Aurora

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Image of Aurora from the International Space Station (Credit: NASA)

Charged Particles Hitting the Atmosphere

- Charged particles follow magnetic field lines
- Charged particles hit atoms and molecules in the atmosphere
- Atoms get excited
- Excited atoms relax back to the ground state and emit photons

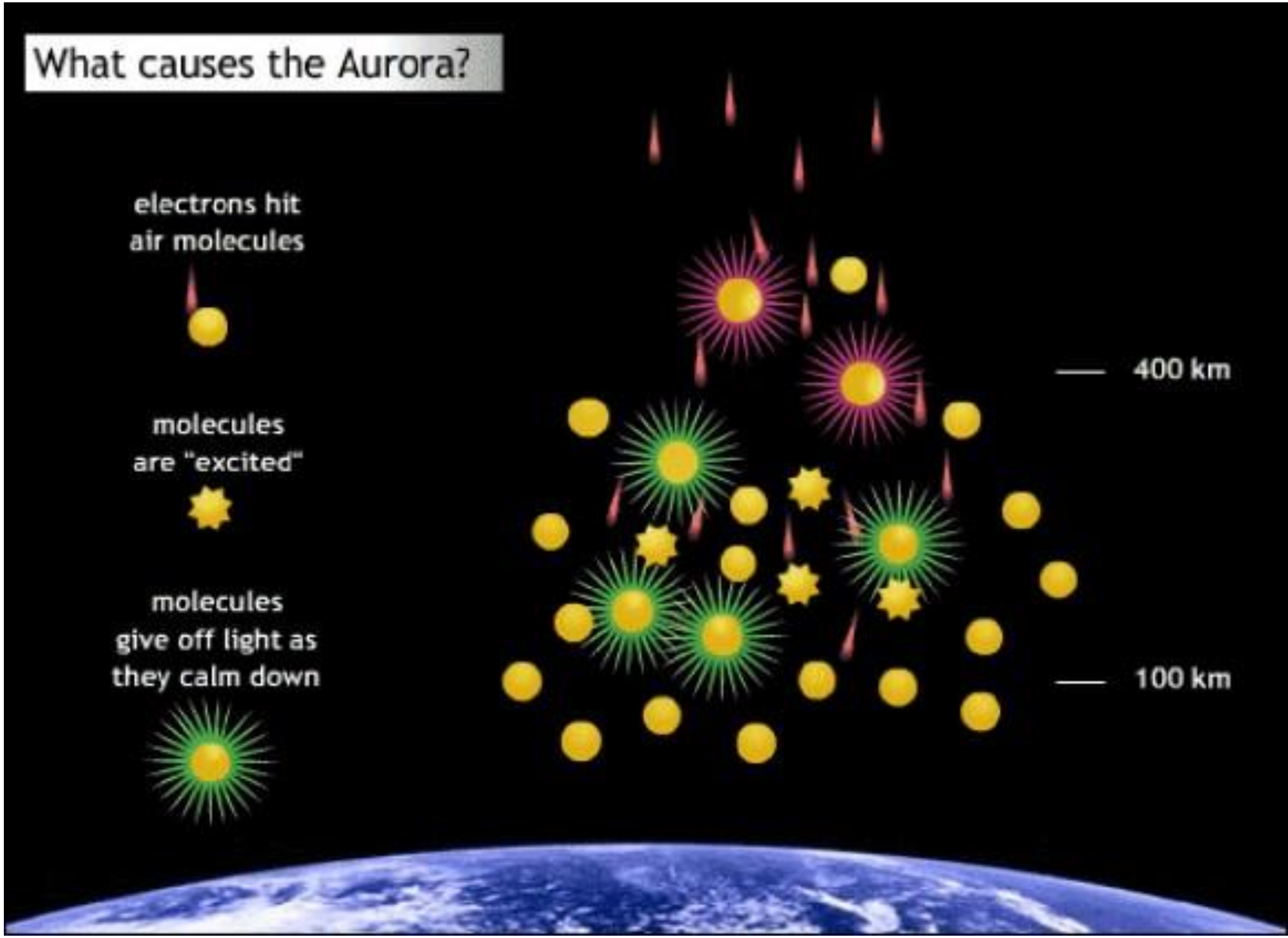
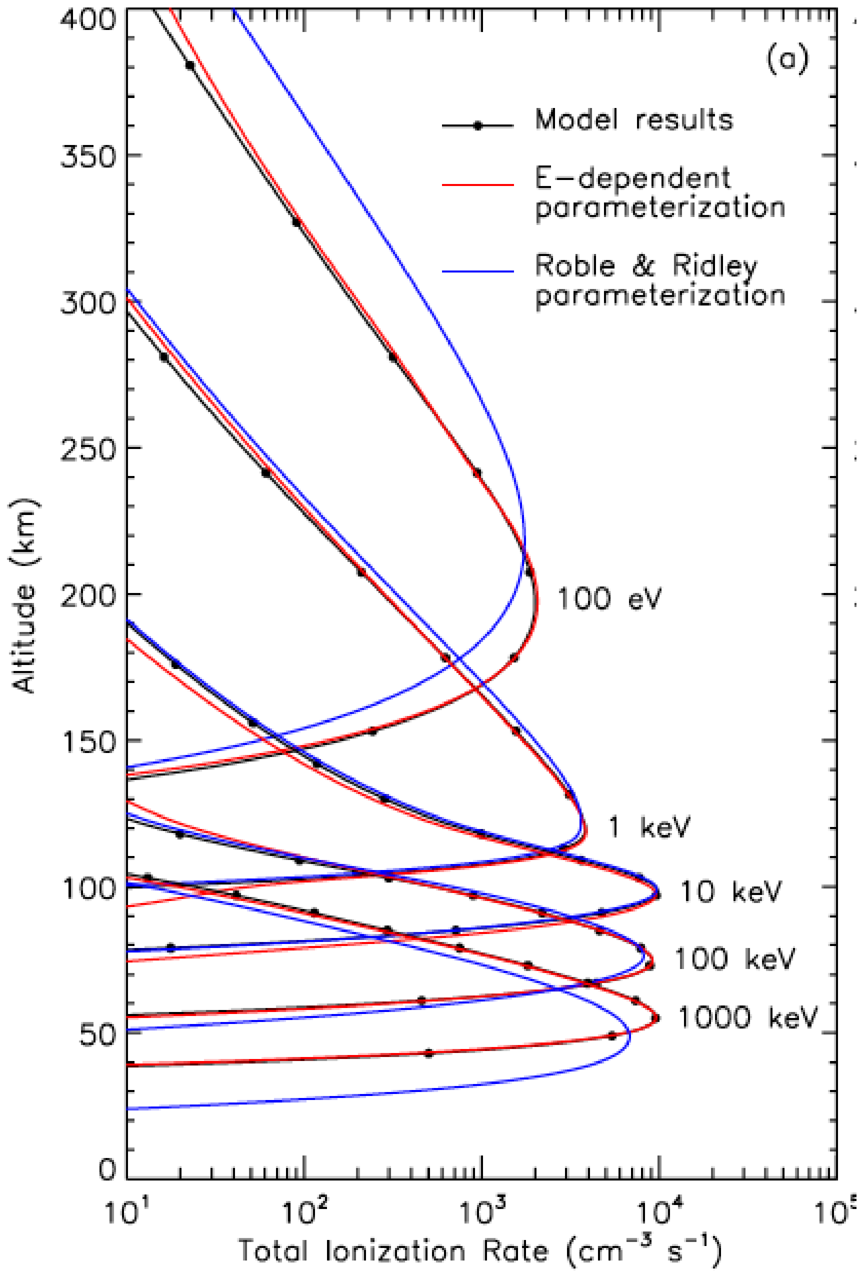


Image credit: NASA

How Do We Categorize Auroras?

- Particle Energies, Colors, and Altitude
  - Green (557.7 nm), ~120 km
  - Red (630.0 nm), ~250 km
  - Pink (multiple nitrogen emissions), ~110 km
- Particle Acceleration Mechanisms
  - Solar wind direct entry (e.g. cusp)
  - Pitch-angle scattered particles (e.g. diffuse aurora, pulsating aurora)
  - Parallel acceleration by E-fields (e.g. discrete aurora, Alfvenic aurora)
- Location, Morphology, and Dynamics
  - Quiet Arcs
  - Streamers
  - Poleward Boundary Intensifications (PBIs)
  - Omega Bands / Torches
  - Patchy pulsating aurora

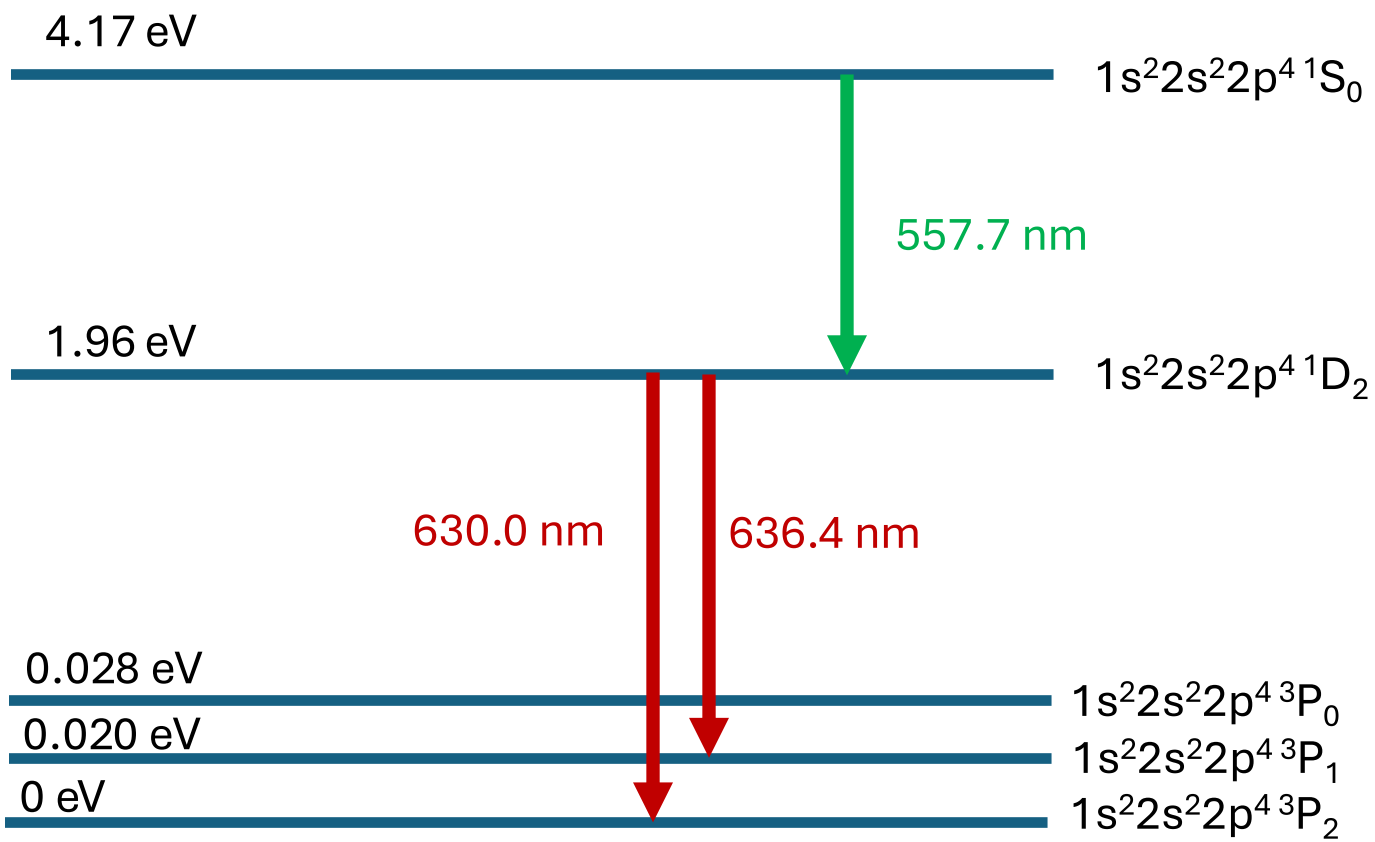
Particle Energies and Penetration Depths



- Higher energy particles penetrate deeper into the atmosphere.
- Soft precipitation (100 eV):
  - Stops around 200 km
  - Mostly produces 630.0 nm red line
- Moderate energies (1-10 keV):
  - Stops between 100-120 km
  - Mostly produces 557.7 nm green line
- Hard precipitation (> 10 keV):
  - Penetrate down into mesosphere
  - Produce nitrogen emissions
  - Can have significant effects on mesospheric chemistry.

Fang et al. (2008)

Oxygen Emissions



$$\lambda = \frac{hc}{\Delta E}$$

- ^1S to ^1D transition produces green photons (557.7 nm, 4.17 eV – 1.96 eV = 2.21 eV)
- ^1D to ^3P transition produces red photons (mostly 630.0 nm, some 636.4 nm, very rarely 639.2 nm)
- ^1S to ^3P transition produces ultraviolet light (295.8 nm or 297.2 nm), but it is much less likely than ^1S to ^1D transition

Colors from Different Altitudes

- $O(^1D)$ has a lifetime of 110 s
  - metastable state
  - If $O(^1D)$ can relax without emitting a photon by colliding with another molecule (quenching).
  - At low altitudes (higher atmospheric density), there is a higher probability of $O(^1D)$ getting hit by a molecule before it emits a red photon.
- $O(^1S)$ has a lifetime of 0.91 s
  - Much easier to emit green photons, even at low altitudes.

Common Visible Nitrogen Emissions

- N_2 first positive emissions:
  - Large group of emissions in the red and IR
  - One example:

$$N_2 + e \rightarrow {N_2}^* + e$$
$${N_2}^* \rightarrow N_2 + 654.5\ \mathrm{nm}$$

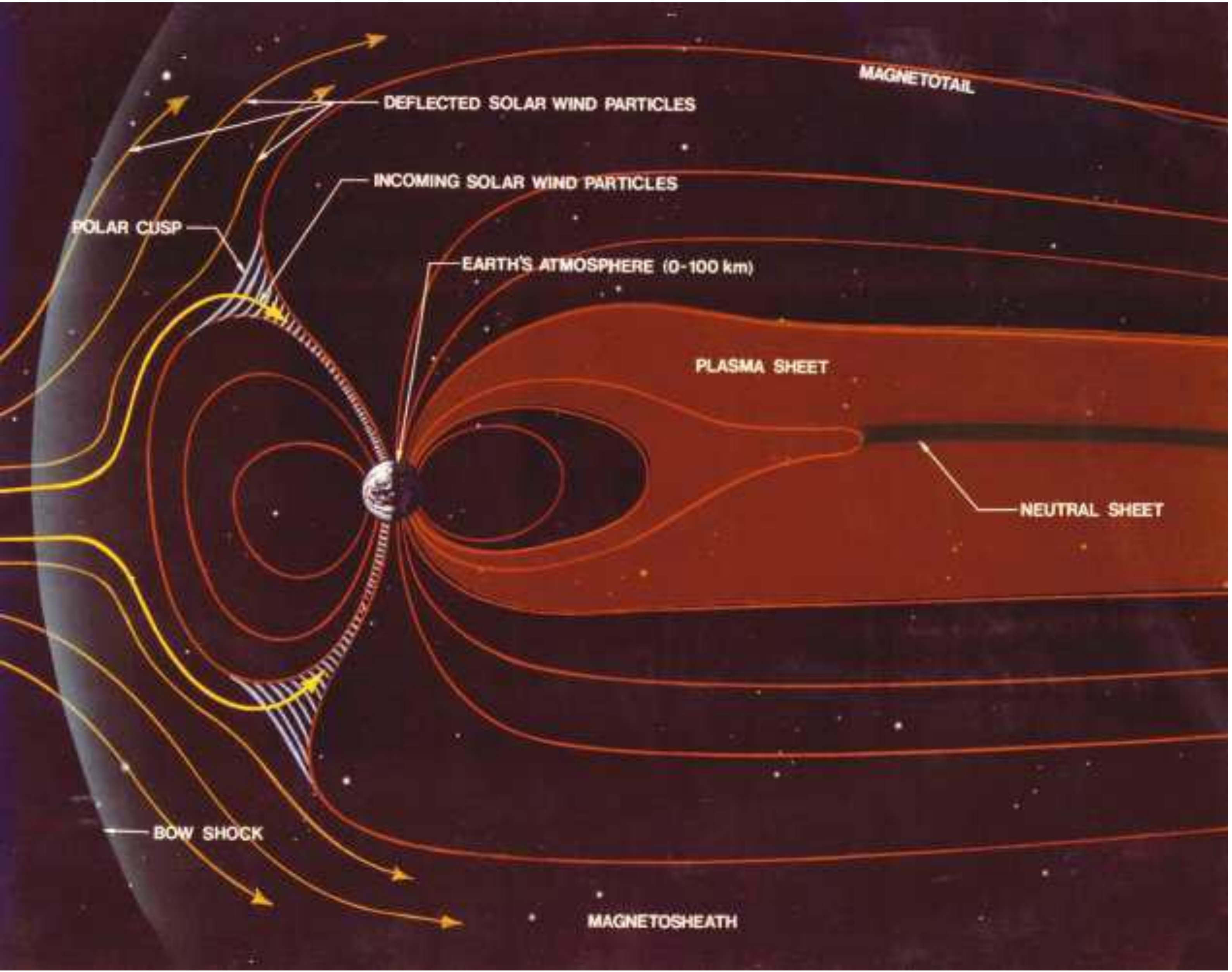
- ${N_2}^+$ first negative emissions:
  - Large group of emission in the blue and UV
  - One example:

$$N_2 + e \rightarrow {N_2}^{+*} + 2e$$
$${N_2}^{+*} \rightarrow {N_2}^+ + 427.8\ \mathrm{nm}$$

- These red and blue emissions tend to mix into something that looks pink/magenta/purple

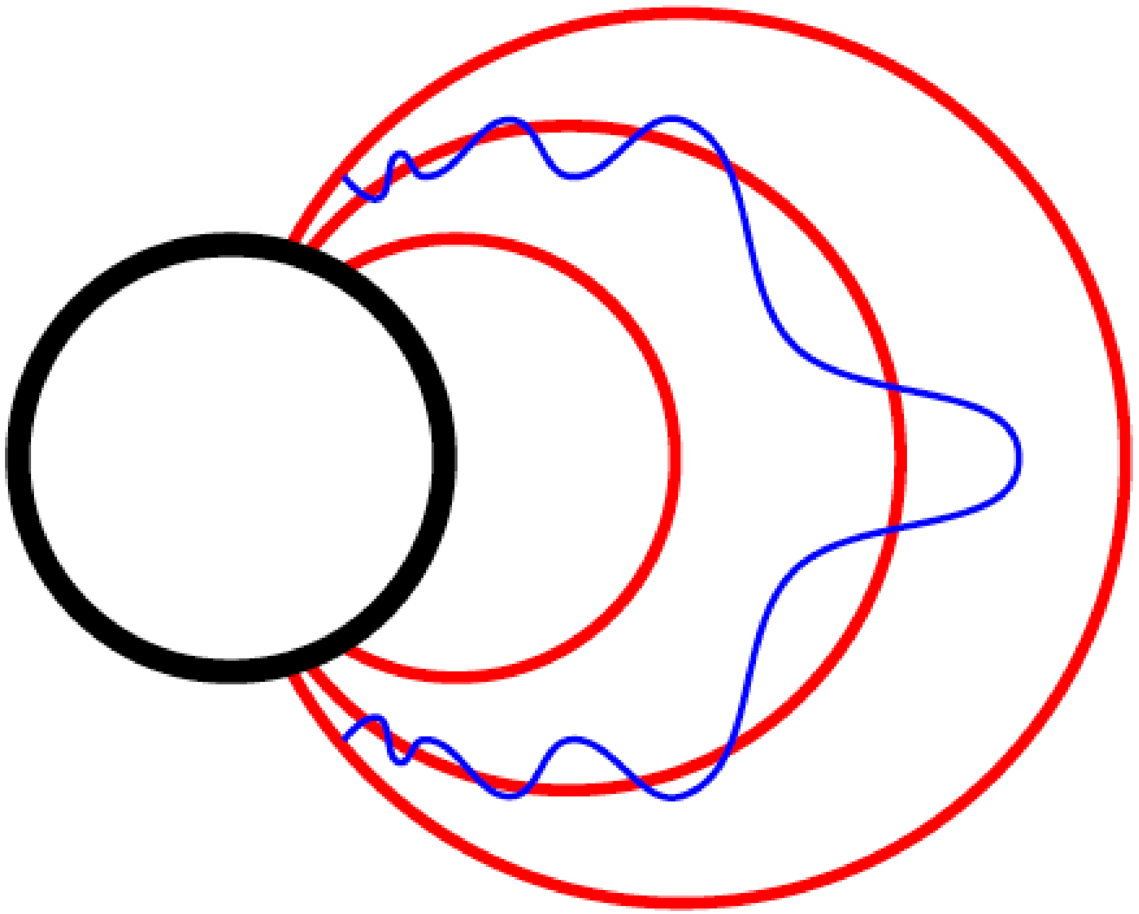
(Credits: Canadian Space Agency, University of Calgary, Astronomy North)

Particle Access to the Atmosphere



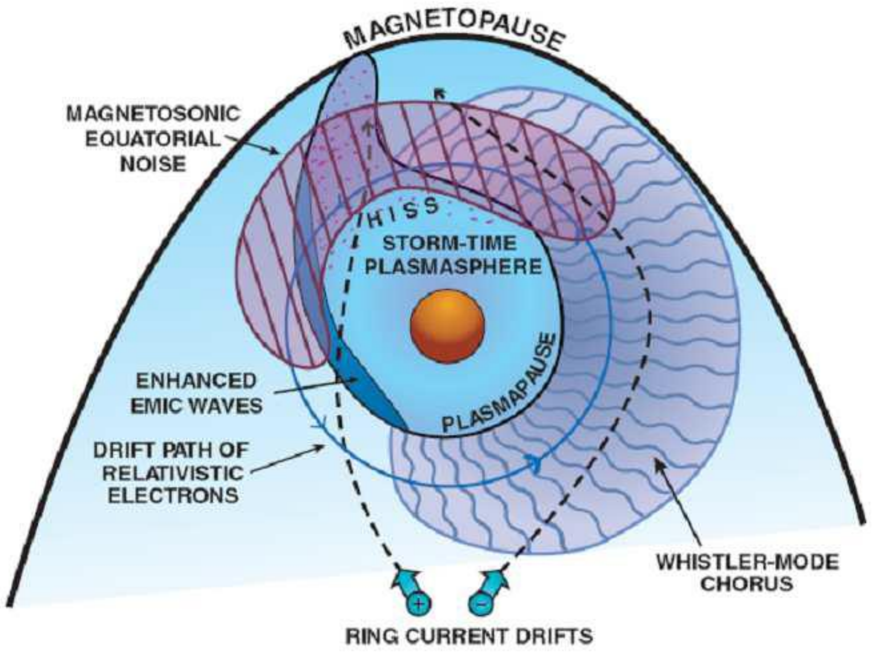
- Common (and mostly wrong) pop-science explanation of the aurora:
  - Solar wind energetic particles follow Earth's magnetic field to the poles
- Problems with this explanation:
  - Solar wind electrons can only reach the atmosphere directly through the cusp
  - Magnetosheath electrons are typically 100 eV: cusp auroras tend to be faint red glows.
- Most forms of aurora are caused by particles from the magnetosphere.

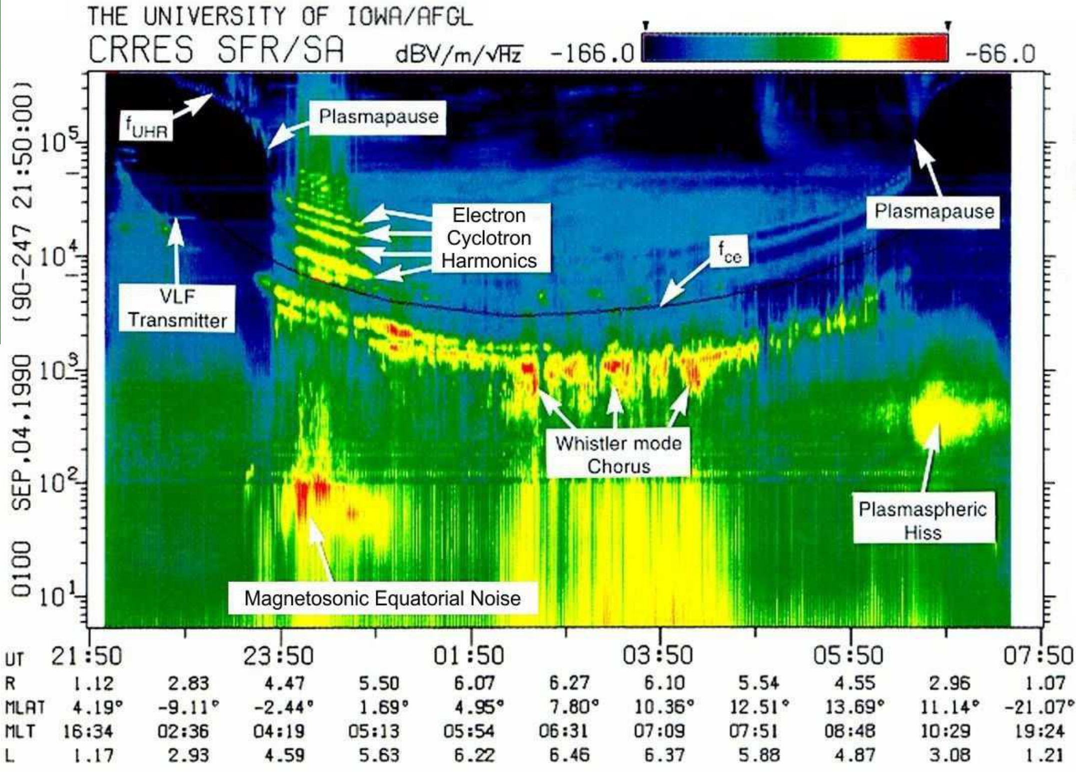
Trapped Particles



- Most particles in the inner magnetosphere are trapped and bouncing between magnetic mirror points.
- To reach the atmosphere, the particle's velocity must be in a narrow cone of angles nearly parallel to **B** called the loss cone.
- Interactions with radio waves can randomize particle velocities and scatter them into the loss cone.

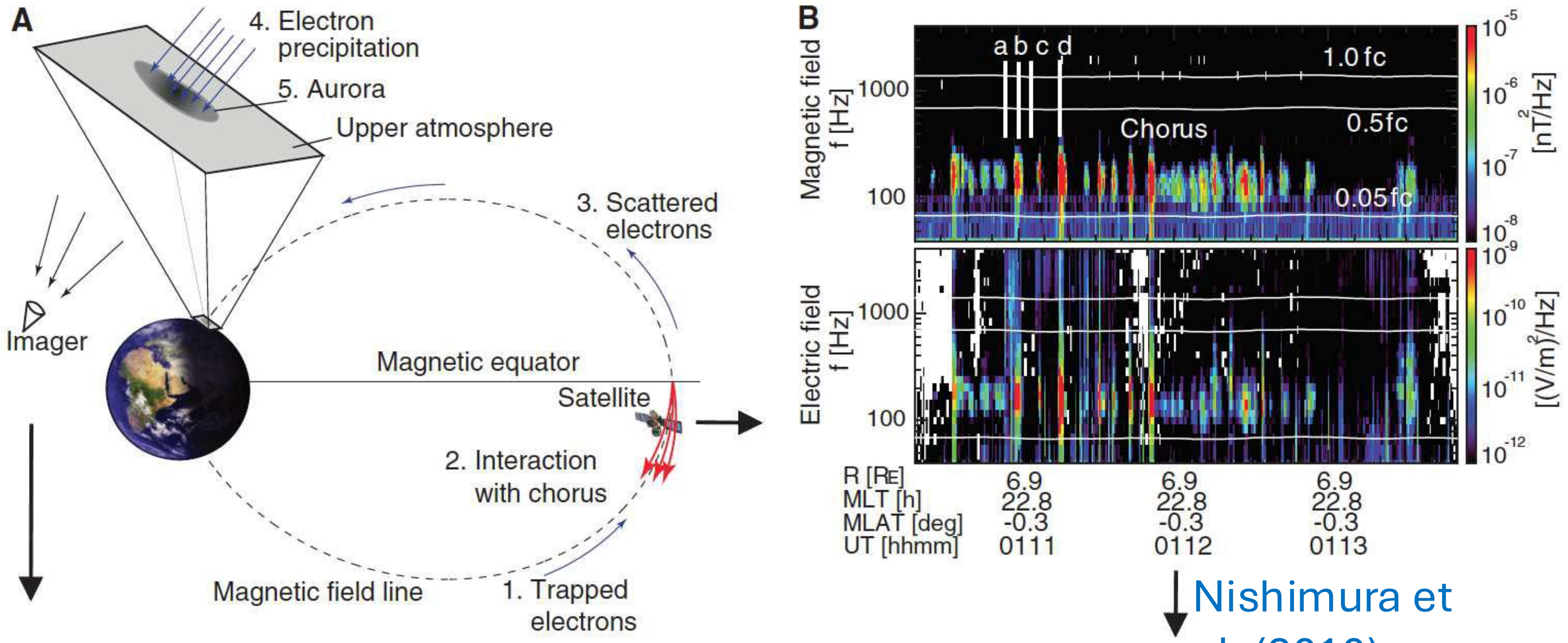
Diffuse Aurora



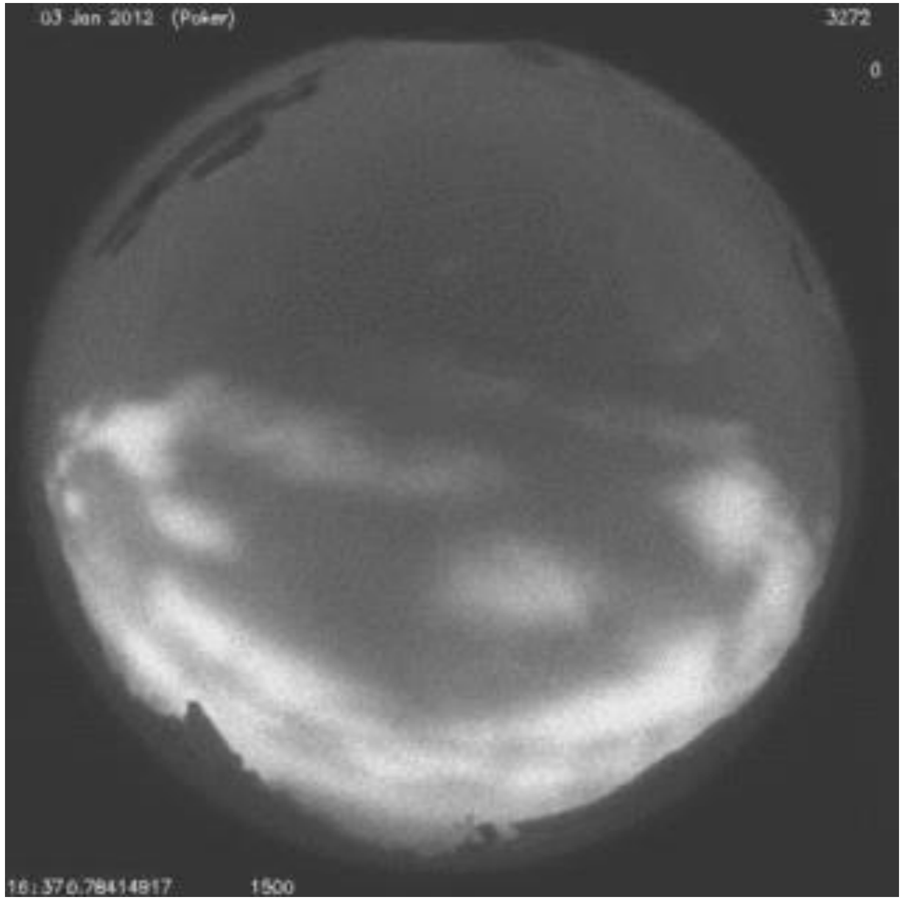


- Unstructured diffuse glows that fill the sky.
- 1-10 keV. Mostly 557.7 nm.
- Most common after midnight.
- Scattered electrons from the inner magnetosphere.
- Primarily scattered by “whistler mode chorus” radio waves.

Pulsating Aurora

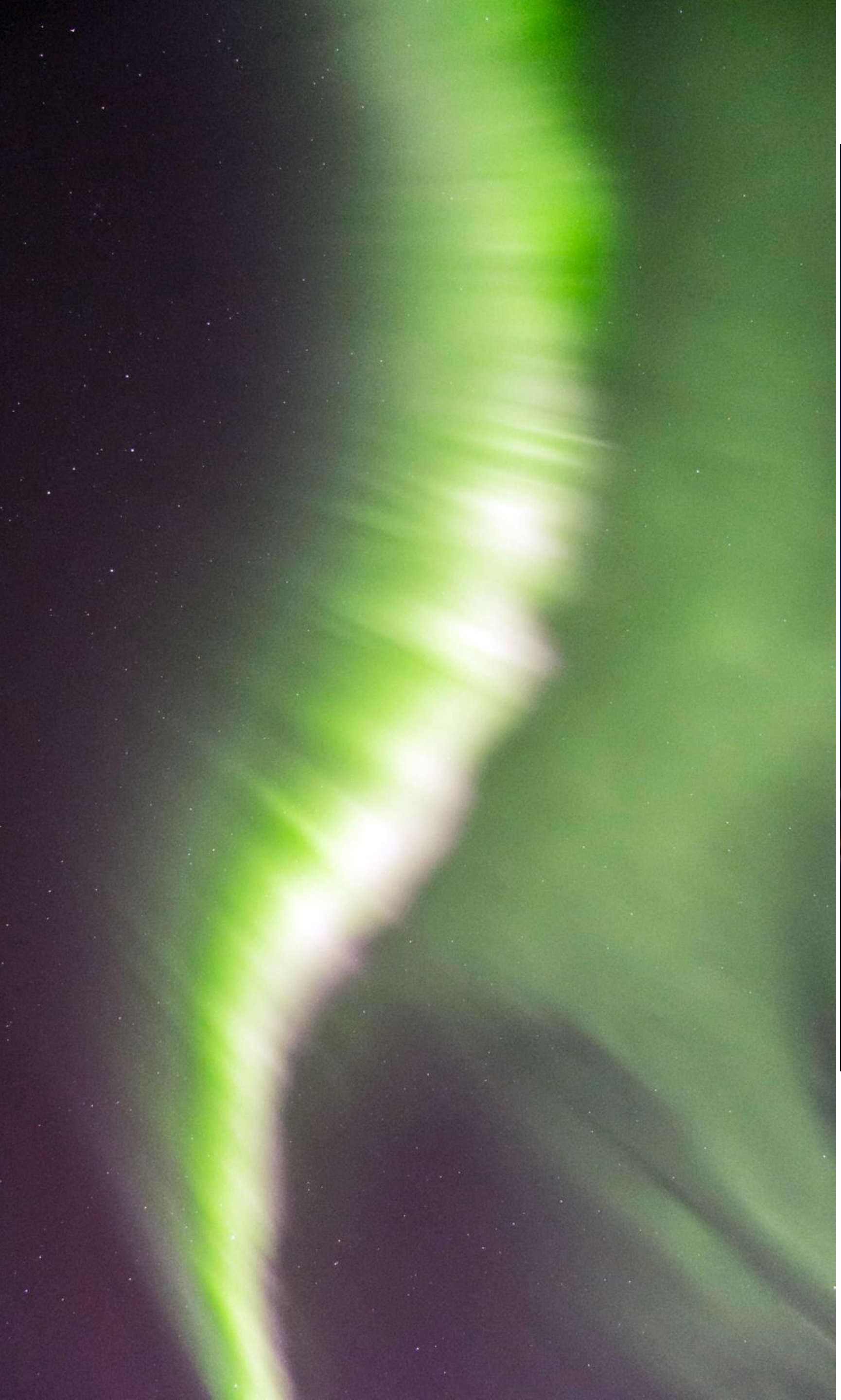


Nishimura et al. (2010)



Movie credit: NASA
https://www.nasa.gov/feature/goddard/nasa-measuring-the-pulsating-aurora

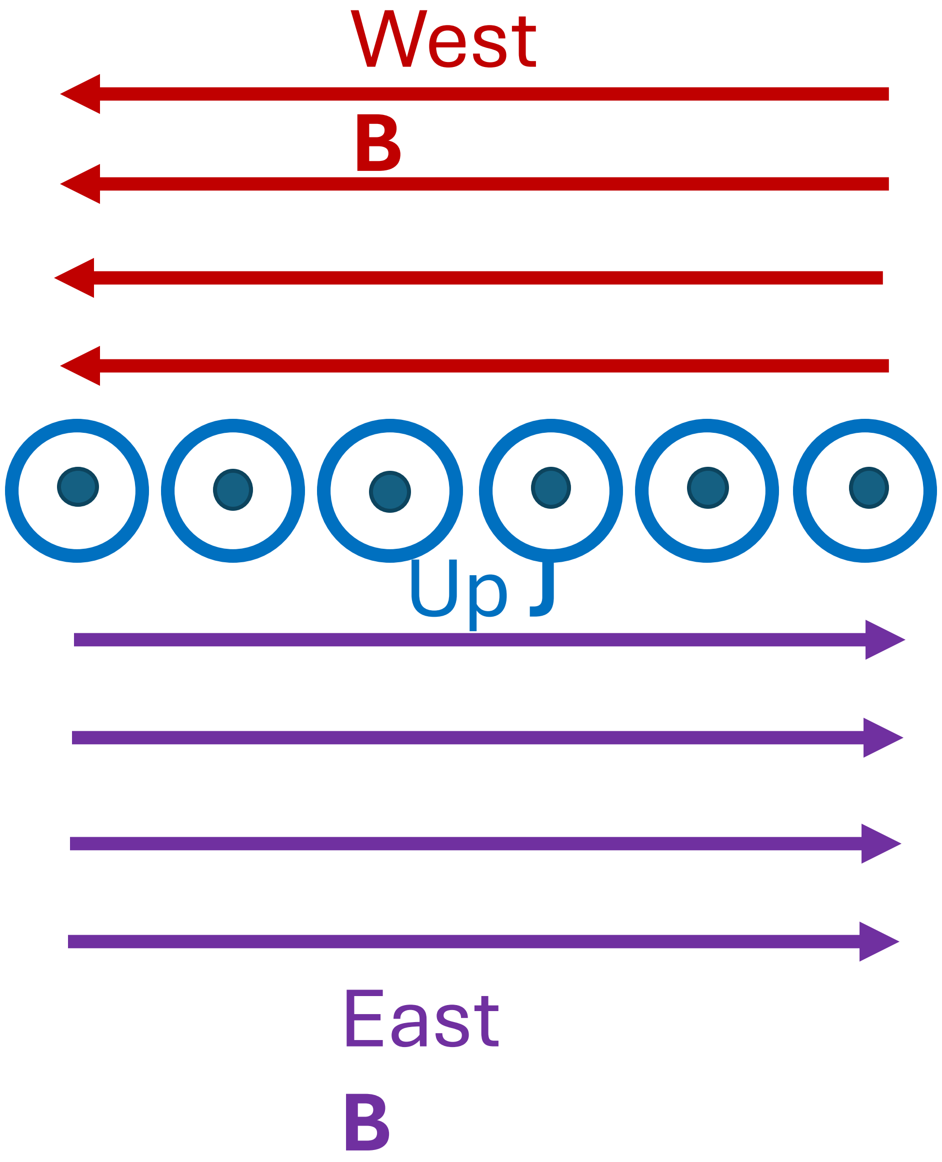
- Patches of aurora that blink (or pulsate) on and off with periods of 1-10 s.
- Typically more energetic than diffuse aurora (10-60 keV).
- Also scattered from inner magnetosphere
- Scattered by localized burst of chorus waves.

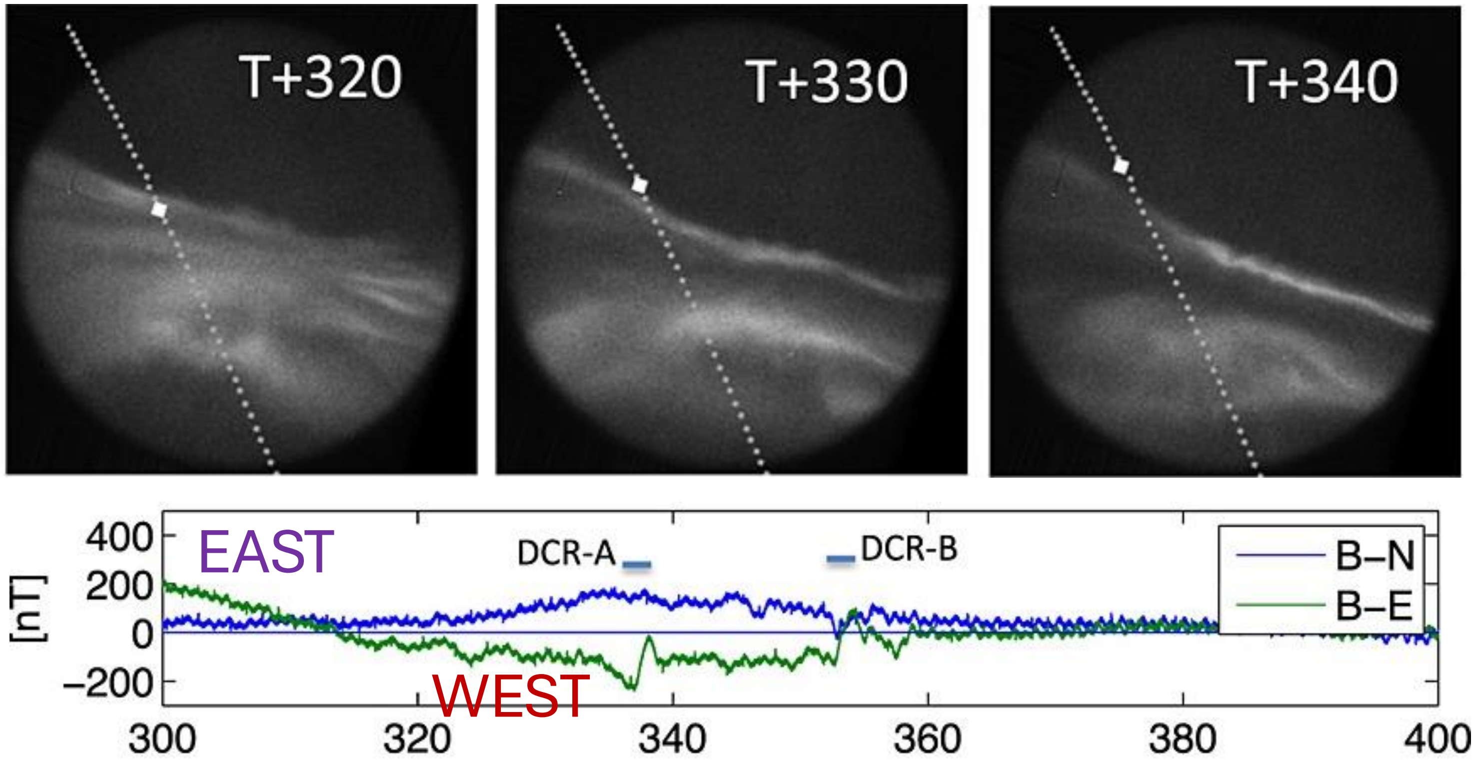


Discrete Aurora

- Well defined “curtains” or “auroral arcs” with distinct edges
- Sheets of field-aligned currents (FAC)

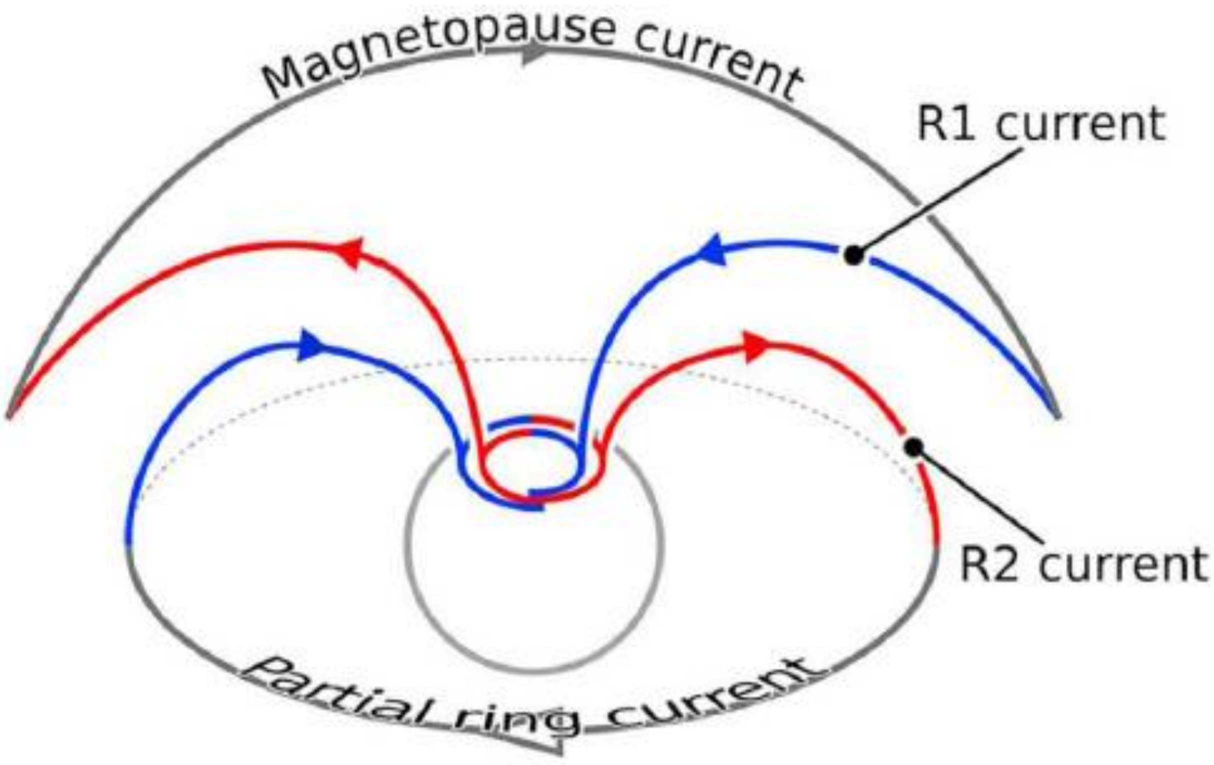
Magnetic Fields from Current Sheets

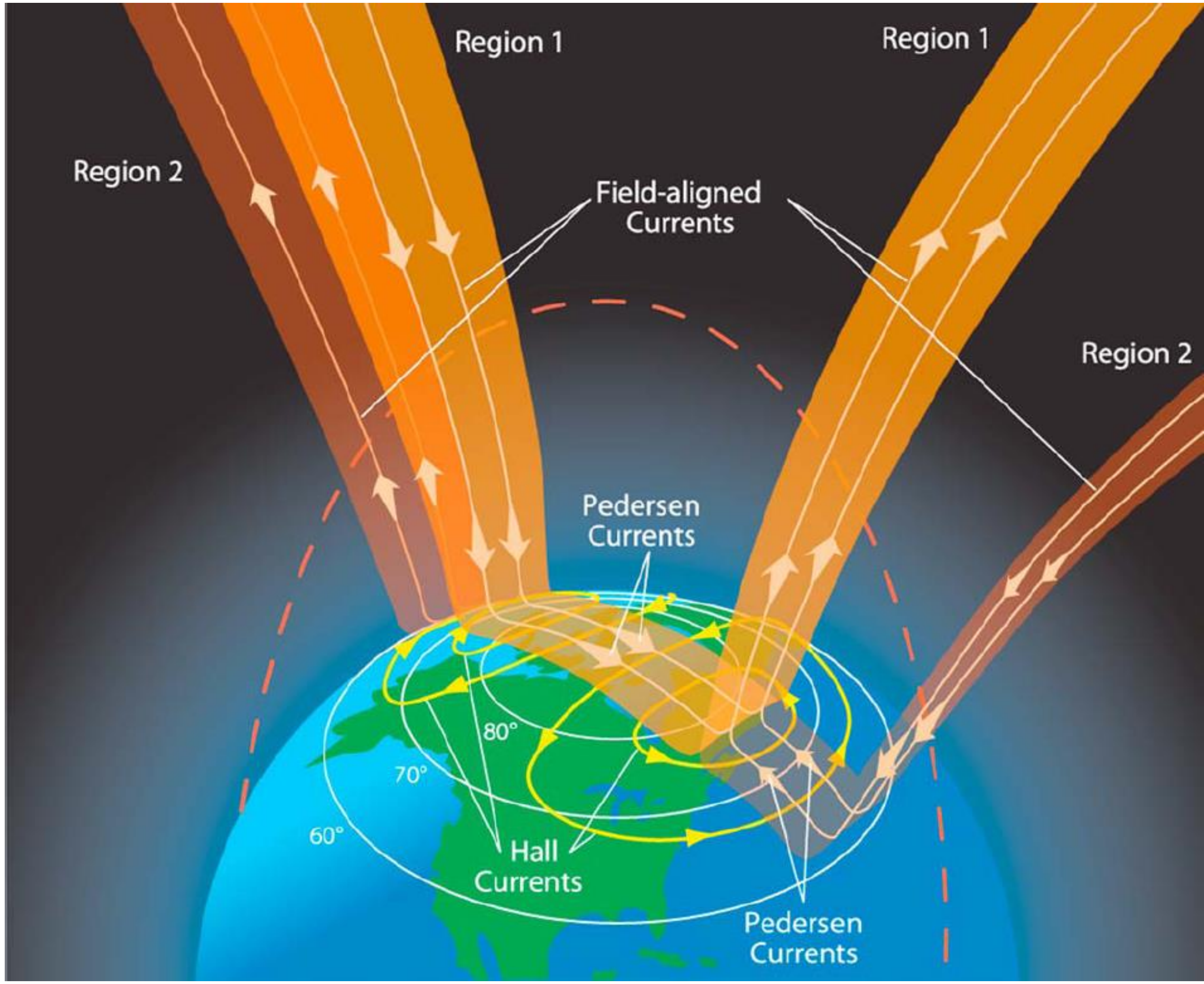




MICA sounding rocket observations from Lynch et al. (2015)

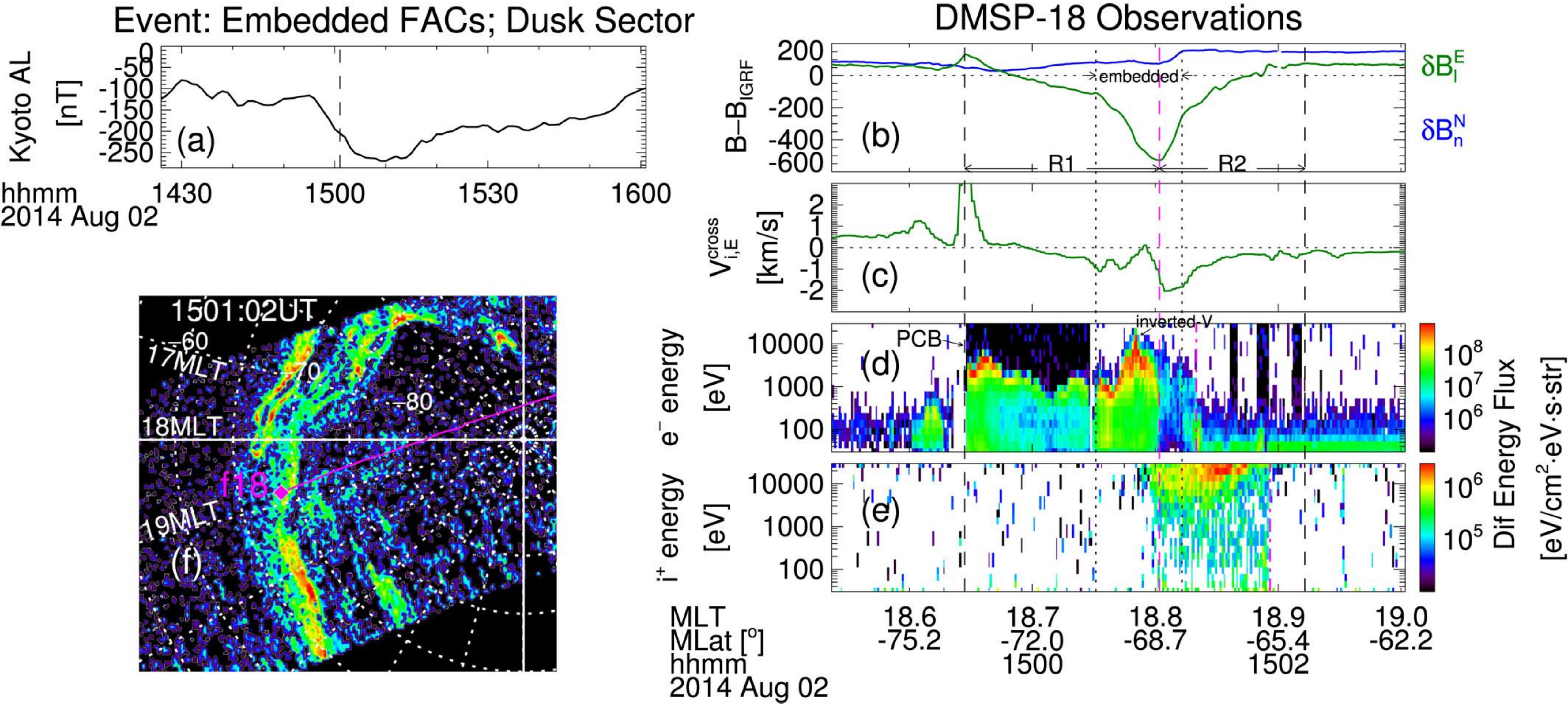
Field-Aligned Current Systems

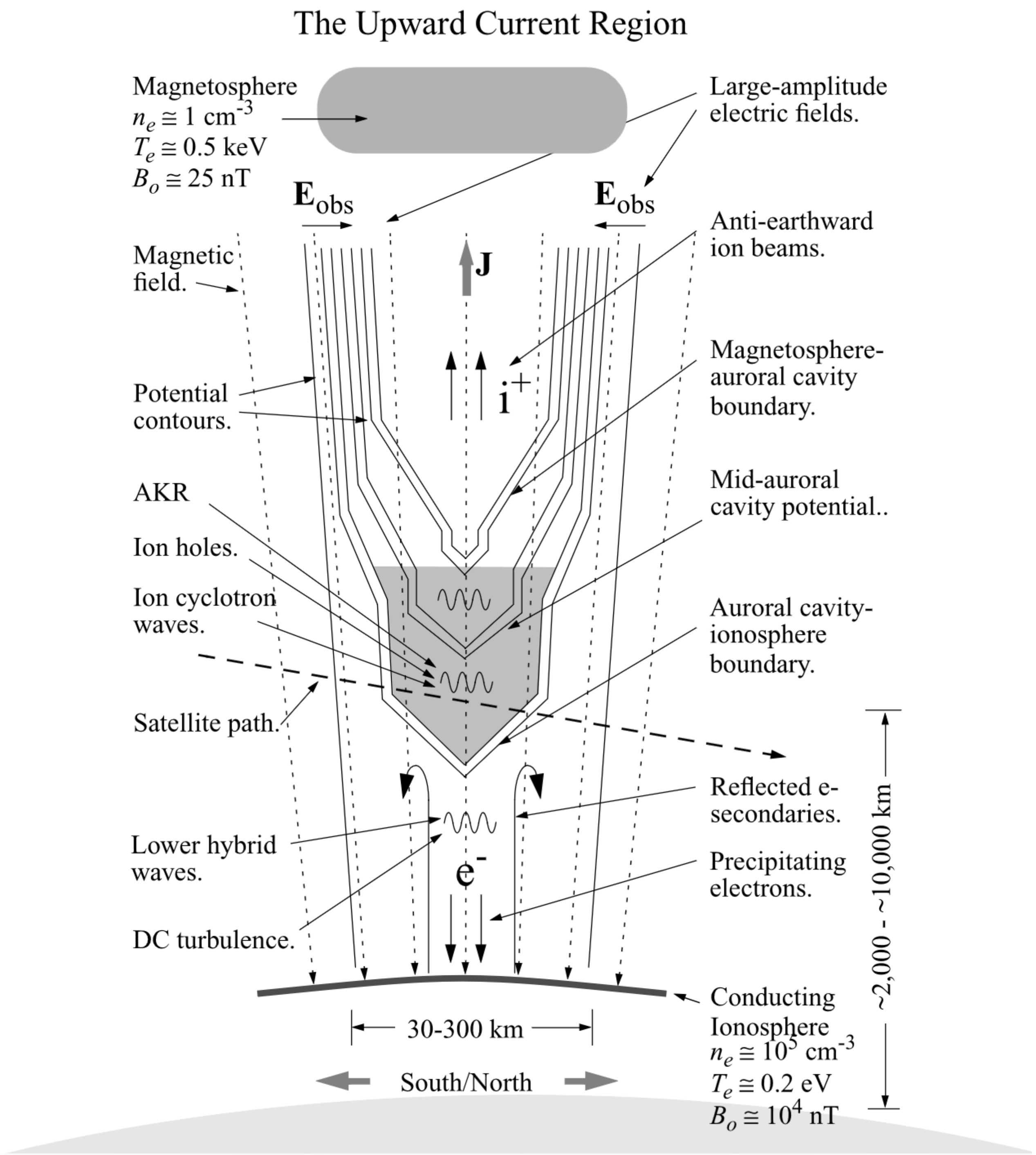


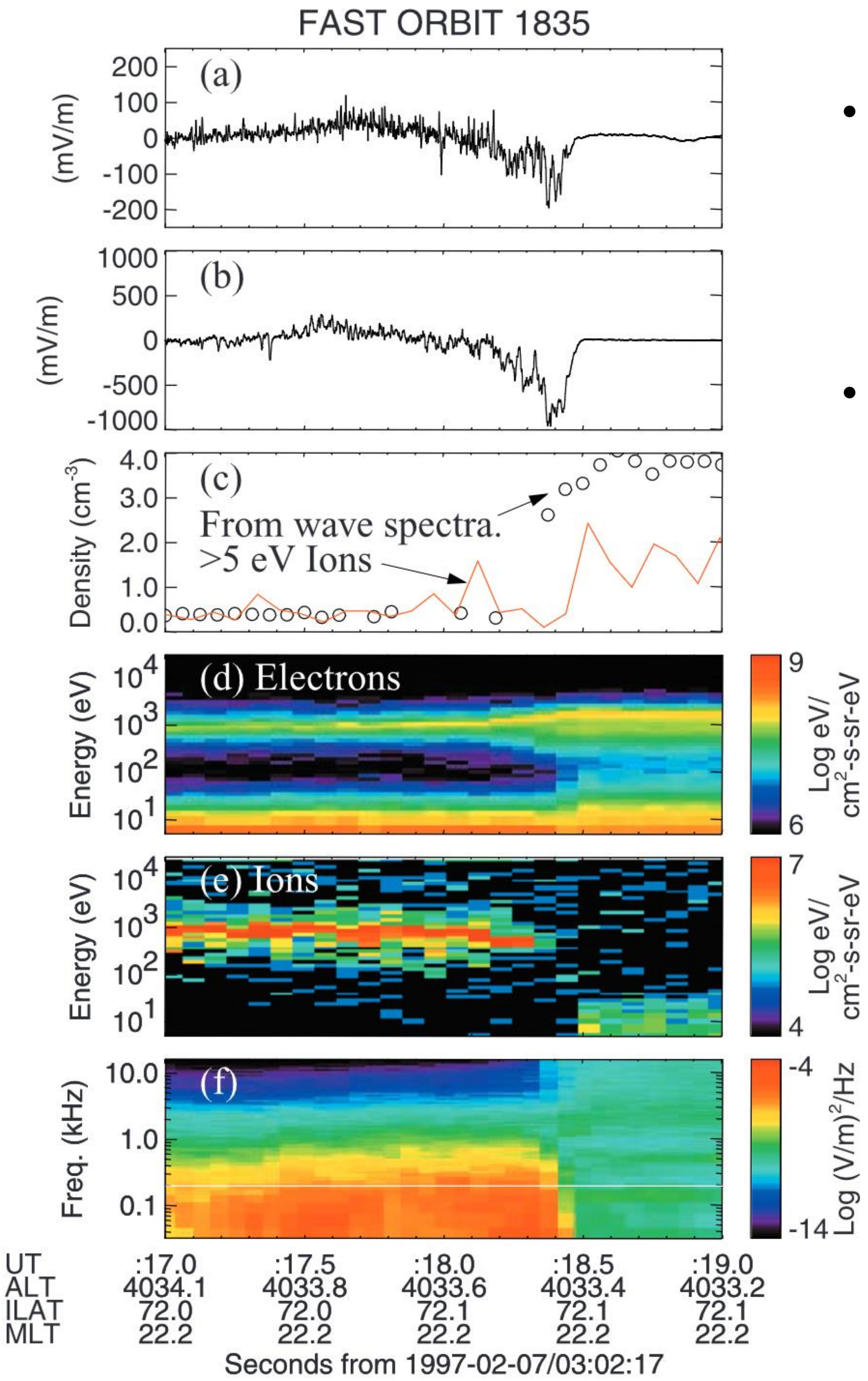


“Inverted-V” Discrete Aurora

Liu et al. (2021) https://doi.org/10.1029/2021JA029207



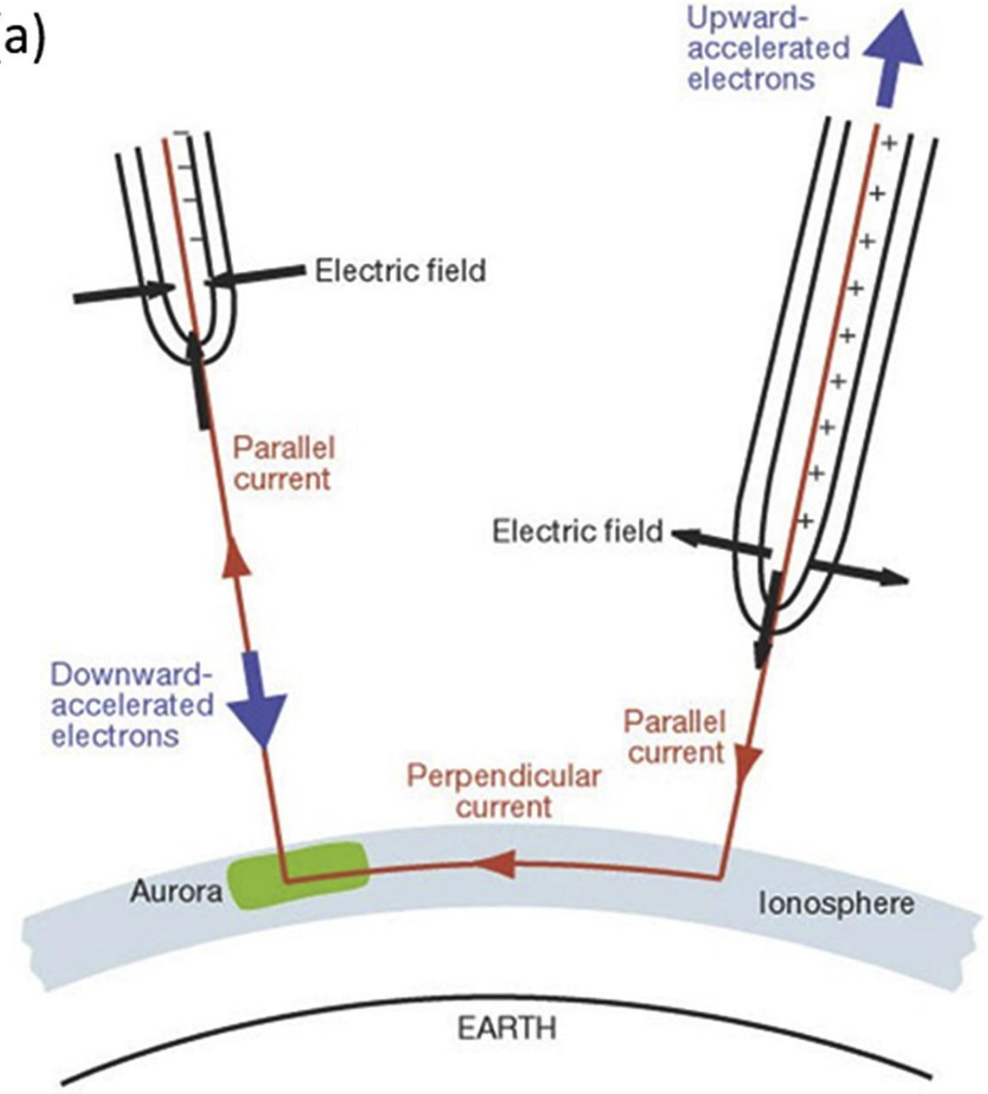




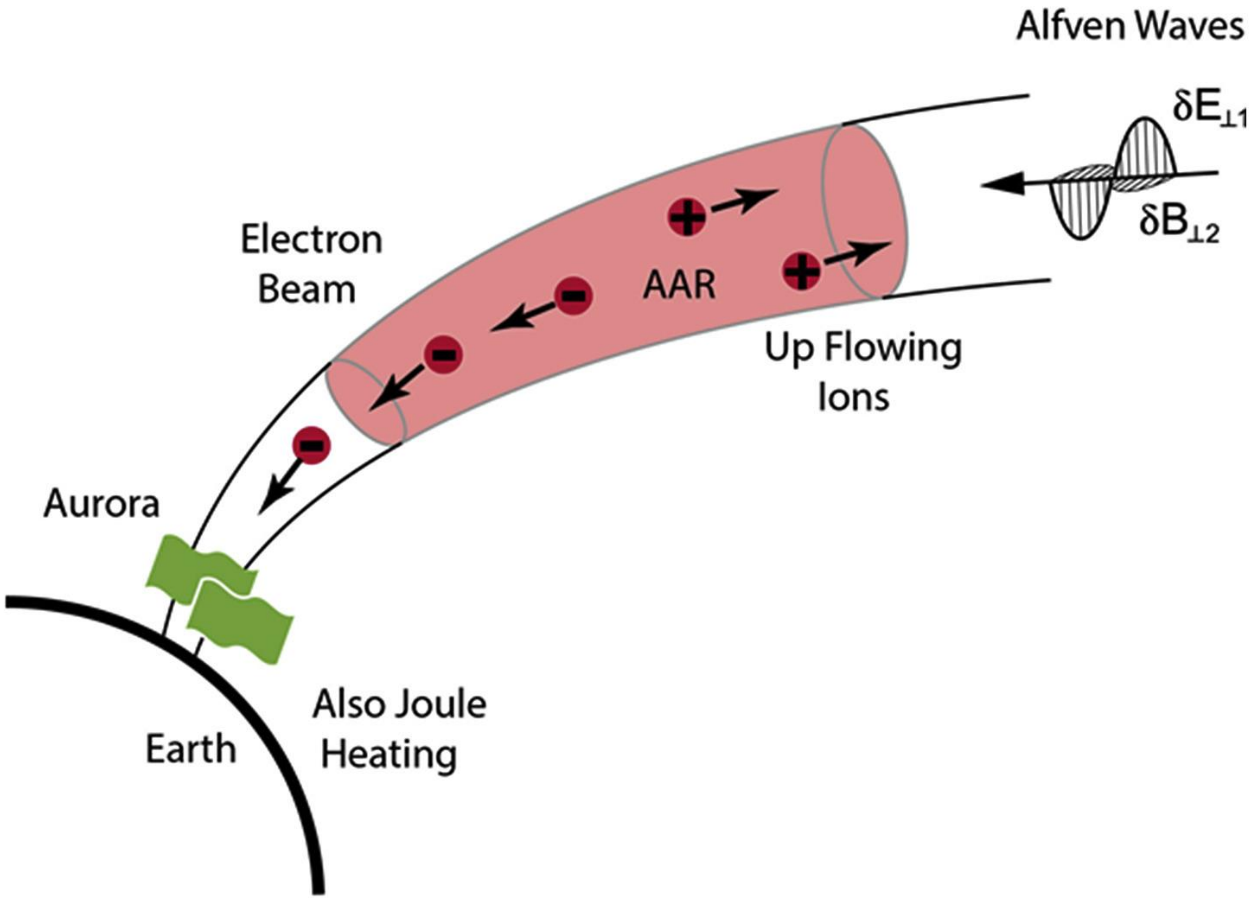
- FAST observations of the aurora acceleration region.
- Ergun et al. (2004) doi:10.1029/2004JA010545

Quasi-Static vs Alfvenic Acceleration

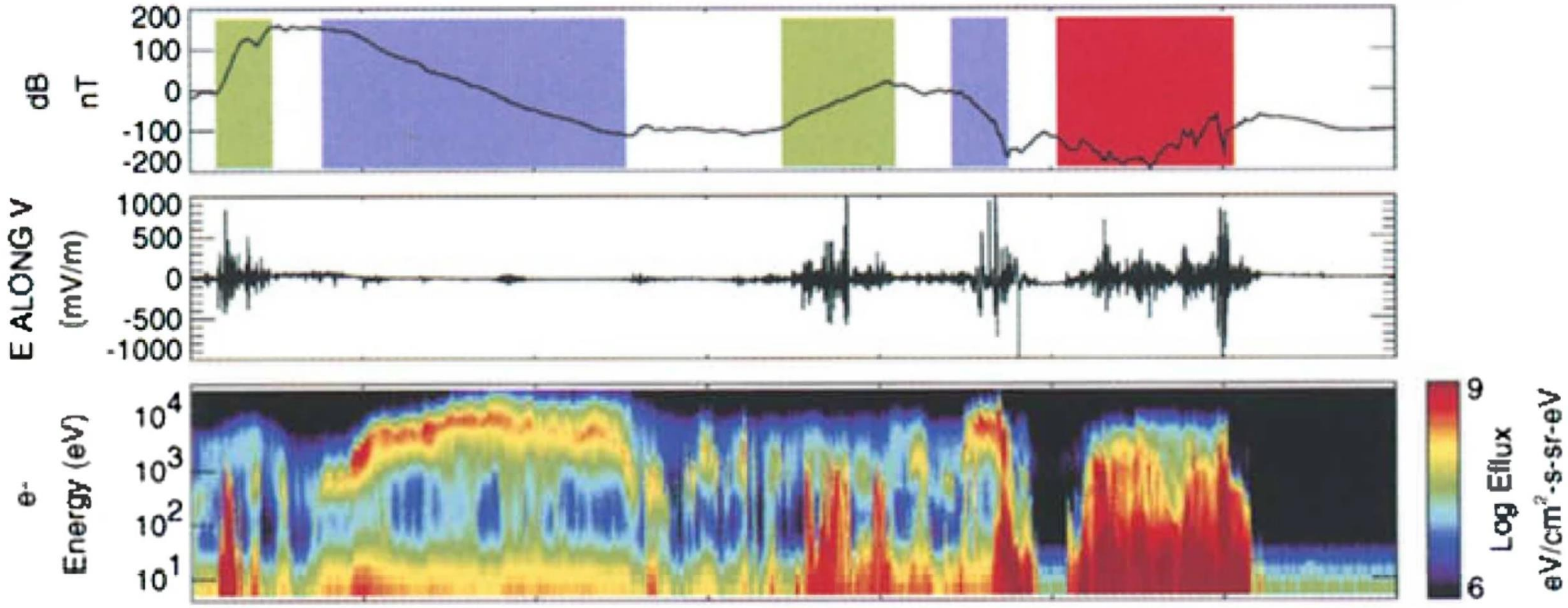
(a)



(b)

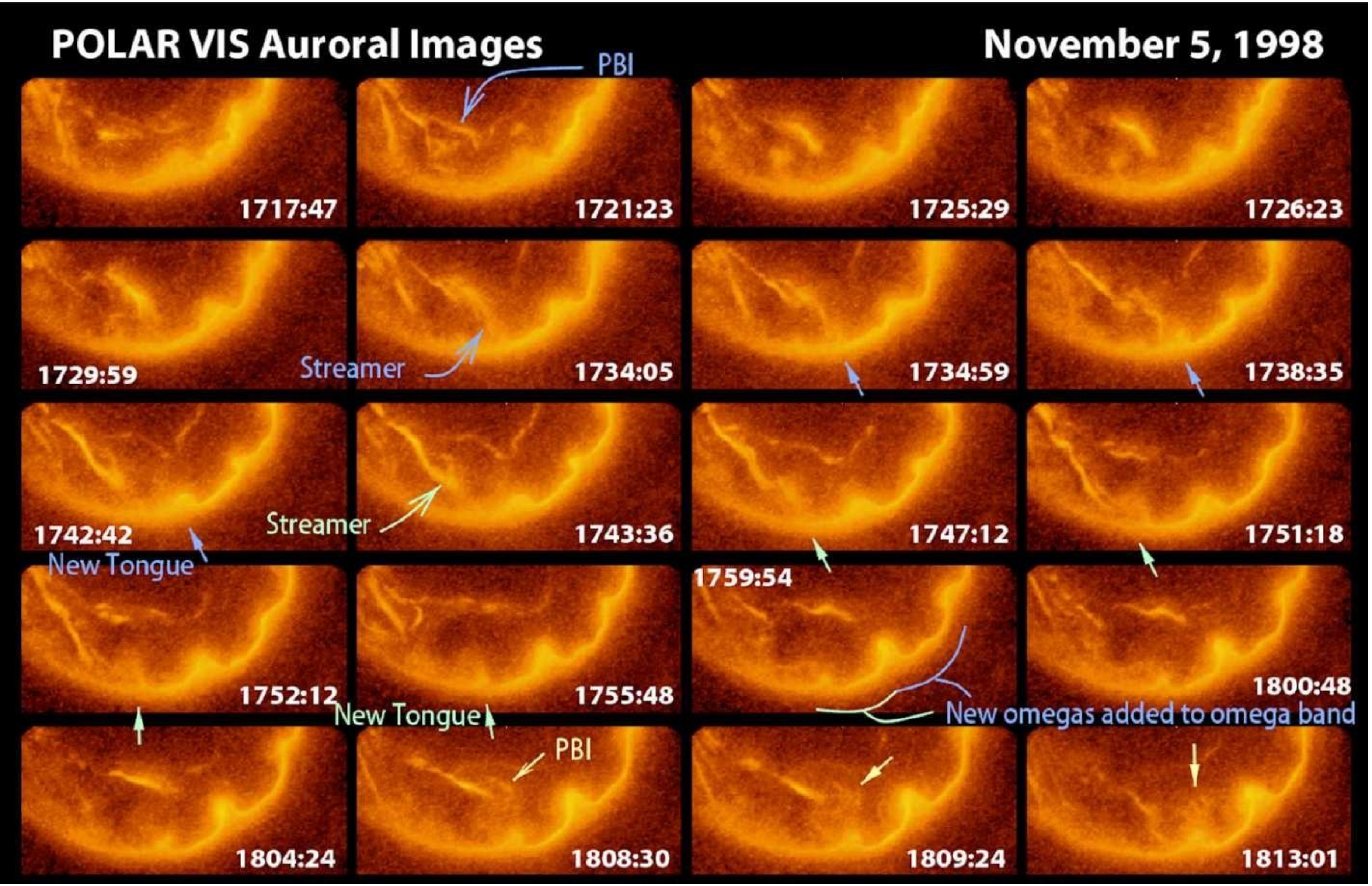


Monoenergetic vs Broadband Aurora



FAST data. Figure from Paschmann (2003).

Mesoscale Auroral Forms

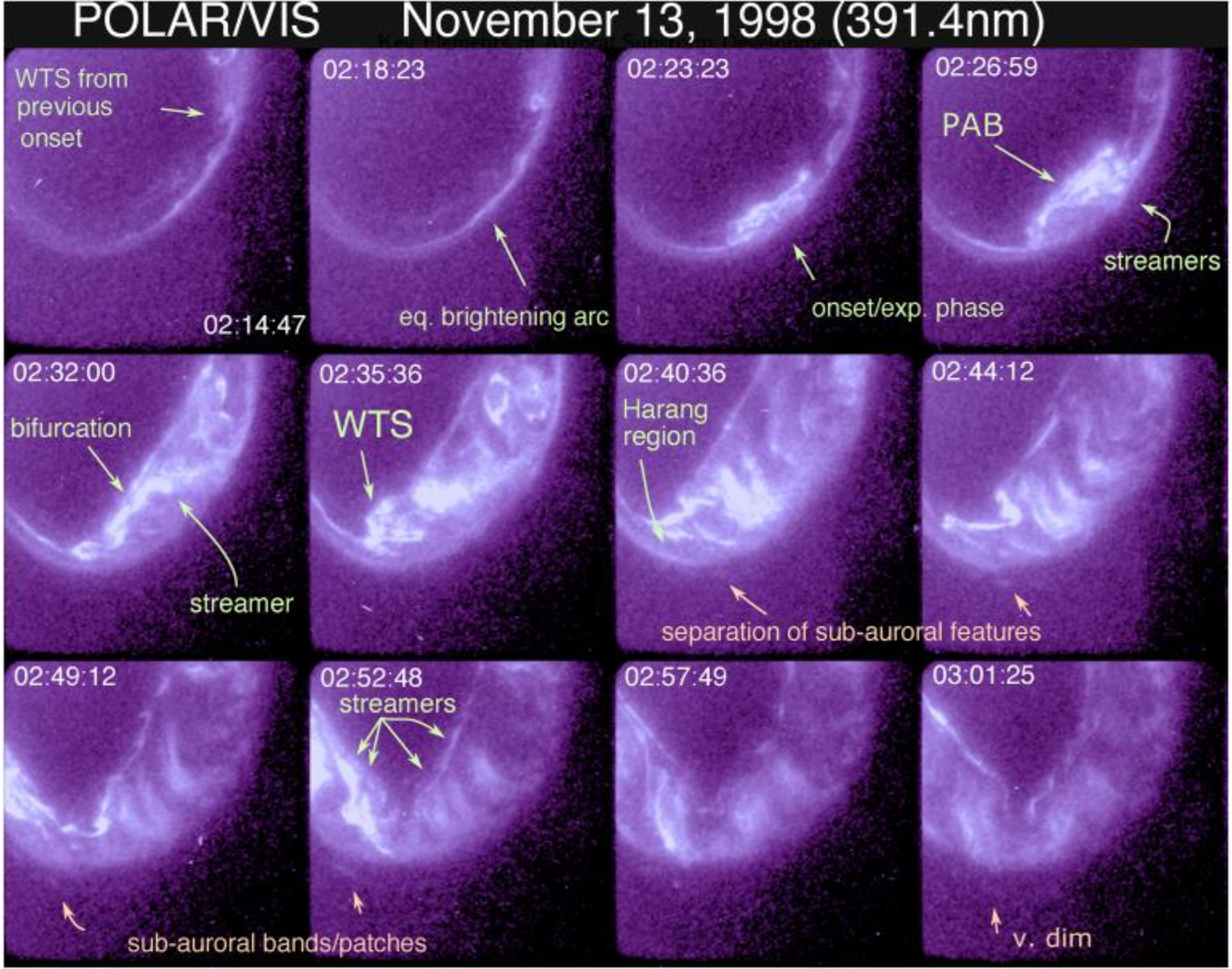


Further Reading:

Forsyth, C., Sergeev, V.A., Henderson, M.G. *et al.* Physical Processes of Meso-Scale, Dynamic Auroral Forms. *Space Sci Rev* **216**, 46 (2020). https://doi.org/10.1007/s11214-020-00665-y

Substorms

- Auroral substorm: A sudden release of energy from the magnetotail
- Phases:
  - Growth phase: multiple quiet discrete arcs (hours)
  - Onset: One arc rapidly brightens (5-10 minutes)
  - Expansion phase: Aurora expands poleward. Also forms westward traveling surge (WTS)
- Magnetosphere releases ~10^{16} J of energy in less than 1 hour.



From Henderson (2021)