</u>.



HIGH-LATITUDE COUPLING



UPPER-ATMOSPHERE PHYSICS

Atmospheric Density column under Hydrostatic Equilibrium (above ~100 km):

$$N(z_0) = \int_{z_0}^{\infty} n(z_0) \exp\left[-\frac{z - z_0}{kT / m_i g} \right] dz = Hn(z_0)$$

z	is altitude
g(z)	is acceleration of gravity
r	is mass density
k	is Boltzmann's constant
m_i	is molecular weight of species

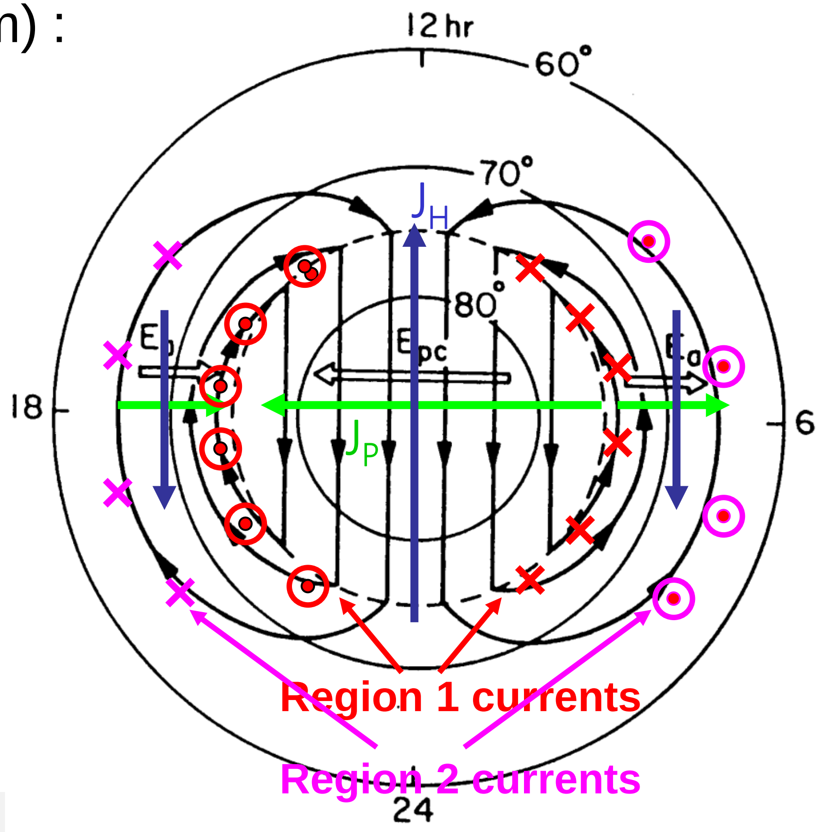
Electromagnetic Energy Dissipation (Poynting's theorem) :

$$\vec{J} \cdot \vec{E} = \underbrace{\left(\Sigma_P \vec{E} + \Sigma_H \vec{b} \times \vec{E} \right)}_{\text{Horizontal current}} \cdot \vec{E} = \underbrace{\Sigma_p E^2}_{\text{Joule heating}}$$

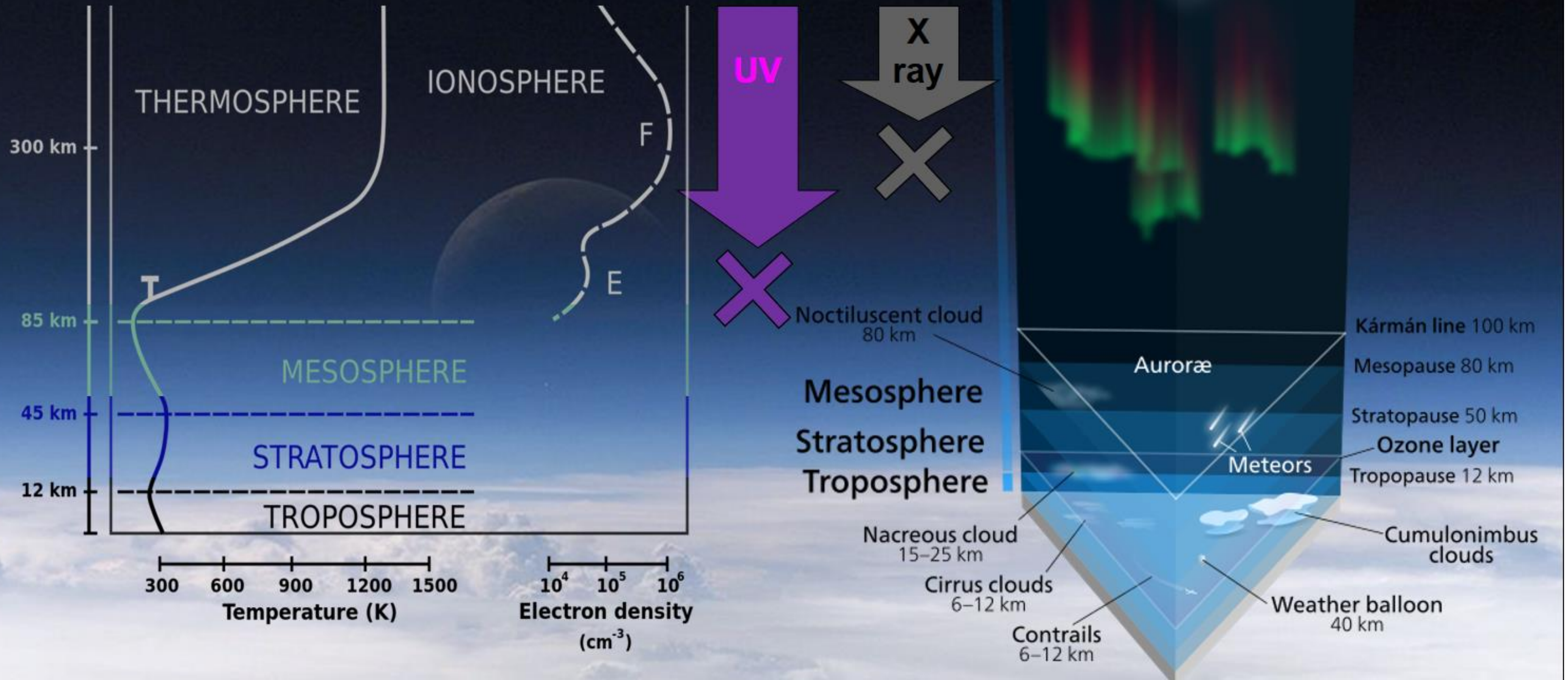
Field-aligned Current: $j_{||} = -\nabla \cdot \vec{J}$

E including neutral wind is:

$$\vec{E} \rightarrow \vec{E}' = (\vec{E} + \vec{U} \times \vec{B}) = -(\underbrace{\vec{V}}_{\text{Plasma drift velocity}} - \underbrace{\vec{U}}_{\text{Neutral wind velocity}}) \times \vec{B}$$



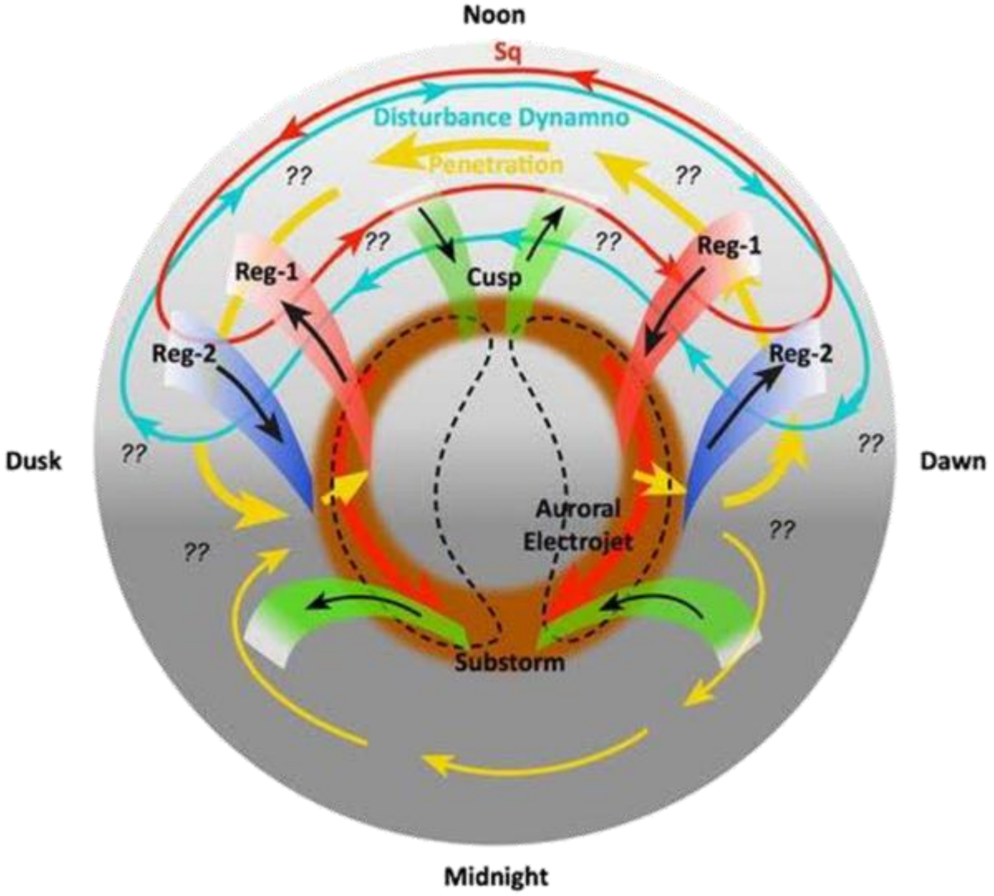
ATMOSPHERIC COUPLING

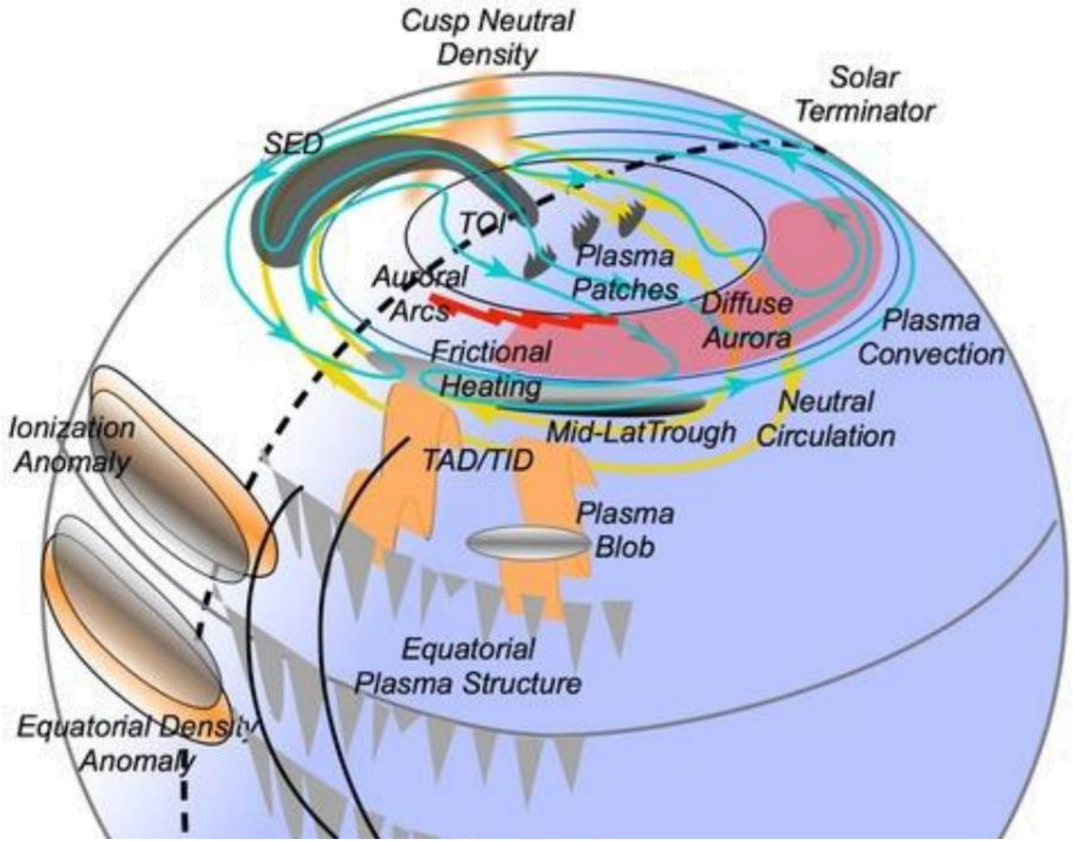


On the one side, highly energetic **solar radiation is absorbed in the thermosphere**, through ionization/dissociation of molecules, and thus **creating the ionosphere**.

ATMOSPHERIC COUPLING

<u>On the other side</u>, MTI is strongly influenced by **wave motions from the lower atmosphere**, and is coupled through **energetic particle precipitation and field-aligned currents**.





Heelis and Maute (2020)

UPPER-ATMOSPHERE PHYSICS

Thermodynamic equation:

$$\frac{\partial T_n}{\partial t} = \underbrace{\frac{ge^z}{p_0 C_p}\frac{\partial}{\partial Z}\left\{\frac{K_T}{H}\frac{\partial T_n}{\partial Z} + K_E H^2 C_p \rho\left[\frac{g}{C_p} + \frac{1}{H}\frac{\partial T}{\partial Z}\right]\right\}}_{\text{Molecular conduction}} - \underbrace{\mathbf{v}_n \cdot \nabla T_n}_{\text{Advection}} - \underbrace{W\left(\frac{\partial T_n}{\partial Z} + \frac{R^* T_n}{C_p \bar{m}}\right)}_{\text{Adiabatic}} + \underbrace{\frac{Q^{\exp} - e^z L^{\exp}}{C_p}}_{\text{Heating}} - \underbrace{L^{imp} T_n}_{\text{Radiation}}$$

Momemtum equations:

Zonal velocity

$$\frac{\partial u_n}{\partial t} = \underbrace{\frac{ge^z}{p_0}\frac{\partial}{\partial Z}\left[\frac{\mu \partial u_n}{H \partial Z}\right]}_{\text{Viscosity}} + \underbrace{f^{corr} v_n}_{\text{Coriolis}} + \underbrace{\lambda_{xx}\left(v_{ExB,x} - u_n\right) + \lambda_{xy}\left(v_{ExB,y} - u_n\right)}_{\text{Ion drag}} - \underbrace{\mathbf{v}_n \cdot \nabla u_n}_{\text{Horizontal advection}} + \underbrace{\frac{u_n v_n}{R_E}\tan\lambda}_{\text{Mommentum}} - \underbrace{\frac{1}{R_E \cos\lambda}\frac{\partial \Phi}{\partial \phi}}_{\text{Pressure gradient}} - \underbrace{W\frac{\partial u_n}{\partial Z}}_{\text{Vertical advection}} - \underbrace{hd_u}_{\text{Horizontal diffusion}}$$

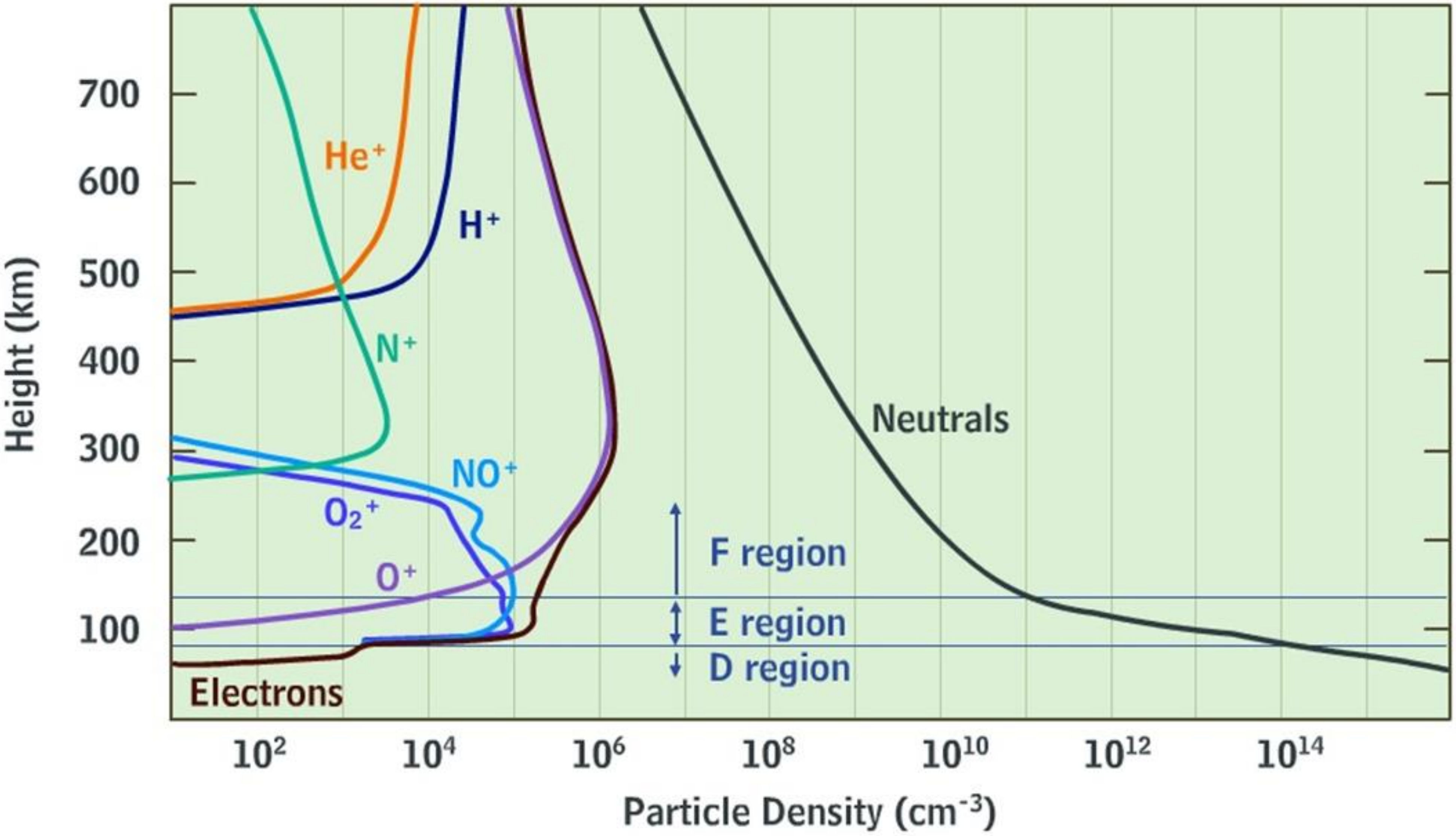
Meridional velocity

$$\frac{\partial v_n}{\partial t} = \underbrace{\frac{ge^z}{p_0}\frac{\partial}{\partial Z}\left[\frac{\mu \partial v_n}{H \partial Z}\right]}_{\text{Viscosity}} - \underbrace{f^{corr} v_n}_{\text{Coriolis}} + \underbrace{\lambda_{yy}\left(v_{ExB,x} - u_n\right) + \lambda_{xy}\left(v_{ExB,y} - u_n\right)}_{\text{Ion drag}} - \underbrace{\mathbf{v}_n \cdot \nabla v_n}_{\text{Horizontal advection}} + \underbrace{\frac{u_n v_n}{R_E}\tan\lambda}_{\text{Mommentum}} - \underbrace{\frac{1}{R_E}\frac{\partial \Phi}{\partial \lambda}}_{\text{Pressure gradient}} - \underbrace{W\frac{\partial v_n}{\partial Z}}_{\text{Vertical advection}} - \underbrace{hd_v}_{\text{Horizontal diffusion}}$$

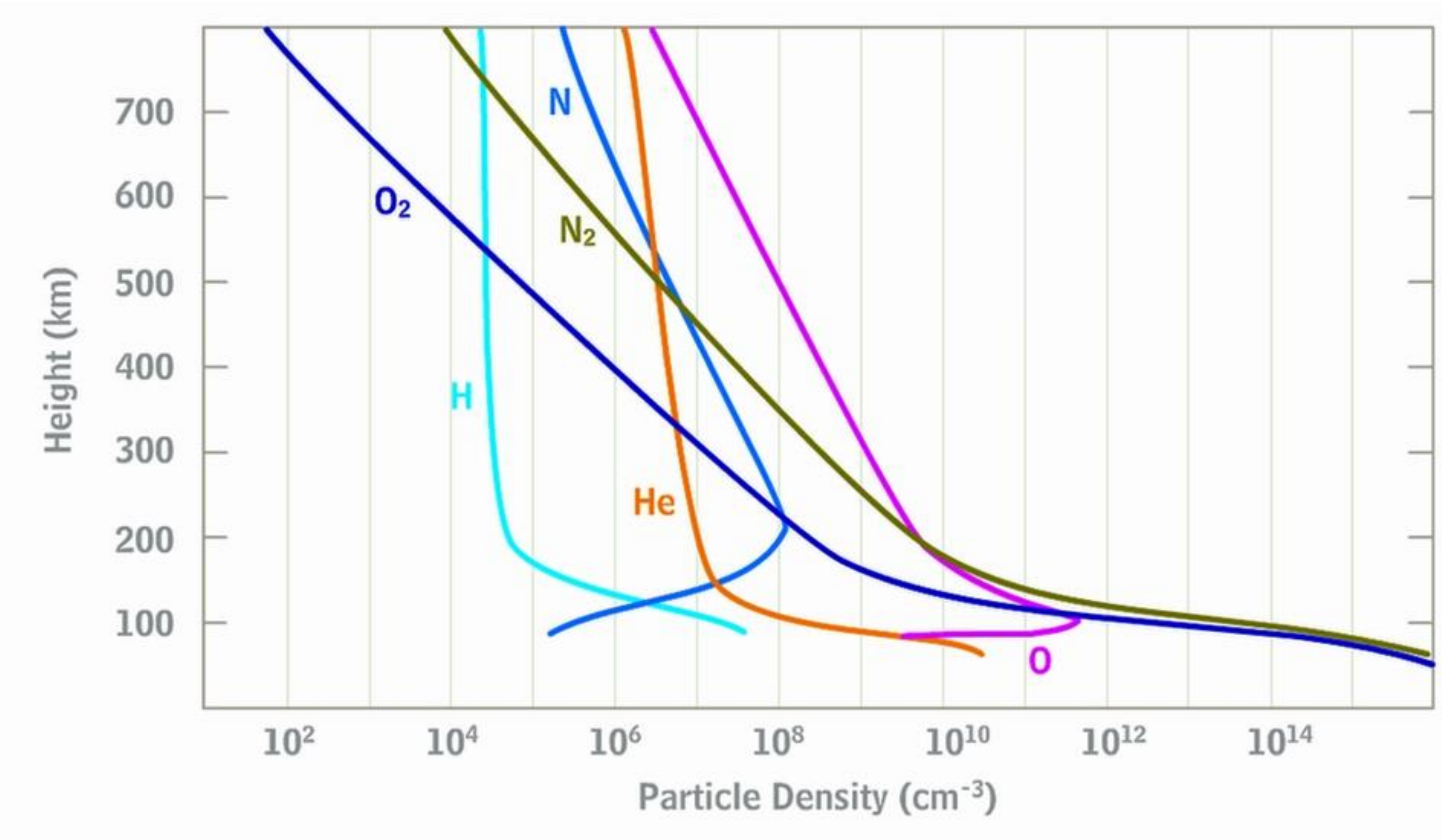
Continuity equation:

$$\frac{d\Psi}{dt} = \underbrace{-e^z \tau^{-1}\frac{d}{dz}\left\{\frac{m}{m_{N_2}}\left(\frac{T_0}{T}\right)^{0.25}\alpha^{-1} L\Psi\right\}}_{\text{Molecular diffusion}} + \underbrace{e^z\frac{d}{dz}\left\{K(z)e^{-z}\frac{d\Psi}{dz}\right\}}_{\text{Eddy diffusion}} - \underbrace{V \cdot \nabla\Psi}_{\text{Horizontal advection}} - \underbrace{\omega\frac{d\Psi}{dz}}_{\text{Vertical advection}} + \underbrace{S - R}_{\text{production and recombination}}$$

UPPER ATMOSPHERE COMPOSITION



NEUTRALS



Height (km)
700
600
500
400
300
200
100
O_2
N_2
N
H
He
O
10^2
10^4
10^6
10^8
10^{10}
10^{12}
10^{14}
Particle Density (cm^{-3})

UPPER-ATMOSPHERE CHEMICAL PROCESSES

Photoionization:

$h\upsilon + O \Rightarrow O^{+} + e^{-}$

$h\upsilon + O_2 \Rightarrow O_2^{+} + e^{-}$

$h\upsilon + N_2 \Rightarrow N_2^{+} + e^{-}$

Collisional Ionization:

$e^{-} + O \Rightarrow O^{+} + 2e^{-}$

Charge Exchange:

$H + O^{+} \Rightarrow H^{+} + O$

$O_2 + O^{+} \Rightarrow O_2^{+} + O$

$N_2 + O^{+} \Rightarrow N_2^{+} + O$

Conversion:

$N_2^{+} + O \Rightarrow NO^{+} + O$

$N_2 + O^{+} \Rightarrow NO^{+} + O$

Recombination:

$O + O + N_2 \Rightarrow O_2 + N_2$

Dissociative Recombination:

$O_2^{+} + e^{-} \Rightarrow O + O$

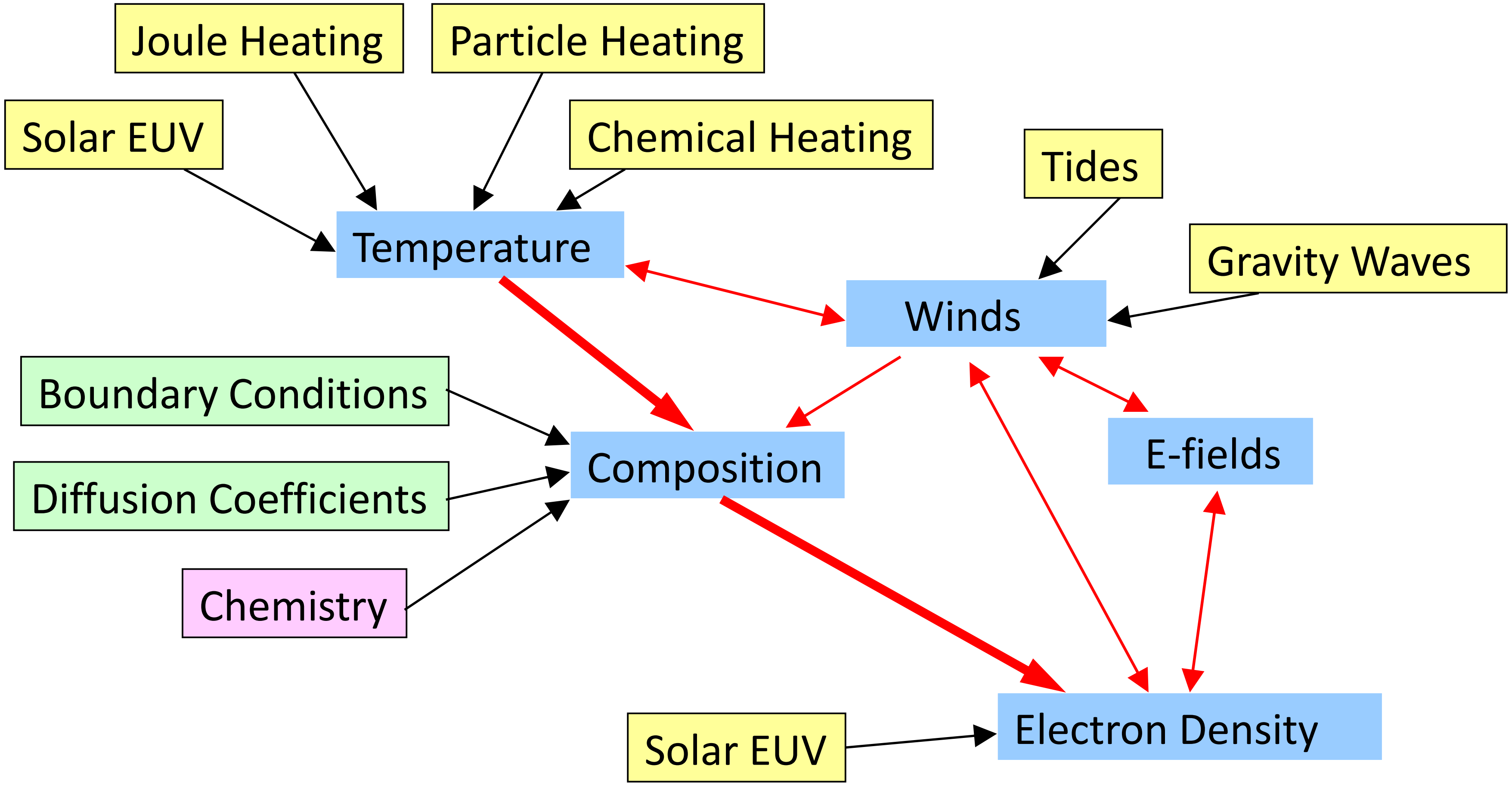
$N_2^{+} + e^{-} \Rightarrow N + N$

$NO^{+} + e^{-} \Rightarrow N + O$

Radiative Recombination:

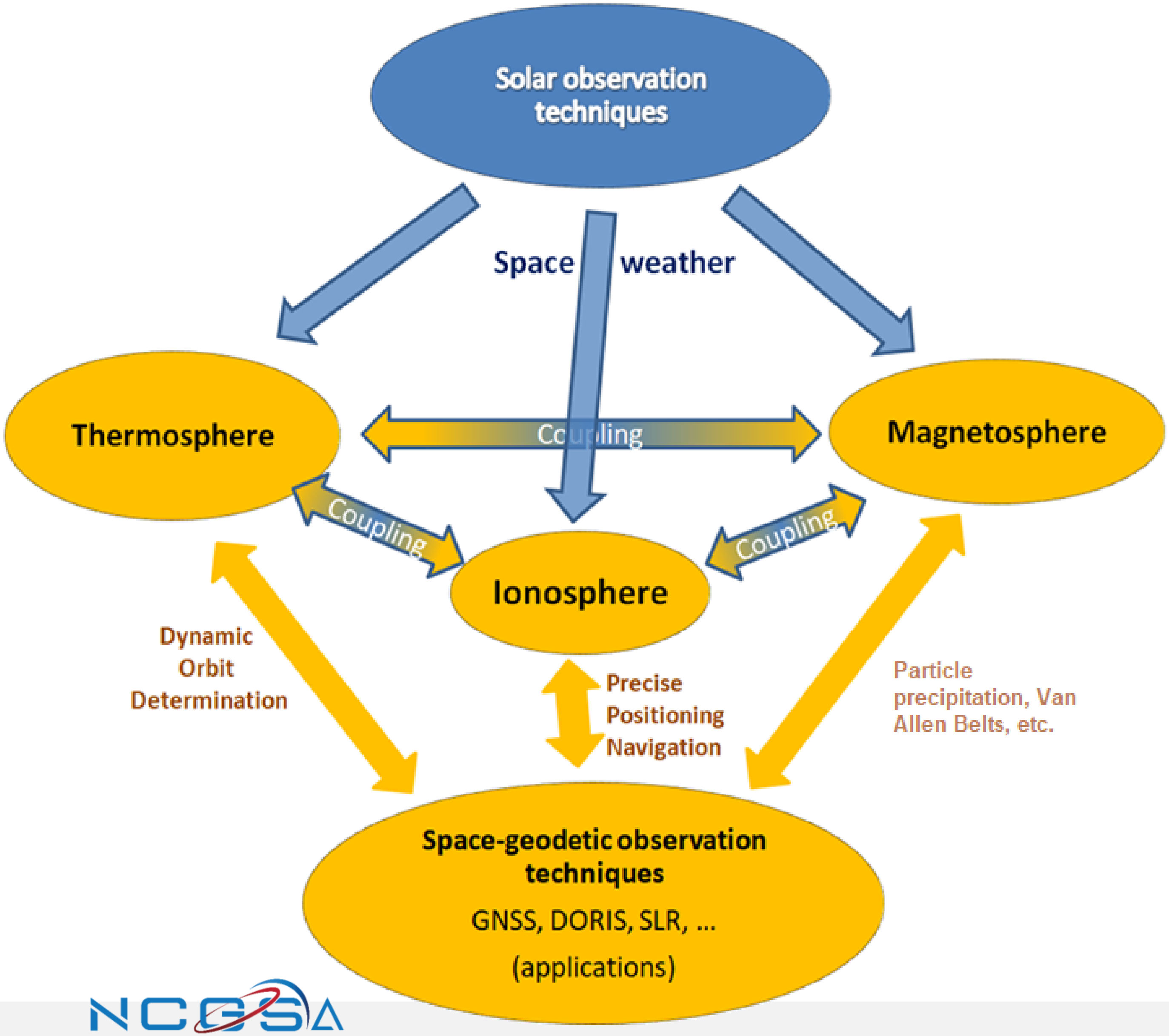
$O^{+} + e^{-} \Rightarrow h\upsilon + O$

UNDERSTANDING UPPER-ATMOSPHERE PHYSICS



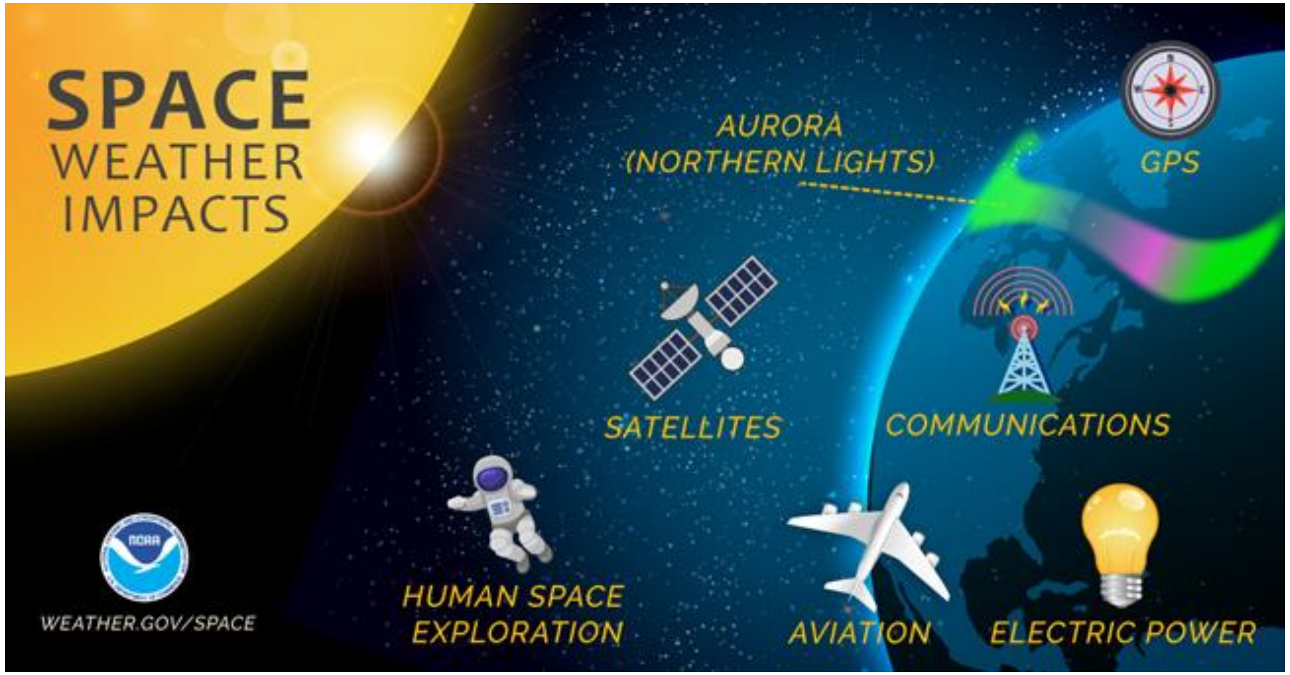
GEODETIC SPACE WEATHER RESEARCH

Research on upper atmosphere aims to contribute for a better **understanding** of Space Weather phenomena within the coupled MIT system, and for the formulation of **predictive models** of the near-Earth space environment.



SPACE WEATHER IMPACTS

- **Radio signal propagation** in the ionosphere, affecting GNSS, communications, etc.;
- **Drag force** on **Low Earth Orbit** (LEO) satellites; and
- **Power and internet outages** due to intense **electric currents** induced during geomagnetic storms, **killer electrons**, etc.



A CHALLENGE TO UNDERSTAND THE MIT SYSTEM

Addressing the challenges related to the coupled MIT system requires significant advances in **geodetic observations** of plasma and neutral density, “compositions”, and “velocities”, observations of energetic particles and “magnetic field perturbations” both in space and on ground, as well as **advanced theoretic and numerical modeling** capabilities.

NCGSA
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SELECTED PUBLICATIONS 2020-2021

2020

JGR Space Physics

RESEARCH ARTICLE
10.1029/2019JA027703

Special Section:
Long-term changes and trends in the Middle and Upper Atmosphere

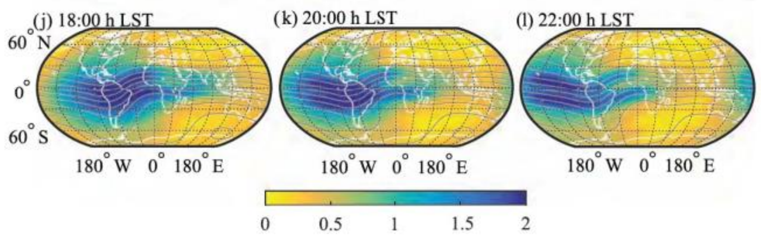
New Modes and Mechanisms of Long-Term Ionospheric TEC Variations From Global Ionosphere Maps

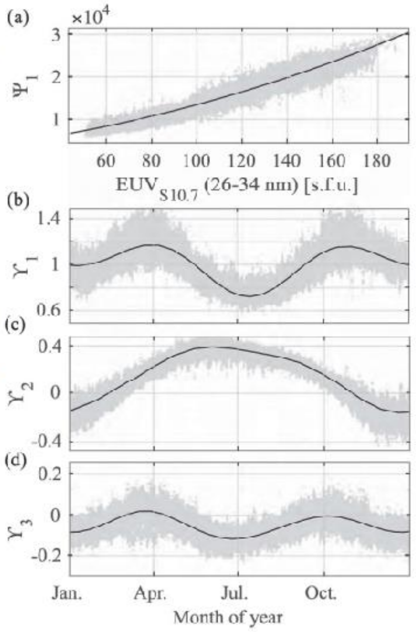
Andres Calabia[1,2] and Shuanggen Jin[1,2,3]

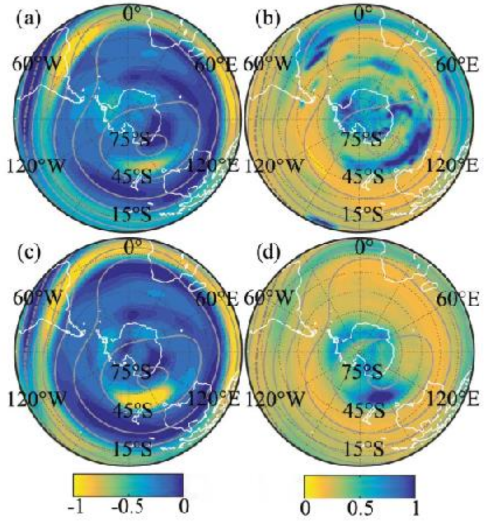
[1]School of Remote Sensing and Geomatics Engineering, Nanjing University of Information Science and Technology, Nanjing, China, [2]Jiangsu Engineering Center for Collaborative Navigation/Positioning and Smart Applications, Nanjing, China, [3]Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai, China

Key Points:

- The solar and the magnetospheric forcing are the main drivers of nonperiodic ionospheric TEC variations
- Main periodic contributions to TEC variations are related to the frequencies of the solar rotation, annual, and subharmonics
- TEC anomaly has been found at about 15° from the South magnetic dip at the night side, more prominent around 52°S 155°E







Journal of Atmospheric and Solar–Terrestrial Physics 199 (2019) 105207

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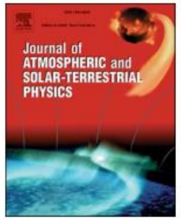
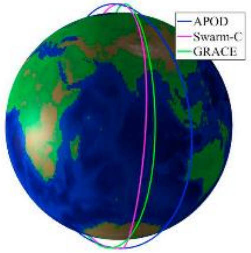
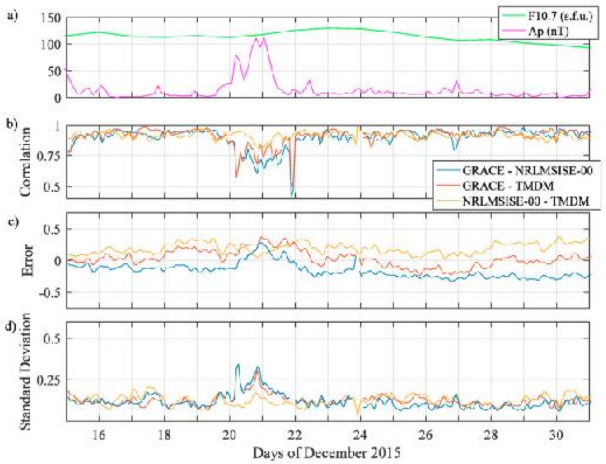


Assessment of new thermospheric mass density model using NRLMSISE-00 model, GRACE, Swarm-C, and APOD observations

Andres Calabia, Geshi Tang *, Shuanggen Jin **

School of Remote Sensing and Geomatics Engineering, Nanjing University of Information Science and Technology, Nanjing, 210044, China





Space Weather
2021
AGU ADVANCING EARTH AND SPACE SCIENCE
RESEARCH ARTICLE
10.1029/2020SW002645

Upper-Atmosphere Mass Density Variations From CASSIOPE Precise Orbits

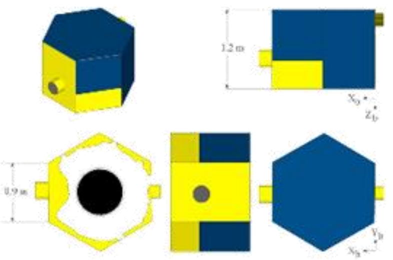
Andrés Calabia[1,2] and Shuanggen Jin[1,3]

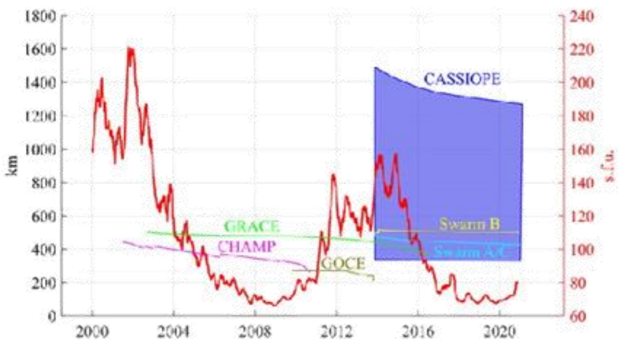
[1]School of Remote Sensing and Geomatics Engineering, Nanjing University of Information Science and Technology, Nanjing, China, [2]School of Land Surveying, Geodesy and Mapping Engineering, Universidad Politécnica de Madrid, Madrid, Spain, [3]Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai, China

Special Section:
Small Satellites for Space Weather Research and Forecasting Workshops

Key Points:

- Thermospheric mass densities are estimated from CAScade SmallSat and IOnospheric Polar Explorer precise orbits
- The detailed thermospheric mass density responses are obtained during the February 2014 geomagnetic storm
- CASSIOPE-derived thermospheric mass density is better than the NRLMSIS-00 model to reflect responses to the storm





JGR Space Physics
RESEARCH ARTICLE
10.1029/2021JA029540

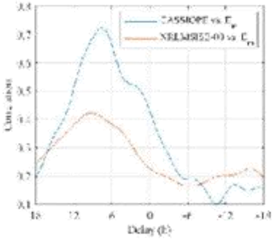
Thermospheric Mass Density Disturbances Due to Magnetospheric Forcing From 2014–2020 CASSIOPE Precise Orbits

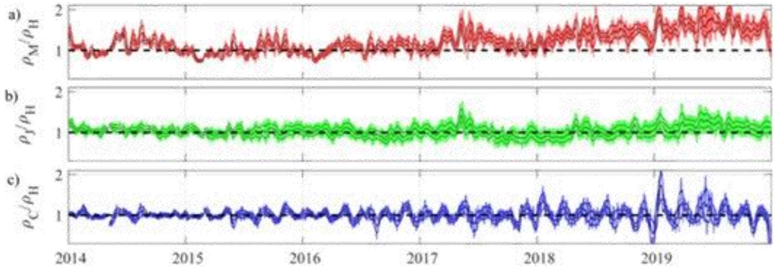
Andrés Calabia[1] and Shuanggen Jin[1,2]

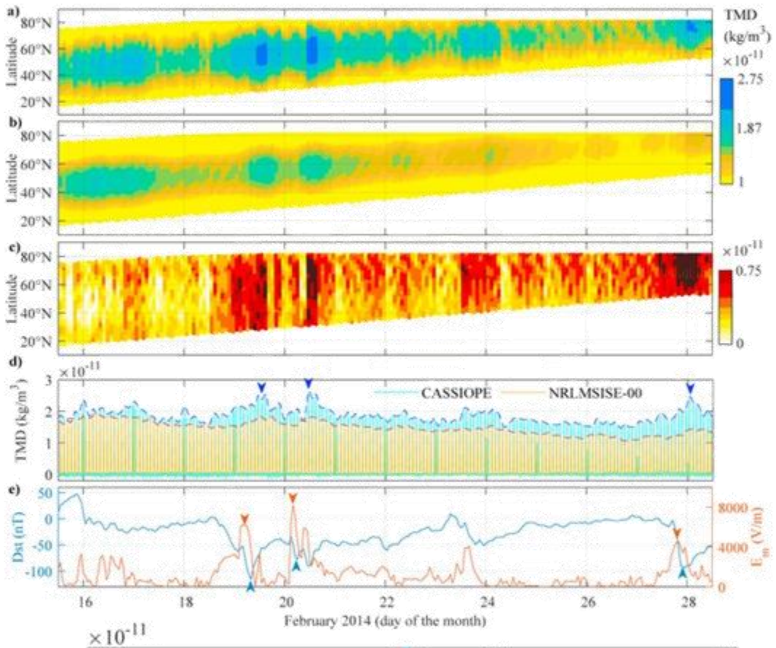
[1]School of Remote Sensing and Geomatics Engineering, Nanjing University of Information Science and Technology, Nanjing, China, [2]Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai, China

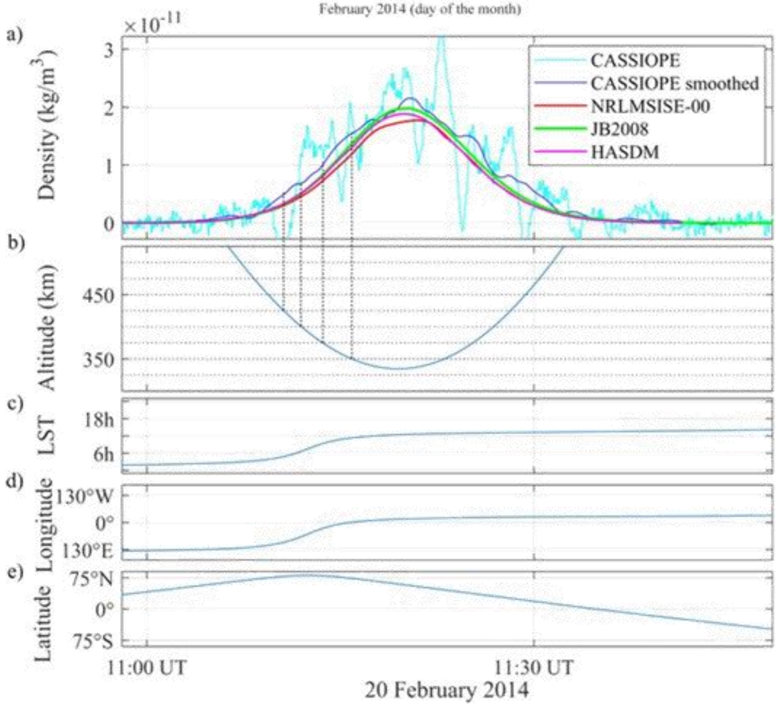
Key Points:

- Thermospheric mass densities from 2014 to 2020 are estimated from CAScade SmallSat and IOnospheric Polar Explorer Global Navigation Satellite System (GNSS) precise orbits
- The high-resolution thermospheric mass densities inferred from commercial-off-the-shelf GNSS receivers are validated
- The density disturbances due to magnetospheric forcing are investigated for correlations and time-delay responses to models and indices









JOINT STUDY GROUP: MIT COUPLING

Implemented at International association of Geodesy (**IAG**) Inter-Commission Committee on Theory (**ICCT**); joint with IAG Global Geodetic Observing System (**GGOS**), Focus Area on Geodetic Space Weather Research (**FA-GSWR**); **IAG Commission 4 Positioning & Applications**; and **IAG Sub-Commission 4.3 Atmosphere Remote Sensing**.

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MultiDark
Multimessenger Approach for Dark Matter Detection

Computational Astrophysics Laboratory, RIKEN

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WCRP

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Thank you!

Dr. Andres Calabia Aibar

Space geodesy, navigation, and remote sensing. Data analysis and algorithm development.

Research interests
Upper atmosphere environments and coupling between Earth and space weather, the repercussions of these environments on satellites, and the utilization of geodetic techniques to interpret the planetary variability, and to test, validate, and develop geophysical models.