Mesoscale processes in magnetosphere–ionosphere coupling – Part I

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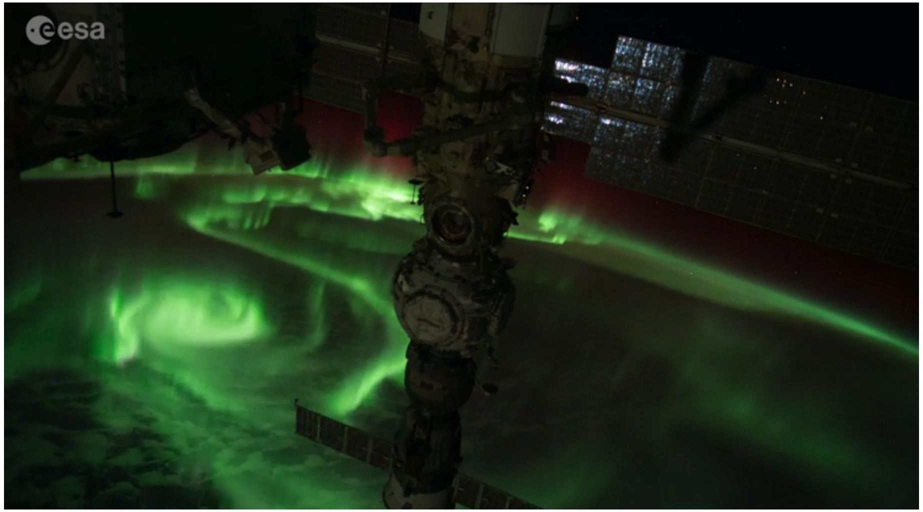
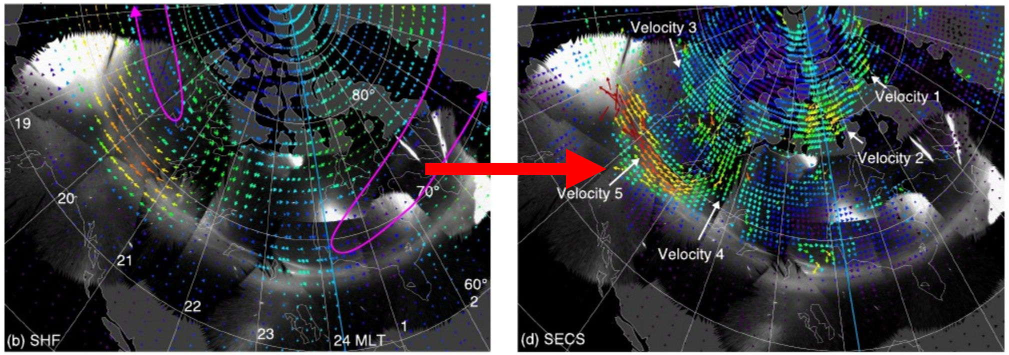
Why are mesoscales such a hot topic?

- Transition between the global scales (system-size) and the microscales
  - Complex physics, coupled processes
- Relevant to space weather: regional impacts, local peaks
- Elusive and challenging to measure and simulate
- New tools (instruments, models, methods) are enabling their study better than before
  - constellations of spacecraft
  - networks of ground-based instruments
  - cutting-edge global models (ion-kinetic description, adaptive resolution, coupled models…)

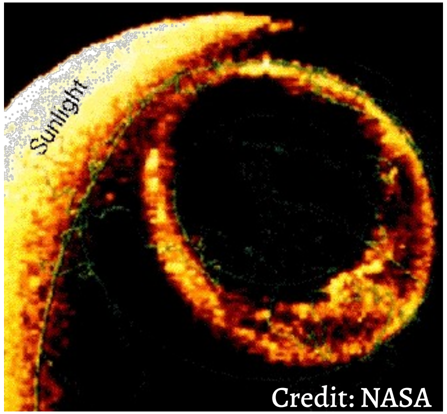


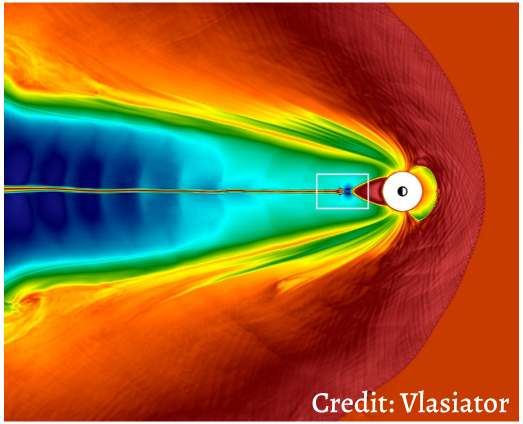
Video credit: ESA/NASA



Adapted from Nishimura et al. (2024)

What are mesoscales in this lecture?





- **Temporal scales:** minutes / tens of minutes
  - Way shorter than geomagnetic storms (days)
  - Also shorter than substorms (couple of hours)
- **Spatial scales in the ionosphere:** 10–1000 km
  - auroral arc width: ~5–30 km
  - auroral oval latitudinal extent: from ~3° (~300 km, quiet time) to > 10° (~1100 km, storm)
  - 1 h in magnetic local time (MLT) at auroral latitudes (~65°): ~700 km
- **Spatial scales in the magnetosphere:** hundreds of km to a few Earth radii (1 R_E = 6371 km)
  - dayside magnetopause standoff distance: ~10 R_E
  - magnetotail extent on the nightside: > 100 R_E
  - magnetotail current sheet thickness: 0.1–1 R_E (depending on conditions)

Outline

Part I: Introduction to magnetosphere–ionosphere (MI) coupling

1. Brief overview of ionospheric physics
2. MI coupling mechanisms
3. Studying mesoscale processes in the ionosphere

Part II: Examples of mesoscale processes in MI coupling

1. Dayside couplings
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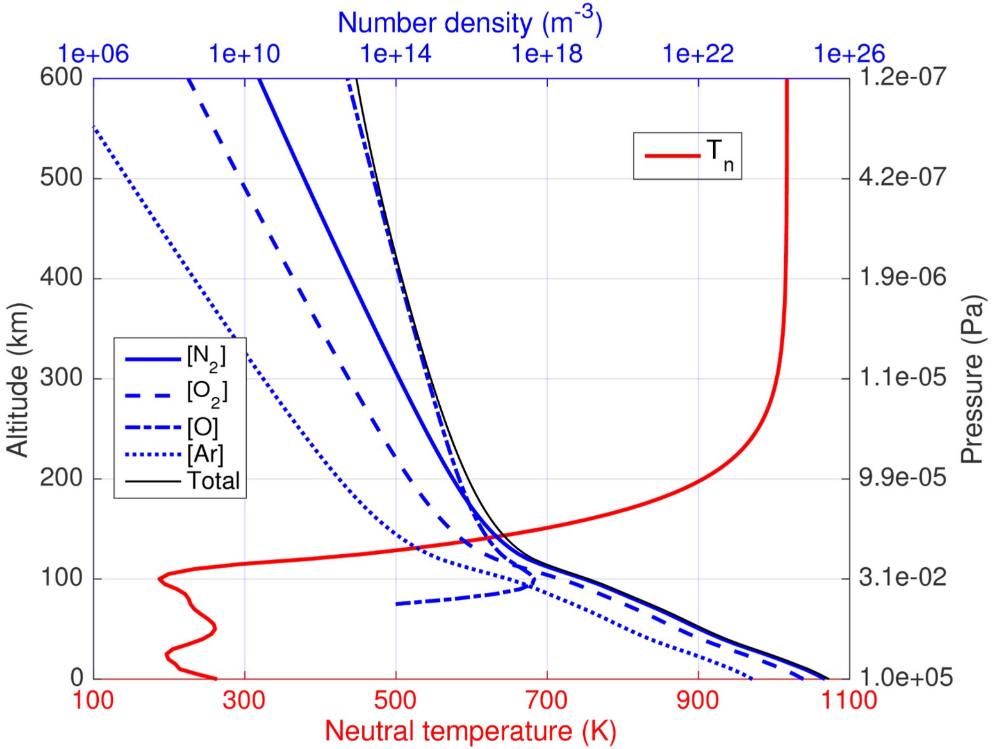
Outline

The neutral atmosphere

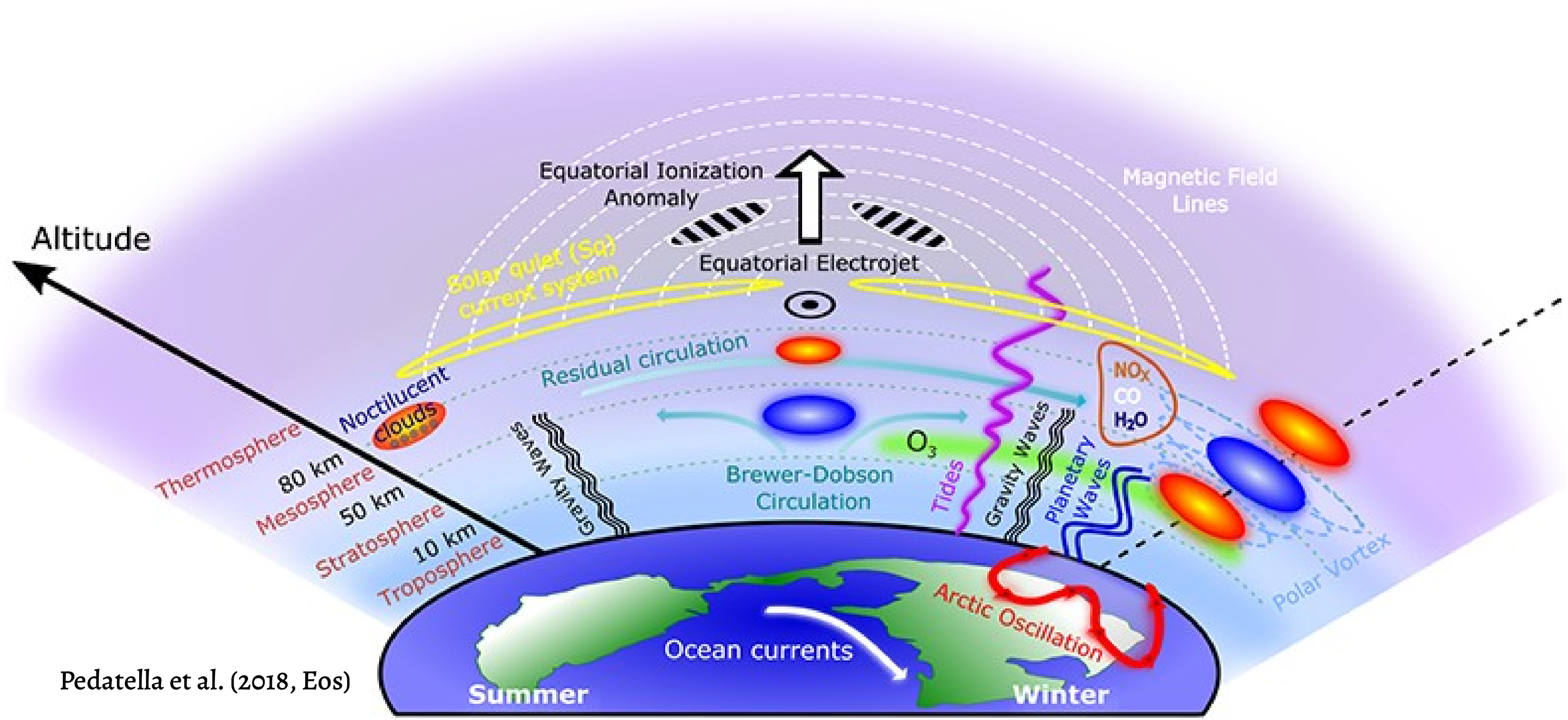
- The neutral atmosphere is divided into **4 regions**, based on the temperature profile: troposphere, stratosphere, mesosphere, and thermosphere



Grandin (2017, PhD thesis)

- 0–100 km altitude: well-mixed gas (78% N_2, 21% O_2, 1% other)
- > 100 km: composition changes (e.g. O, NO, H, He…), each species has its own scale height
- Seasonal variations, global circulation patterns, atmospheric waves…
- Temperatures and densities are sensitive to solar activity (esp. in the thermosphere)

Atmospheric dynamics and chemistry are complex...

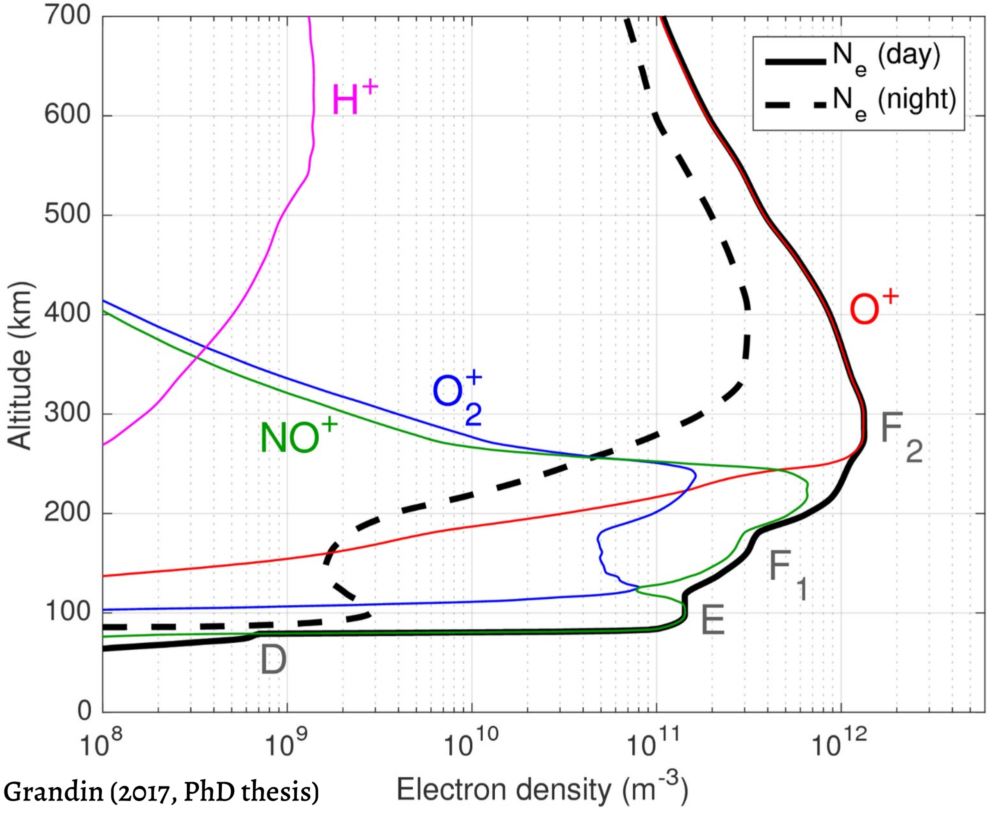


Pedatella et al. (2018, Eos)

...but this is not the topic of this lecture!

Formation & structure of the ionosphere

- Solar EUV and X-ray photons can dissociate molecules and ionise neutrals
- The ionosphere forms as the result of the balance between (photo)ionisation, chemistry, and transport



Grandin (2017, PhD thesis)

- We divide it in 3 regions based on the electron density profile: *D*, *E* and *F*
- Weakly ionised gas: $n_e/n_n \approx 0.1\%$ at the main peak
- ***D* region** (60–90 km): positive and negative ions, disappears at night
- ***E* region** (90–150 km): mainly molecular ions (O_2^+ and NO^+), very depleted at night (except…)
- ***F* region** (>150 km): often exhibits two peaks (F_1: molecular and F_2: atomic), main peak near 300 km

Ionospheric currents: a result of collisions

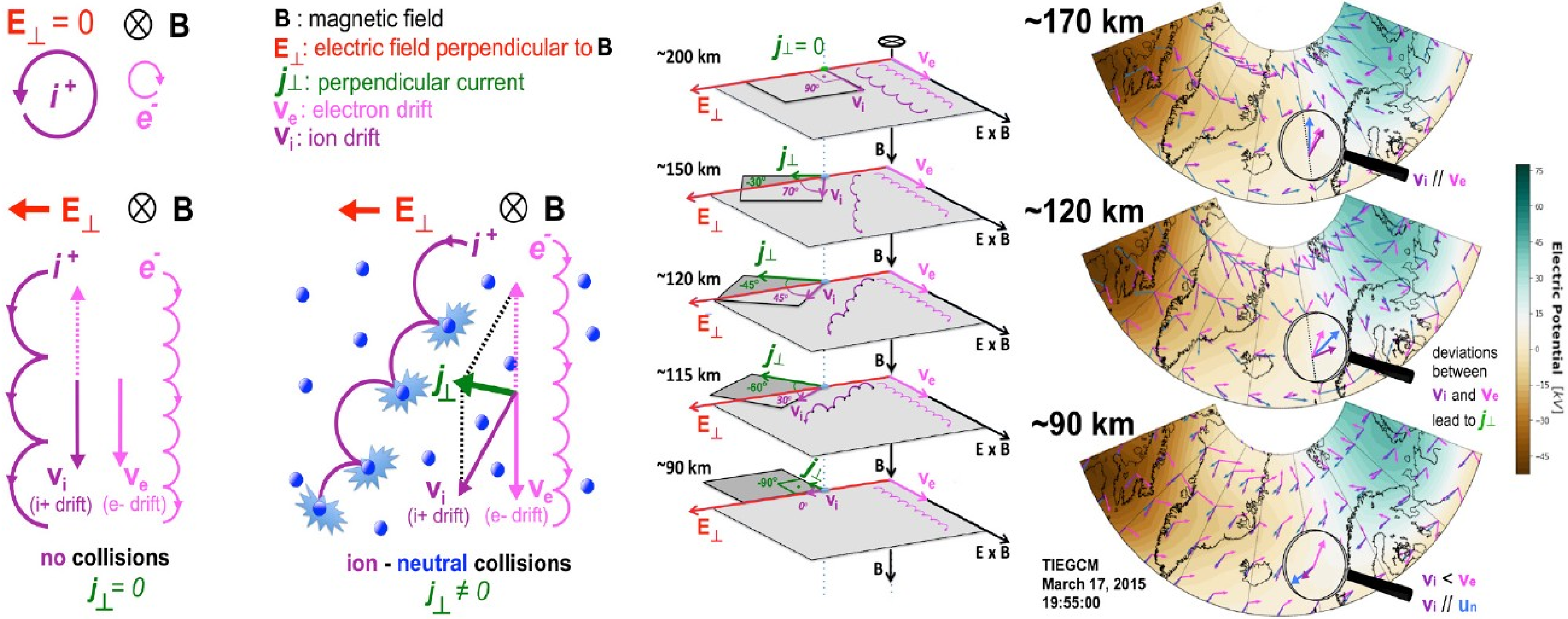


Figure credit: T. Sarris (Daedalus Report for Assessment, ESA, 2020)

Va bene, but how do we get electric fields in the ionosphere?

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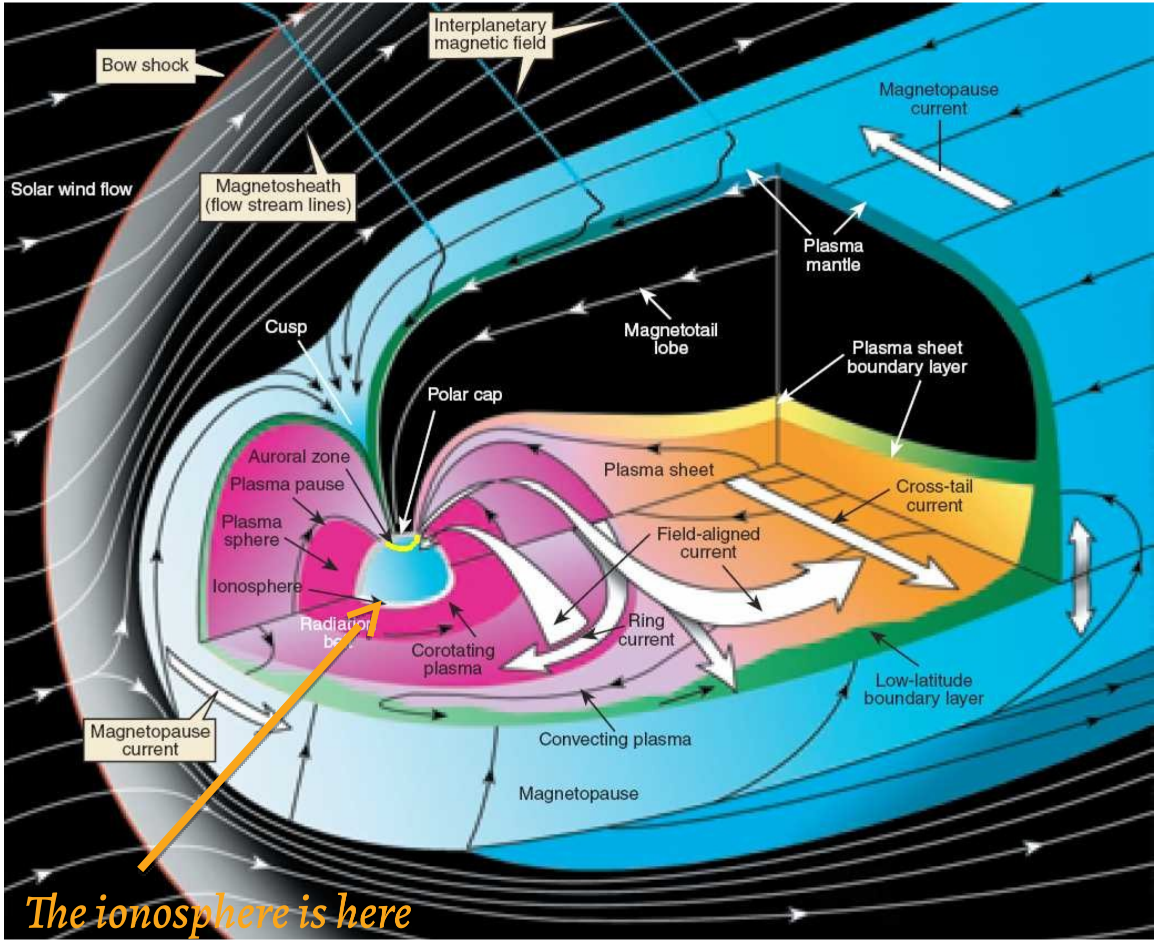
The magnetosphere–ionosphere system



From http://www.universetoday.com/wp-content/uploads/2014/12/mbs1.png

- The ionosphere is strongly coupled to the magnetosphere through multiple processes
- Ionospheric ions escape and populate the inner magnetosphere
- Magnetospheric electrons and protons can precipitate into the ionosphere
- Current systems couple both regions together
- Magnetospheric plasma convection (cf. Dungey cycle) is mirrored in the ionosphere

Zoom onto atmosphere/ionosphere processes

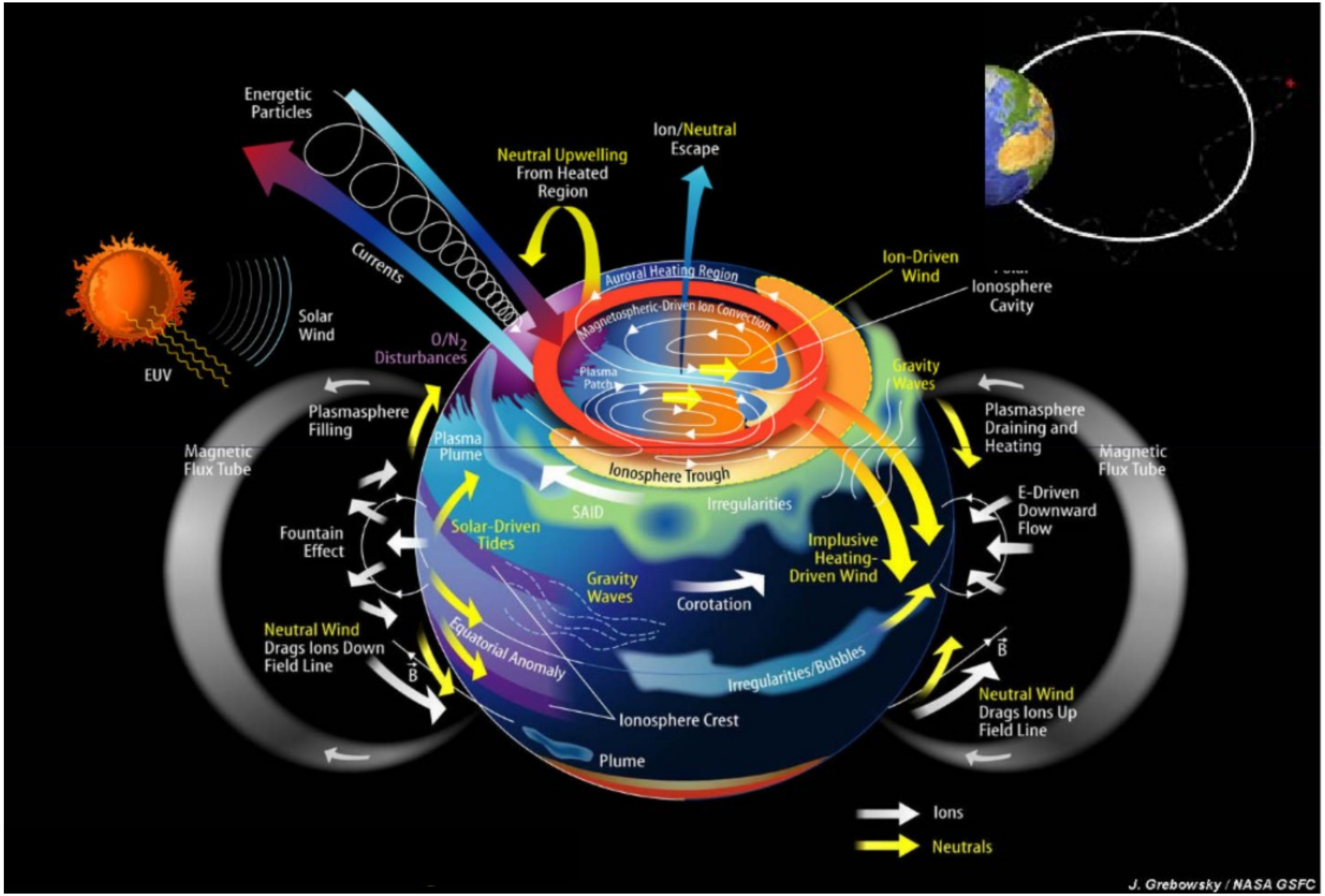
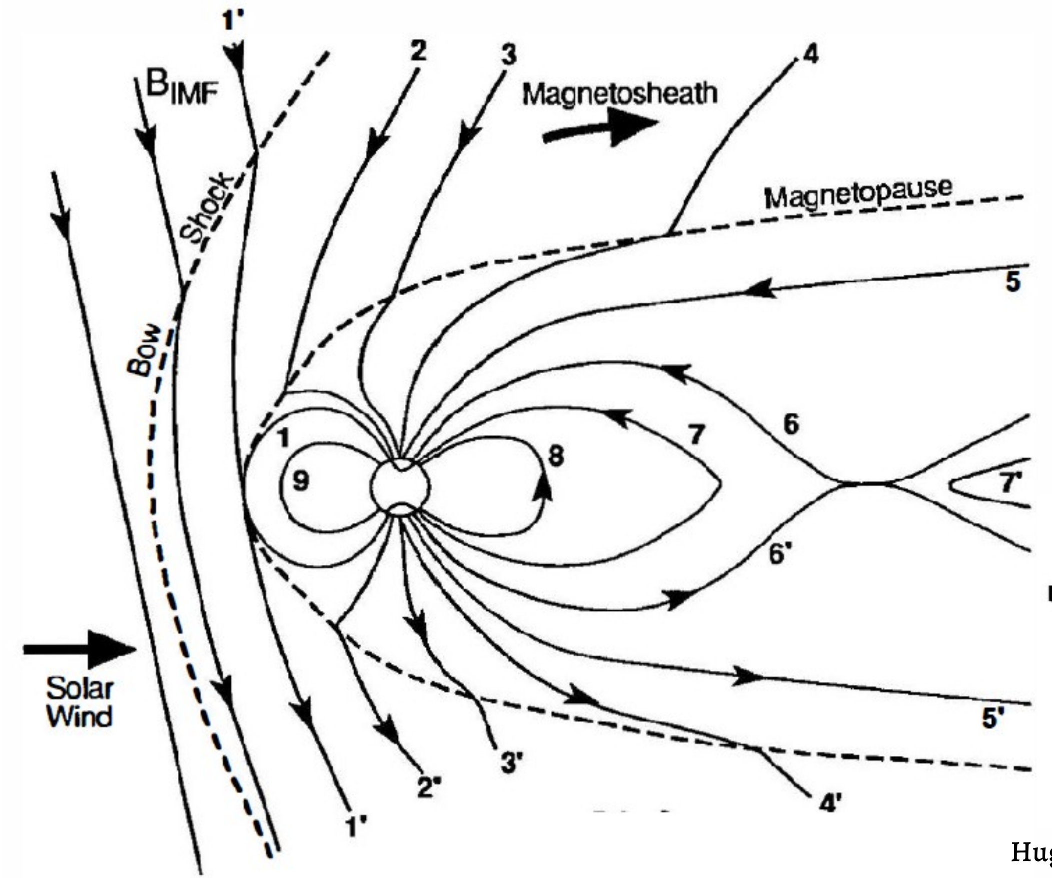


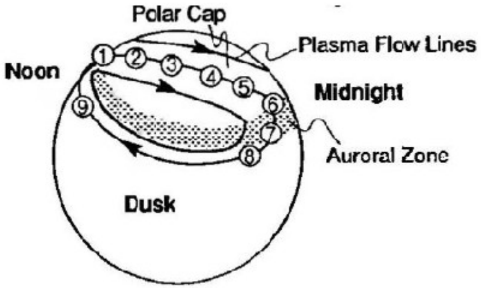
Figure credit:
Joe Grebowsky

The Dungey cycle

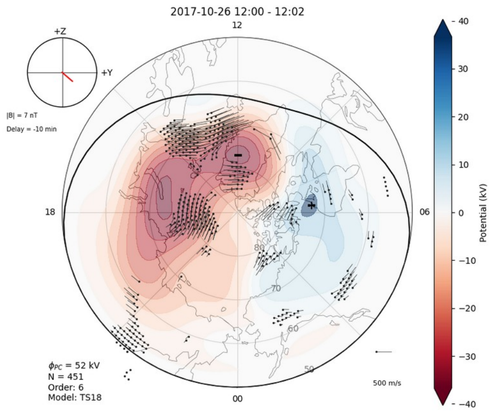
Idealised case of purely southward IMF

- Because of the frozen-in condition, the magnetospheric convection is mirrored in the polar cap ionosphere
- With purely southward IMF, we have a two-cell convection pattern
- For real-life scenarios, the convection cells can be distorted (effect of B_y) or there can be four convections cells (northward IMF)





Hughes (1995)



Credit: SuperDARN Canada

Polar cap convection & ionospheric current patterns

So: how do we get electric fields in the ionosphere?

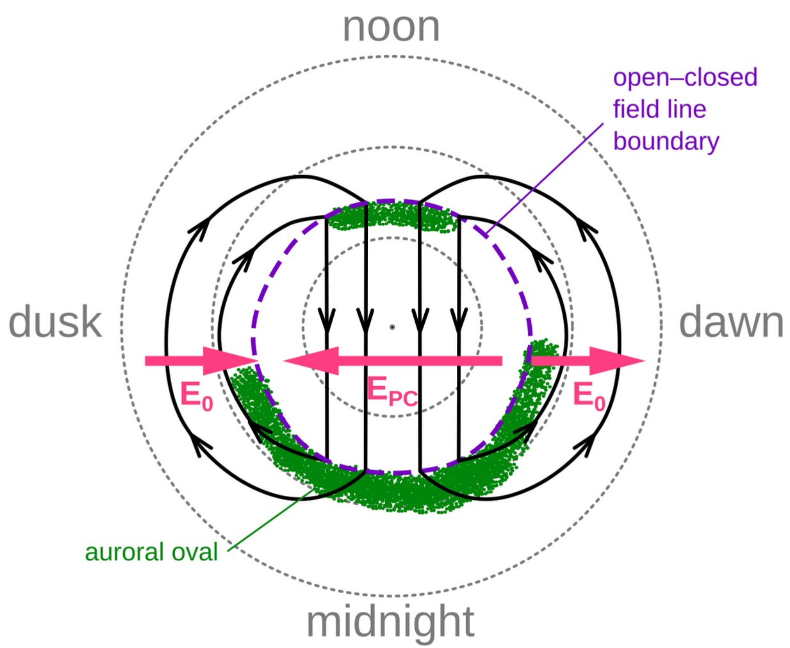
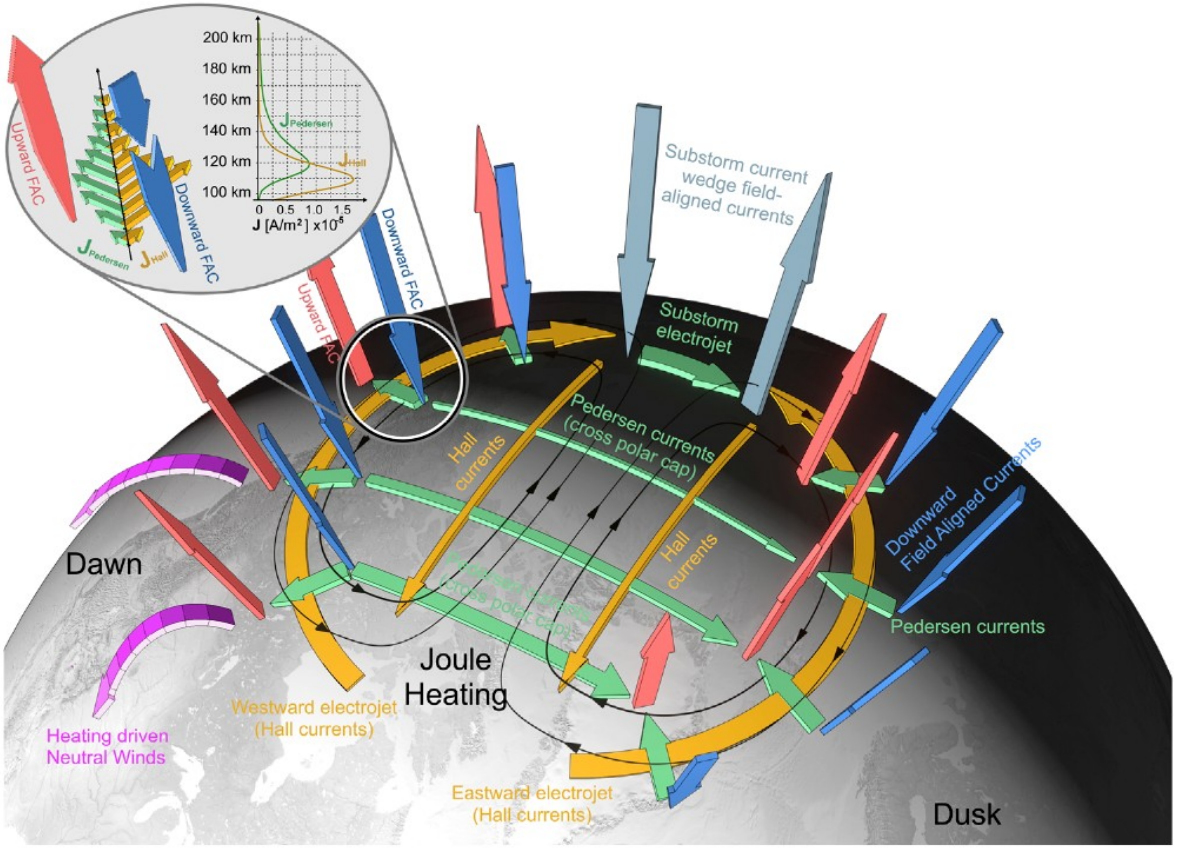


Figure credit: M. Grandin



Frozen-in condition: $\mathbf{E} = -\mathbf{V} \times \mathbf{B}$

Figure credit: E. Doornbos (Sarris et al., 2023)

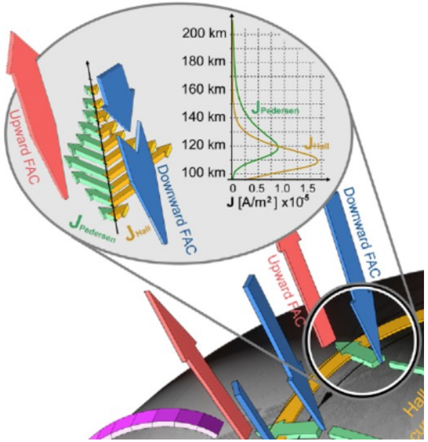
Ionospheric conductivities

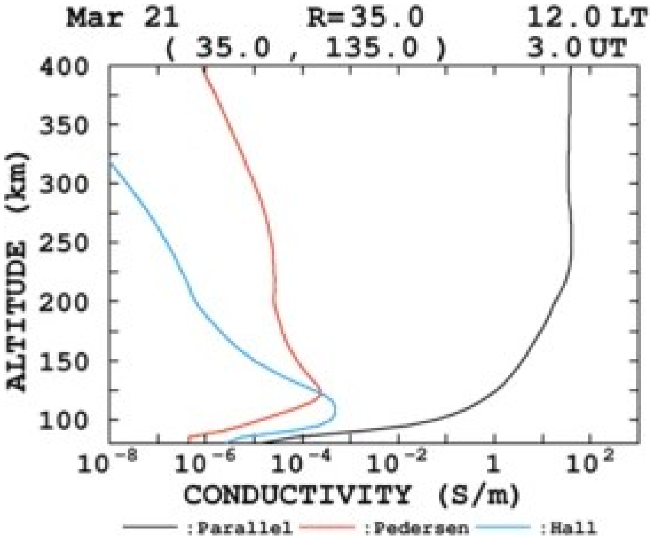
- Conductivity tensor, three terms: $\sigma_{//}$, σ_P, σ_H
- Unit: S/m
- Current density: $\mathbf{j} = \sigma_{//}\,\mathbf{E}_{//} + \sigma_P\,\mathbf{E}_\perp - \sigma_H\,\mathbf{E}\times\mathbf{B}/B$
- Sources: solar EUV, galactic cosmic rays, particle precipitation
- Conductances Σ = height-integrated conductivities σ
- Pedersen conductivity: a key parameter in Joule heating,

  $q_{JH} = \mathbf{j}\cdot\mathbf{E} = \sigma_P\,(\mathbf{E}' + \mathbf{u}\times\mathbf{B})^2$ [in W/m³]

  with **u** the neutral wind velocity, and

  E (**E'**) the electric field in the neutral (Earth-fixed) frame





Yamazaki & Maute (2017)

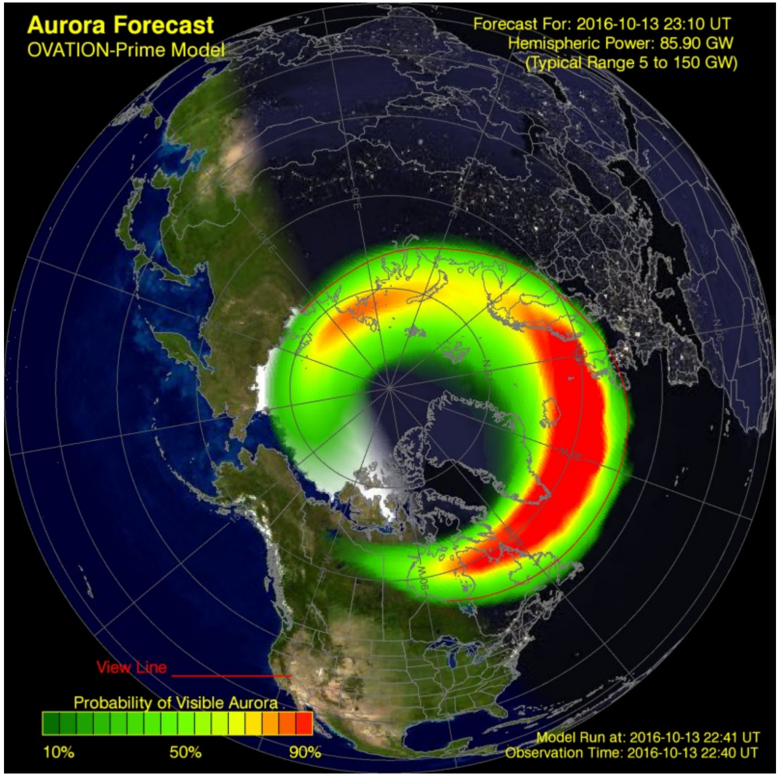
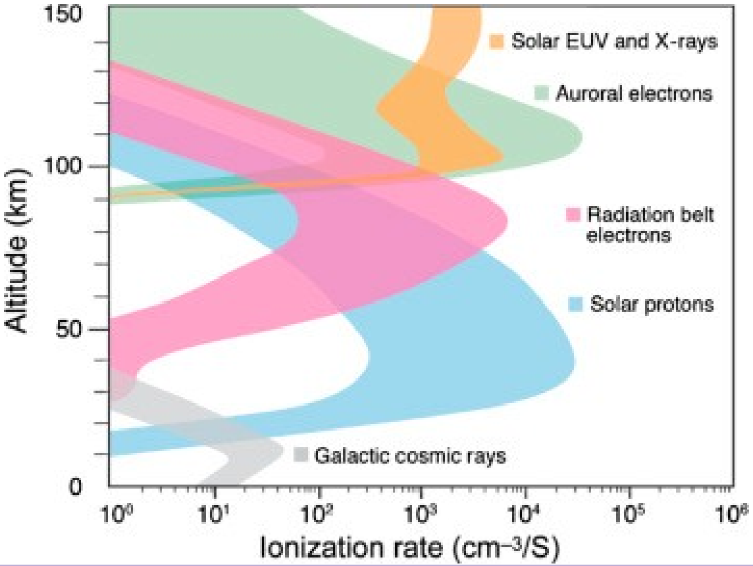


Figure credit: NOAA/OVATION-Prime

Particle precipitation

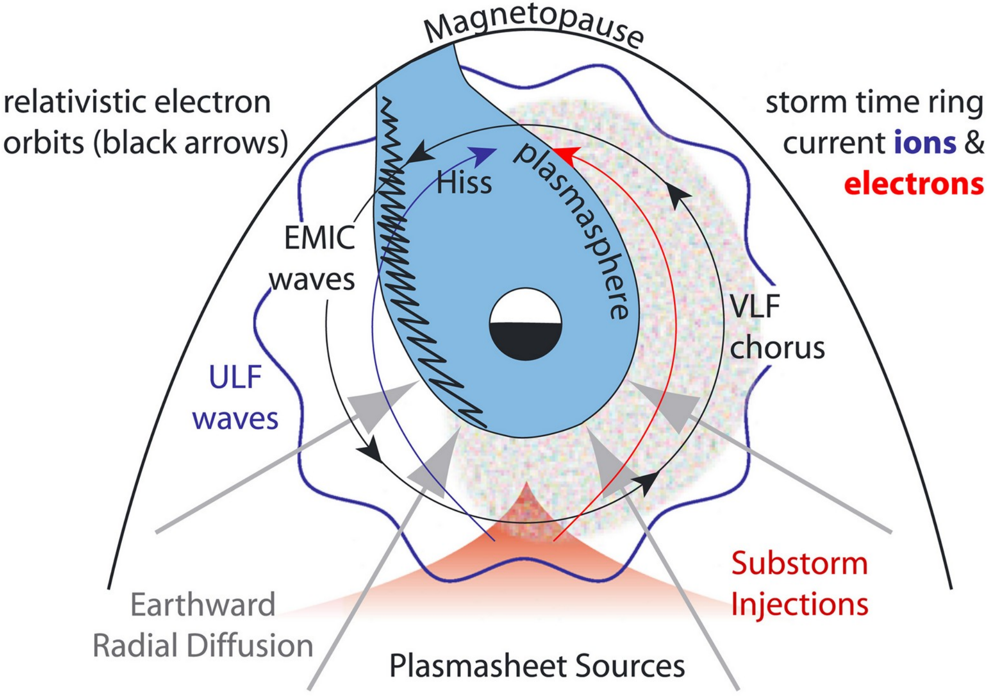
- Magnetospheric electrons and protons precipitate into the ionosphere, mainly within the auroral oval
- Sources: injection via reconnection, pitch-angle scattering due to wave–particle interactions and B-field line curvature



Sinnhuber & Funke (2020)

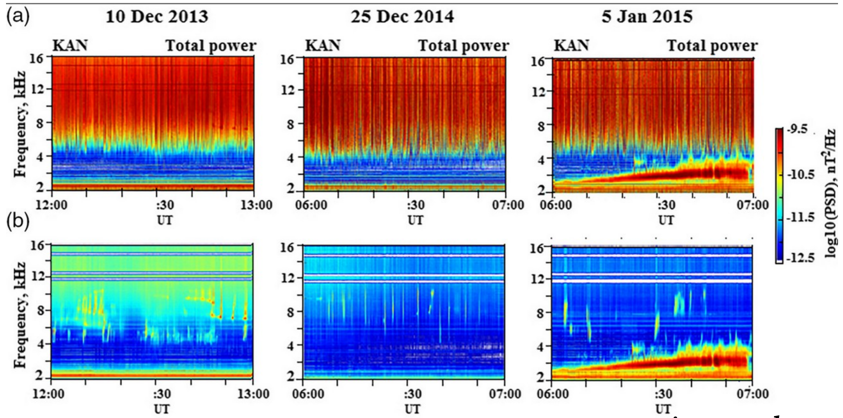
- Energy range: eV to MeV
- Effects: conductances, optical emissions, chemistry, heating

Waves in the inner magnetosphere



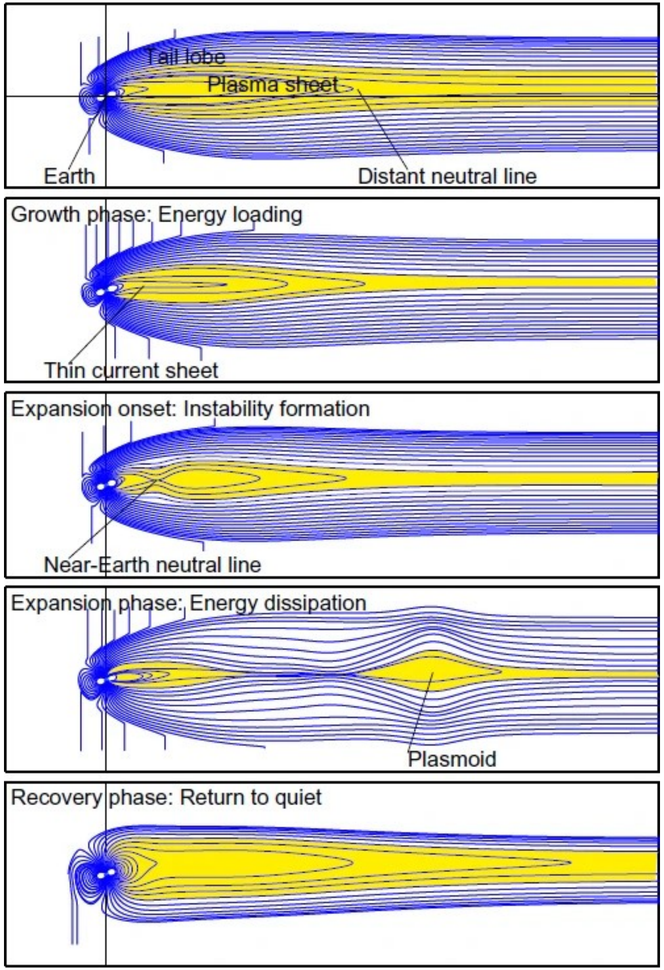
Li & Hudson (2019)

- ULF waves (1 mHz – 10 Hz)
  - field line resonance, geomagnetic pulsations
- VLF waves (10–30 kHz)
  - kinetic instabilities
  - structured (chorus) or unstructured (hiss)
  - crucial role in radiation belt physics

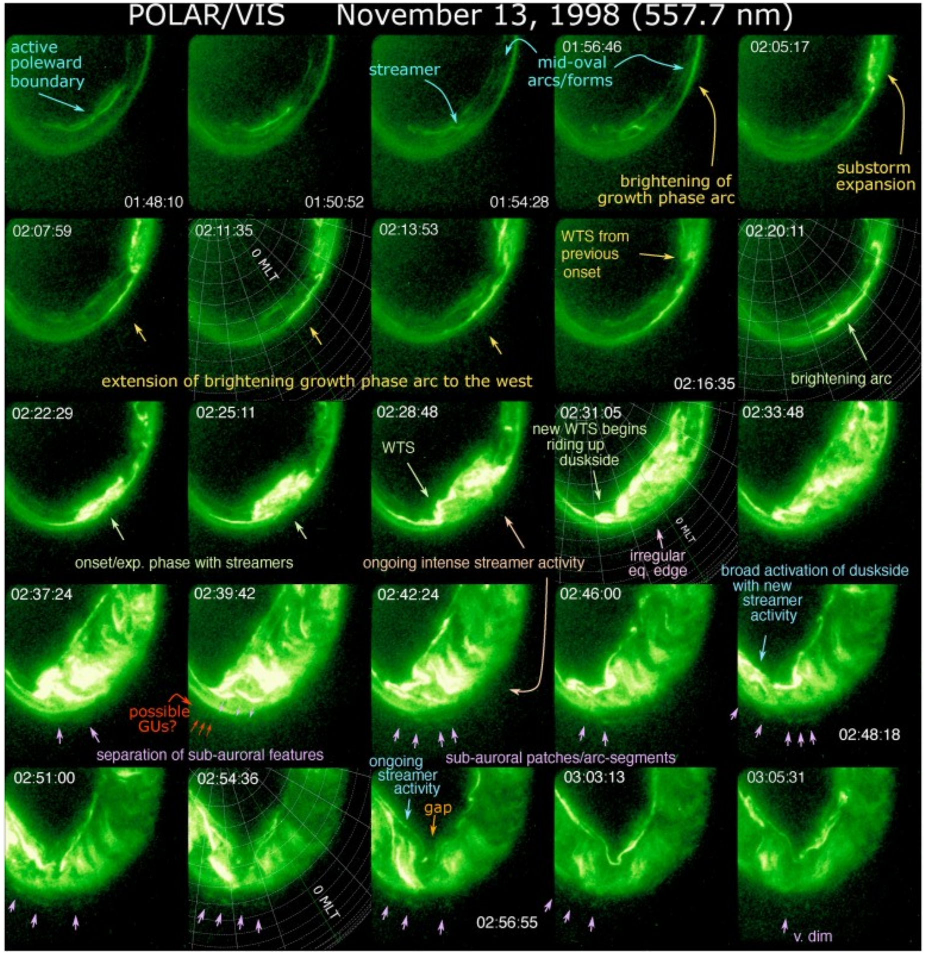


Manninen et al. (2021)

Magnetospheric vs auroral substorm



Pulkkinen (2007)



Henderson (2021)

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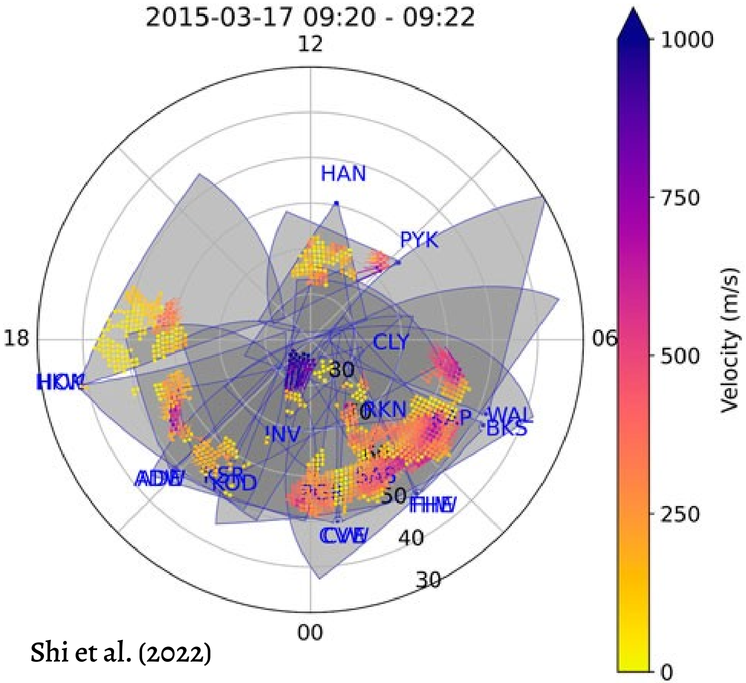
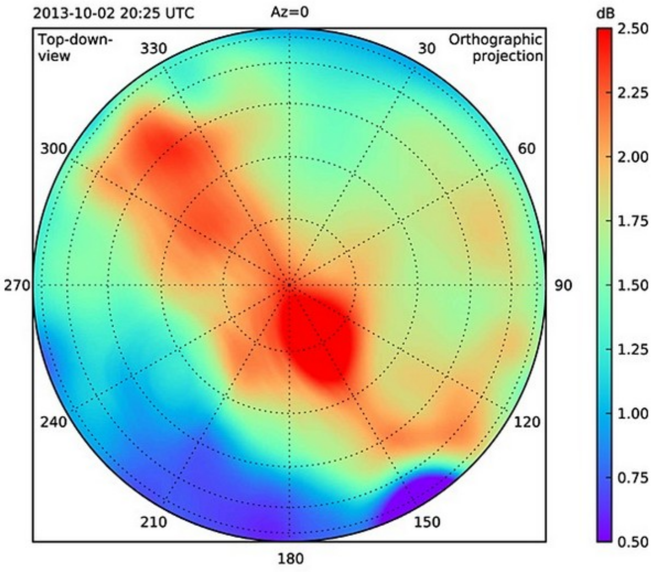
Ground-based instruments: Radio

SuperDARN



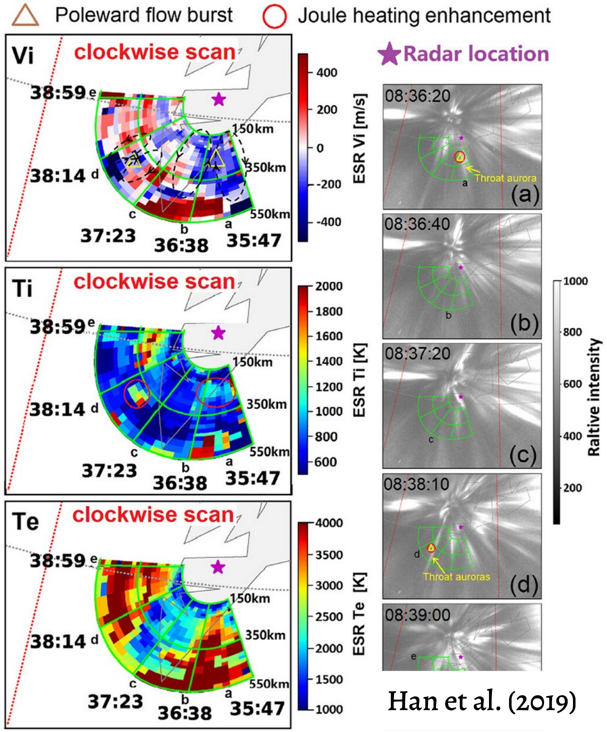
Shi et al. (2022)

Imaging riometer



McKay et al. (2015)

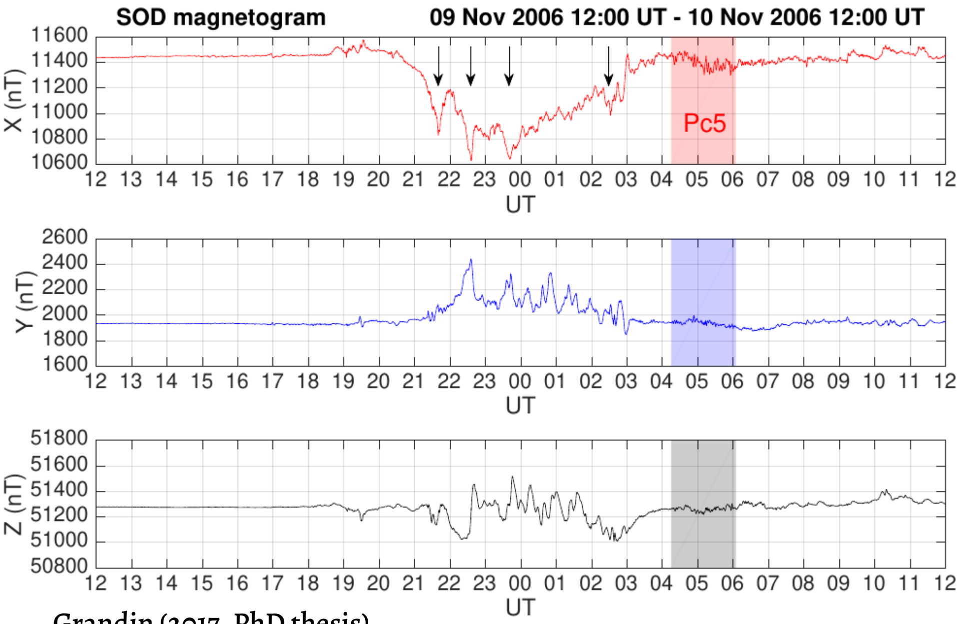
Incoherent scatter radar



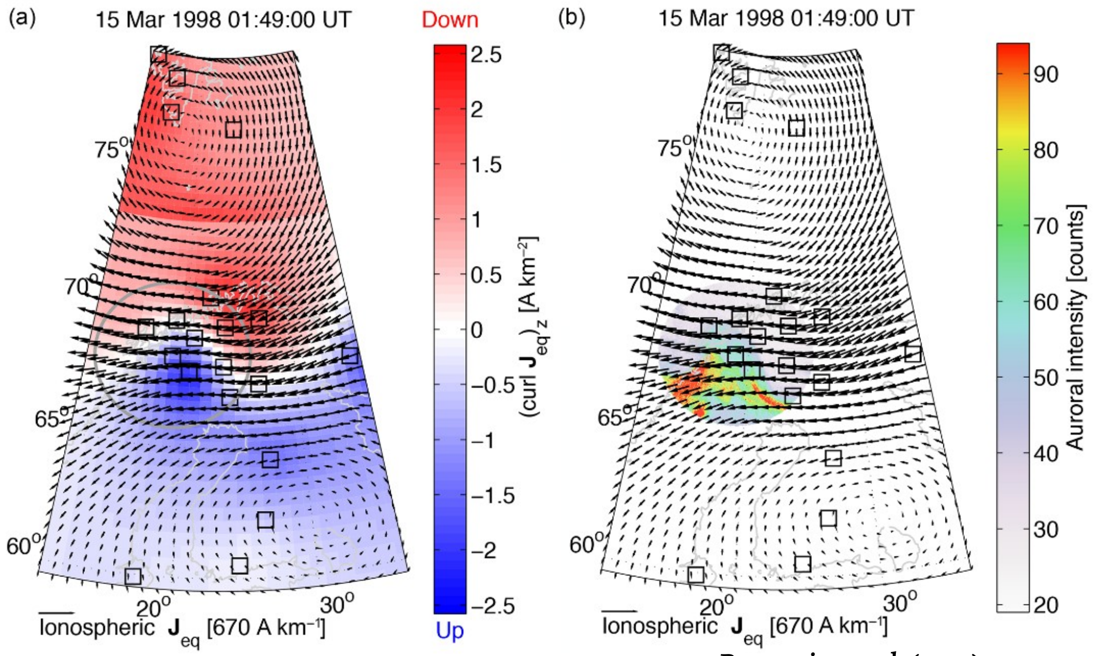
Han et al. (2019)

Ground-based instruments: Magnetometers

- Components: X (north), Y (east), Z (down)
- Signatures of substorms, geomagnetic pulsations…
- Networks: IMAGE (Fennoscandia), SuperMAG (world), INTERMAGNET (world)
- Determination of equivalent currents



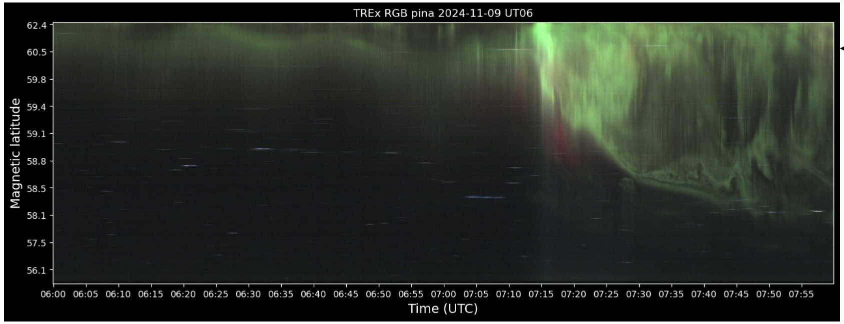
Grandin (2017, PhD thesis)



Partamies et al. (2017)

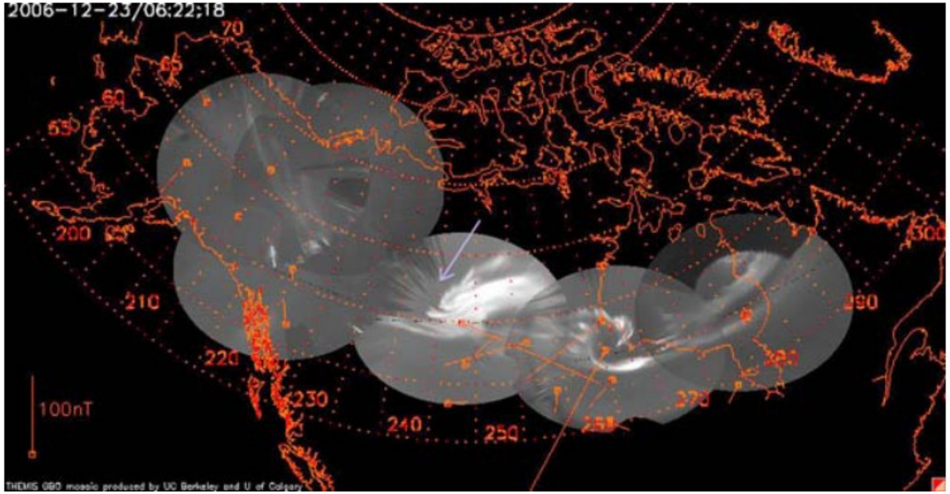
Ground-based instruments: Optics

All-sky imagers



keogram: N–S slice vs time

Data credit: University of Calgary



Mende et al. (2008)

Scanning Doppler imager

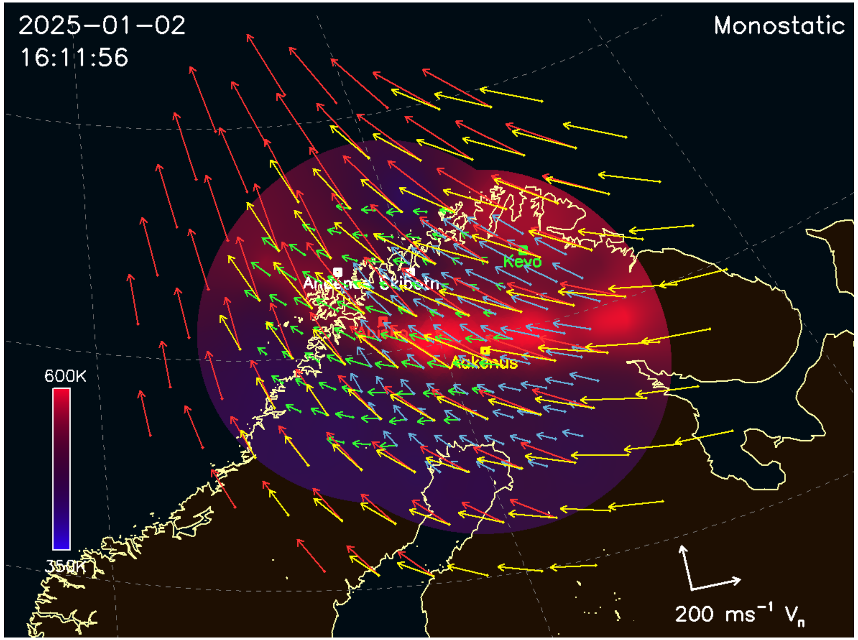
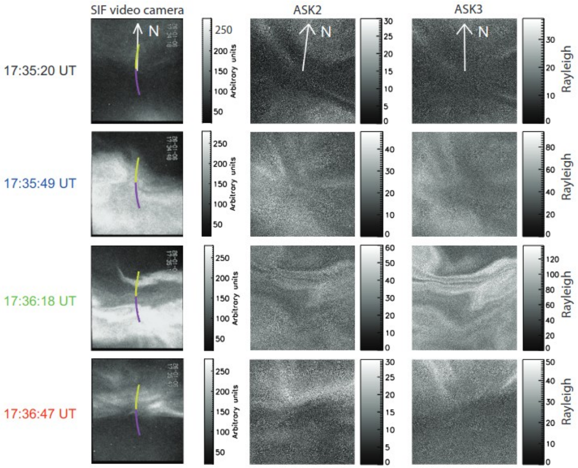
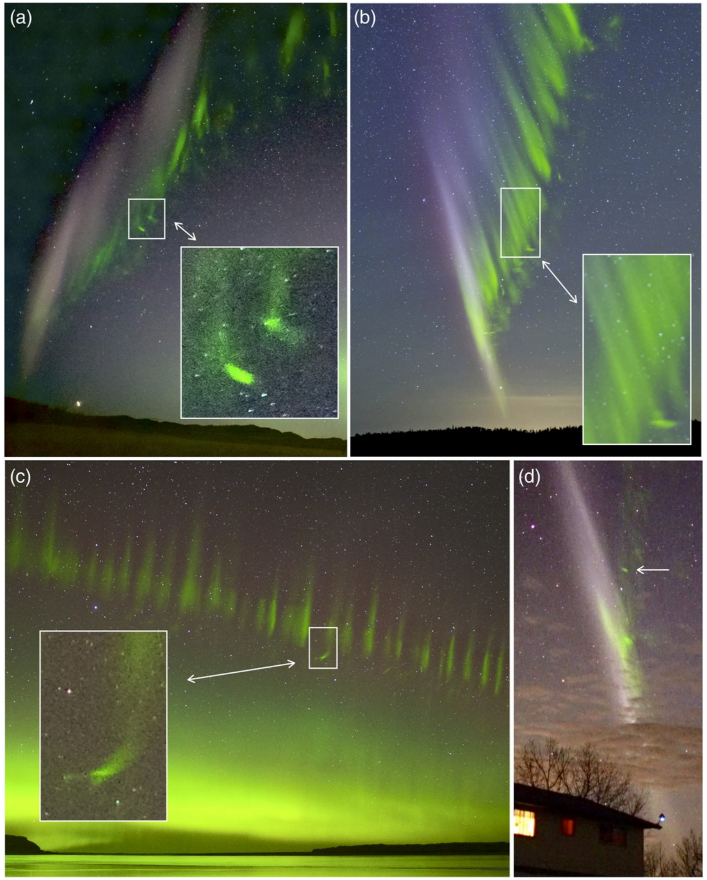


Figure credit: M. Conde

Citizen science to study mesoscale aurora



Dahlgren et al. (2008)

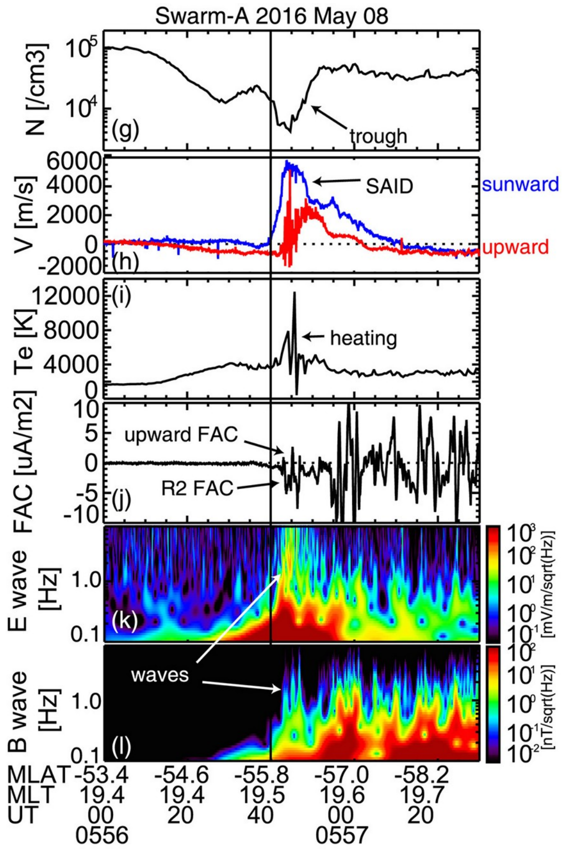


Semeter et al. (2020) [photographers: Alexei Chernenkoff, Shawn Malone, Stephen Voss, and Alan Dyer]

- Traditional optical instruments are most of the time either all-sky cameras or narrow-field imagers
- Commercial cameras enable skilled photographers to produce science-grade optical data particularly well-suited to studying mesoscale structures (and smaller!)
- Ongoing efforts aim to leverage citizen science to investigate optical phenomena, especially at subauroral latitudes

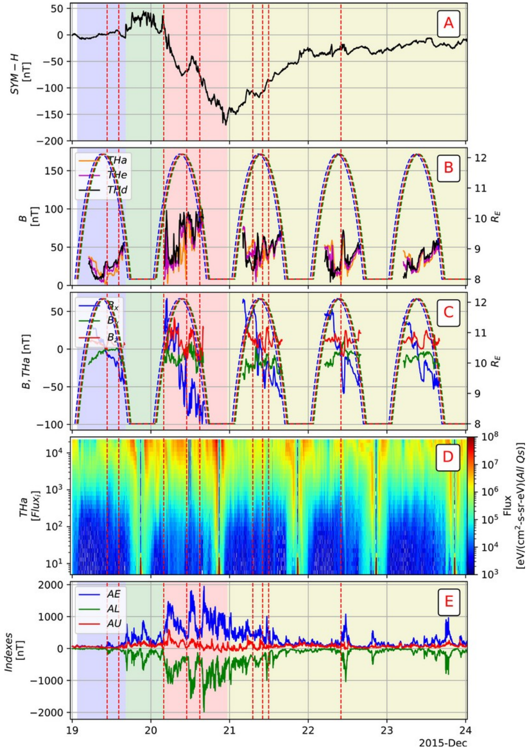
Satellite observations

In situ at LEO [e.g. Swarm]



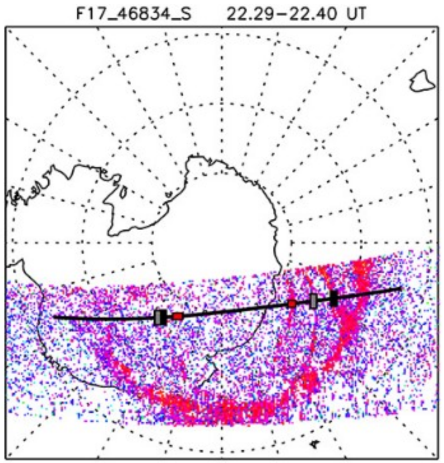
Adapted from Nishimura et al. (2019)

In situ in the magnetosphere [e.g. THEMIS]



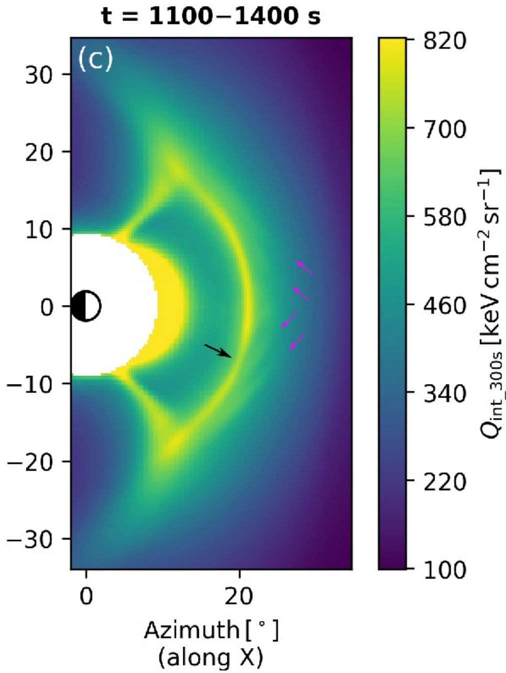
Alqeeq et al. (2024)

Imaging at LEO [e.g. DMSP/SSUSI]



Adapted from Reidy et al. (2018)

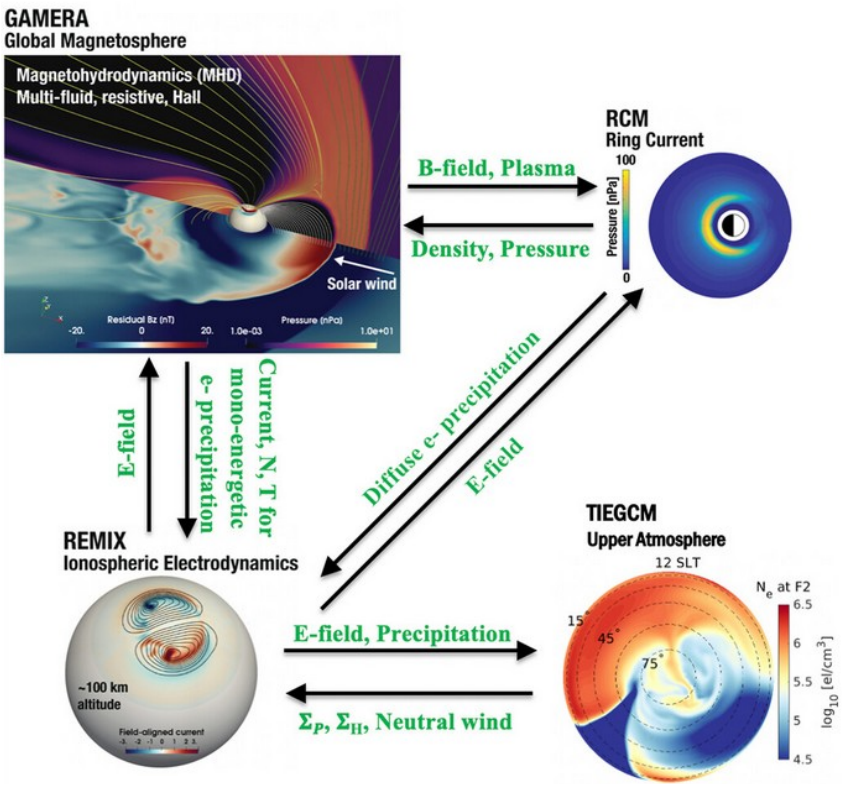
Imaging from the magnetosphere [e.g. SMILE/SXI]



Adapted from Grandin et al. (2024)

Numerical simulations

Coupled models of geospace [e.g. MAGE]



Adapted from Lin et al. (2021)

Global atmospheric models [e.g. WACCM]

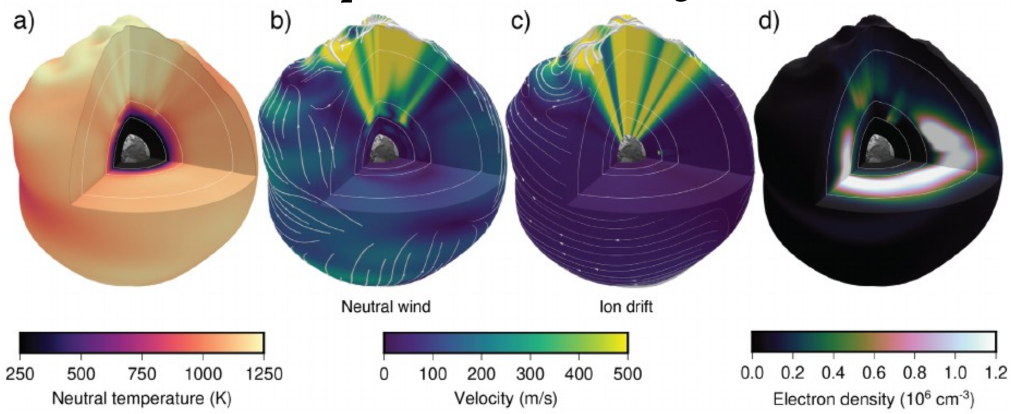
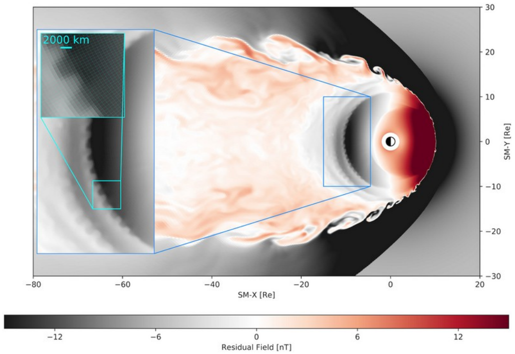


Figure credit: E. Doornbos (Daedalus Report for Assessment, ESA, 2020)

Global magnetospheric models [e.g. GAMERA, Vlasiator]



Sorathia et al. (2020)

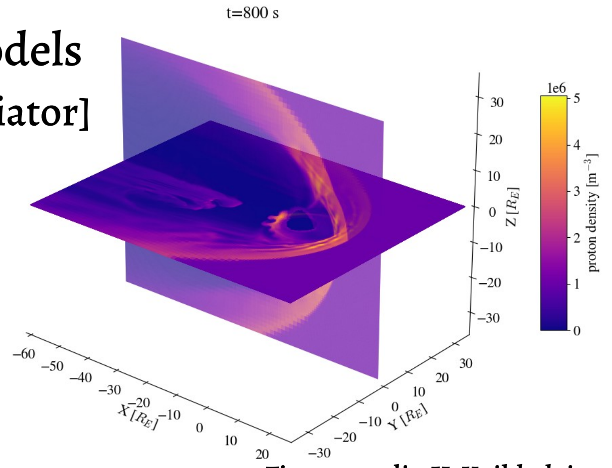


Figure credit: V. Koikkalainen


To be continued…
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