Ionosphere-Thermosphere Dynamics

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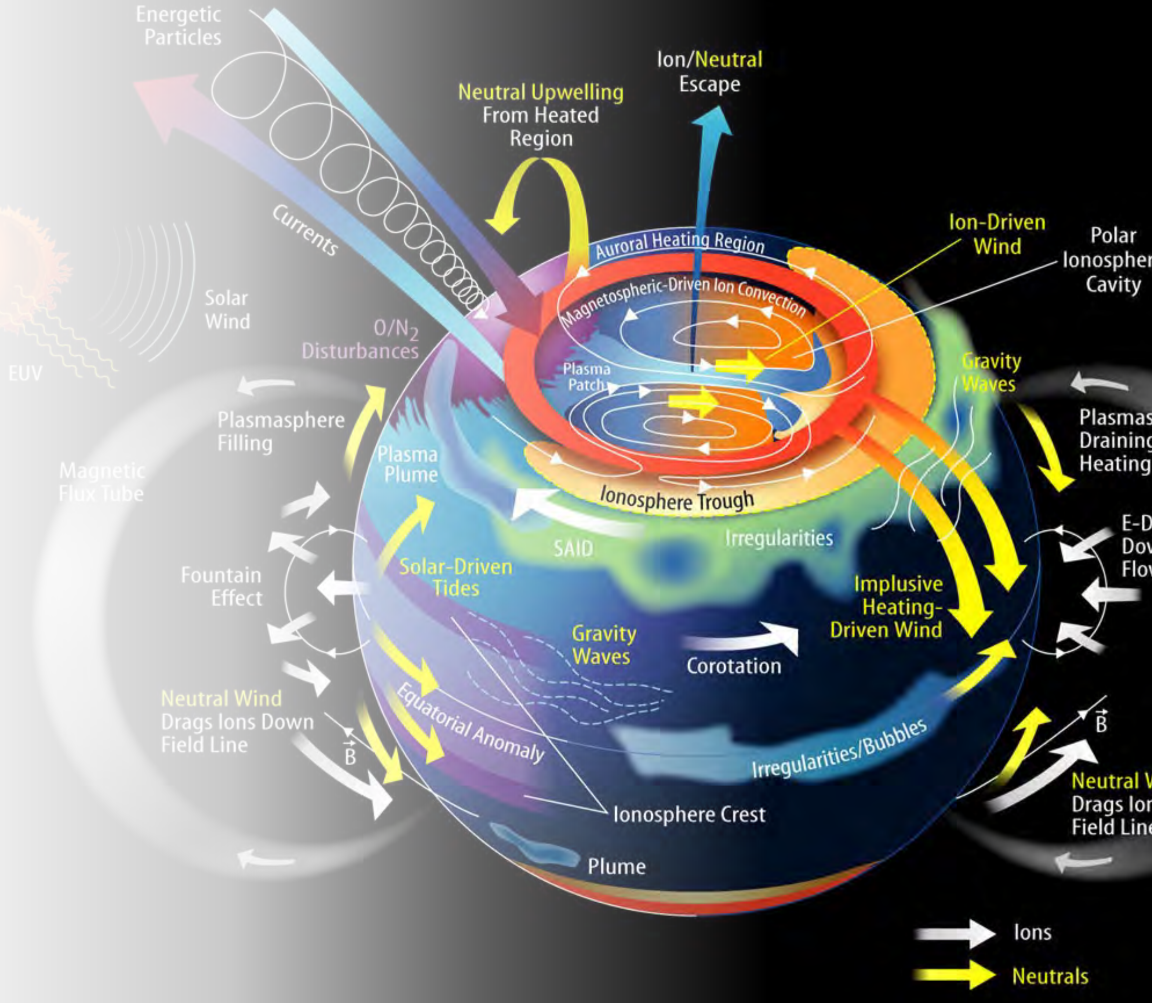
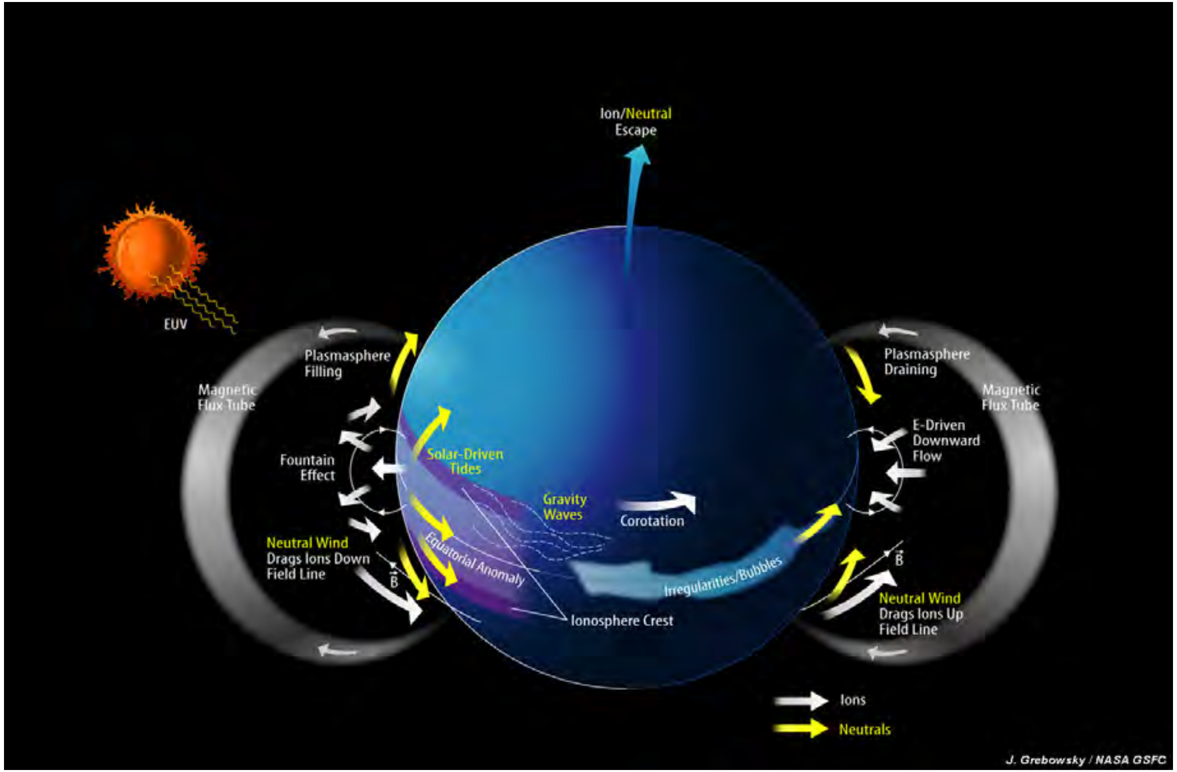


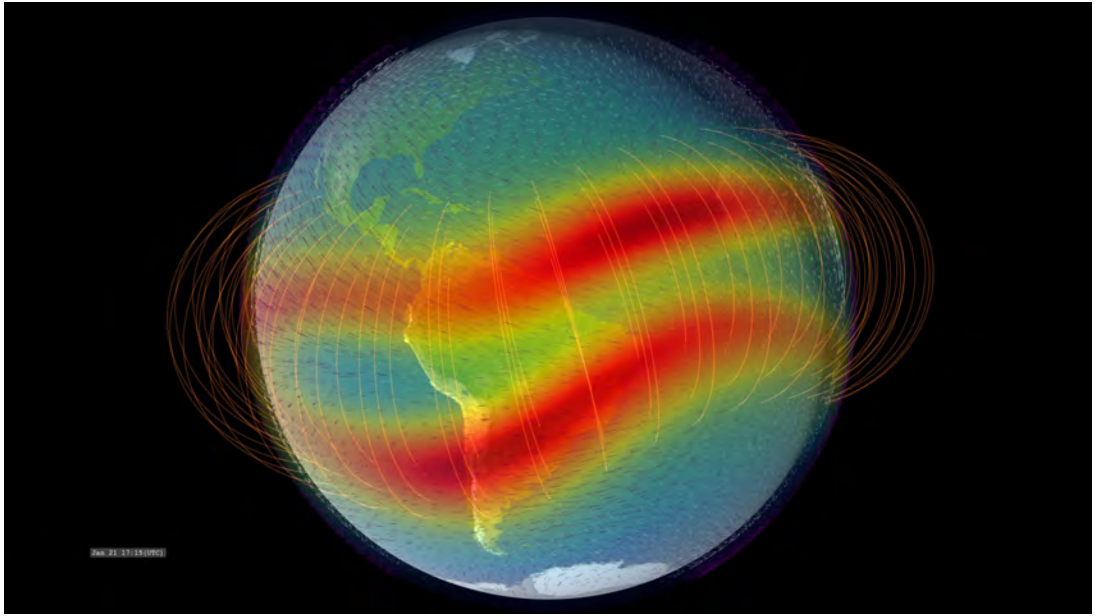
IT System with Solar EUV Forcing Only



If the solar EUV is the only energy source, most of the IT dynamics would occur in the equatorial to low latitude region.

Dayside Equatorial Ionization Anomaly (EIA)

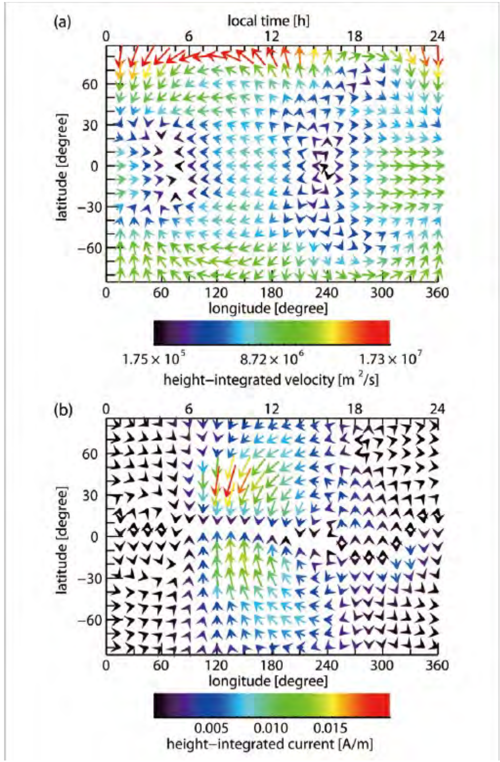
- EIA or Appleton Anomaly: Large-scale feature in the dayside equatorial and low-latitude region.
- Edward Appleton won the Nobel Prize in Physics in 1947 for his seminal work proving the existence of the ionosphere.



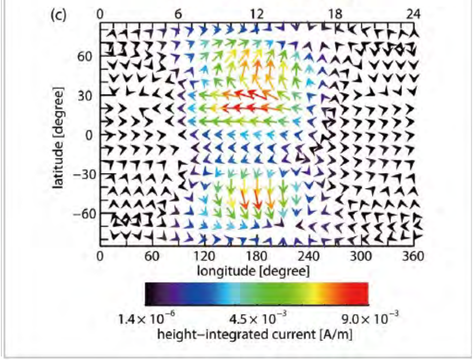
Credit: NASA's Scientific Visualization Studio

E-region Dynamo

An intense convergence of dynamo current to the sunrise sector at the magnetic equator. Here, positive charge is accumulated. In contrast, dynamo current diverges from around the sunset sector at the equator, with negative charge being accumulated.



- Wind velocity field in the thermosphere (September, 0:00 in UT, diurnal component),
- Pedersen dynamo current driven by the neutral winds
- (c) Hall dynamo current.
- The panels (a) to (c) are all integrated over altitudes from 100 to 300 km.



- Jin Hidekatsu

E-region Dynamo

- Effect of poleward winds and Pedersen conductivity near the terminators:
- Eastward electric field (day)
- Westward electric field (night)

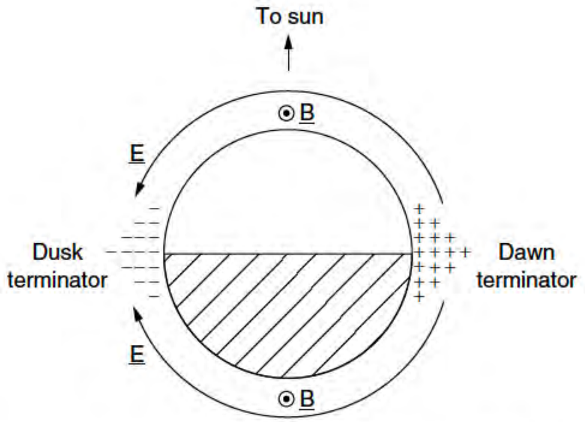
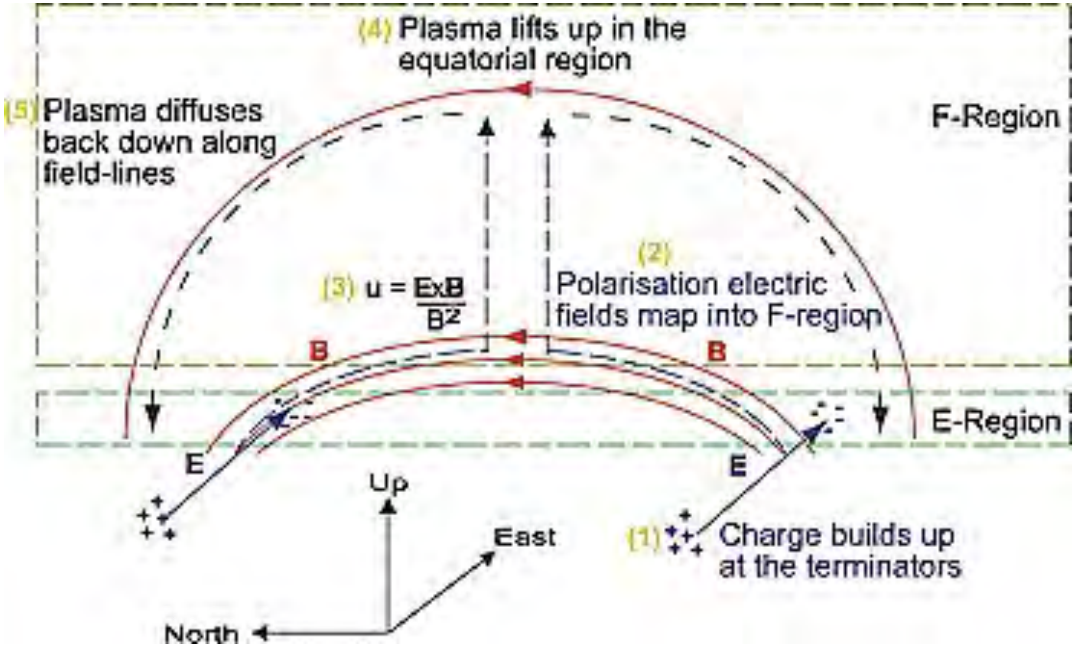


Figure 3.5 Schematic diagram showing the zonal electric field component and its relationship to the charge densities at the terminators. Since the zonal electric field varies slowly with height, the charge density is also a weak function of height from 100 to 500 km.

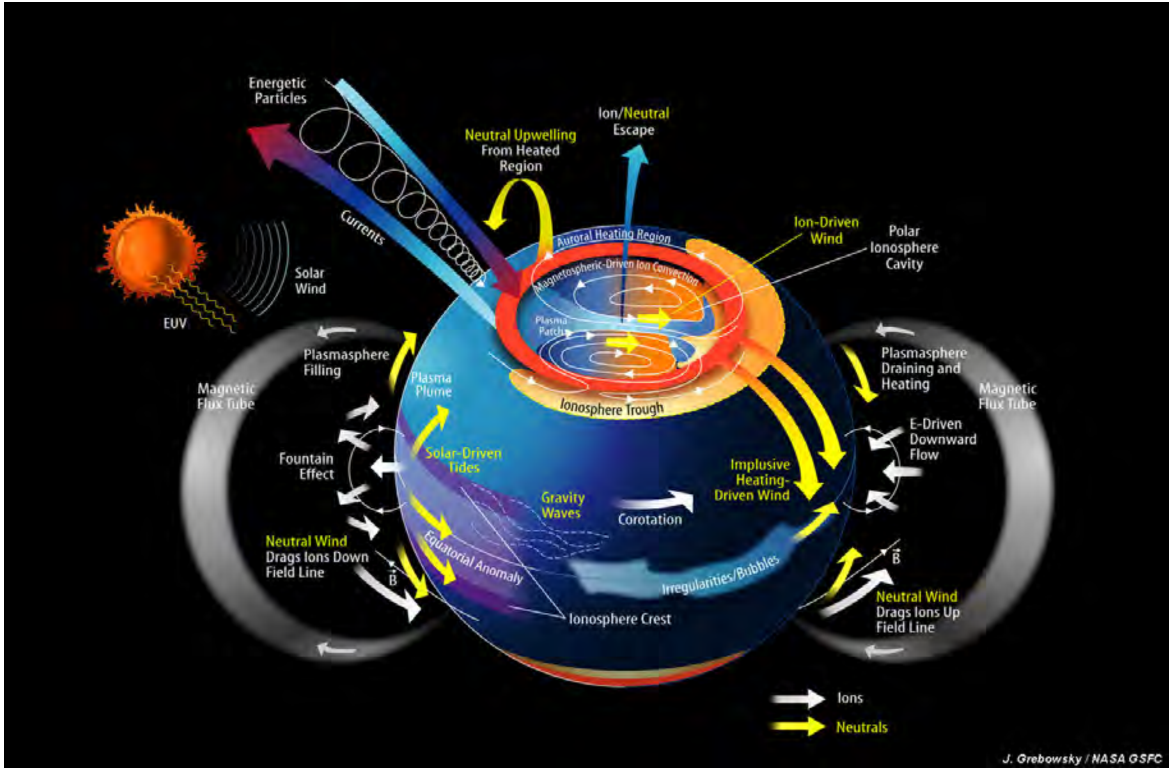
Kelley's Ionosphere book 2009

Appleton anomaly formation mechanism



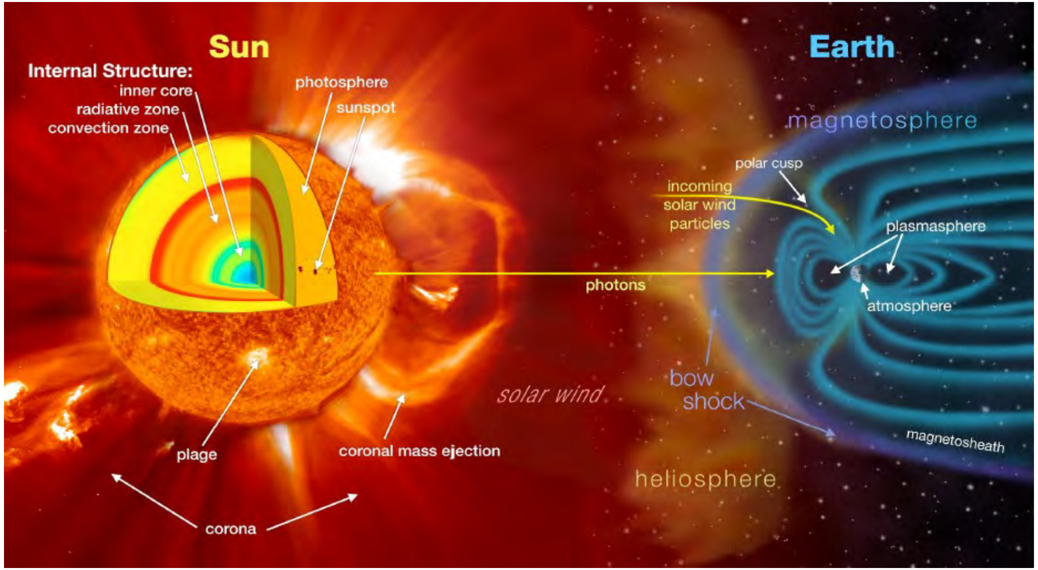
Immel et al. 2006

Adding Solar Wind Forcing



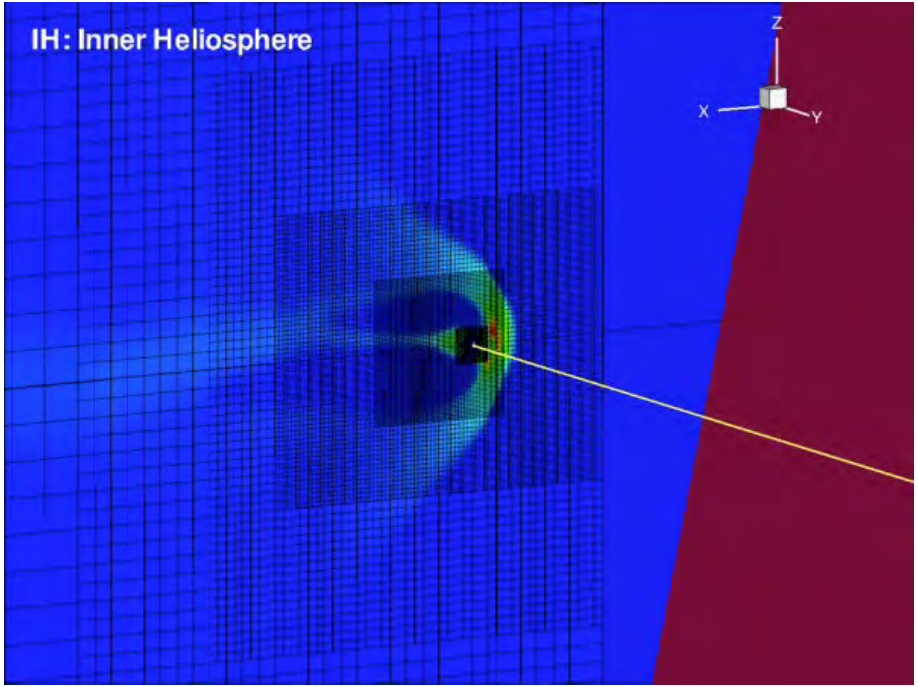
- Adding the solar wind forcing would create various high-latitude dynamics, including convection pattern, FACs and auroral zone.
- During geomagnetic quiet times, the low and high-latitude systems do not interact strongly with each other.

Solar-Terrestrial Relations



- Solar radiation and solar wind are the two ultimate energy sources provided by the Sun to the geospace system.
- The Earth's intrinsic magnetic field deflects much of the solar wind. The solar wind energy entering the magnetosphere drives the dynamics of the geospace system.

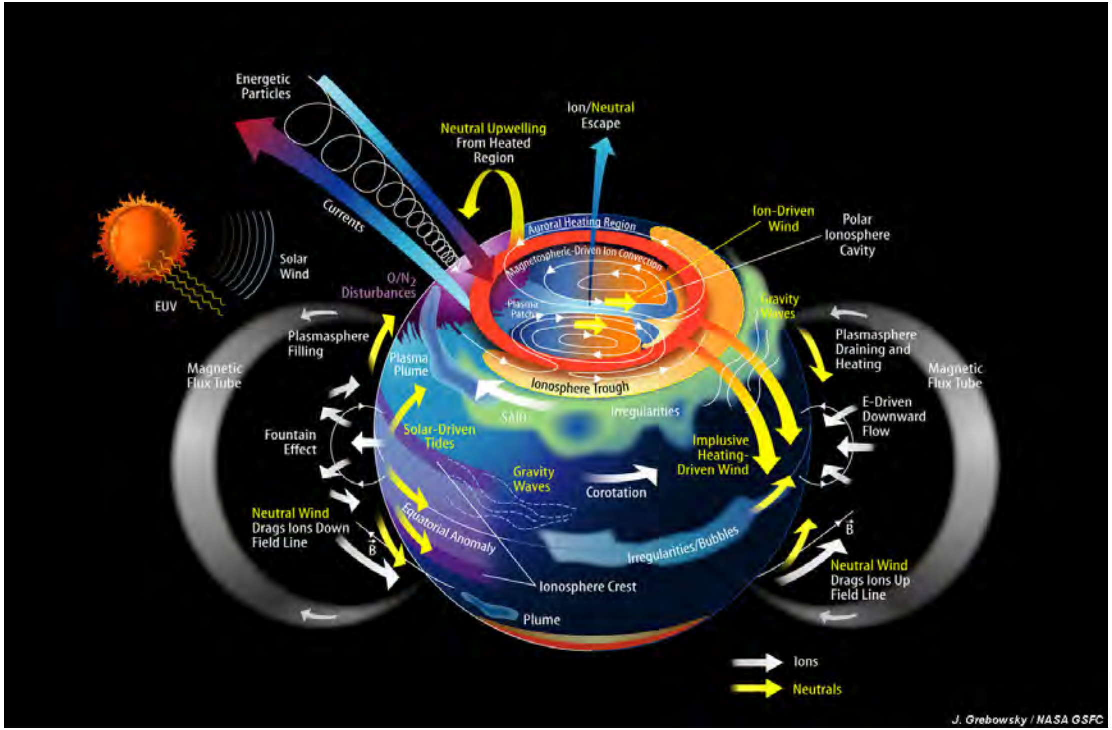
Interaction between Solar Wind and the Earth



Plasma pressure and magnetic fields simulated using University of Michigan Space Weather Modeling Framework (SWMF)

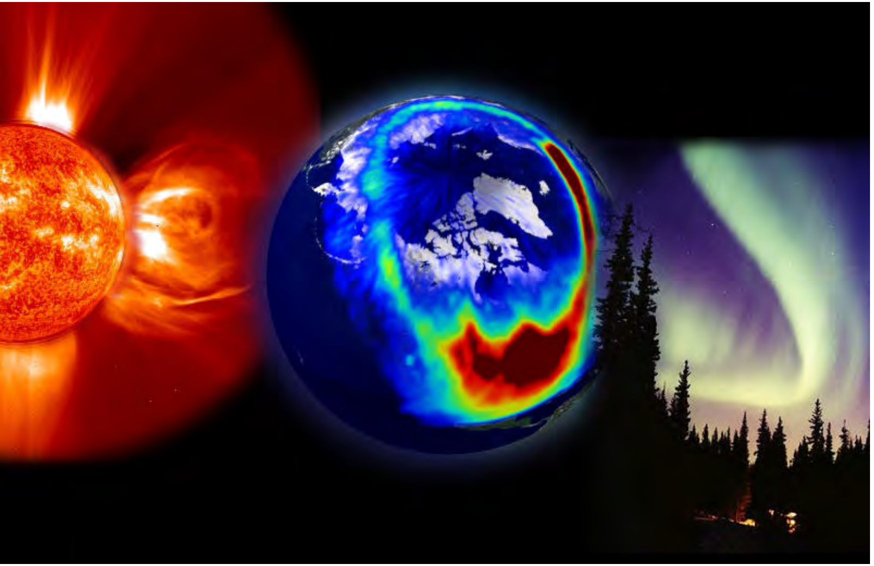
- The geospace system dynamically respond to varying solar wind.

When the Sun “Sneezes”



- Both the solar wind and the solar EUV are highly variable and create “space weather”.
- When they drive the geospace more strongly, for example, during geomagnetic disturbances, the high-latitude system would expand equatorward. At the same time, the equatorial system also expands to higher latitudes. Thus, cross-latitude coupling enhances.

Geomagnetic Disturbances



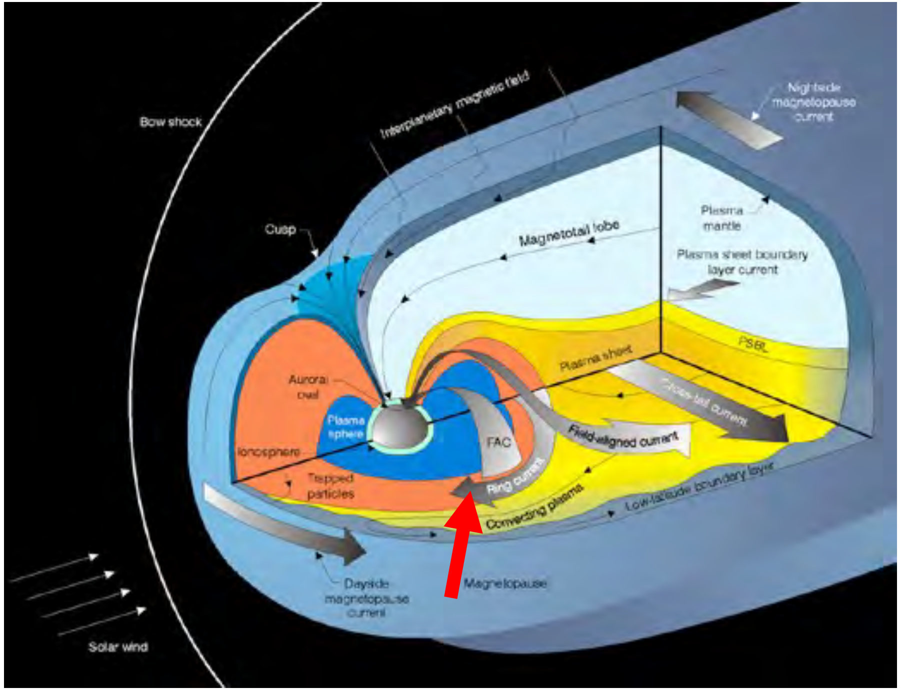
Geomagnetic disturbances are driven by transient solar wind and interplanetary magnetic field structures, such as Coronal Mass Ejection (CME) and Corotating Interaction Region (CIR).

Three major geomagnetic disturbances:

1. **Storm**: largest disturbance; global scale; last a couple of days
2. **Substorm**: nightside disturbance; last a couple of hours
3. **Shock compression**: transient but global disturbance; last several minutes

Geomagnetic Storm

- A geomagnetic storm is a major disturbance of Earth's magnetosphere that occurs when there is a very *efficient energy exchange* from the solar wind into the space environment surrounding Earth.
- There are major changes in the currents, plasmas, and fields in the Earth's magnetosphere.
- Geomagnetic storms are defined by worldwide average of the low-latitude disturbance in the horizontal magnetic field due to *ring current* in the inner magnetosphere.

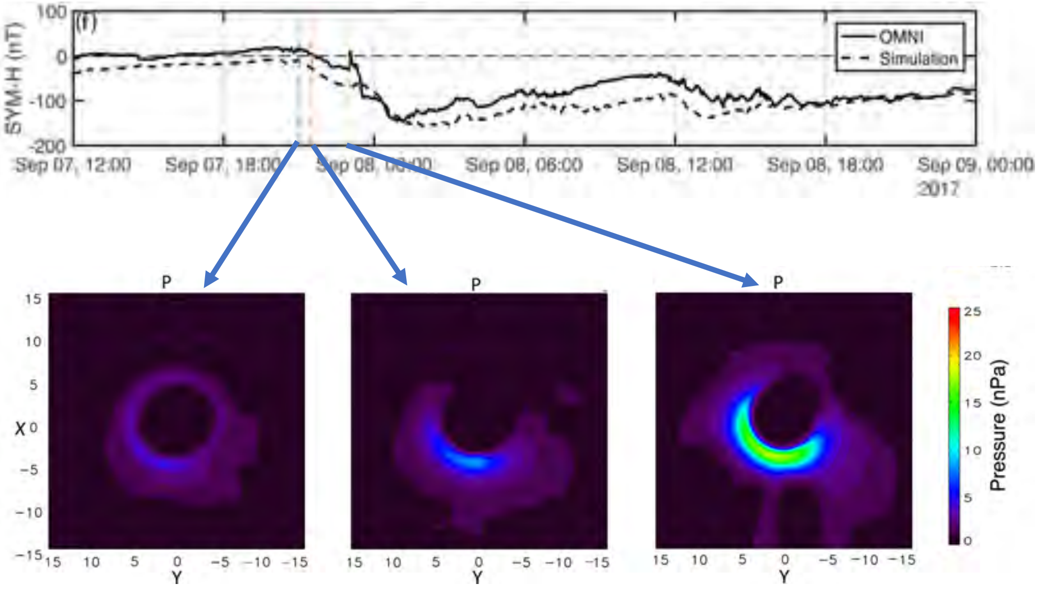


Geomagnetic Storm Identification

- An hourly index D_{st} (disturbance storm-time index) is traditionally used to identify storm and define its magnitude.
  - High temporal resolution version (1-min): Sym-H
  - SuperMAG symmetric ring current index: SMR (Newell and Gjerloev, 2012, JGR)

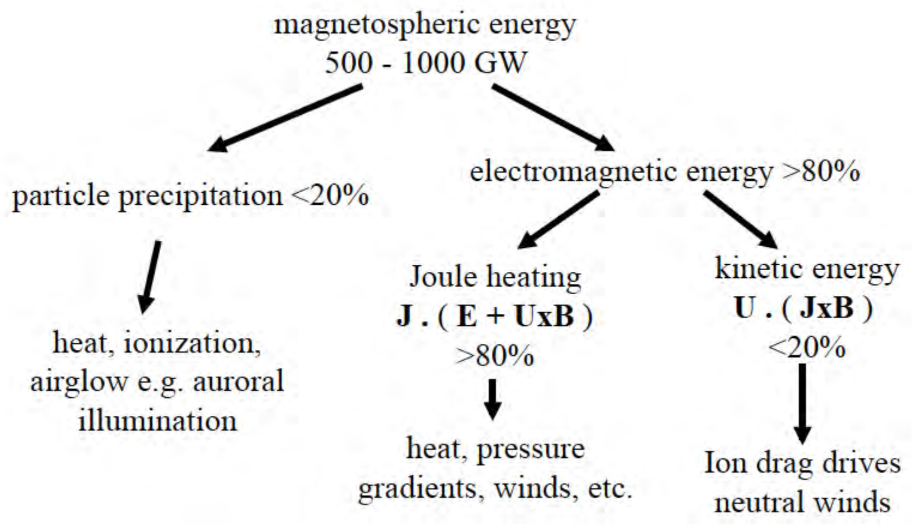
- Geomagnetic storm classification:
  - Minor: -20 nT > D_{st} > -50 nT
  - Moderate: -50 nT > D_{st} > -100 nT
  - Intense: -100 nT > D_{st} > -250 nT
  - Super: -250 nT > D_{st}

Sym-H and ring current evolution



Wang et al. (2019). *GRL*, 46, 7920– 7928.

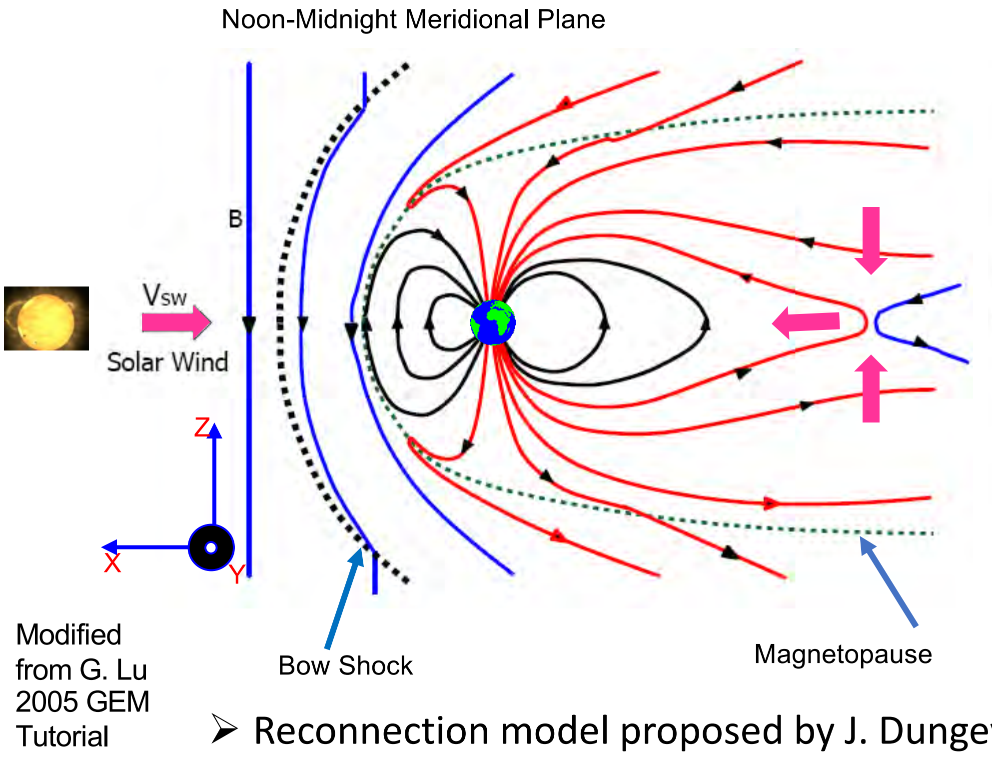
Energy Flow During Storm

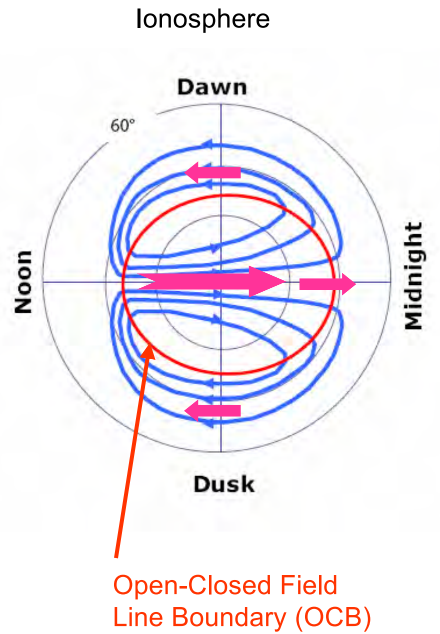


See Lu et al., 1995

- Several hundreds GW energies flow into the IT system in the form of electromagnetic energy (Poynting flux) and particle precipitation.
- Electromagnetic energy (Poynting flux) is the dominant energy source.
- Majority of the electromagnetic energy goes to Joule heating.

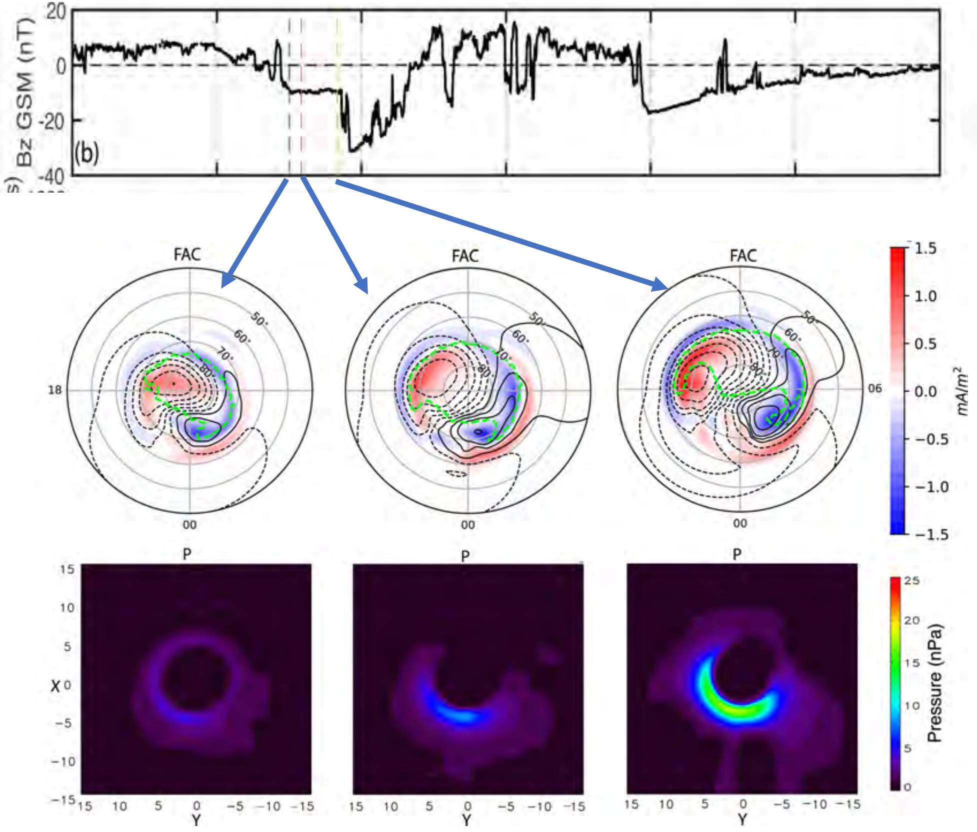
Magnetospheric and Ionospheric Convection: Fluid Description





- Reconnection model proposed by J. Dungey [1961]
- Major energy and momentum coupling mechanism between the solar wind and magnetosphere.

Storm-time Expansion of Ionospheric Convection



- Dayside reconnection enhances after strong IMF southward turning during storm and efficiently transfers energies into the magnetosphere.
- High-latitude ionospheric convection and FACs expand to lower latitudes.
- Mis-match between convection pattern and FACs => penetrating or shielding electric field
- Penetration electric fields can be established globally nearly simultaneous.
- Ring current evolution modulates the convection and FAC patterns.

Wang et al. (2019). *GRL*, 46, 7920–7928.

Ion-Neutral Coupling

- Convecting ionosphere can be a significant source of momentum and energy for the thermosphere via ion–neutral collisions.

- Resulting interactions act to modify the thermospheric circulation, temperature, and composition, which, in turn, affects the ionosphere.

- Extent of the coupling depends on plasma density. For plasma densities of 10^3 to 10^6 cm^{-3}, the characteristic time constant for accelerating the thermospheric particles ranges from 200 hours (several days) to 10 minutes.

Temporal change of ion temperature:

$$\frac{\partial}{\partial t} T_i = \nu_{in}\left(-T_i + T_n + \frac{M_n}{3k}(\bar{v} - \bar{u})^2\right)$$

Time scale for ions to respond to frictional heating:

$$\tau \propto \frac{1}{\gamma_{in}}$$

A few seconds to a few tens of seconds

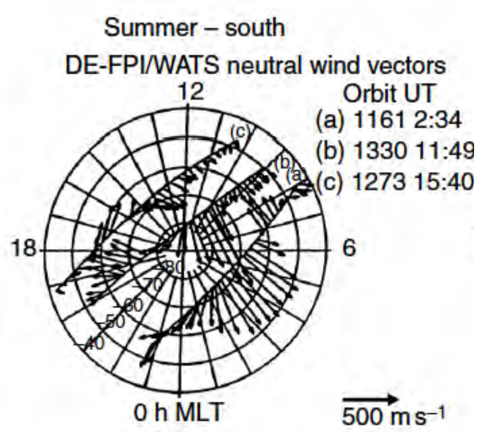
Time scale for neutrals to respond to frictional heating:

$$\tau \propto \frac{1}{\gamma_{ni}} = \frac{n_n m_n}{n_i m_i \gamma_{in}} \gg \frac{1}{\gamma_{in}}$$

Because the neutral density is much higher than the ion density, the time scale for neutrals is much longer than that of ions.

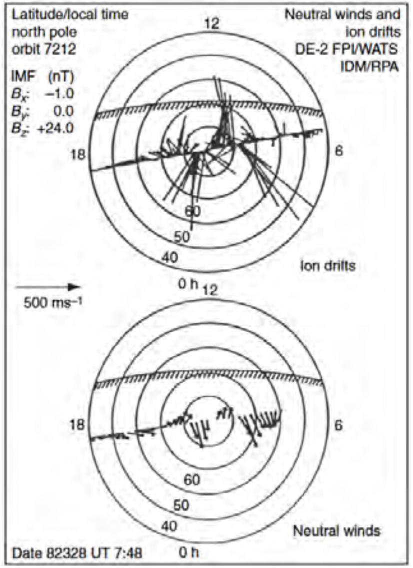
Evidence of Ion-Neutral Coupling at High Latitudes

Southward IMF



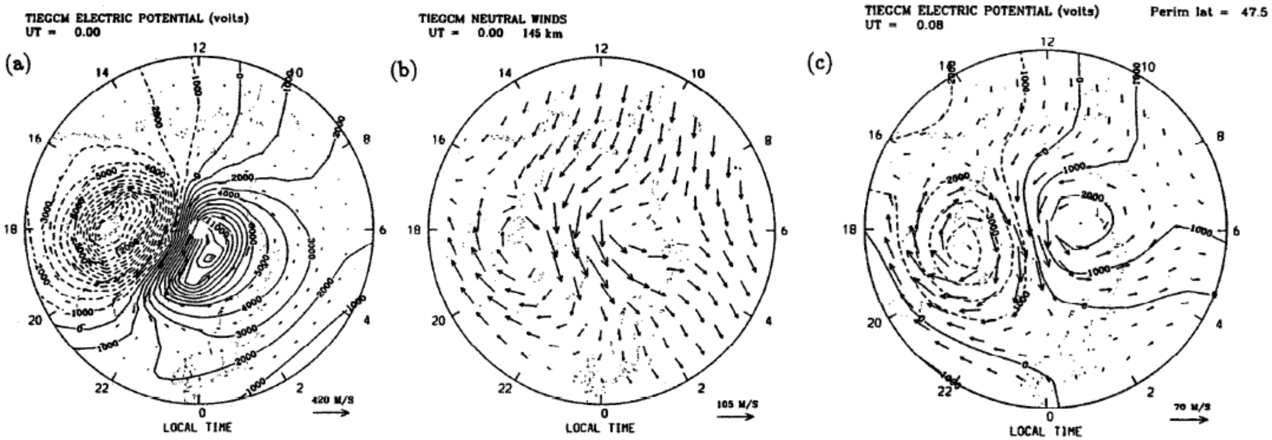
Schunk and Nagy, 2009

Northward IMF



- ➢ High-latitude thermospheric wind pattern mimics the plasma convection pattern.
- ➢ The wind speed is typically smaller than plasma convection speed but much greater than expected if solar heating was the only process driving the flow.

Neutral Flywheel Effects



Richmond and Roble, 1997

- High-latitude winds on average play a secondary role in the magnetosphere-ionosphere electrodynamic coupling.
- However, they can play a more important role immediately following a period of high magnetic activity.
- Neutral winds tend to maintain the ion convection pattern after the external sources are cut-off.