Modeling Particle Precipitation and Subsequent Effects on the Ionospheric Conductivity

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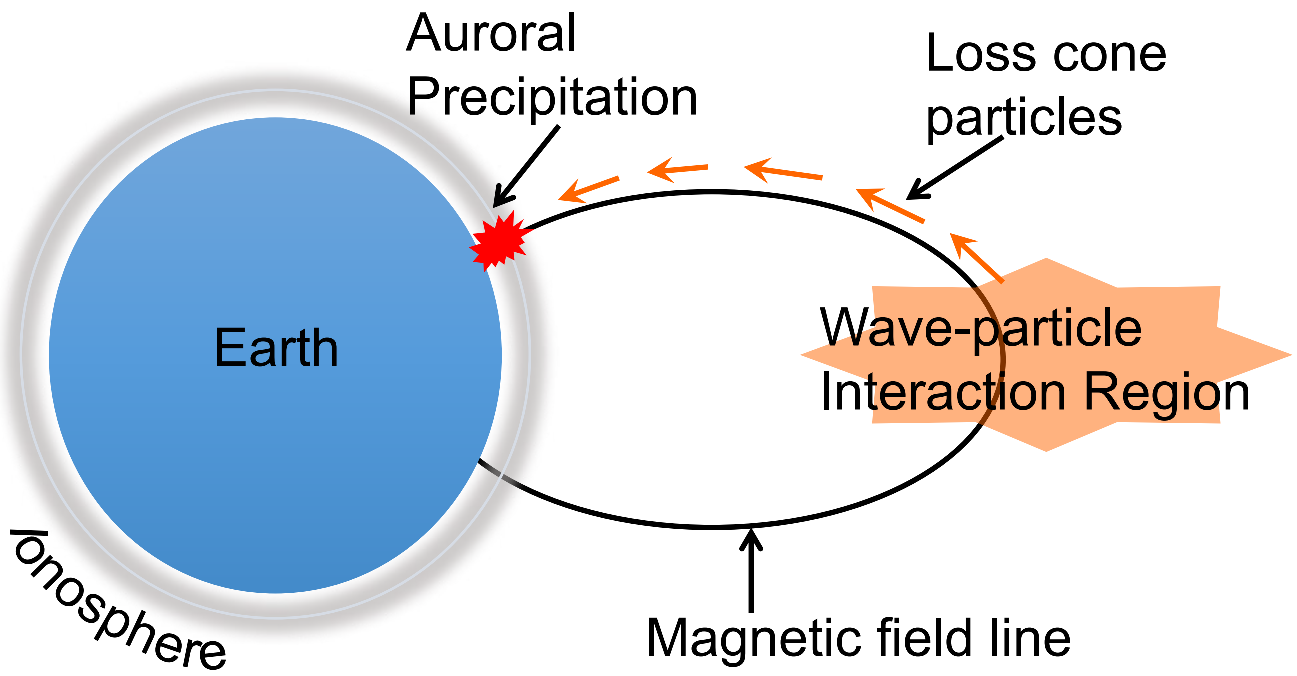
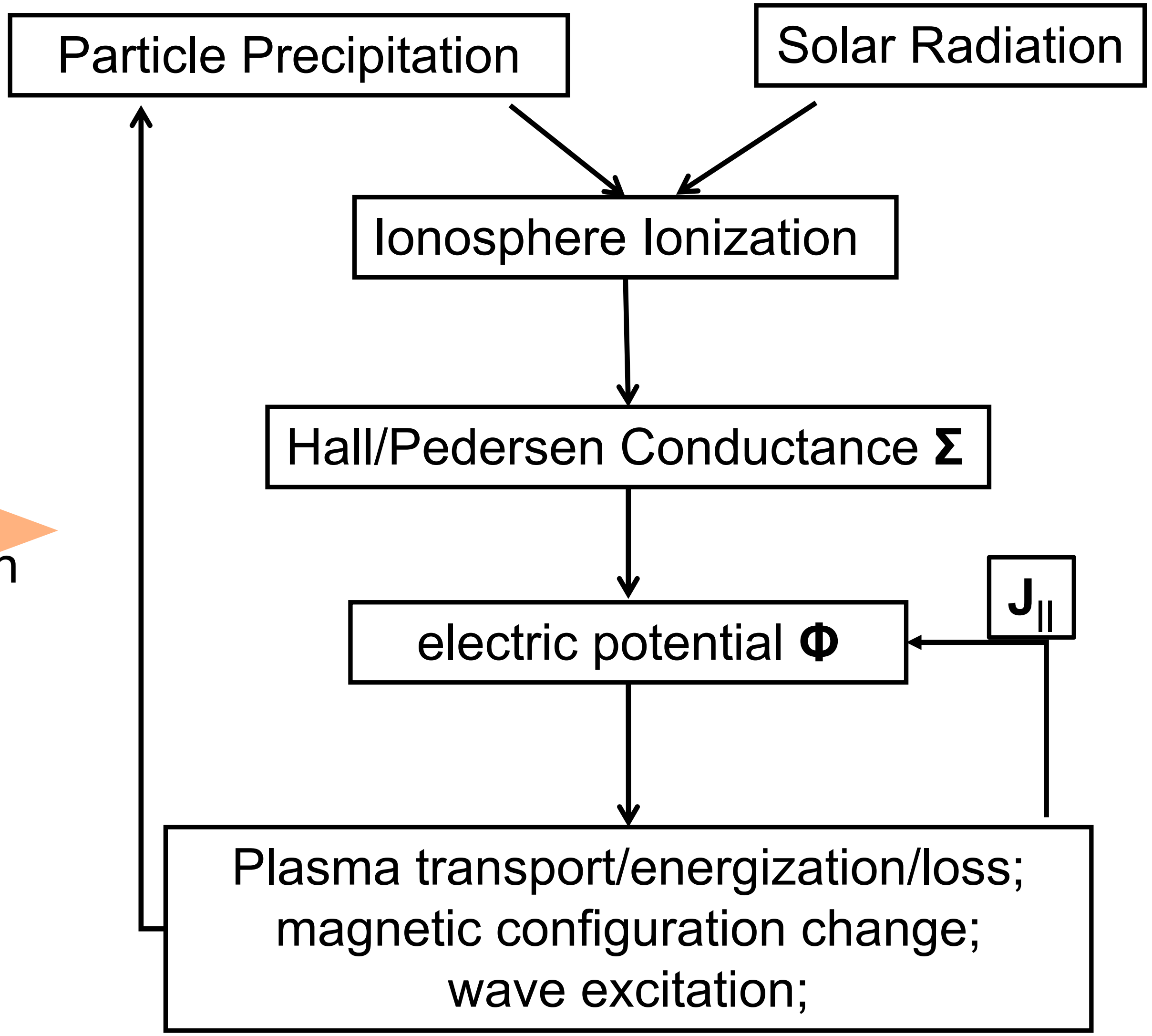
Magnetosphere-Ionosphere Coupling





This is a fully coupled system, which needs a self-consistent treatment.

Kinetic Model

Conductance Calculator

Precipitation flux
f(E,α)

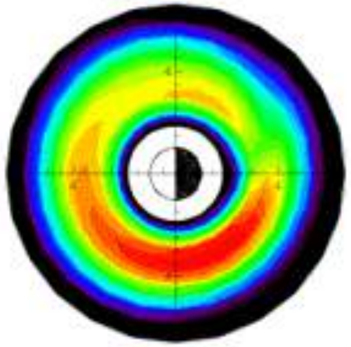
Σ_P, Σ_H

Magnetospheric Ring current

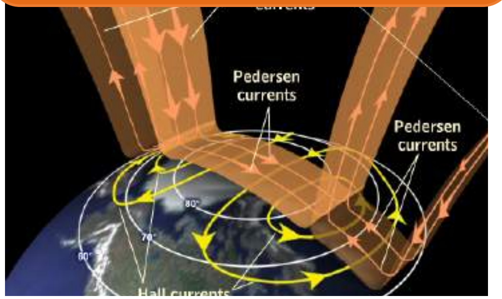
FACs $J_{||}$

Potential Φ

Ionospheric electrodynamics



$$\frac{df}{dt} = \left(\frac{\partial f}{\partial t}\right)_{source} + \left(\frac{\partial f}{\partial t}\right)_{loss}$$



$$\nabla \cdot (\Sigma \cdot \nabla \Phi) = -J_{||} \sin I$$

Conductance calculator

1. Empirical formulism
    - Mean energy <E> of Incident auroral precipitation flux
    - Total energy flux F_E of Incident auroral precipitation flux

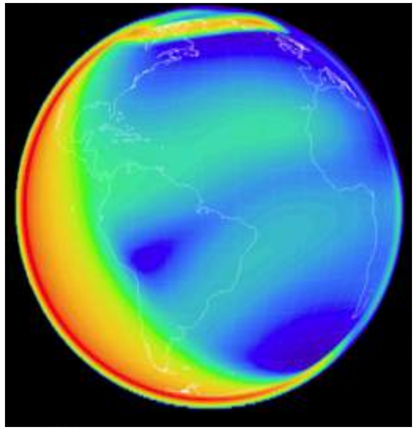
e.g.,

$$\Sigma_P = \frac{40 < E >}{16 + < E >^2} F_E^{0.5}$$

$$\Sigma_H = 0.45 < E >^{0.85} \Sigma_p$$

Robinson, 1987

2. First-principle model (✔)
    - GLOW: a two-stream transport code
    - Inputs:
        - neutral thermosphere species density, electron density
        - neutral, ion, and electron temperatures
        - solar flux
        - Incident auroral precipitation flux spectrum
    - Output:
        - altitude profile of electron density, ionization rates, ionized and excited species density
        - airglow volume emission rates, vertical column brightness
        - Altitude profile of Hall/Pedersen conductivity (conductance)



Solomon, 1988,...2017

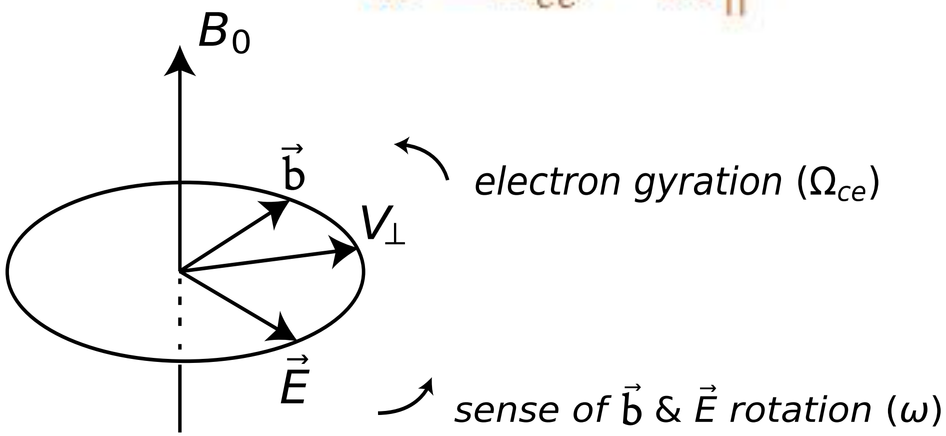
Particle precipitation

- Electron precipitation
  - Chorus & hiss waves (✔)
  - ECH waves
- Ion precipitation
  - EMIC waves (✔)
  - Field line curvature (FLC) scattering (✔)
- These loss processes are solved by diffusion equation with associated pitch angle diffusion coefficient $D_{\alpha\alpha}$.

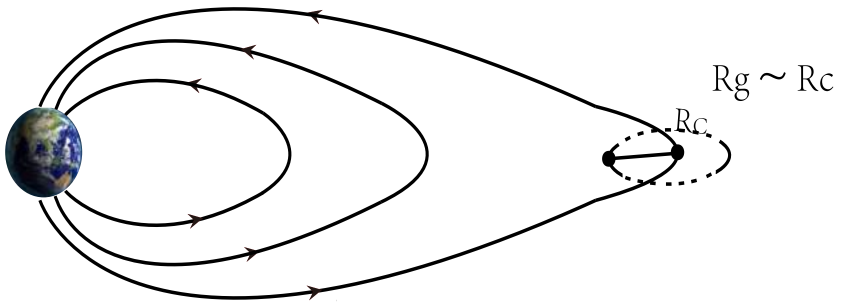
- **In the following simulation, the well-known March 17, 2013 storm event is investigated.**

1) Wave-particle interaction occurs when the resonance condition is satisfied:

$$\omega = \Omega_{ce} - k v_{||}$$



2) FLC scattering occurs when FLC radius is comparable to particles' gyroradius: $\varepsilon = R_G/R_c > 0.1$

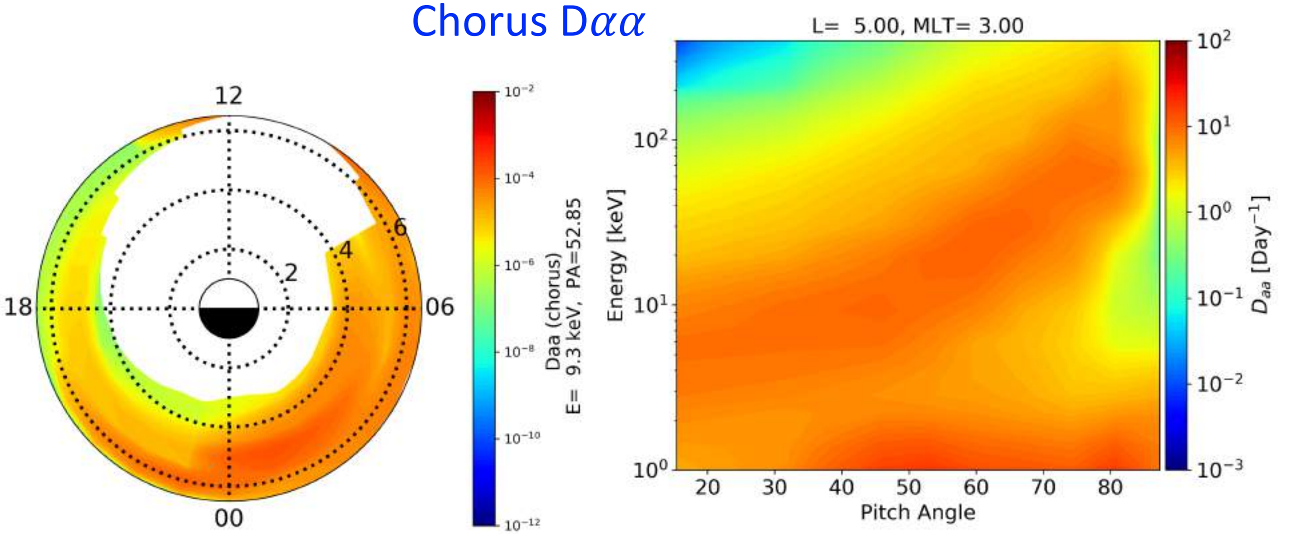


Electron precipitation

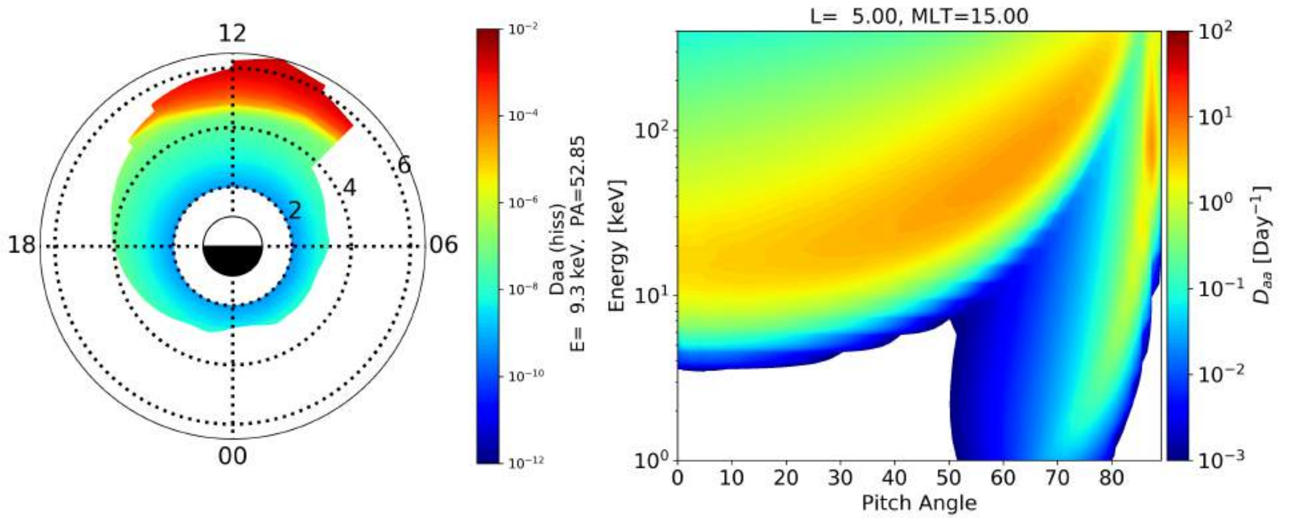
- Chorus waves :
  - outside plasmaspause, across the dawn-to-midnight sector
  - $D\alpha\alpha$ is based on Horne et al., (2013); Glauert et al., (2014)
  - Upper-band chorus: diffuse lower-energy (up to a few keV) electrons
  - Lower-band chorus: diffuse more energetic electrons (1-50 keV at lower pitch angles, >~50 keV at higher pitch angles)

- Hiss waves:
  - inside plasmapause, mainly in the plume
  - $D\alpha\alpha$ is based on Albert (2005)
  - Diffusion is more effective for energetic electrons (>10 keV) at small pitch angles

Chorus $D\alpha\alpha$



Hiss $D\alpha\alpha$



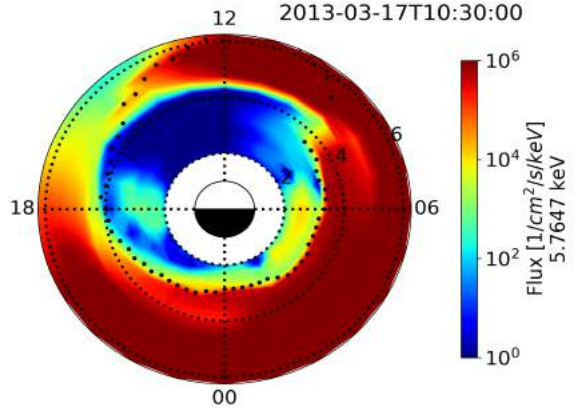
Electron precipitation

- Low-energy (a few keV) electrons precipitate across a wide region outside L=3.5, except in the afternoon

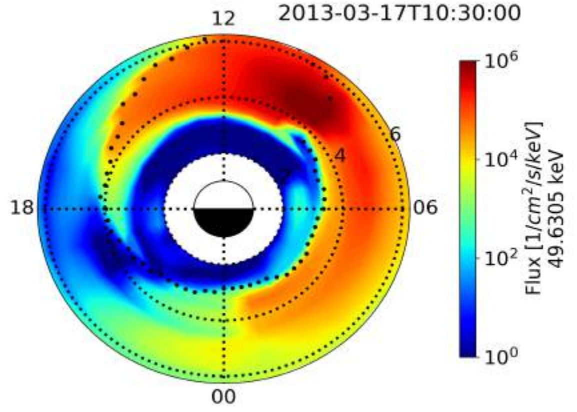
- Medium-energy (tens of kev) electrons precipitate in the dawn sector outside the plasmapause and on the dayside inside the plasmasphere

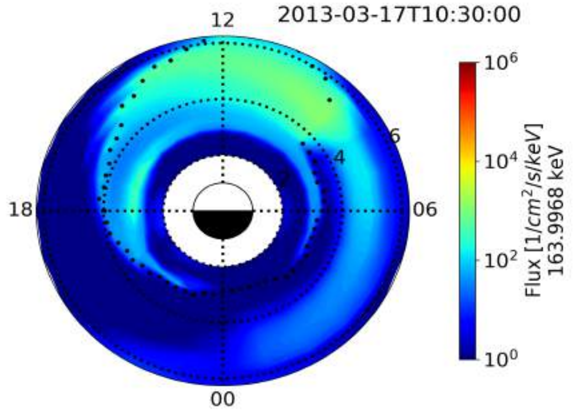
- High-energy (hundreds of keV) electrons precipitate mainly in the plume

5.7 keV



50 keV

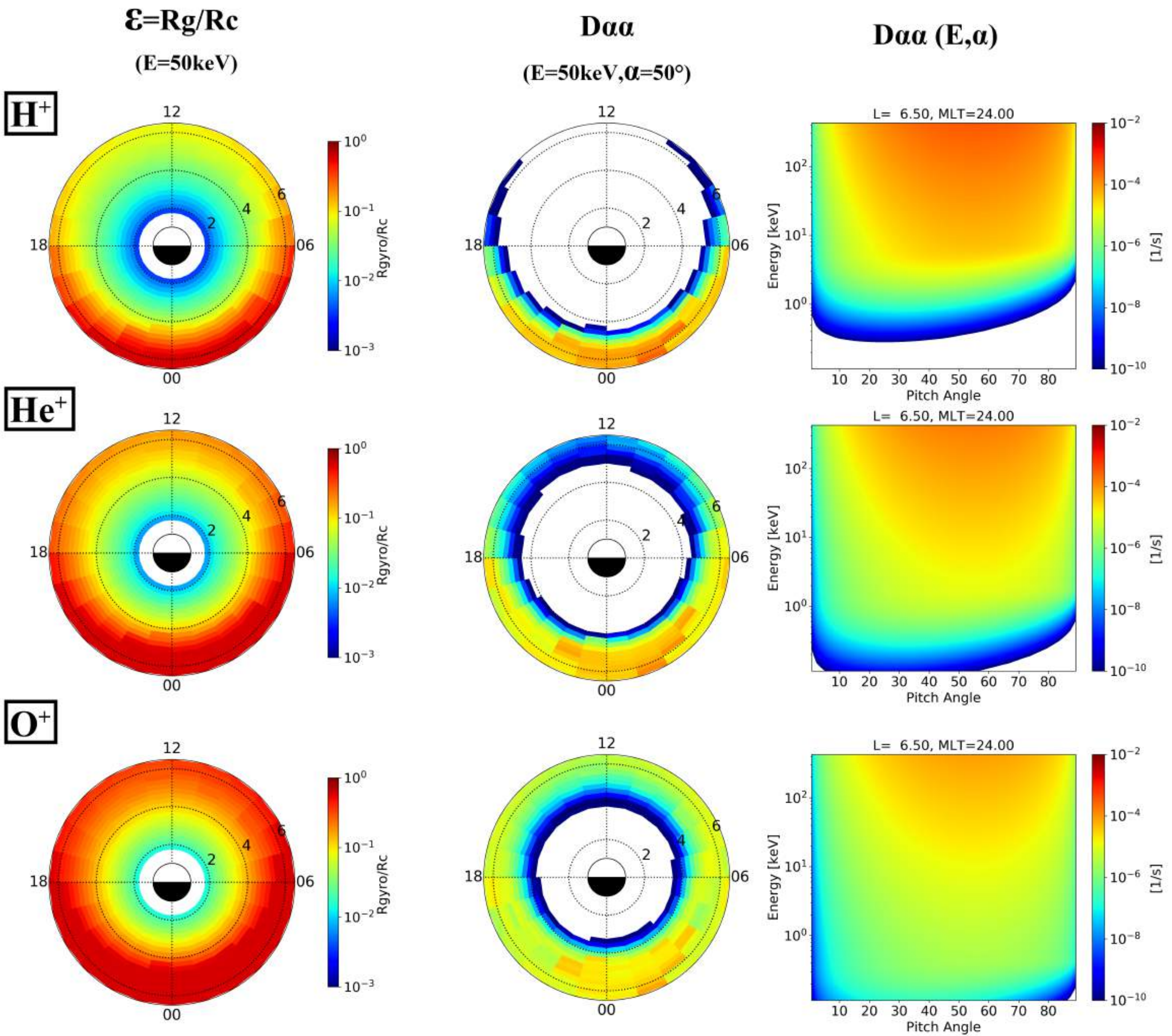




164 keV

Ion precipitation

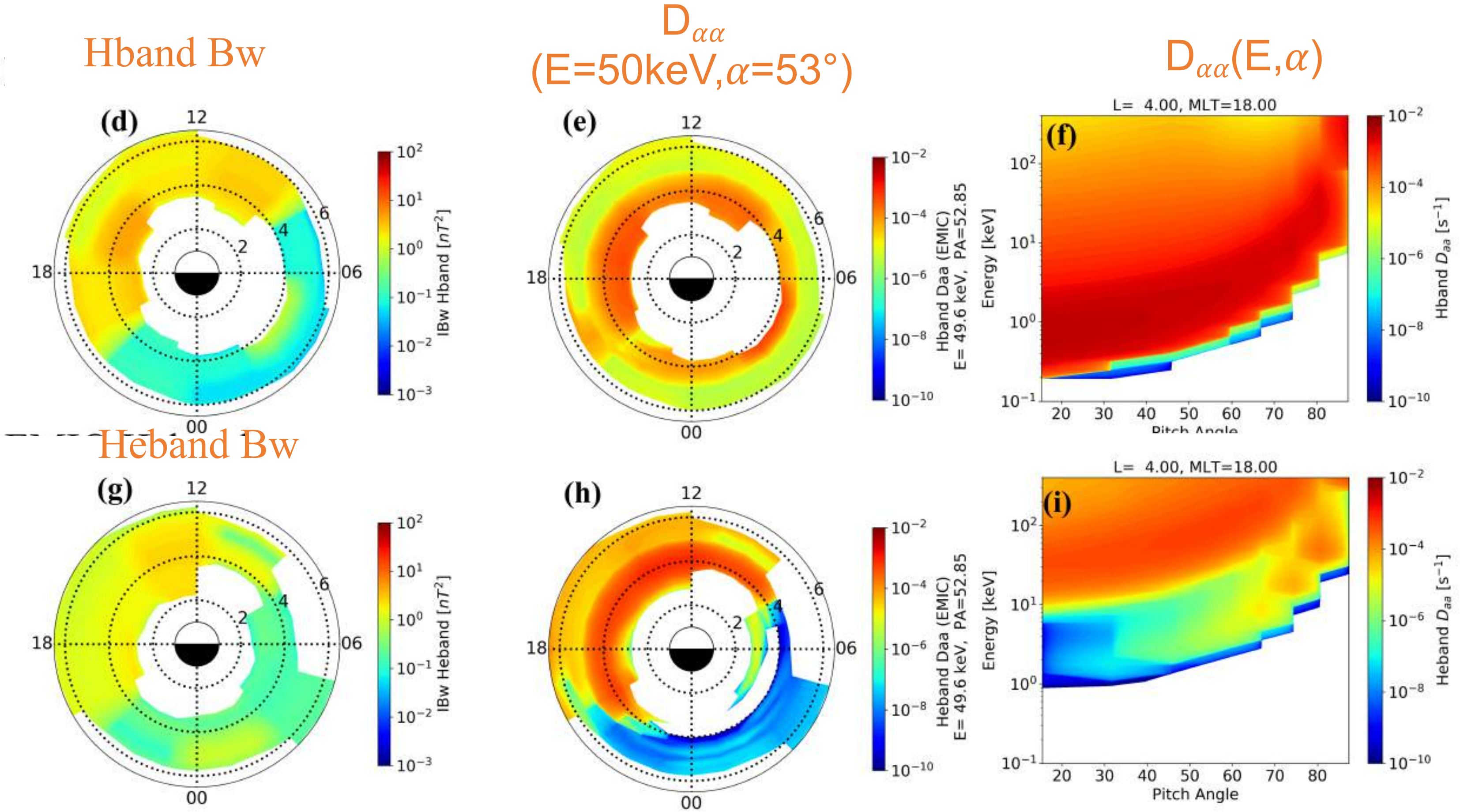
- FLC:
    - The ε parameter is larger on the nightside in the outer region where magnetic field is more stretched.
    - The pitch angle diffusion coefficient $D\alpha\alpha$ is larger for more energetic particles.
    - O+, with a larger gyroradius, can experience pitch angle diffusion in a wider region than other ions.



Ion precipitation

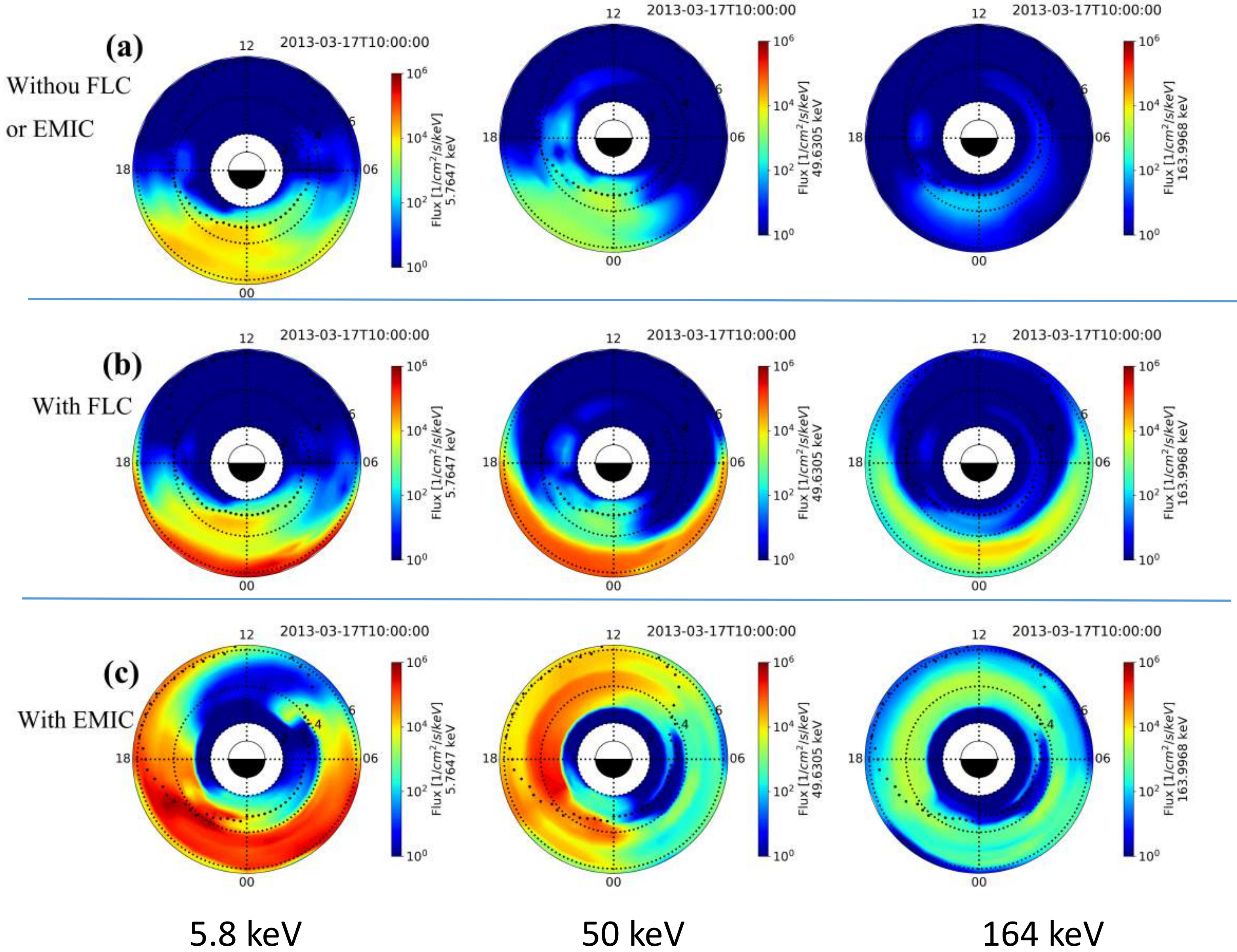
- EMIC:
  - The wave model is based on statistical distribution of EMIC wave intensities from Van Allen Probes observations (*Saikin et al., 2016*).
  - Pitch angle diffusion is large in the dusk and day sectors.

  - H band $D\alpha\alpha$ is larger for lower energy (~1 keV) particles while He band $D\alpha\alpha$ is larger for higher energy (>10 keV) particles.



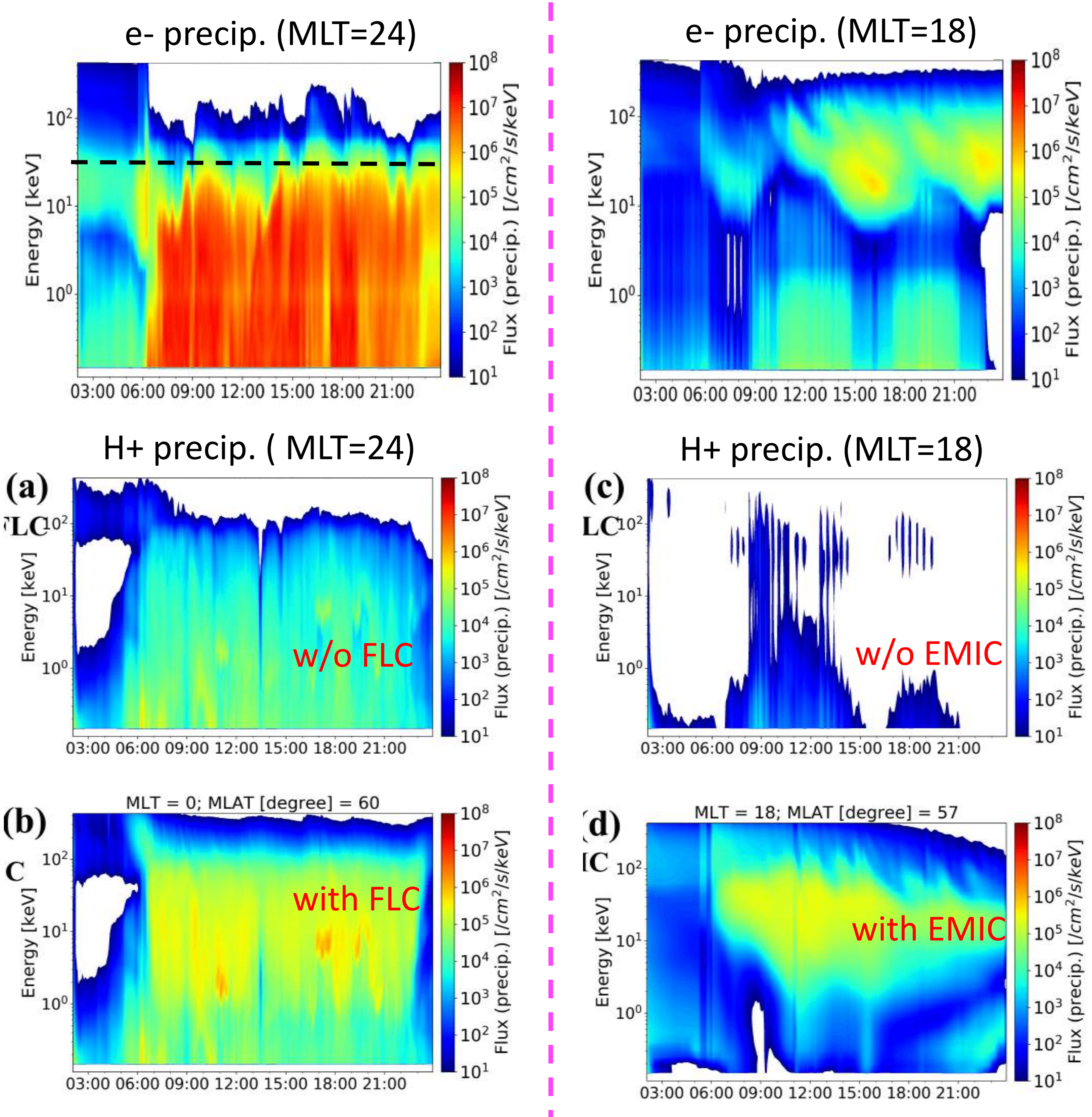
Ion (proton) precipitation

- With adiabatic loss only, large proton precipitation occurs in the dusk-to-midnight sector
- With FLC scattering included, proton precipitation takes place in the outer region on the nightside; more energetic protons experiences diffusion in a wider region
- With EMIC scattering included, low-energy particles precipitate in the nightside, while precipitation of higher-E protons is shifts to dusk and dayside.

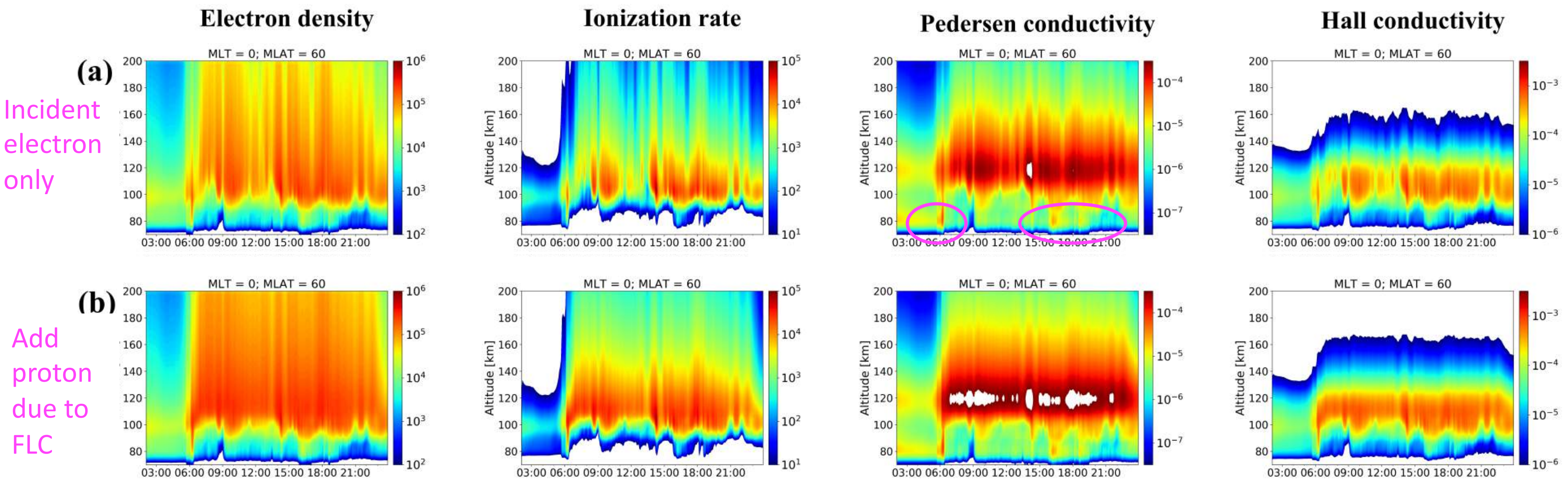


Precipitation spectra

- At midnight (MLT=24):
  - The precipitating electron flux mostly follows a Maxwellian distribution. However, a high-energy tail (> 30 keV) occasionally appear during the storm.
  - FLC scattering induces considerable precipitating proton flux at 1<E<100 keV, but still less intense than electron flux
- At dusk (MLT=18):
  - The precipitating electron flux mostly distributes at high energies
  - Significant proton precipitation is induced by EMIC waves for1<E<100 keV, which is comparable to electron flux

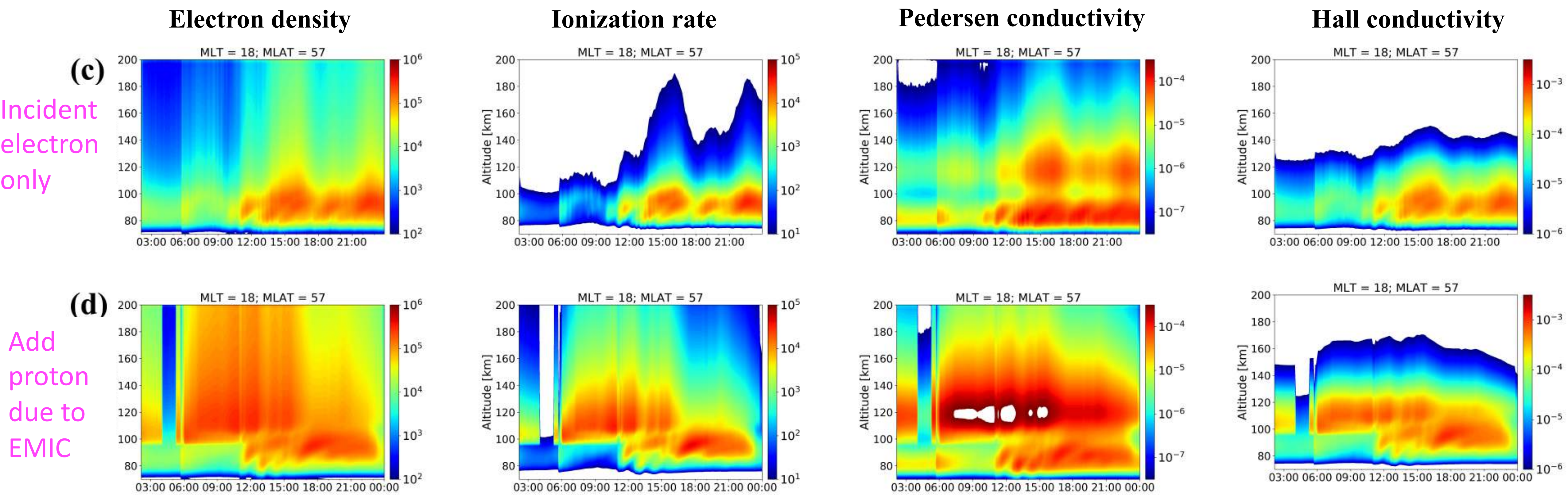


Ionospheric response (MLT=24)



- With the full-spectrum particle precipitation input, the ionospheric dynamics is solved by GLOW model
- With incident precipitating electrons only, the ionization is largely enhanced at low altitudes (<100 km) due to penetration of energetic electrons (>30 keV, the high-energy tail in the spectra). This causes the enhancement of Pedersen conductivity in the D region, resulting in a two-layer conductivity profile.
- With the FLC-induced proton precipitation included, the ionization is enhanced in the E region, amplifying the electron density and the conductivity in the E region.

Ionospheric response (MLT=18)



- When GLOW is driven by incident electrons only at MLT=18, ionization mostly occurs below 100 km (D region). This is because the precipitating electrons are highly energetic due to hiss wave scattering near the plasmapause. The two-layer structure of conductivity appears.
- When EMIC wave-induced proton precipitation is included, the E/F region electron density is largely enhanced. This is caused by the energetic protons that impact the high altitudes.

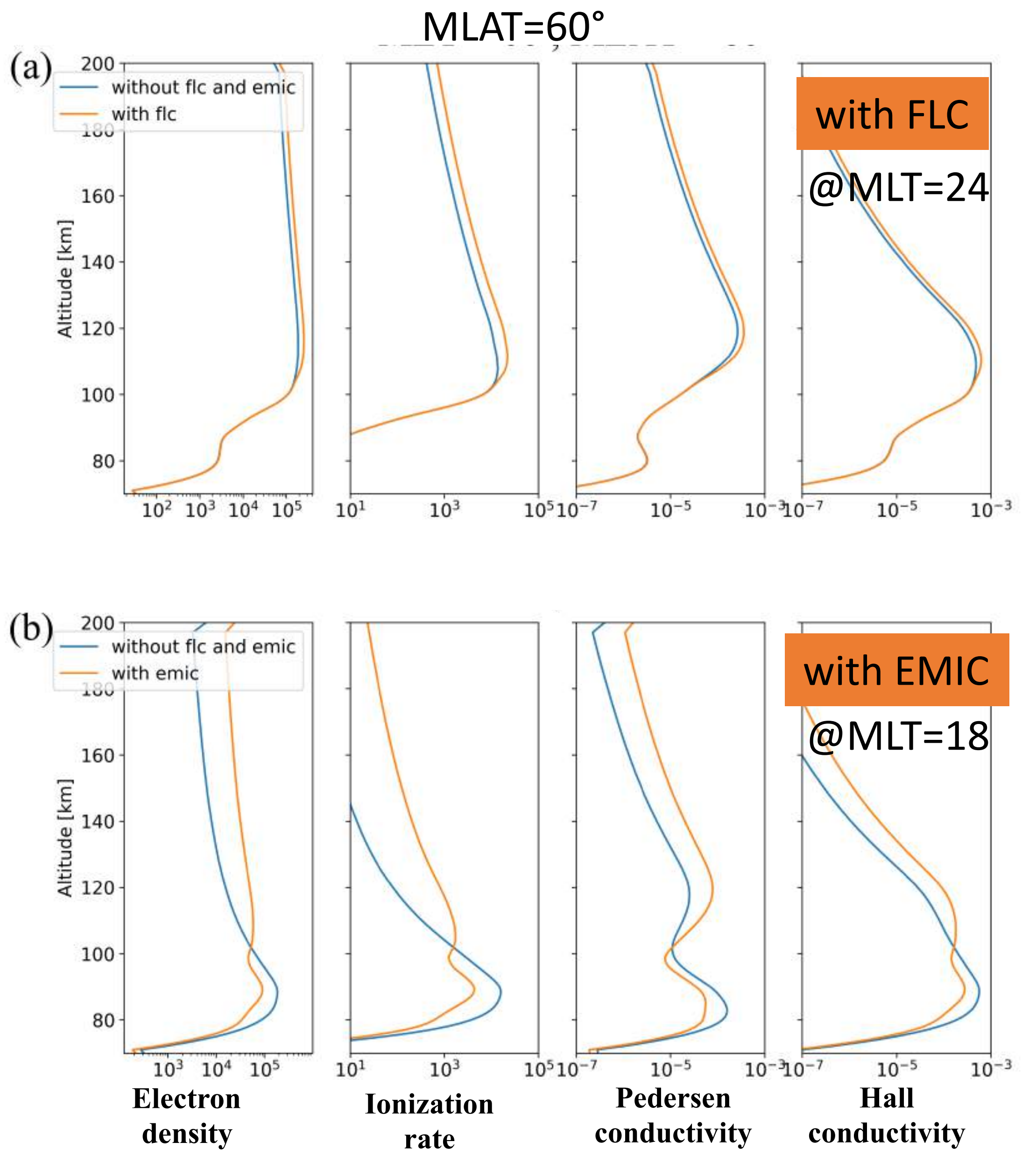
Altitudinal conductivity profiles

Blue lines: incident electron precipitation only
Red lines: proton precipitation added

- Incident electrons (blue lines) can significantly impact the midnight ionosphere, but less impact on dusk (because of much less precipitation)

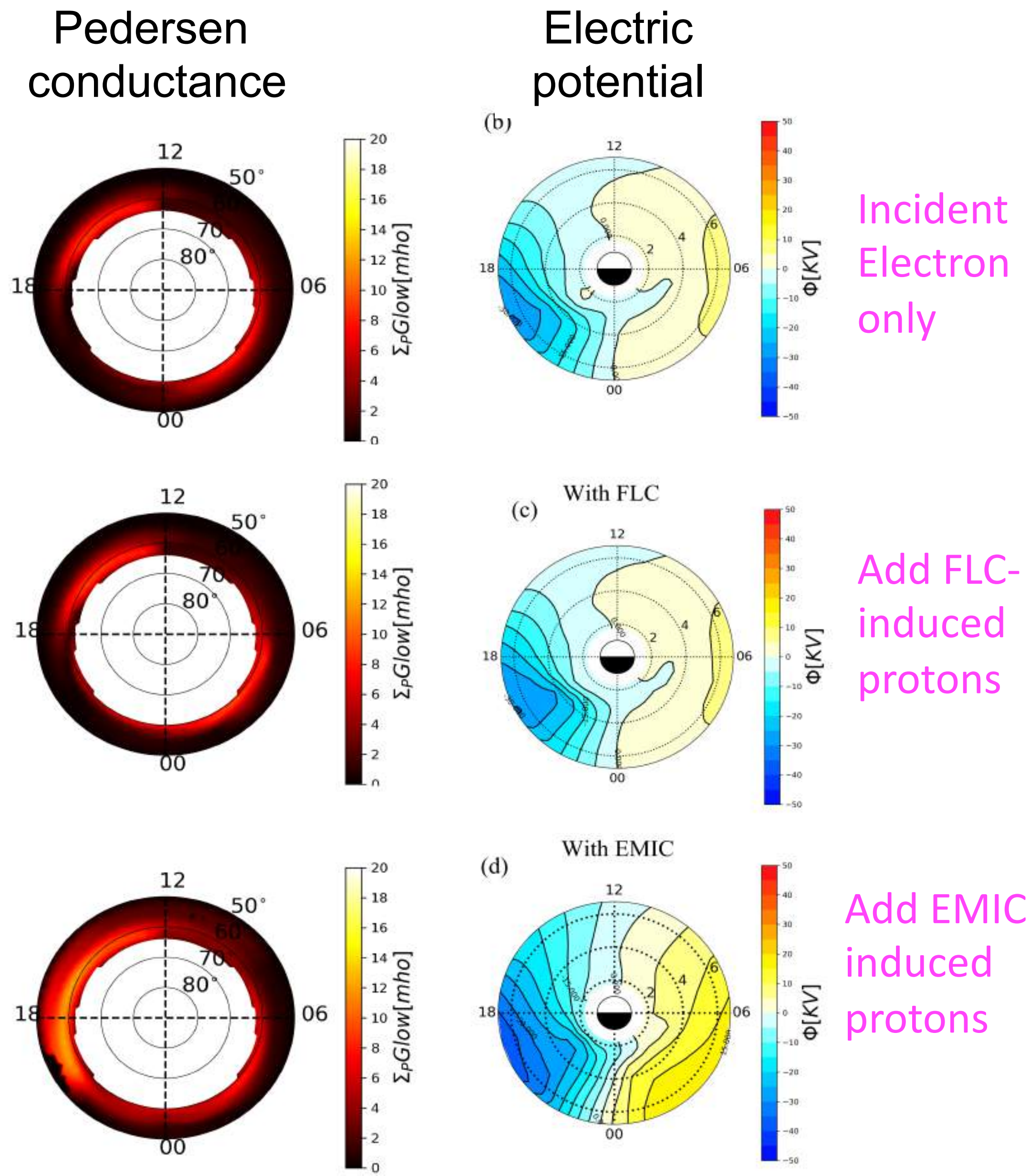
- Contribution of FLC-induced proton precipitation mainly appears in the midnight E/F regions, but is minor as opposed to electrons'
- EMIC wave-induced proton precipitation mainly contribute to the dusk E/F regions' conductivity, which provides remarkable enhancement from electrons' impact

- The latter changes the electrodynamics in the dusk sector since the integrated conductance is considerably changed (see discussion later).



Ionosphere conductance

1. With the incident electron precipitation only, the Pedersen conductance is mostly enhanced in the midnight-to-dawn sector and the noon-to-dusk sector
2. When the FLC-associated precipitating protons are taken into account, the conductance is barely changed. The electric potential remains nearly the same
3. However, when EMIC-associated proton precipitation is included, the conductance is remarkably enhanced in the dusk-to-midnight sector. The electric potential is hence altered, which further influence the particle dynamics in the magnetosphere



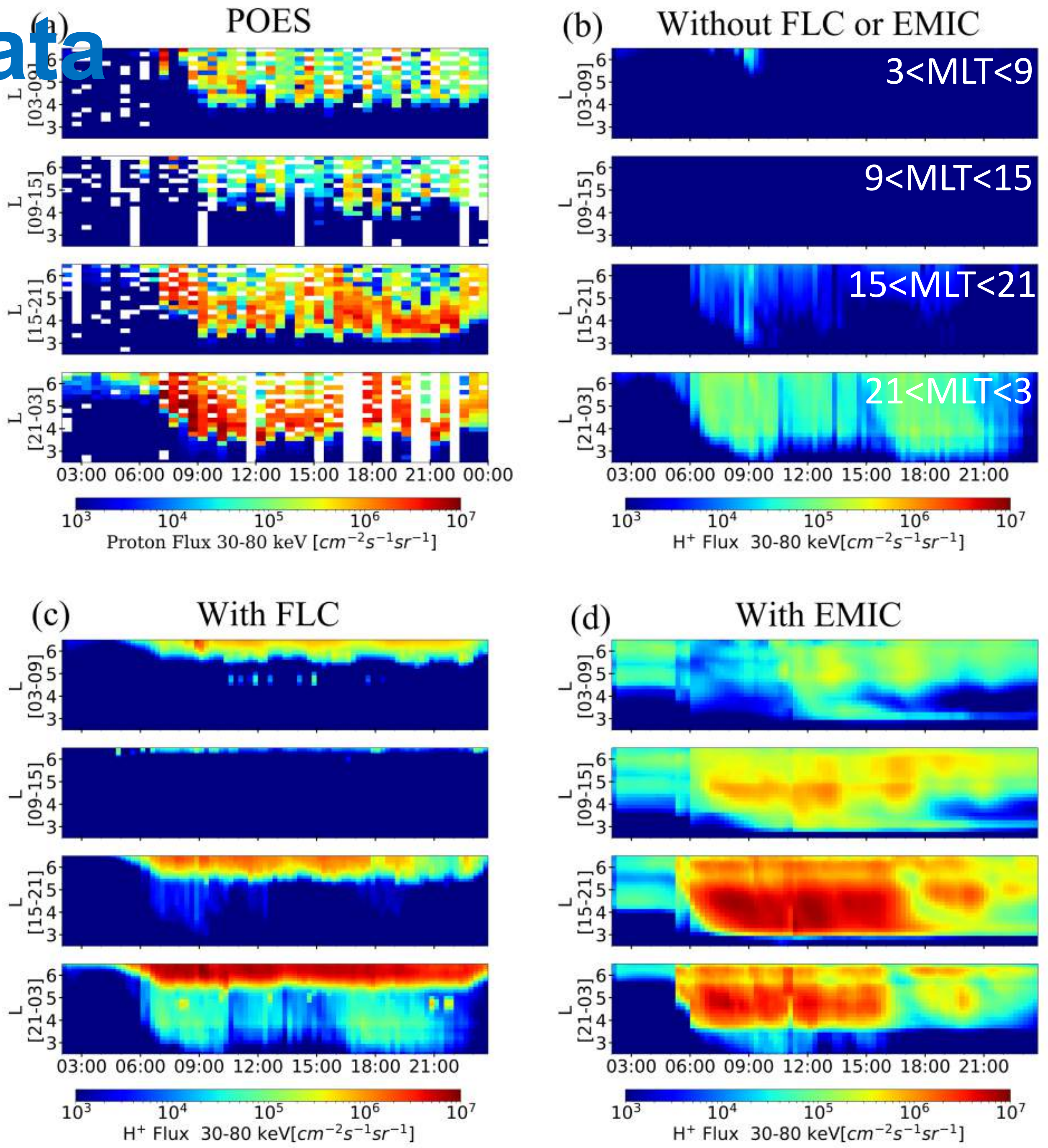
Comparisons to POES data

a. POES observations show that precipitating proton flux dominates the dusk and midnight sectors

b. In the simulation, the adiabatic precipitating loss of 30-80 keV protons (loss cones are widened while particles move towards the Earth) cannot account for the observations.

c. When FLC scattering is included, precipitating proton flux of 30-80 keV is significantly increased merely in the outer region (L>5.5) on the nightside.

d. When EMIC diffusion is included, substantial proton precipitation occurs in the dusk-to-midnight sector outside L>4, showing much better agreement with observations.



Summary

- Ring current particle precipitation due to several mechanisms is simulated, including (1) electron precipitation due to interactions with chorus and hiss waves, (2) proton precipitation due to interactions with EMIC waves and field line curvature (FLC) scattering process.
- Although the electron precipitation is predominant throughout the globe, it is found that proton precipitation is not negligible.
  - FLC scattering process mainly takes place on the nightside in the outer zone where magnetic field lines are stretched. Its associated proton precipitation cannot fully account for the POES observations.
  - EMIC wave diffusion process causes significant precipitation of tens of keV protons, particularly in the dusk sector. This mechanism roughly captures the features in data.
  - Ionospheric conductivity is largely altered due to EMIC-induced precipitating protons, which further changes the ionospheric electrodynamics that in turn feedback on the magnetospheric dynamics.

Thank you for your attention!