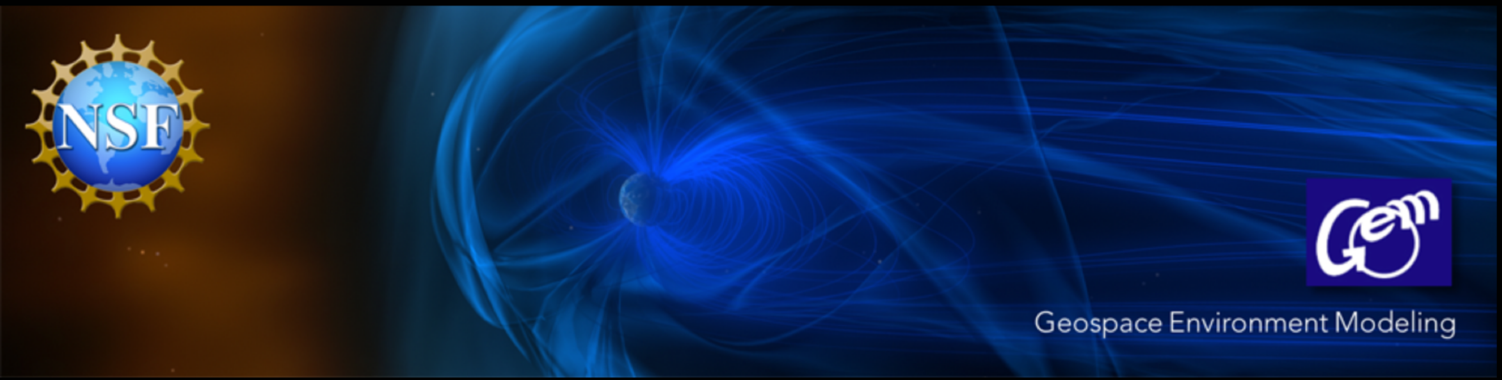


2019 GEM MIC Tutorial

Inner Magnetospheric Waves and Their Impact on the Ionosphere

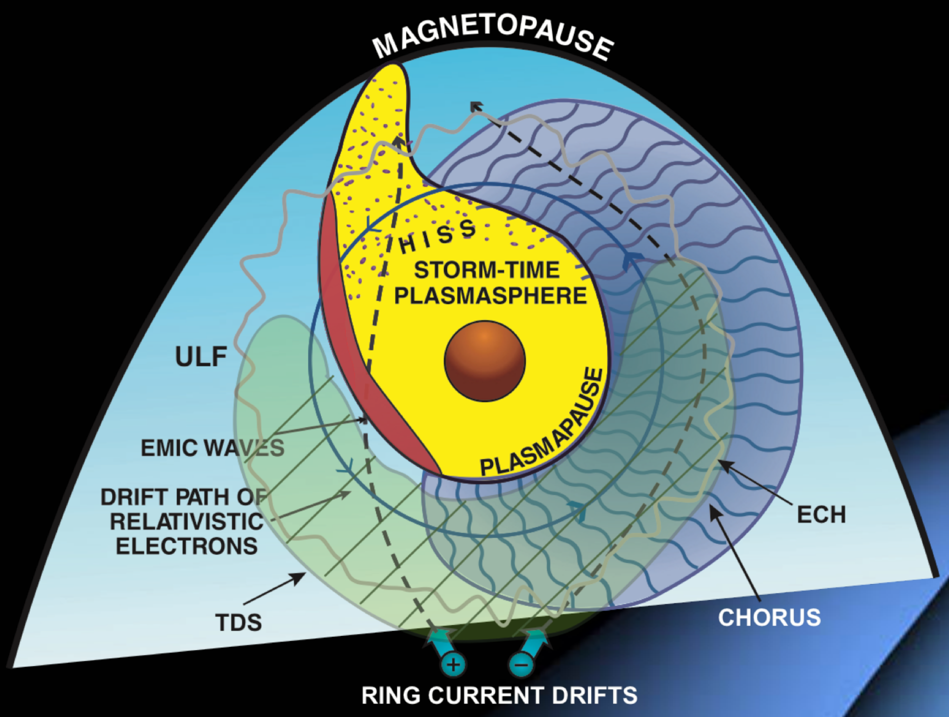
Wen Li (Boston University)

Acknowledgement:
Q. Ma, X.-C. Shen, Y. Nishimura, J. Bortnik, R. M. Thorne,
Van Allen Probes, THEMIS, POES, BARREL, and FIREBIRD team

GEM Summer Workshop, 24 June 2019

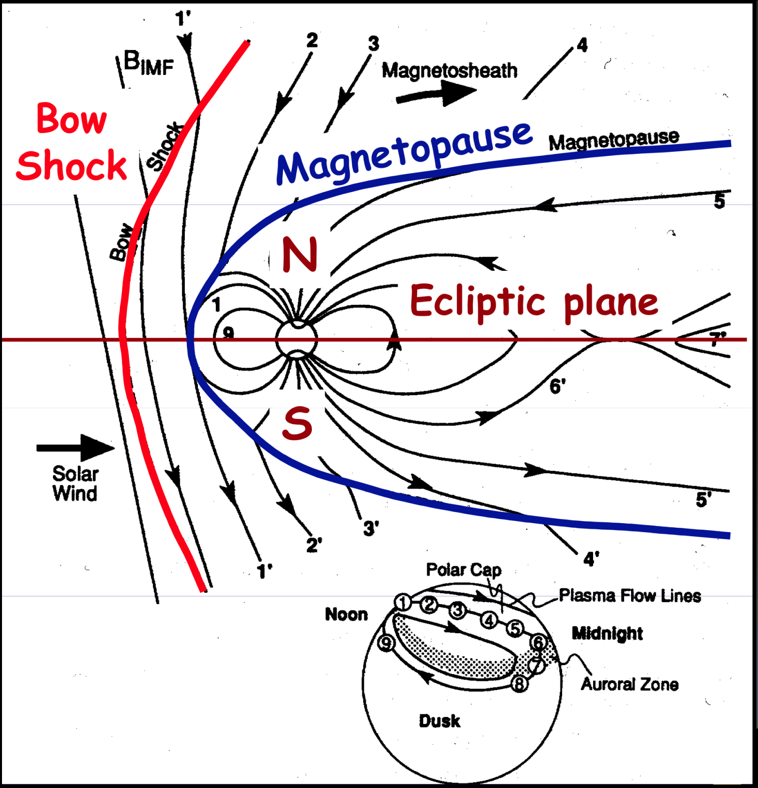
Outline

1. Introduction and Motivation
2. Inner Magnetospheric Waves
3. Wave Impact on the Ionosphere
   - Diffuse/pulsating aurora
   - Ionospheric conductivity
   - Atmospheric chemistry
4. Open Questions and Future Opportunities
5. Summary



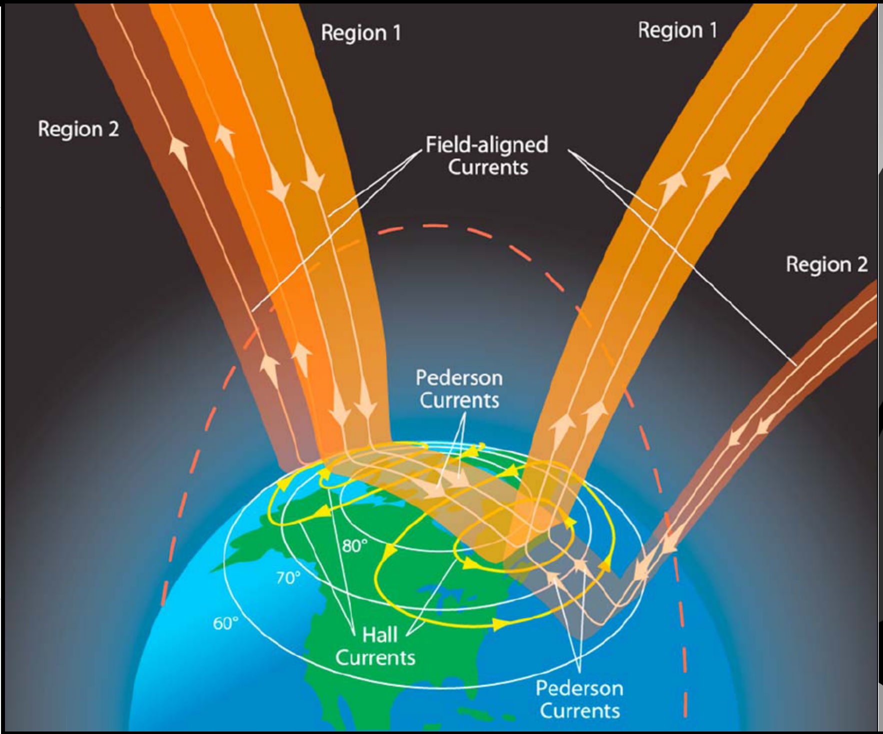
1. Introduction: Magnetosphere-Ionosphere Coupling

M-I Convection



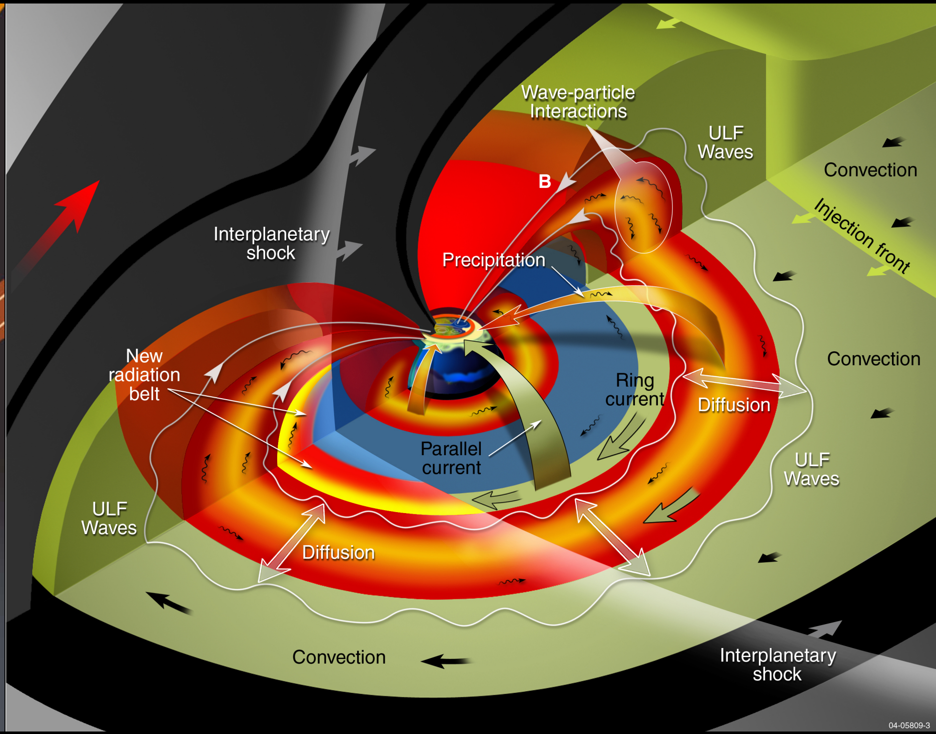
[Hughes 1995]

Large-Scale Currents



[Le+ 2010]

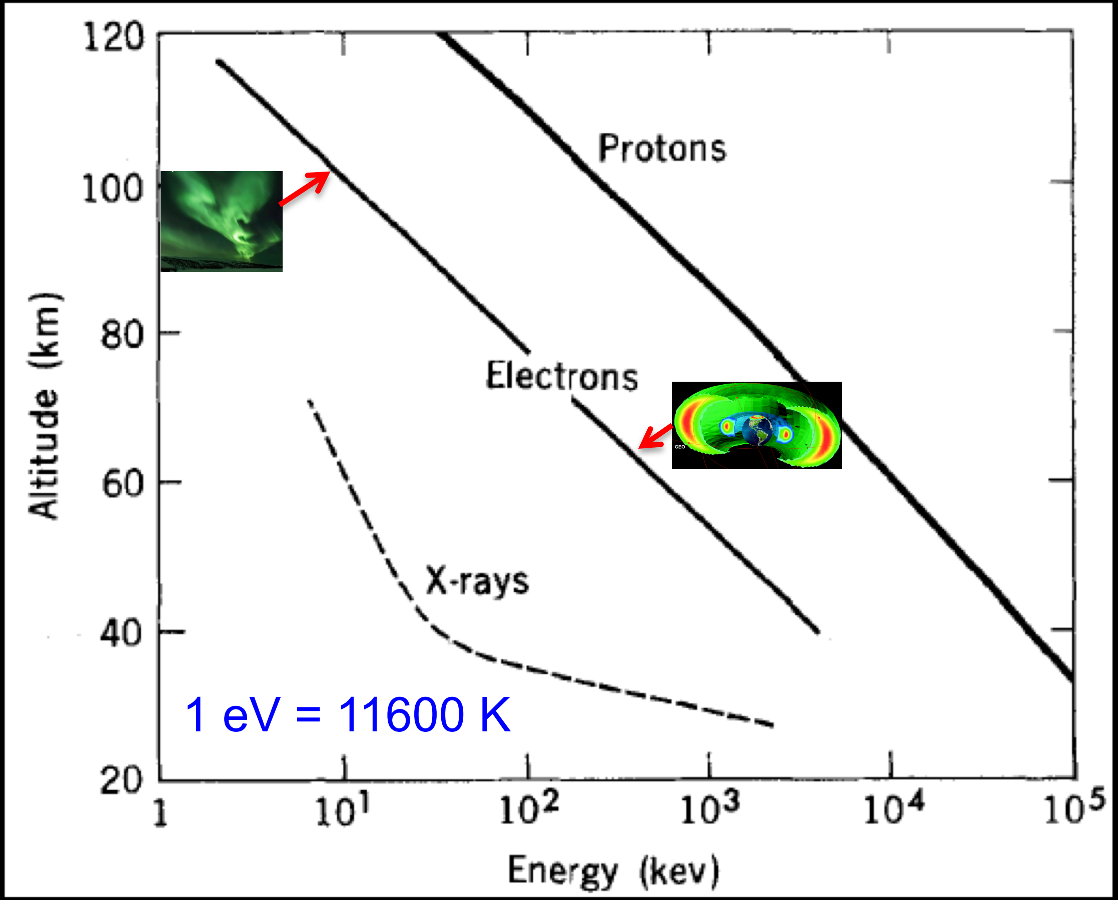
Particle Precipitation



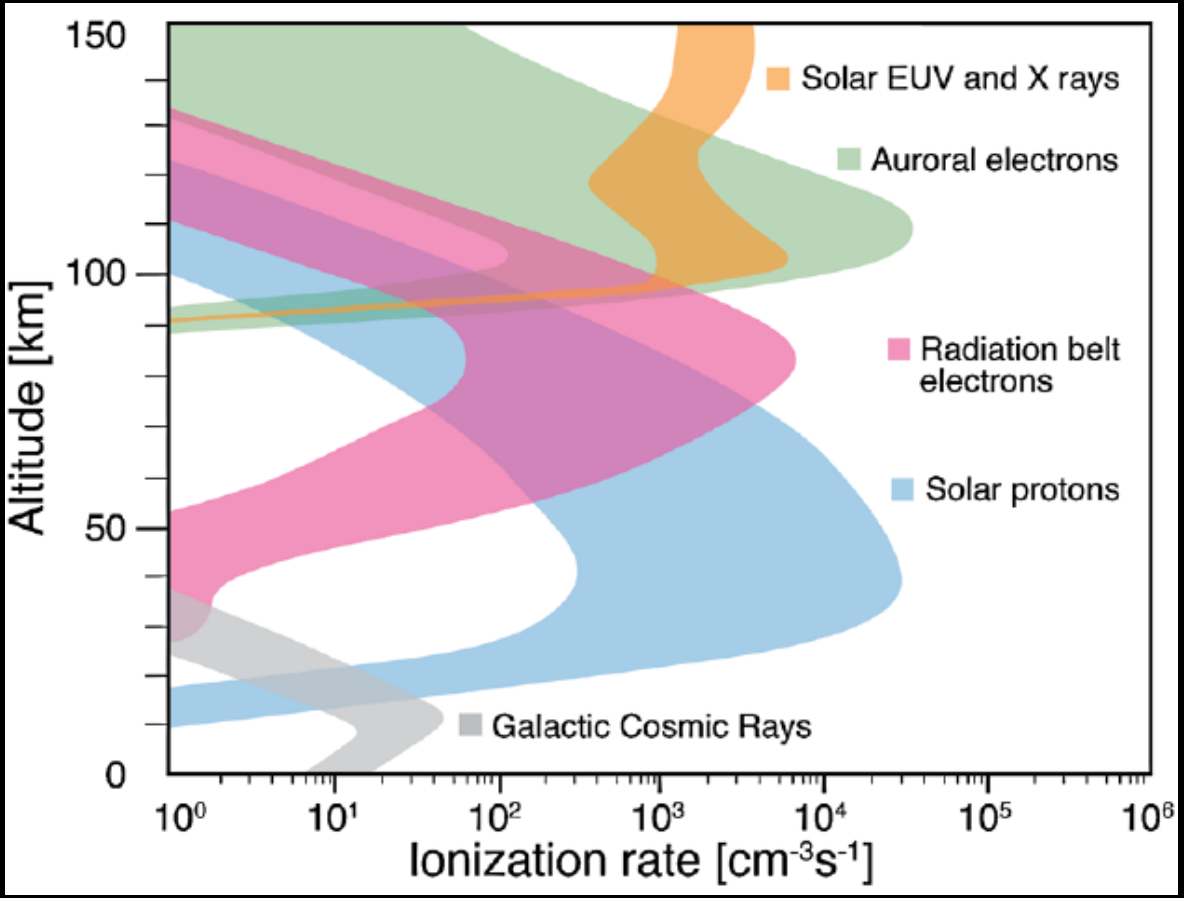
[Mauk+ 2013]

Inner magnetospheric waves → **Particle precipitation** → **Ionosphere**

Particle precipitation into upper atmosphere



[Thorne 1977]

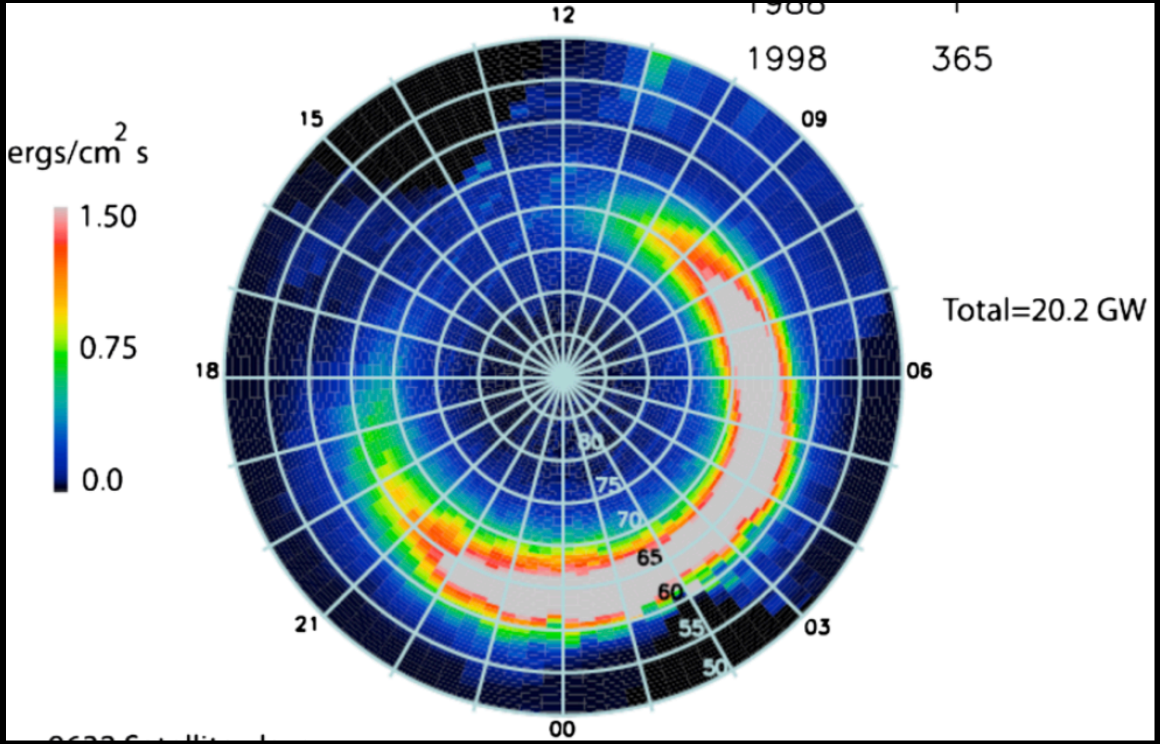


[Baker+ 2012; Mironova+ 2015]

- Energetic particle precipitations (EPP) provide important ionization of the upper atmosphere.
- Auroral and radiation belt particle precipitations are closely relevant to inner magnetospheric waves.

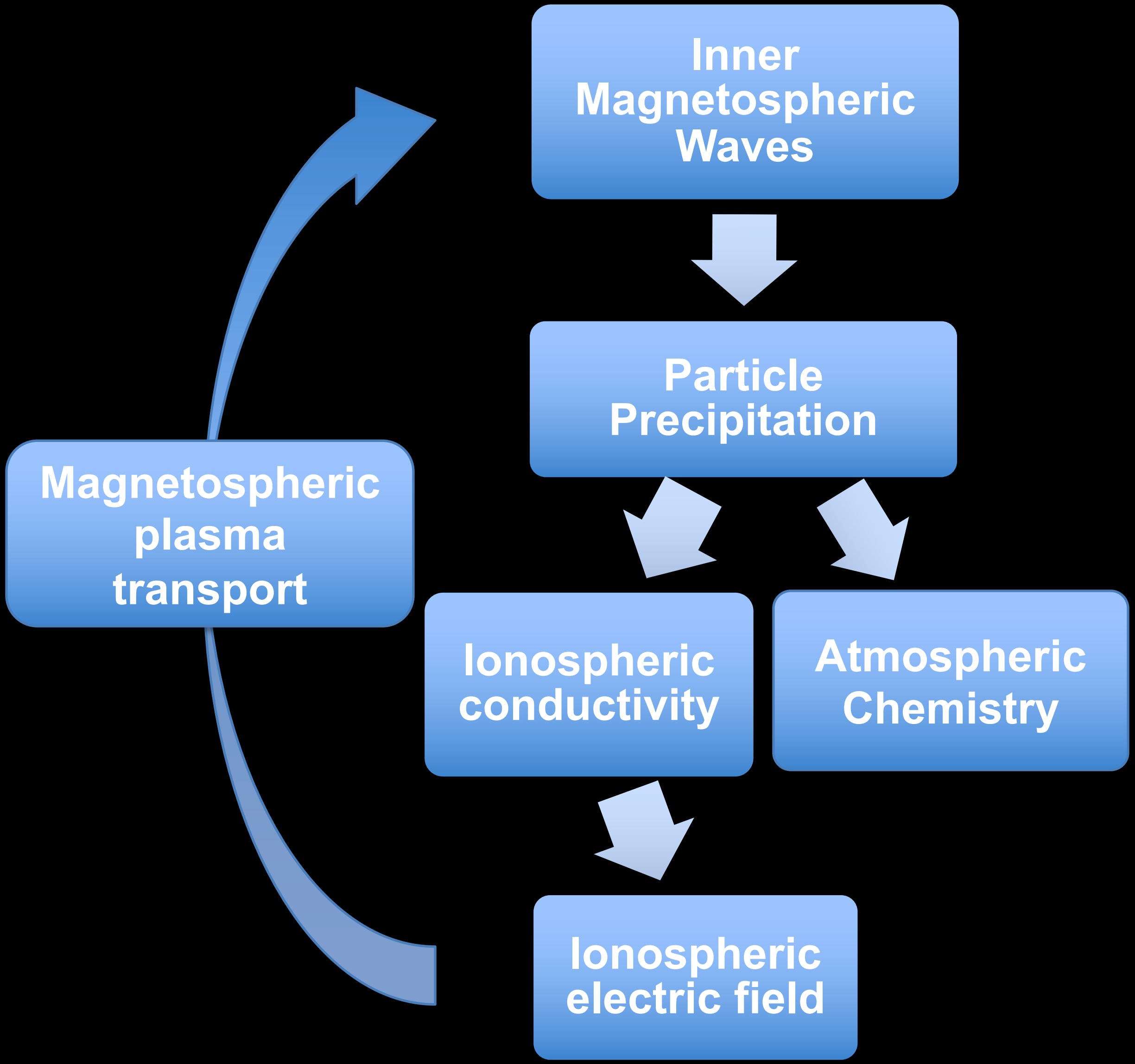
Wave-driven particle precipitation produces aurora

https://www.youtube.com/watch?v=ivL0b-jETrk



Diffuse aurora provides a major source of energy input (71–84%) into ionosphere [Newell+ 2009]

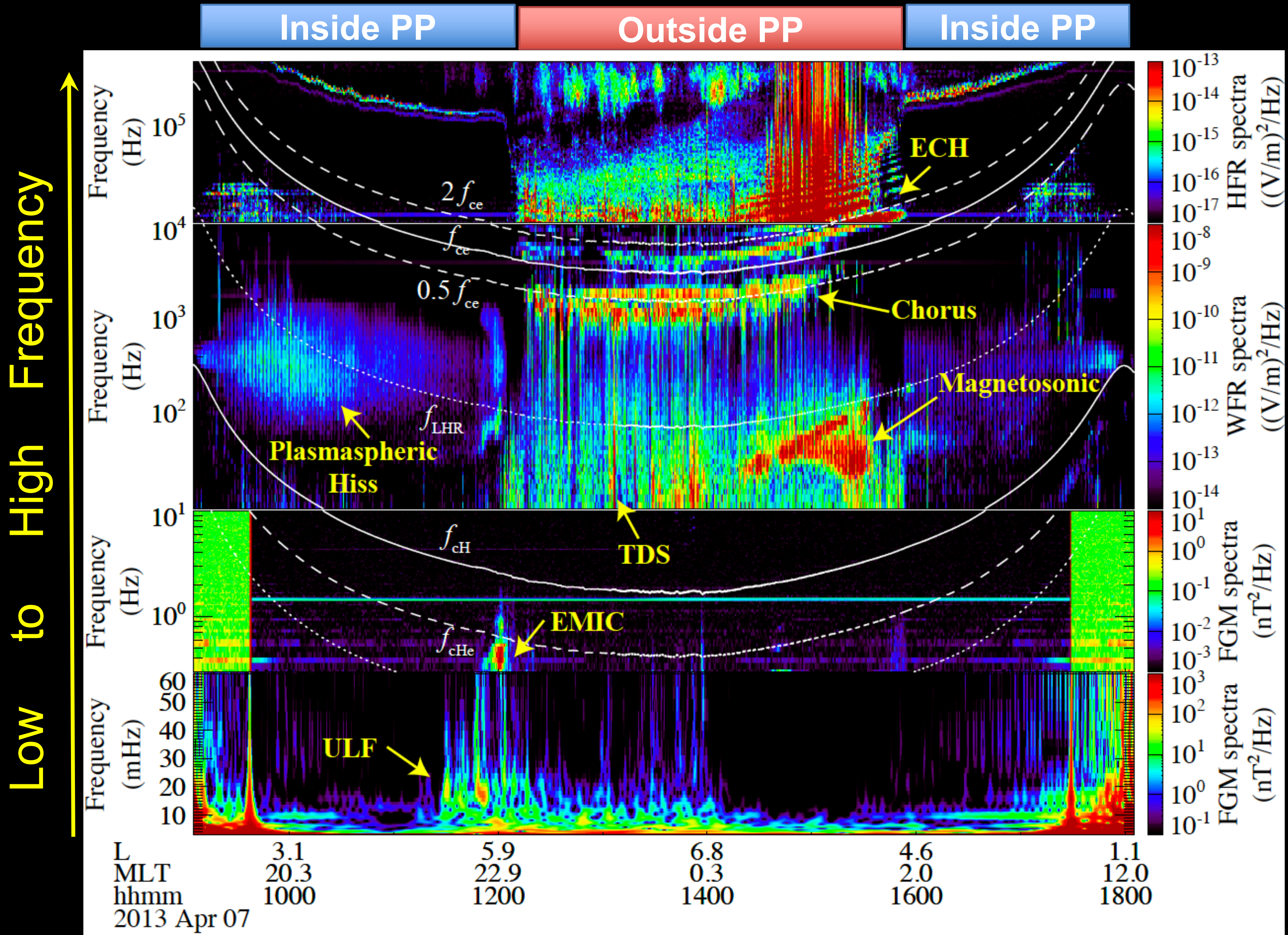
Why should the GEM-CEDAR community care about inner magnetospheric waves?

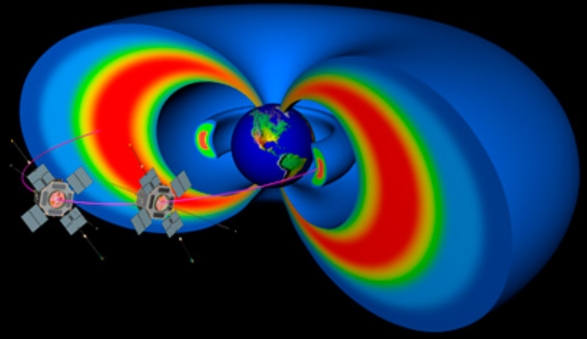


Objectives

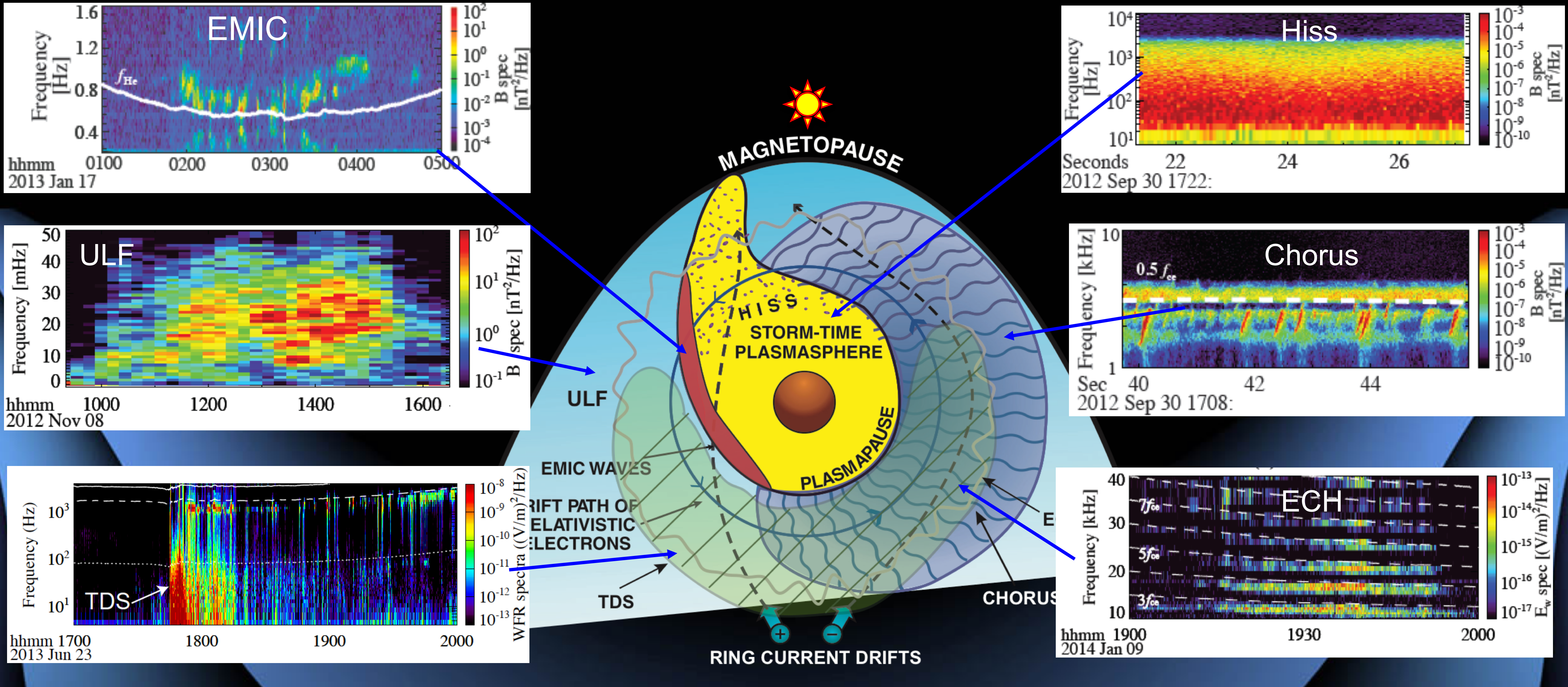
1. What are the typical properties of inner magnetospheric waves?
2. What are their roles in particle precipitation?
3. What is the quantitative impact of inner magnetospheric waves on the ionosphere?

2. Inner Magnetospheric Waves

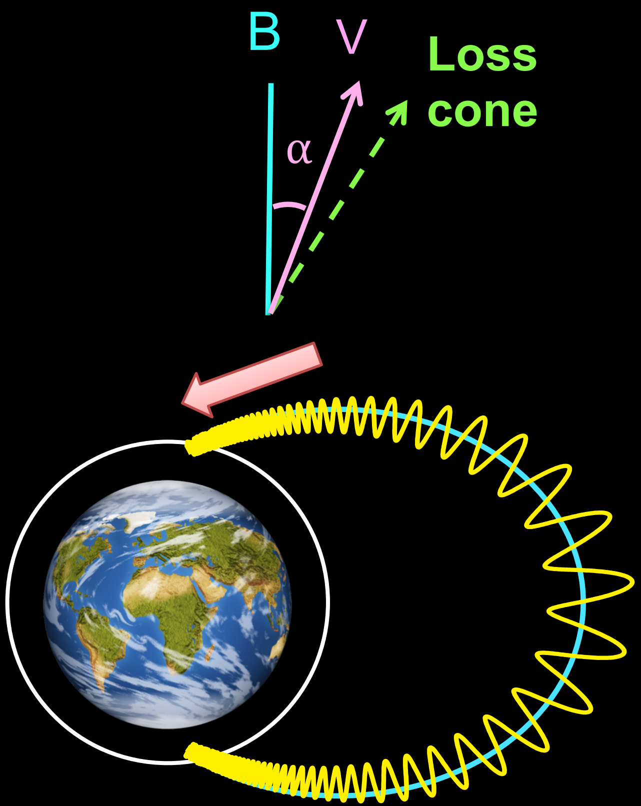




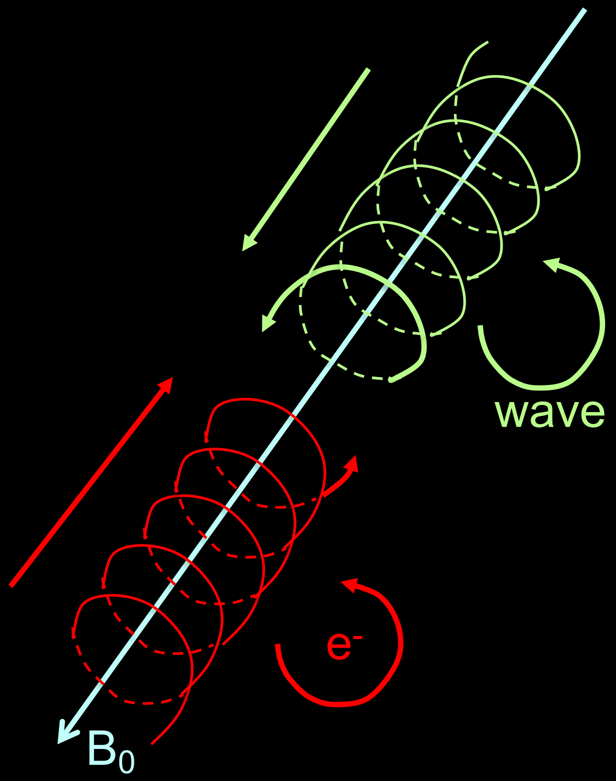
Inner Magnetospheric Waves Driving Particle Precipitation



How do particles precipitate into the upper atmosphere?



$\alpha < \alpha_{lc}$
Precipitate into the atmosphere



Resonance condition

$$\underbrace{\omega - k_{//}v_{//}}_{\text{Doppler-shifted wave frequency}} = \underbrace{n|\Omega|/\gamma}_{\text{Multiples of relativistic particle gyro-frequency}}$$

Doppler-shifted wave frequency

Multiples of relativistic particle gyro-frequency

[Credit: NASA]

[Kennel & Petschek 1966]

Dominant approach of quantifying particle precipitation

Quasilinear Diffusion Theory:

Effects of waves on particles are treated as diffusion

[Kennel & Engelmann 1966; Lyons+ 1972; Glauert & Horne 2005]

$$\boxed{\omega - k_{//} v_{//} = n|\Omega|/\gamma}$$

Local pitch angle diffusion coefficient:

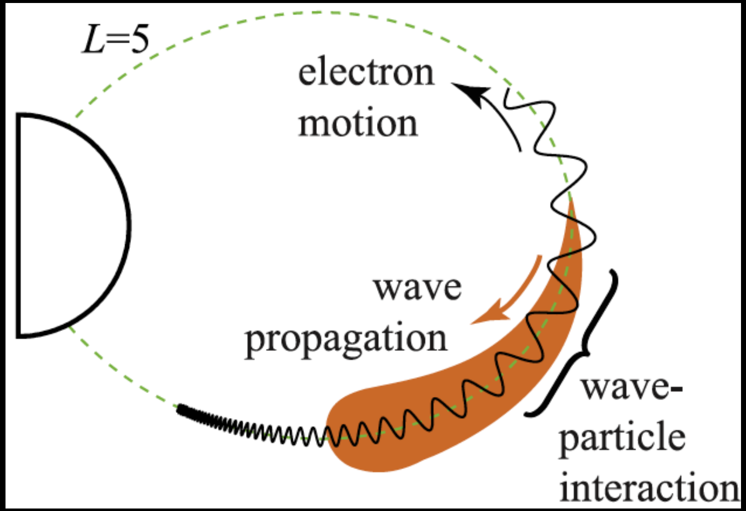
$$D_{\alpha\alpha} = <(\Delta\alpha)^2>/2\Delta t$$

Wave properties along the field line

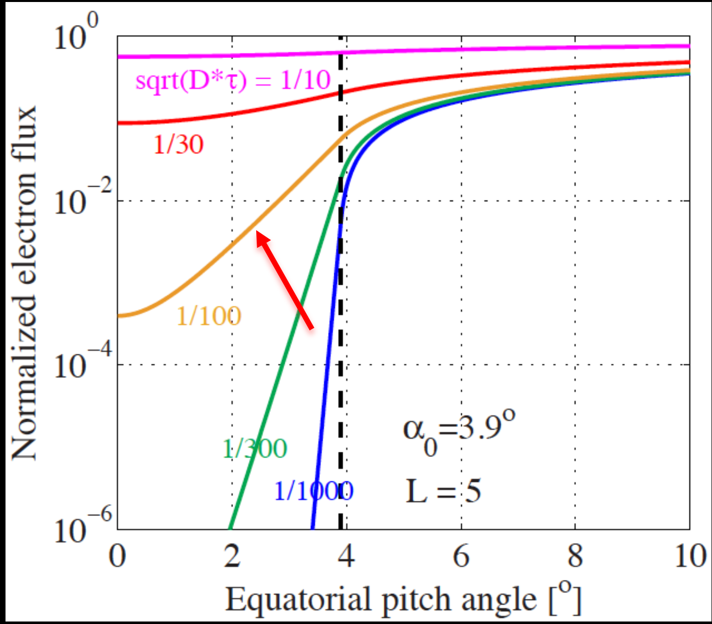
Plasma parameters along the field line

Bounce-averaged pitch angle diffusion coefficient

$$\langle D_{\alpha_{eq}\alpha_{eq}} \rangle = \frac{1}{T} \int_0^{\lambda_m} D_{\alpha\alpha} \frac{\cos\alpha}{\cos^2\alpha_{eq}} \cos^7\lambda d\lambda$$



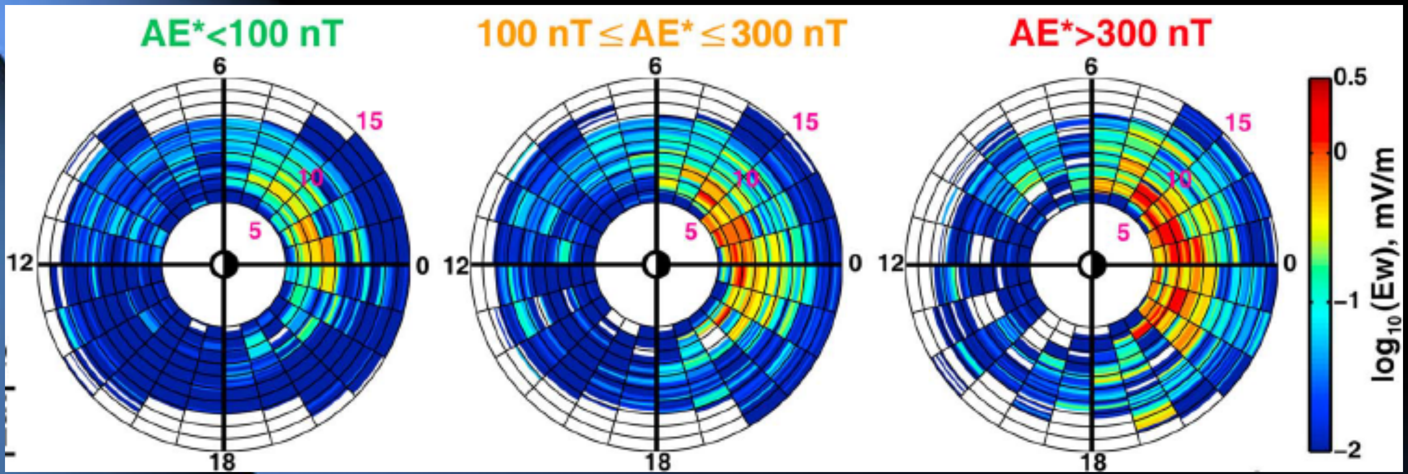
[Bortnik+ 2008]



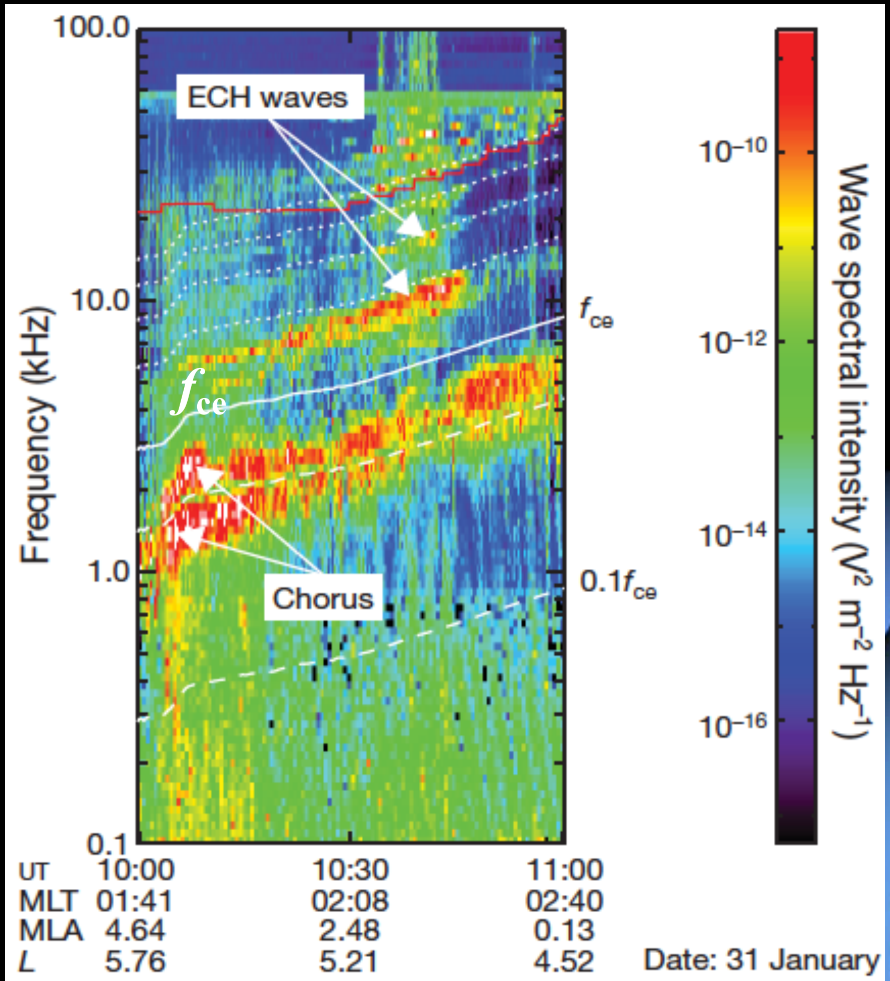
[W. Li+ 2013]

ECH waves: Typical properties

- Electrostatic Electron Cyclotron Harmonic waves (ECH): observed in bands between the different harmonics of f_{ce} [Kennel+ 1970; Meredith+ 2009].
- Typically observed near the magnetic equator outside the plasmapause over 2100–0600 MLT and up to L ~ 15; dependent on geomagnetic activity [Roeder & Koons 1989; Meredith+ 2009; Ni+ 2017].
- Generated by the loss cone instability of the ambient hot plasma sheet electron distribution [Ashour-Abdalla & Kennel 1978; Horne+ 2003; Zhang+ 2013].

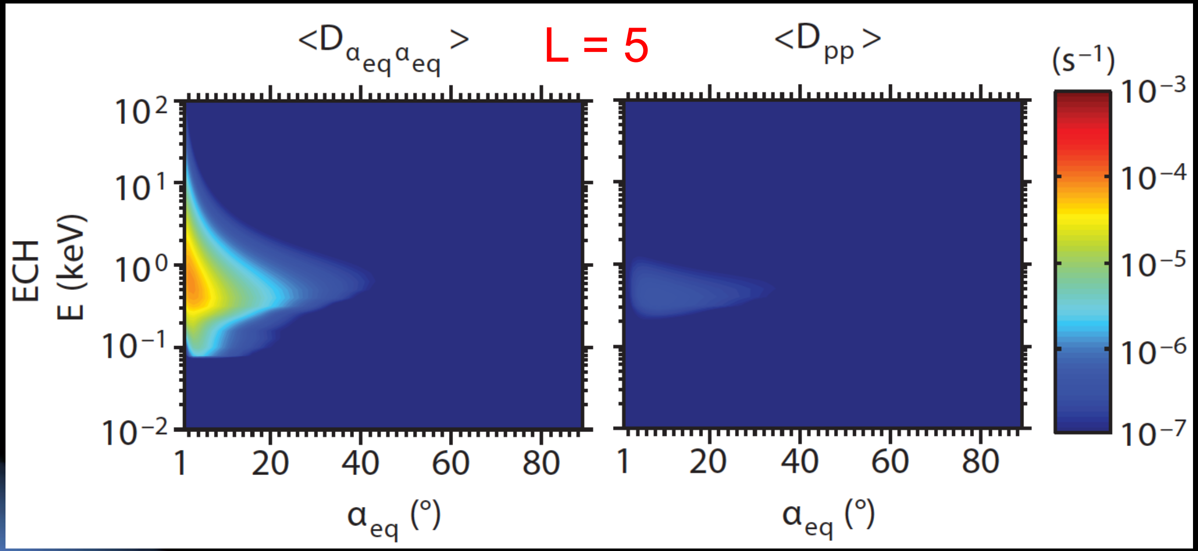


[Ni + 2017]



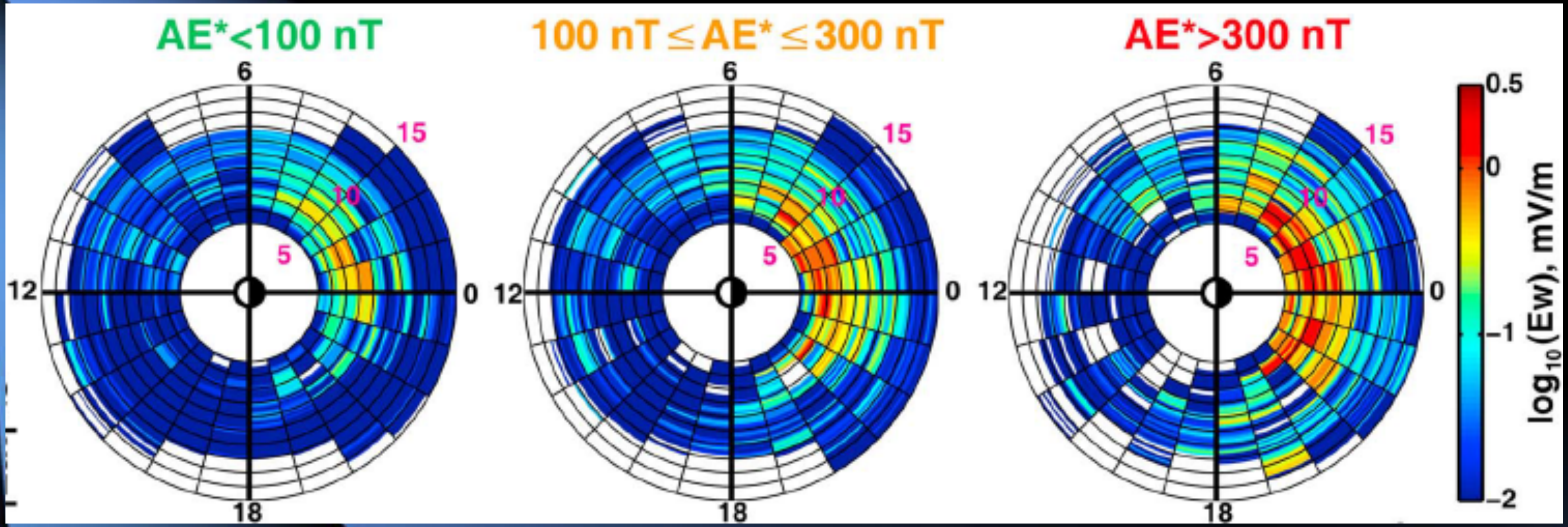
[Thorne+ 2010]

ECH waves: Effects on particle precipitation



[Thorne+ 2010]

ECH waves lead to rapid pitch angle scattering over a narrow range of pitch angle near the loss cone with energies **from ~100 eV to a few keV**.

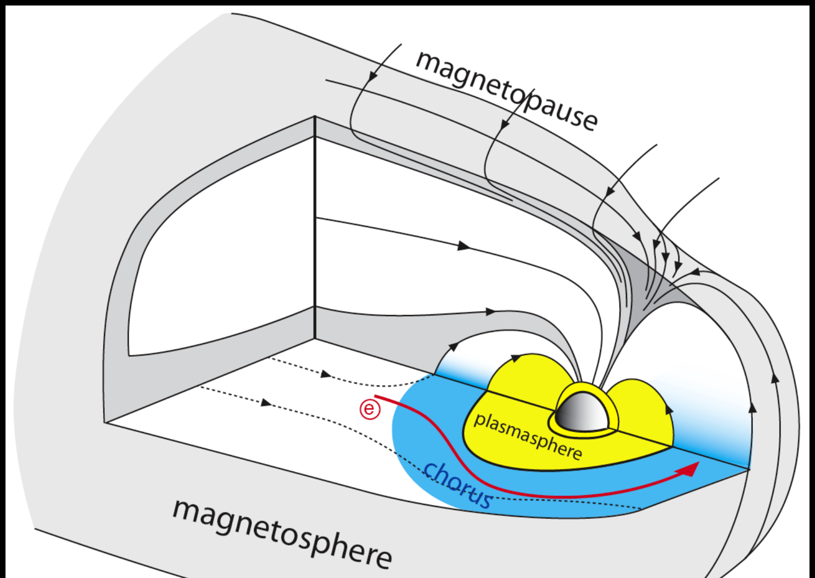


[Ni+ 2017]

ECH waves are suggested to be the dominant driver of the diffuse auroral electron precipitation at $L > 8$.

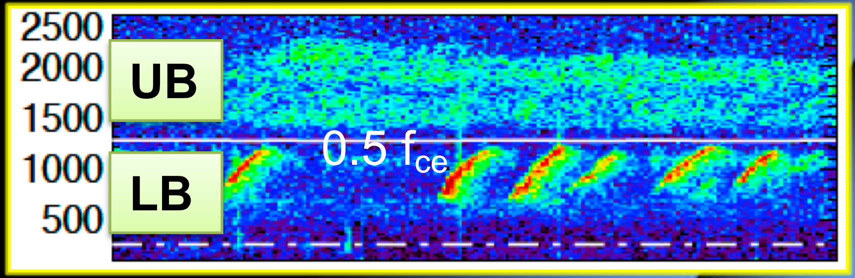
Chorus waves: Typical properties

- Frequency range of 0.1–0.8 f_{ce} with minimum wave power at 0.5 f_{ce} (lower-band and upper-band) [Tsurutani & Smith 1974; Burtis & Helliwell 1976]
- Consists of discrete rising/falling tones or hiss-like emissions [Santolik+ 2003; W. Li+ 2012]
- Generated through cyclotron resonance with anisotropic electrons (1–100 keV) injected from the plasmasheet [Kennel & Petschek 1966; W. Li+ 2008]
- Typically observed outside the plasmapause from premidnight to afternoon sector [Tsututani & Smith 1974; Meredith+ 2003, 2012; W. Li+ 2009; Agapitov+ 2018]

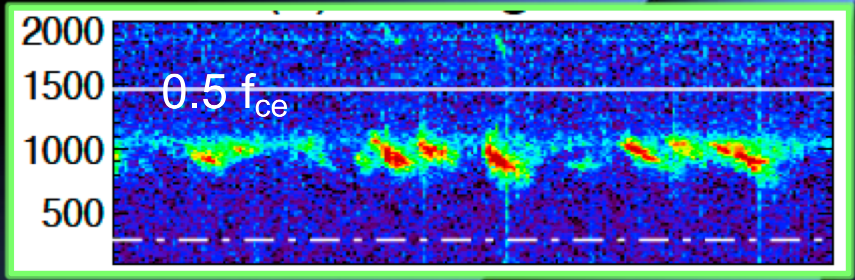


[W. Li+ 2009]

Rising tone



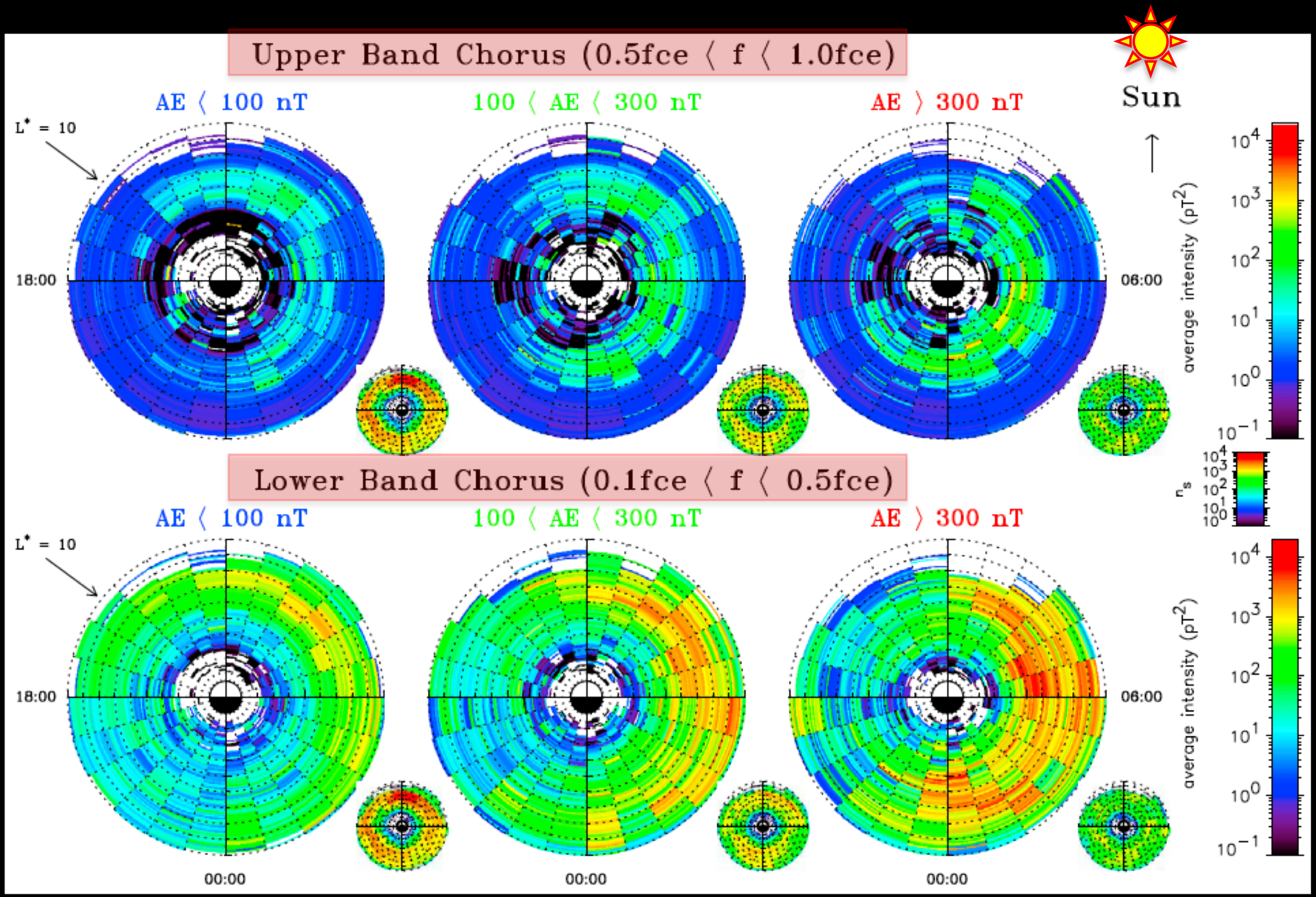
Falling tone



[W. Li+ 2012]

Chorus waves: Global distribution

|MLAT| < 15°

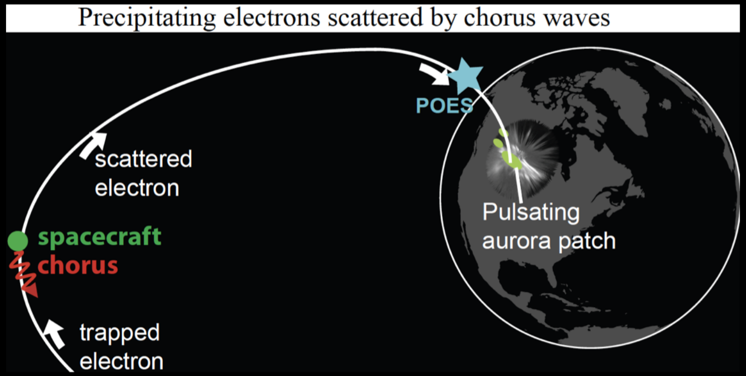


[Meredith+ 2012]

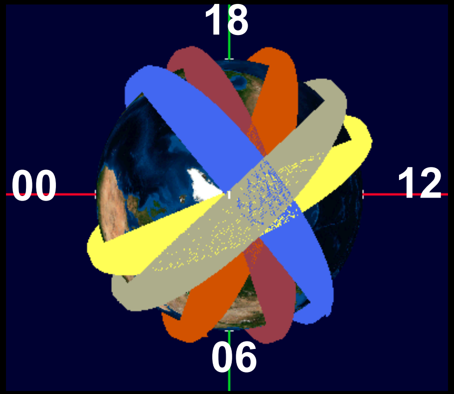
- ✧An important accelerator of radiation belt electrons [e.g., Horne+ 2005; Thorne+ 2013; Reeves+ 2013; Tu+ 2014; Ma+ 2018]
- ✧Cause pitch angle scattering of 1s–10s keV electrons, thus provide a major contribution to produce diffuse and pulsating aurora [Thorne+ 2010; Nishimura+ 2010; Khazanov+ 2014; Ni+ 2016]

✧Chorus wave intensity depends on geomagnetic activity.
✧LB is strongest during active times over 4 < *L < 9 and 23–12 MLT.**
✧UB is weaker than LB and limited to lower *L.**

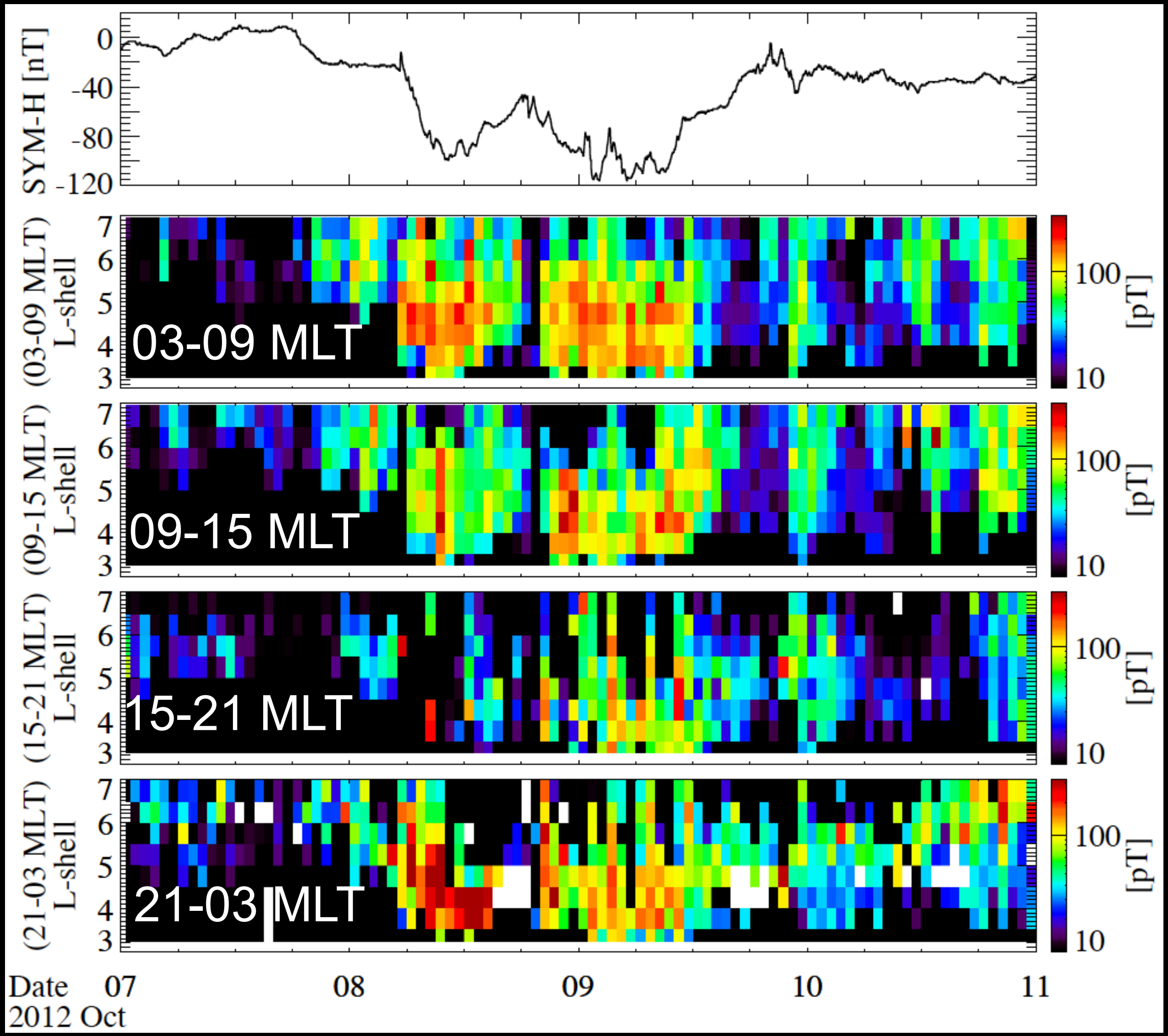
Electron precipitation used as proxy to construct global chorus wave evolution



Orbit of 5 POES spacecraft



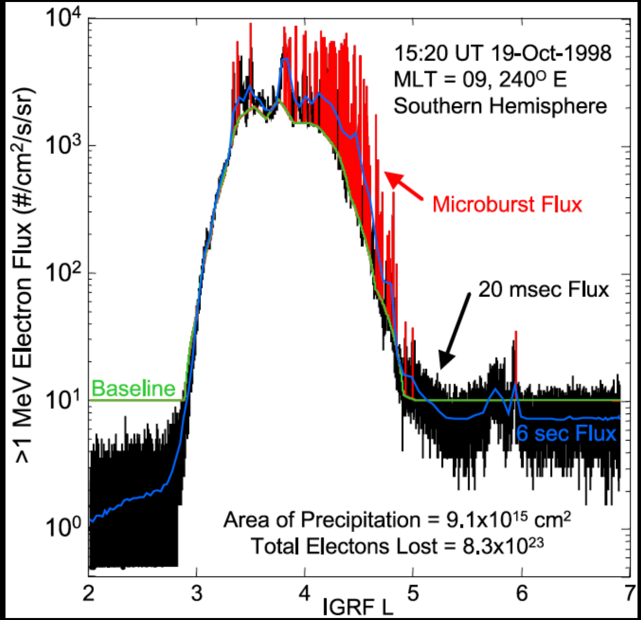
Advantage:
Multiple POES provide event-specific chorus evolution on a global scale



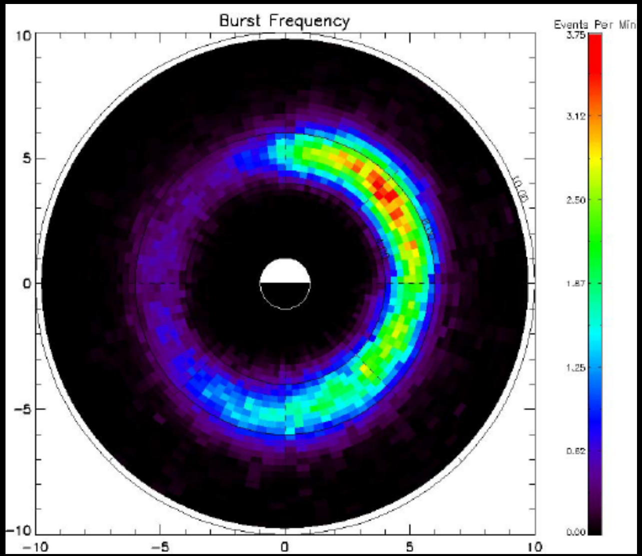
[W. Li+ 2013]

Bursty chorus & Microbursts

Short (~100 ms) bursts of precipitation

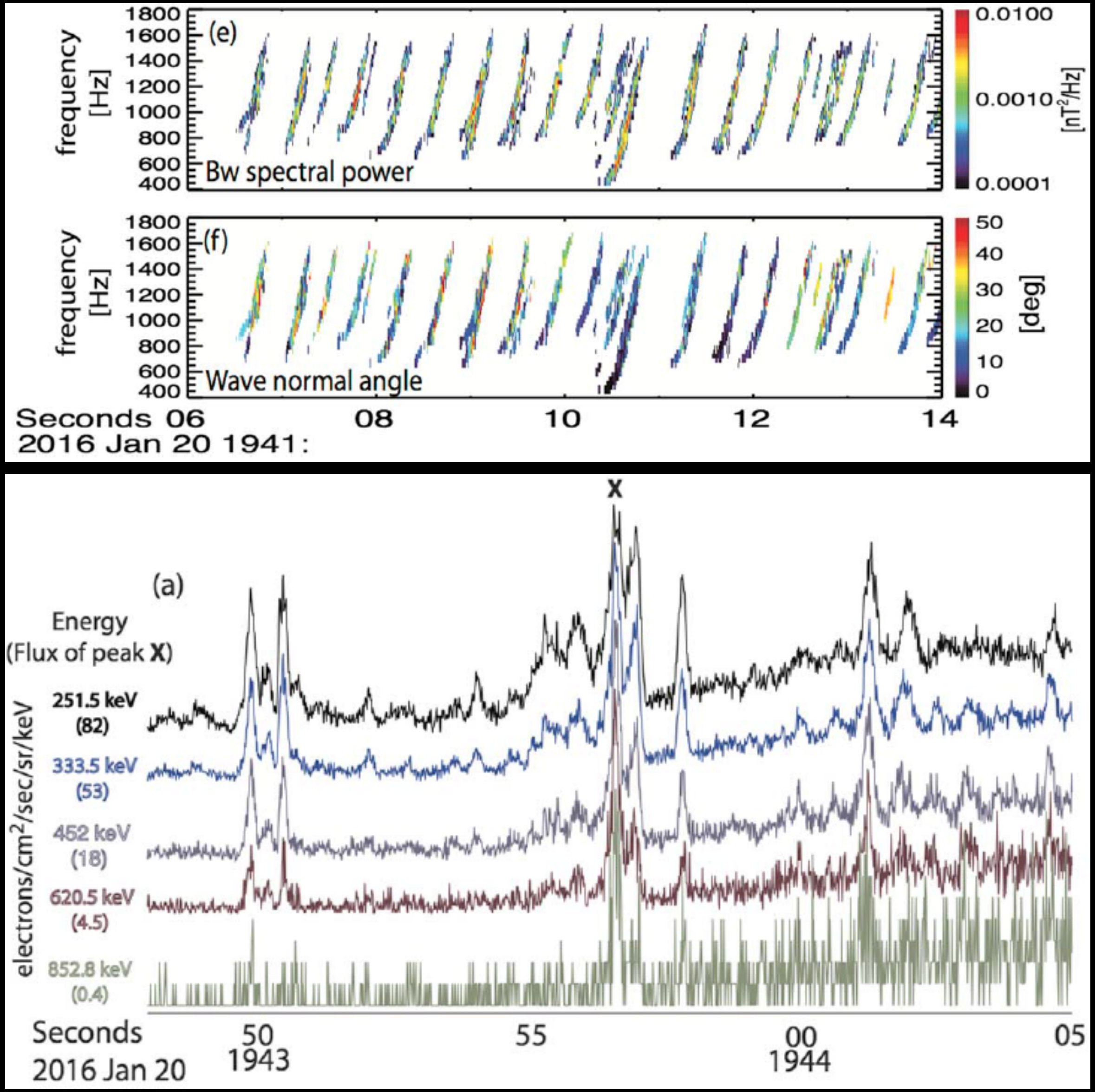


[O'Brien+ 2004]



Typically occur
- L shell: 4–6
- MLT: 22–12 hr

[Crew 2013]



[Breneman+ 2017]

Bursty chorus & Microbursts

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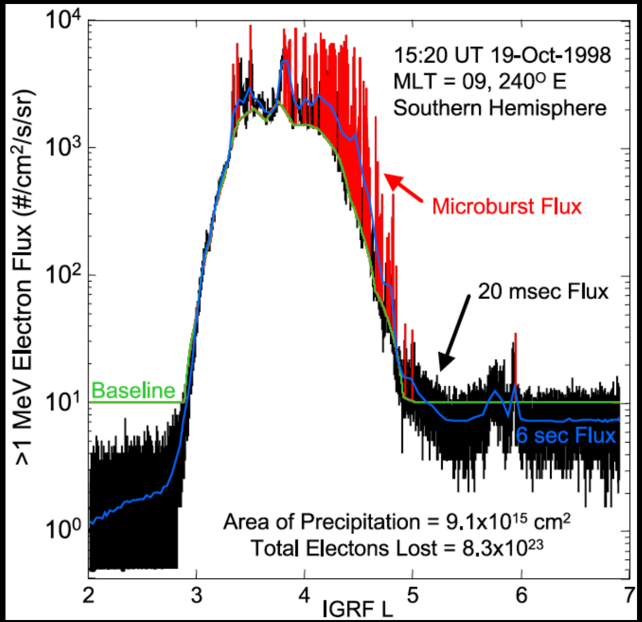
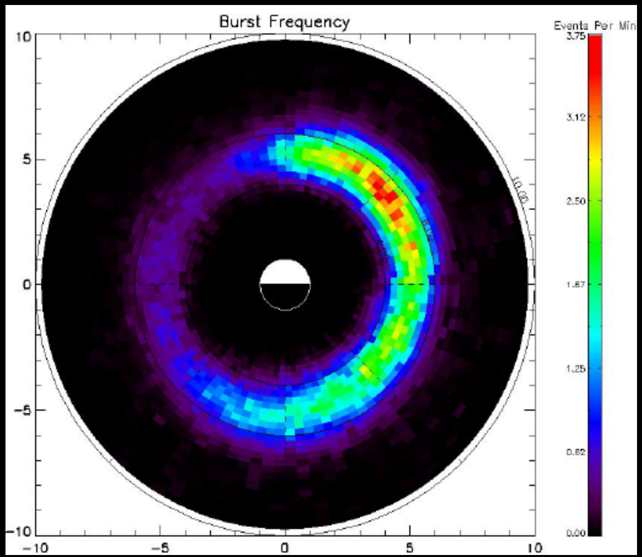


[O'Brien+ 2004]



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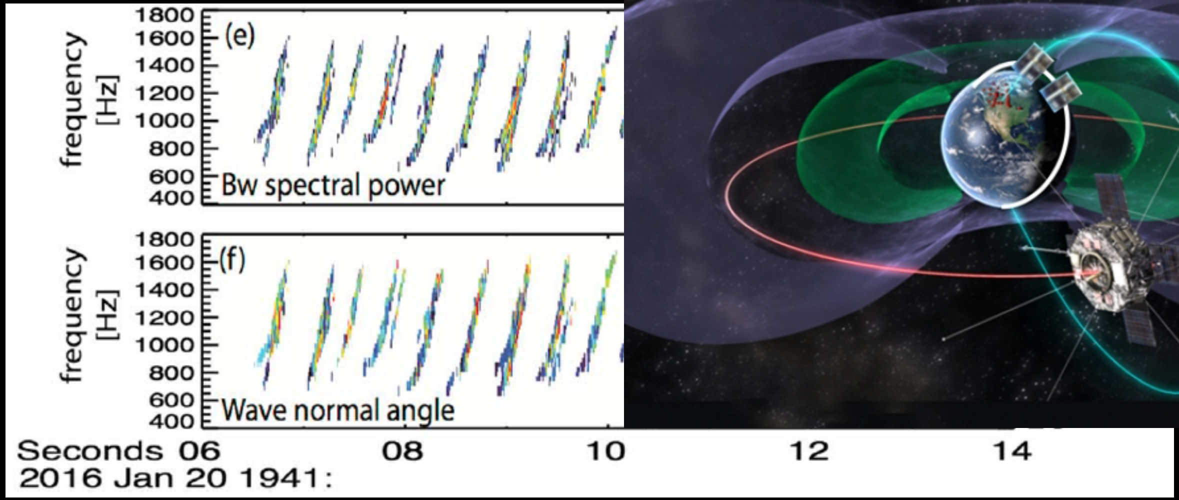
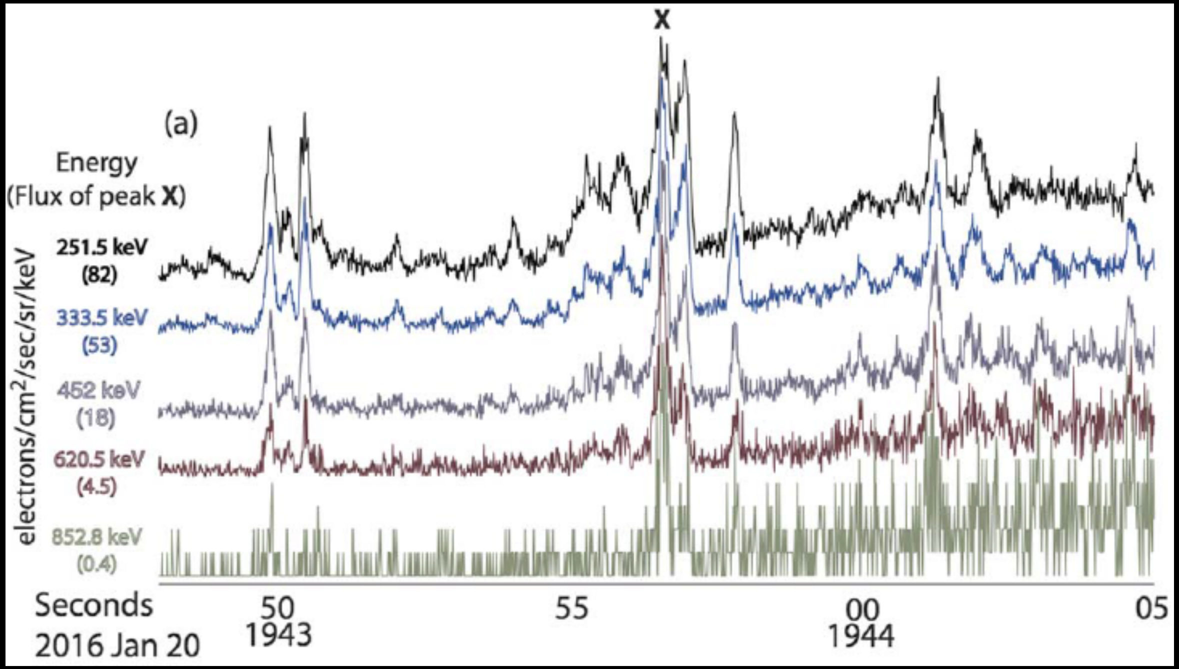
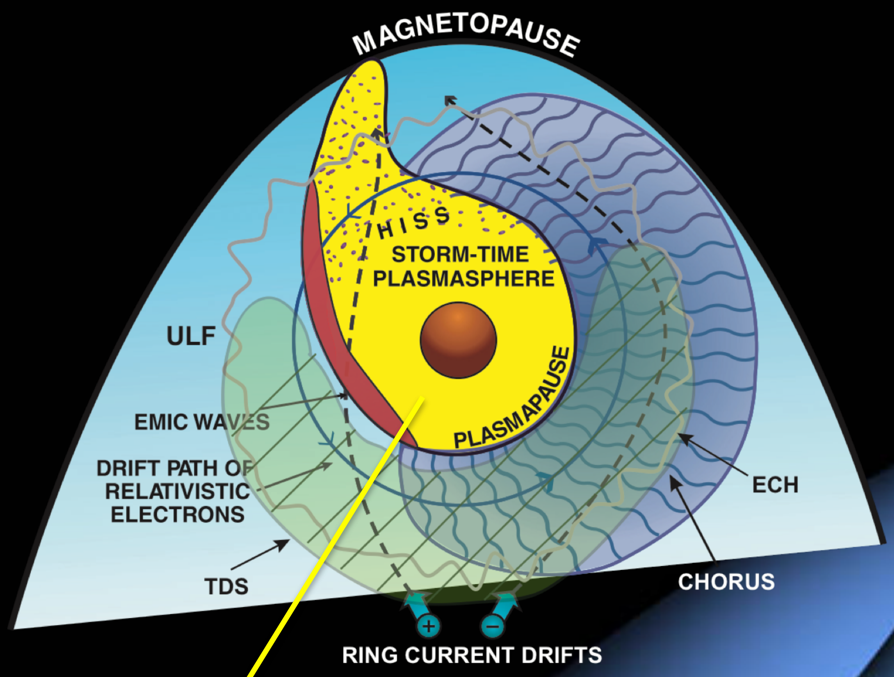


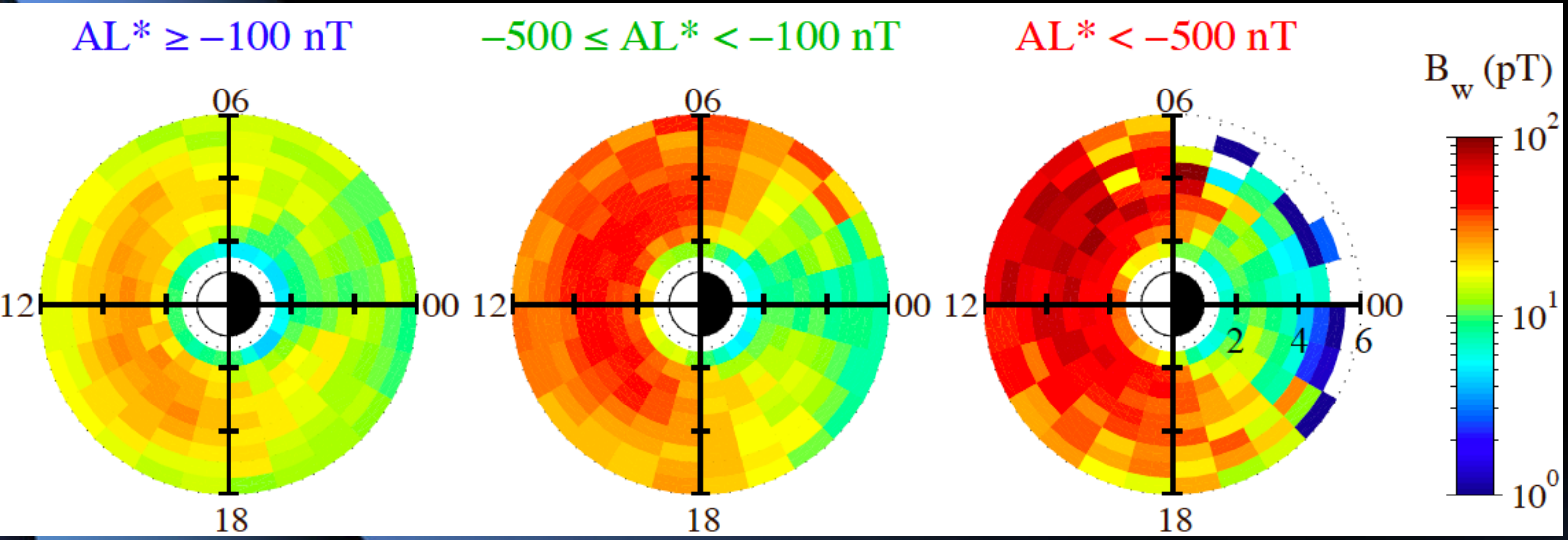


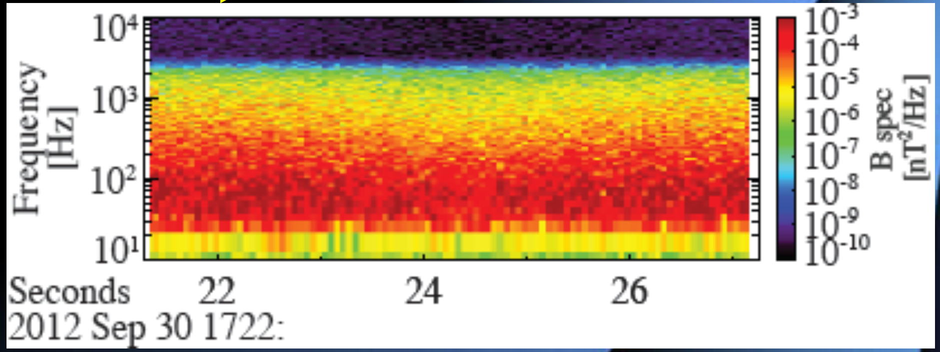
[Breneman+ 2017]

Plasmaspheric hiss: Typical properties

- Incoherent, broadband whistler-mode emission (20 Hz–2 kHz) [Thorne+ 1973; Meredith+ 2004; Bortnik+ 2008; W. Li+ 2015; Malaspina+ 2016]
- Observed in the high-density region inside the plasmasphere or plumes
- Hiss B_w is activity dependent; stronger on the dayside than that on the nightside [Meredith+ 2004; W. Li+ 2015; Malaspina+ 2016]







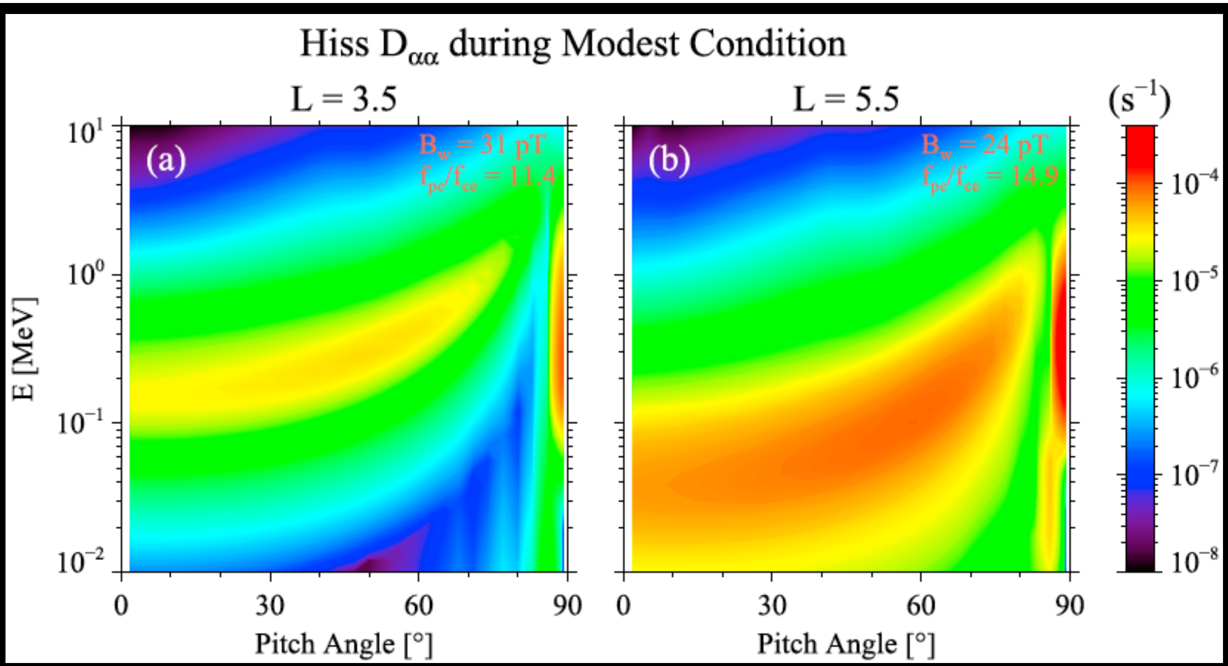
[W. Li+ 2015]

AL*: the minimum AL in preceding 3 hours

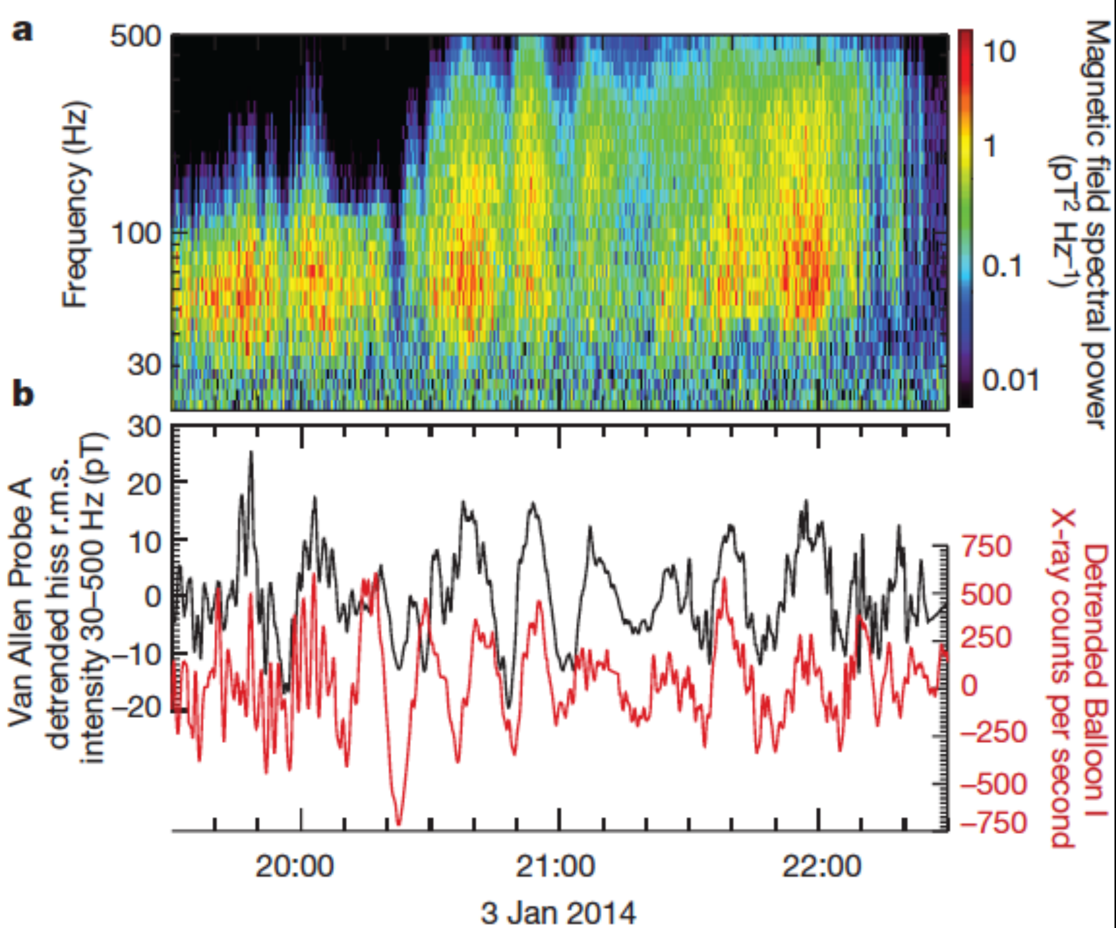
[W. Li+ 2013]

Plasmaspheric hiss: Effects on electron precipitation

- Hiss typically causes precipitation of energetic electrons over 10s–100s keV, but usually is not as efficient as chorus.
- Inside the plasmasphere hiss plays an important role in precipitation loss of electrons through pitch angle scattering [Lyons & Thorne 1973; Meredith+ 2006; Ma+ 2016; Ripoll+ 2017].



[Ma+ 2016]



[Breneman+ 2015]

Hiss intensities are well correlated with X-ray counts from BARREL, suggesting energetic electron precipitation driven by hiss.

Plasmaspheric hiss: Effects on electron precipitation

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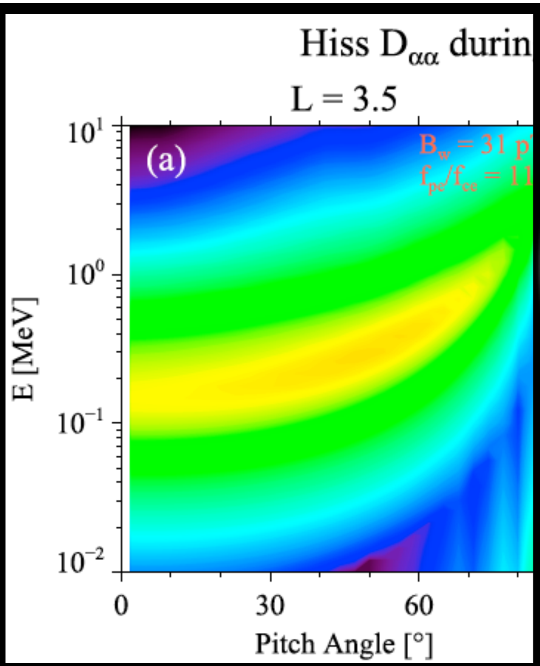
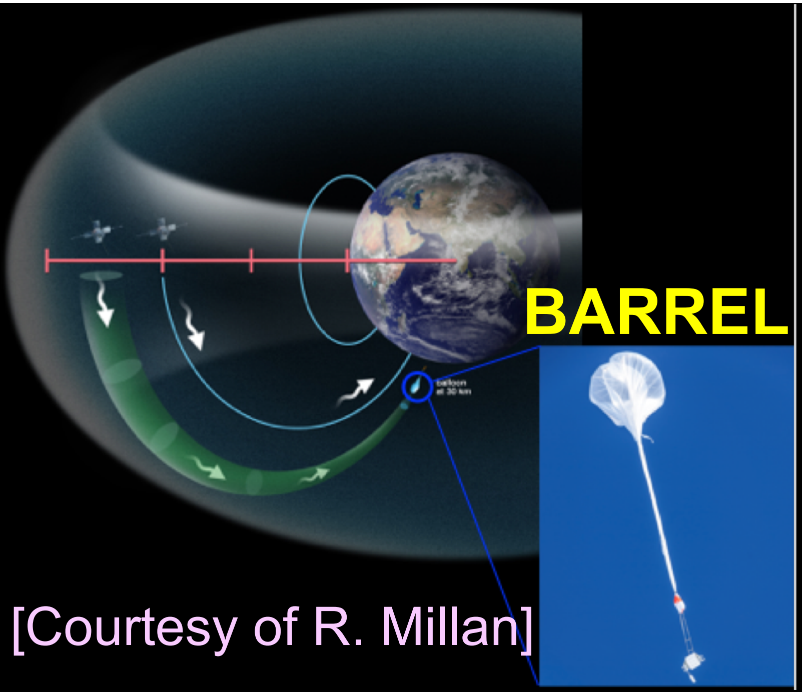
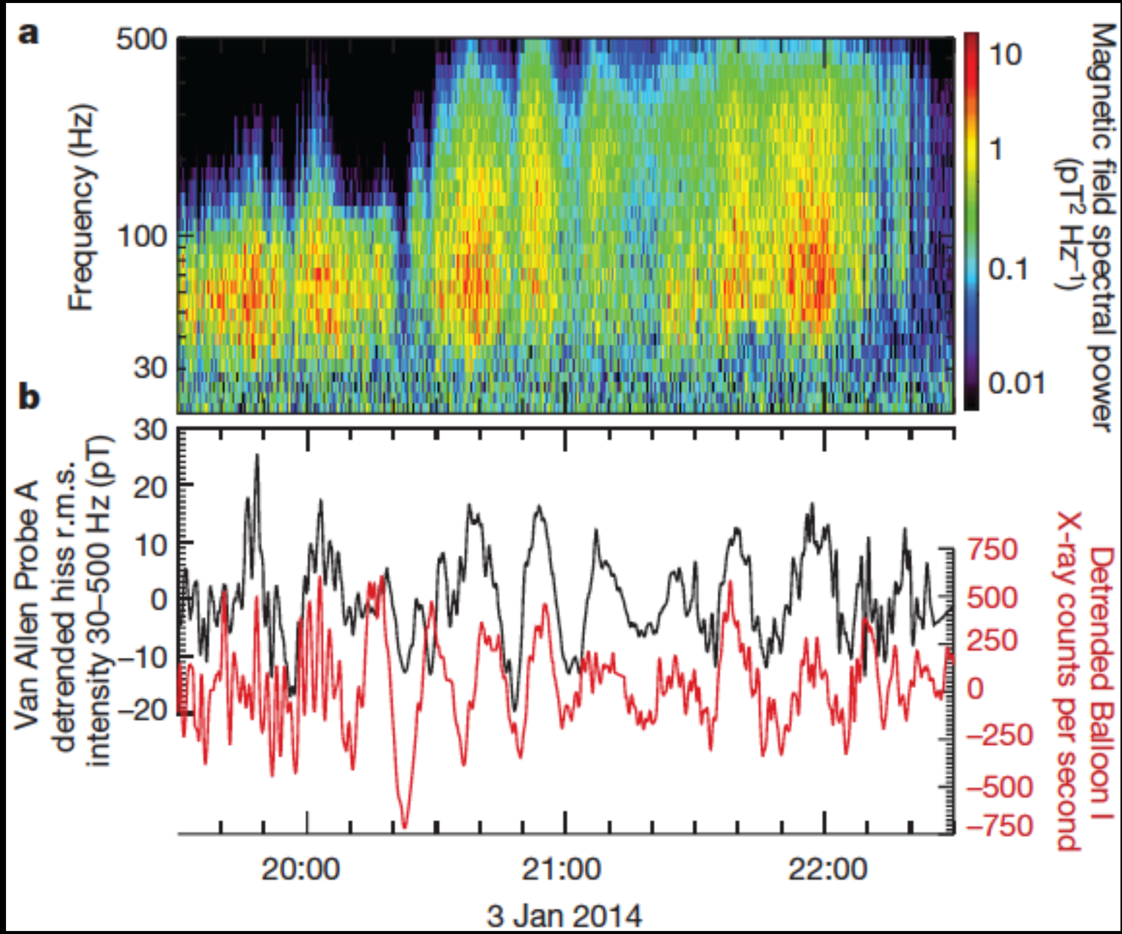


[Ma+ 2016]



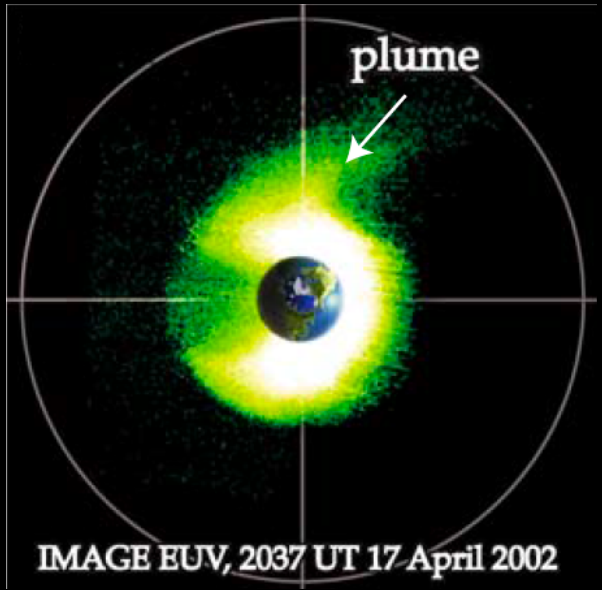
[Courtesy of R. Millan]



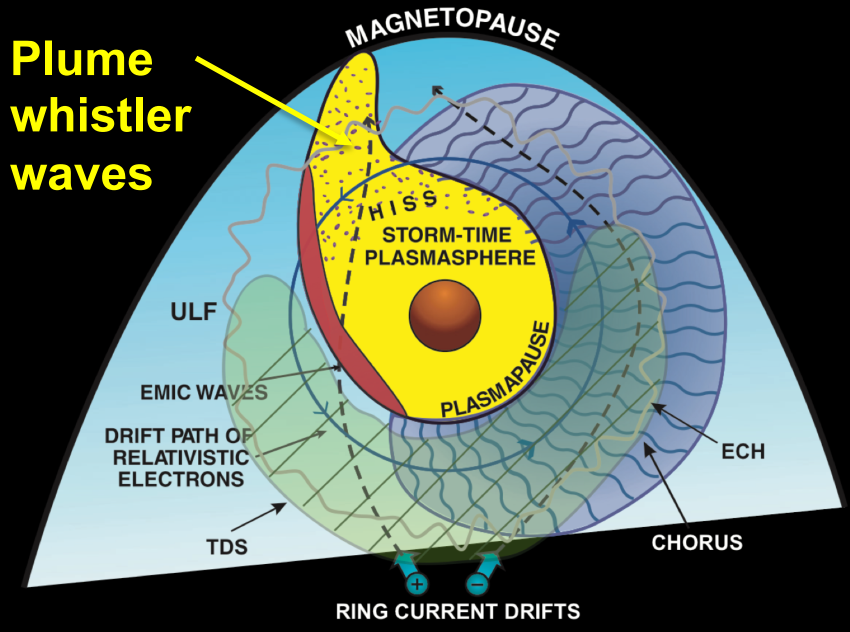
[Breneman+ 2015]

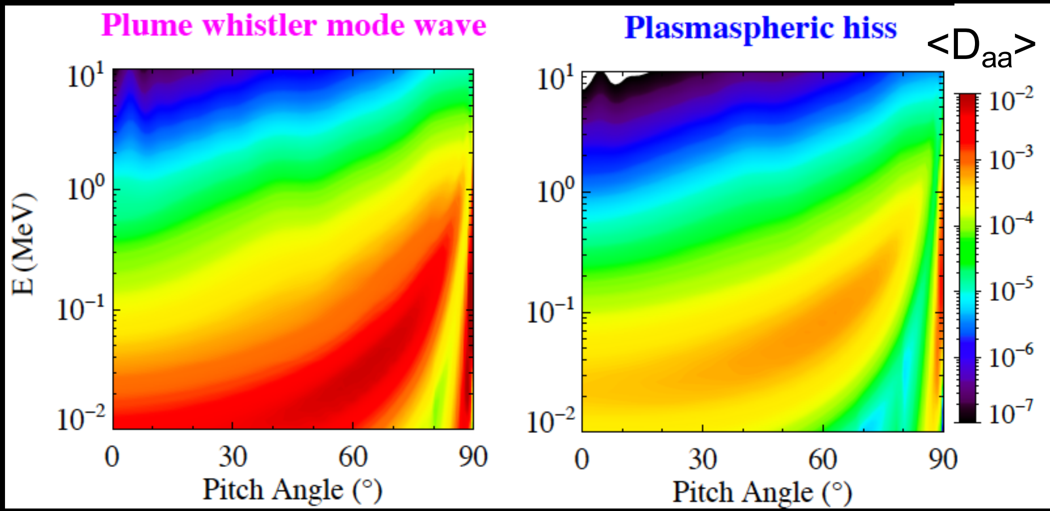
Hiss intensities are well correlated with X-ray counts from BARREL, suggesting energetic electron precipitation driven by hiss.

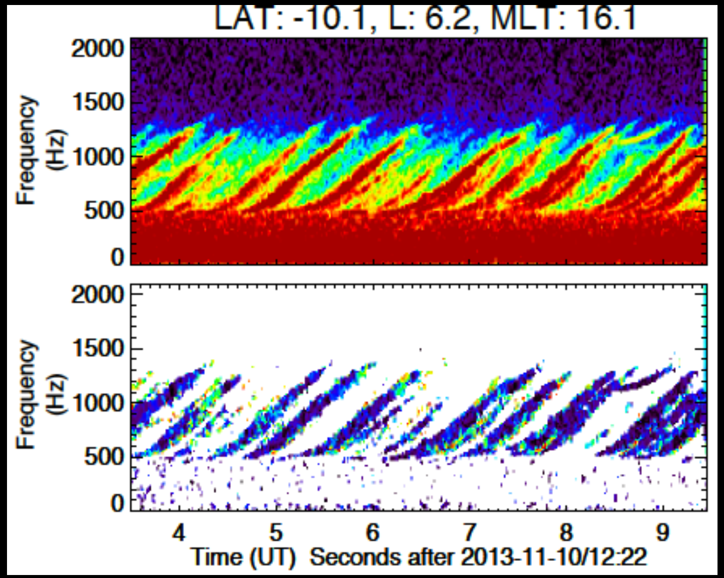
Whistler mode waves in plumes



[Goldstein 2006]

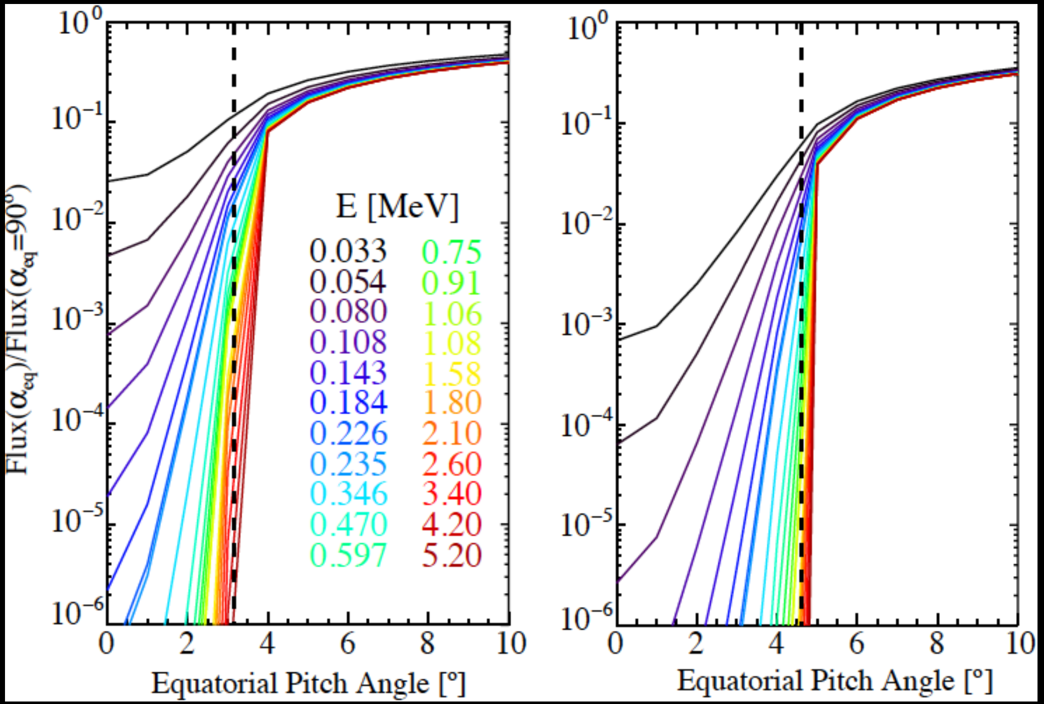






- Plume whistler waves are typically stronger than plasmaspheric hiss [Shi+ 2019; Teng+ 2019].
- More efficient in electron precipitation than typical plasmaspheric hiss.

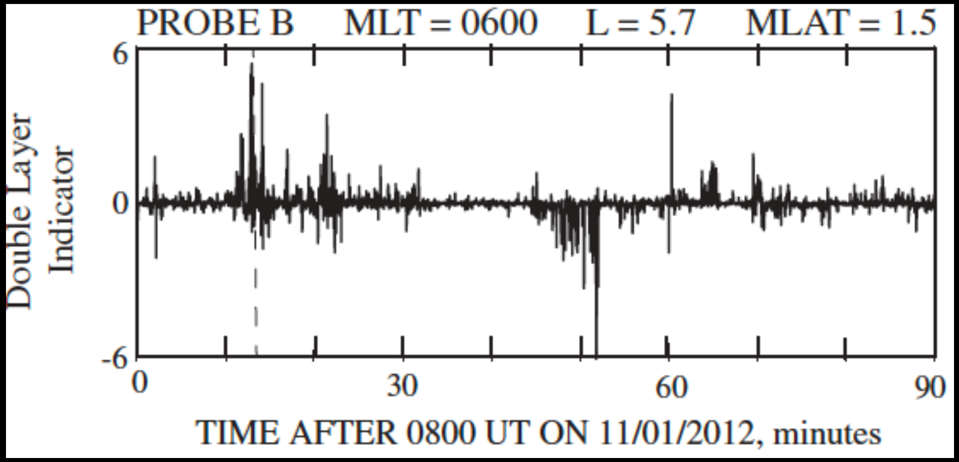
[Teng+ 2019]



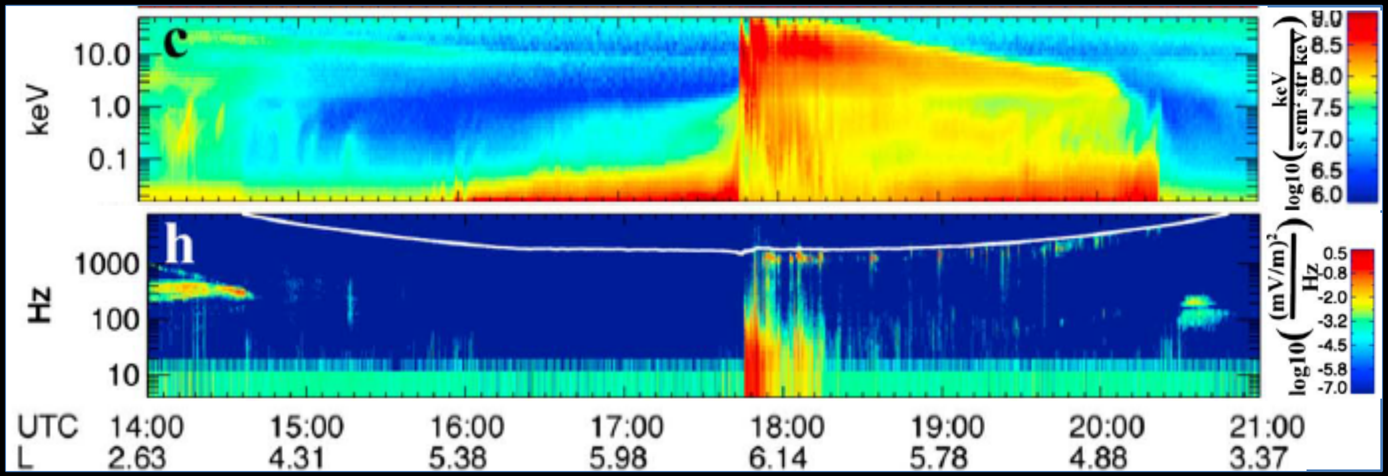
[W. Li+ 2019]

Time domain structures: Typical properties

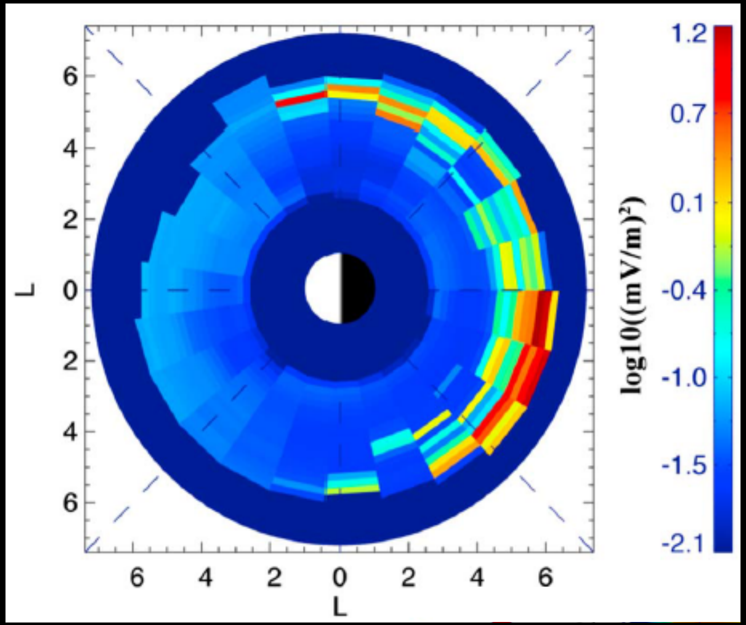
- Time domain structures (TDS): Packets of electric field spikes (~1 ms duration) up to ~100 mV/s [Mozer+ 2013, 2014; Agapitov+ 2015; Malaspina+ 2014, 2015]
- Typically associated with dipolarization injection fronts; observed over the dusk-to-dawn sector [Malaspina+ 2014]
- Potentially scatter equatorial electrons towards the loss cone with energies <10s keV [Artemyev+ 2014; Mozer+ 2013, 2016; Vasko+ 2015, 2017]



[Mozer+ 2013]



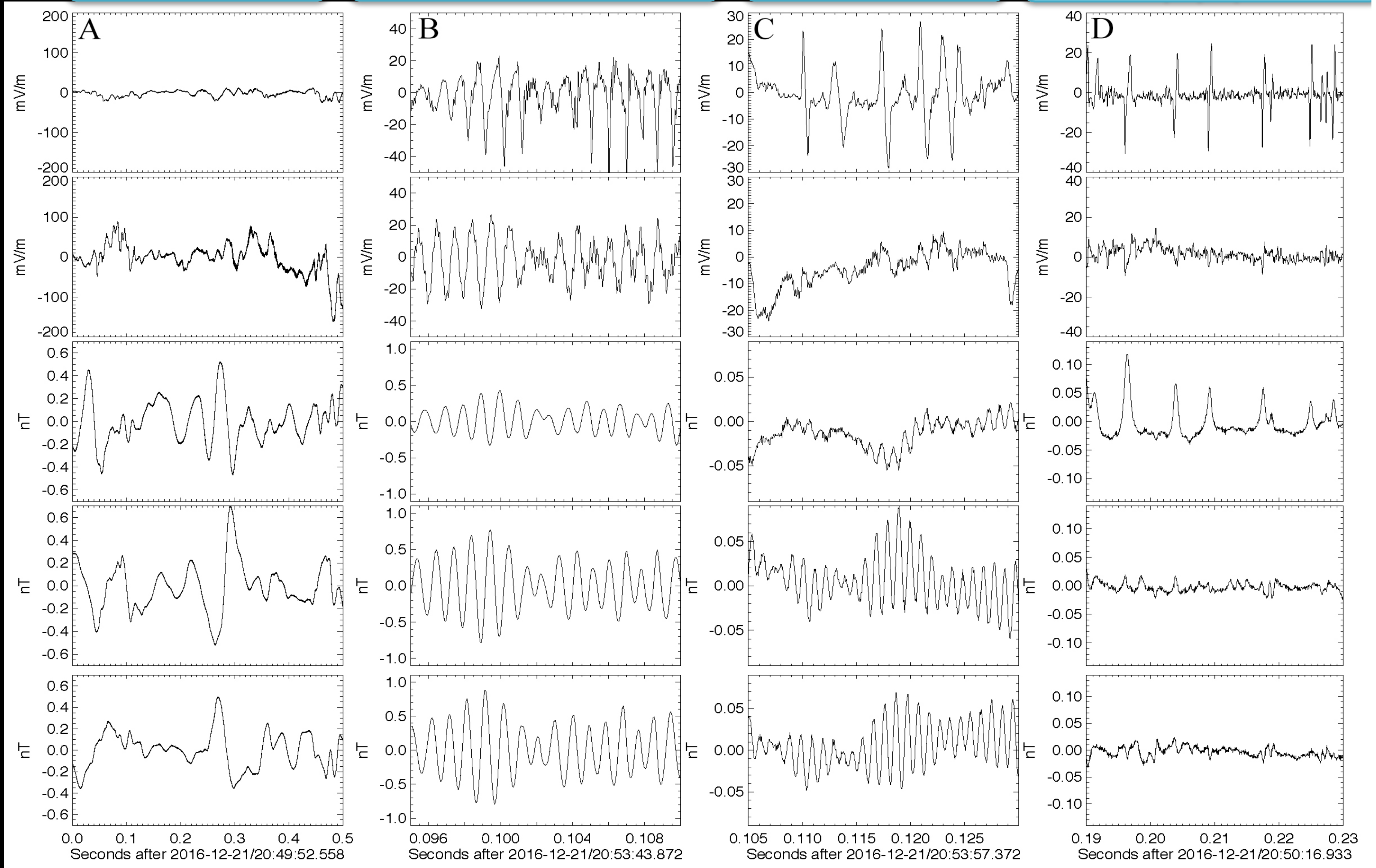
[Malaspina+ 2015]



[Malaspina+ 2014]

Other nonlinear waves – another zoo!

Kinetic Alfven waves	Nonlinear whistler-mode waves	Phase space holes	Phase space holes with |B| spikes

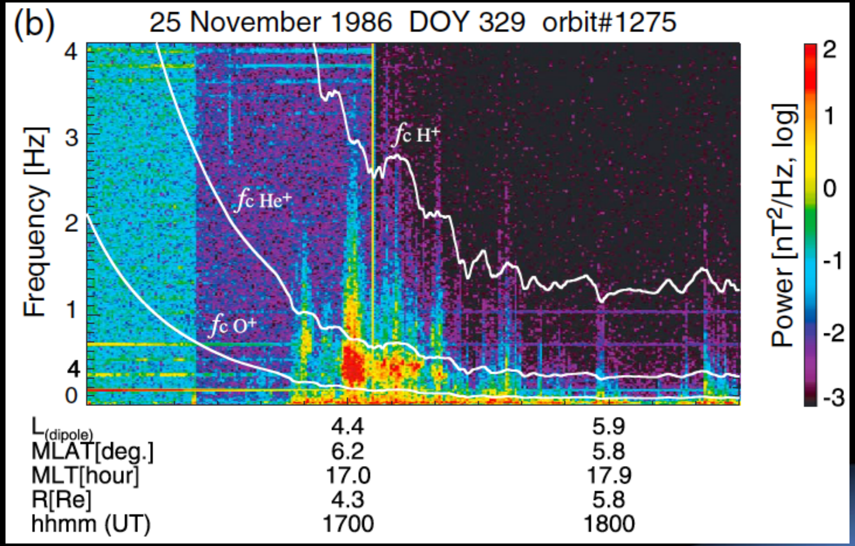


Inner magnetosphere is full of nonlinear waves.
[Chaston+ 2014, 2018; Mozer+ 2014, 2015, 2016; Artemyev+ 2014, 2015; Malaspina+ 2014; Vasko+ 2015; Osmane+ 2017]

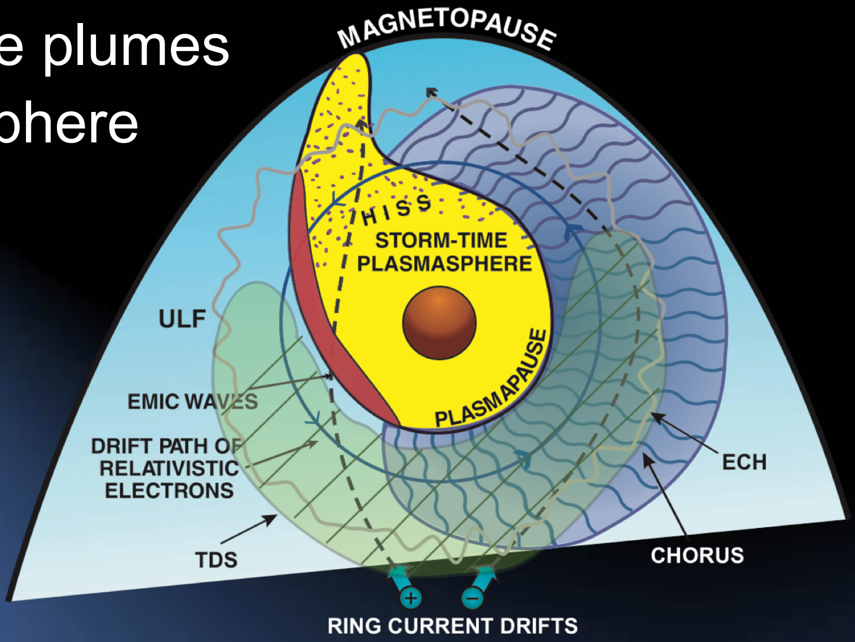
[Malaspina+ 2018]

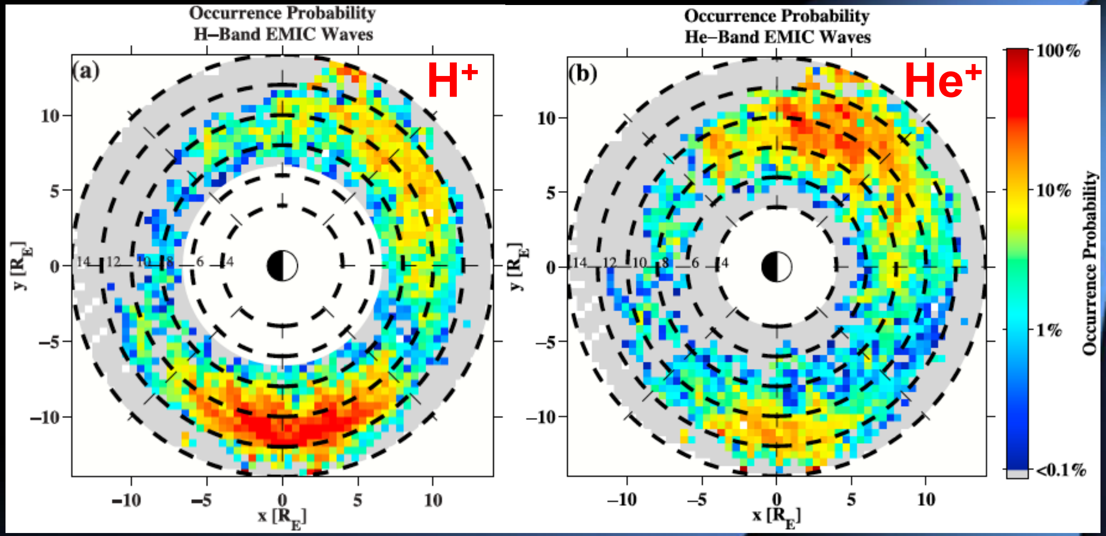
EMIC waves: Typical properties

- ElectroMagnetic Ion Cyclotron (EMIC) Waves: Three bands below H^+, He^+, and O^+ with typical frequencies 0.1–5 Hz [Erlandson & Ukhorskiy 2001; Engebretson+ 2002; Usanova+ 2008; Min+ 2012]
- Generated by ion cyclotron instability with energy of 10–100 keV ring current protons [Jordanova+ 2008]
- Favored regions
  - ➢Overlap region between ring current and plasmasphere
  - ➢Dayside drainage plumes
  - ➢Outer magnetosphere



[Keika+ 2013]

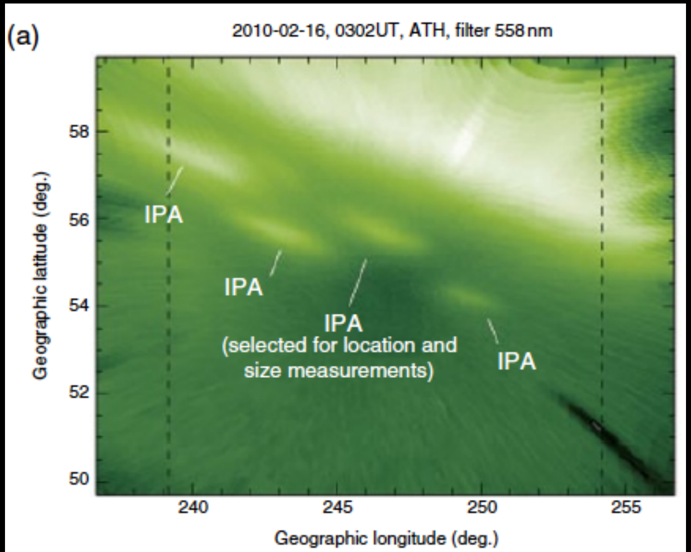


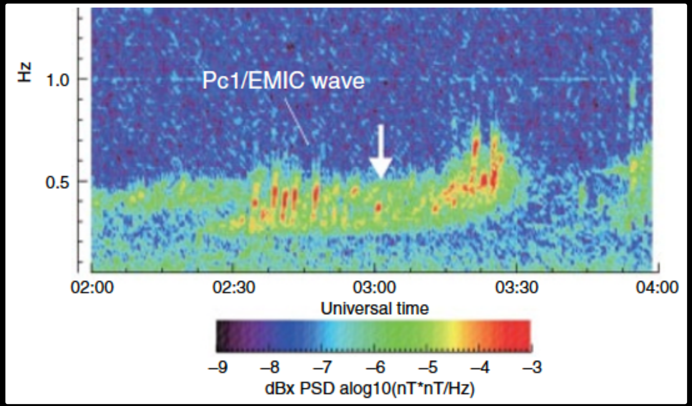


[Min+ 2012]

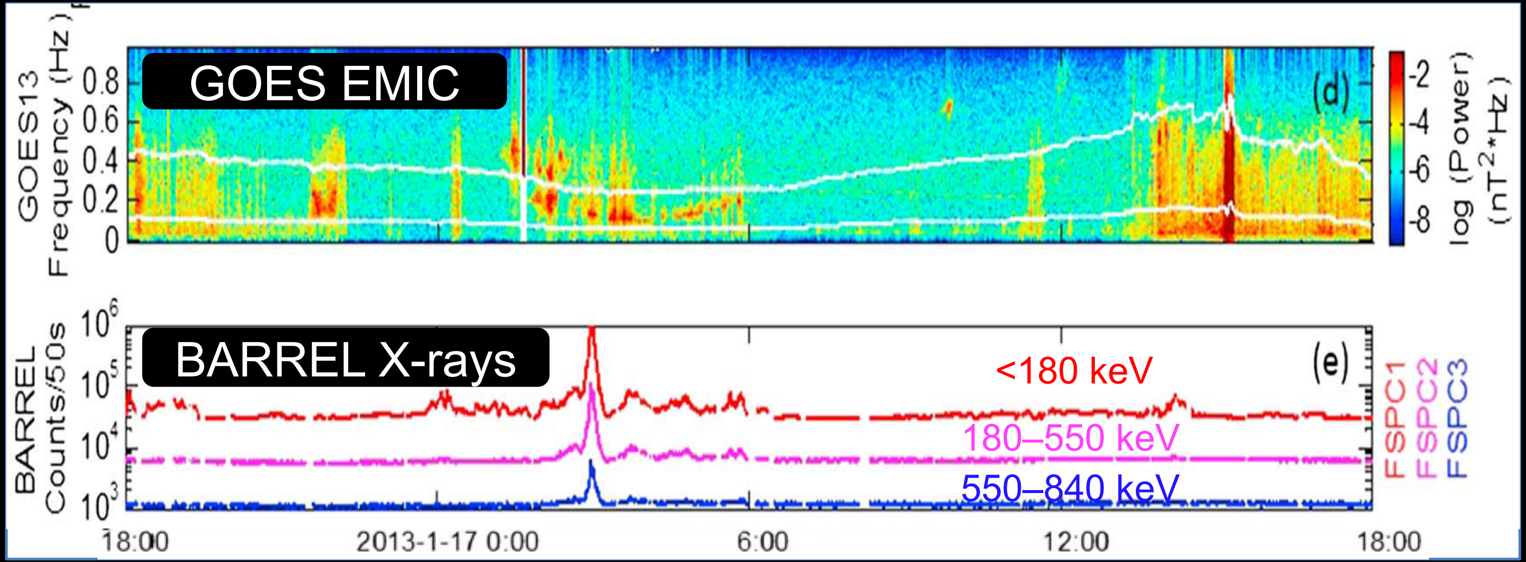
EMIC waves: Effects on particle precipitation

- Can cause precipitation of both 10–100 keV protons and > ~MeV electrons [Jordanova+ 2008; Miyoshi et al., 2008; Blum+ 2013; Sakaguchi+ 2015; Capannolo+ 2018, 2019]

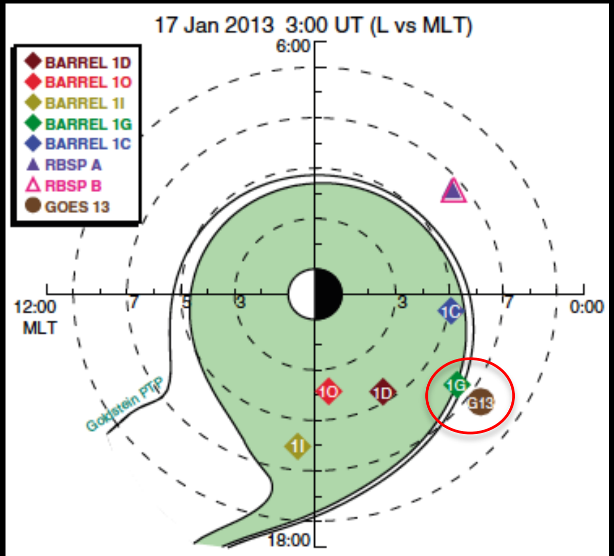




EMIC waves produce isolated proton aurora [Sakaguchi+ 2015]

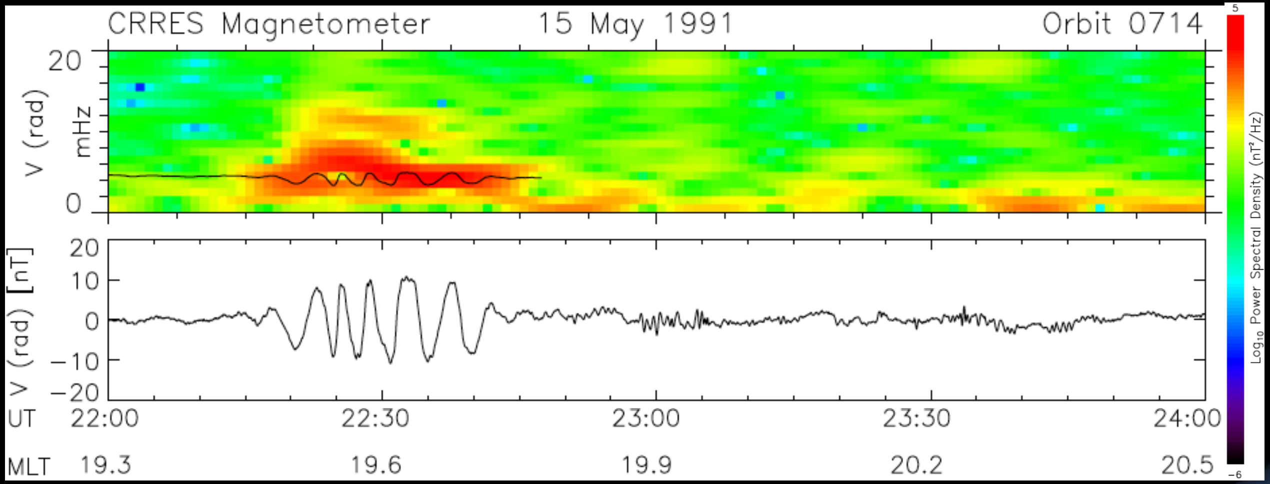


GOES and BARREL conjunction shows that EMIC waves drive relativistic electron precipitation [Z. Li+ 2014]

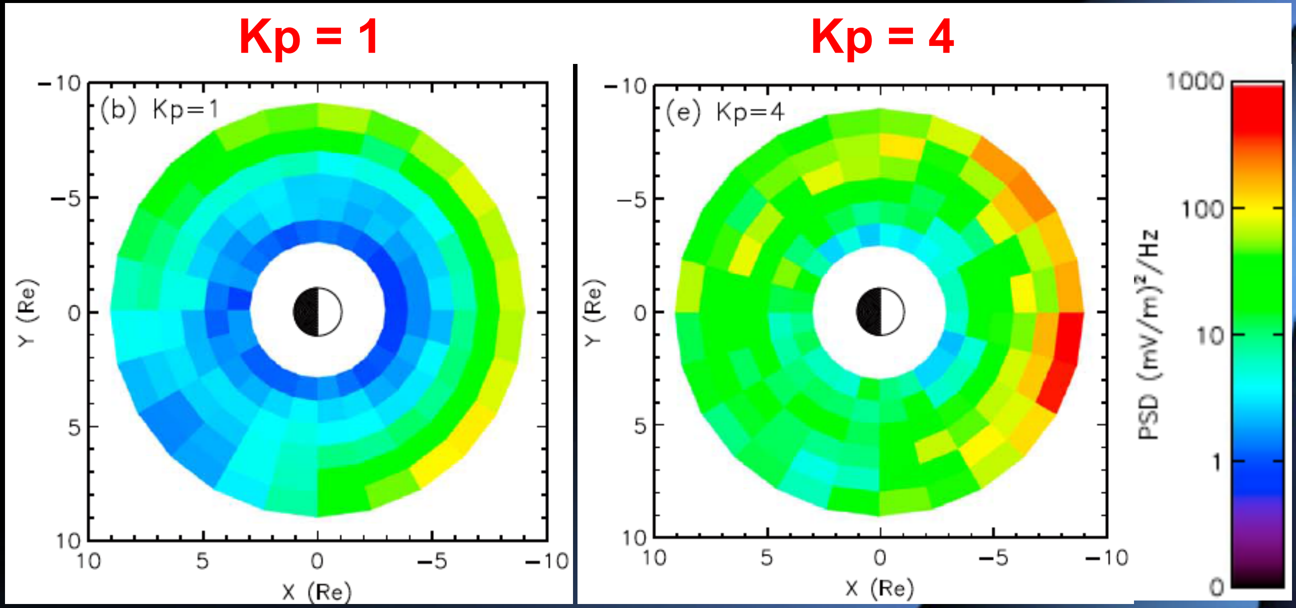


ULF waves (Pc4–5): Typical properties

- Ultra Low Frequency (ULF) waves (Pc4–5): 1–20 mHz [Jacobs+1964]; include Alfvenic and compressional modes.
- ULF wave power tends to be stronger on the dayside than nightside; depends on activity [Ali+ 2016; Liu+ 2016]
- Generation mechanism
  - ➢ Kelvin-Helmholtz instability near the magnetopause [Mann+ 1999; Claudepierre+ 2008]
  - ➢ Time-varying compressions of the dayside magnetosphere due to solar wind [Kivelson & Southwood 1988; Kepko+ 2002]
  - ➢ Free energy in the ion plasma sheet [Hasegawa 1969; Korotova+ 2009]

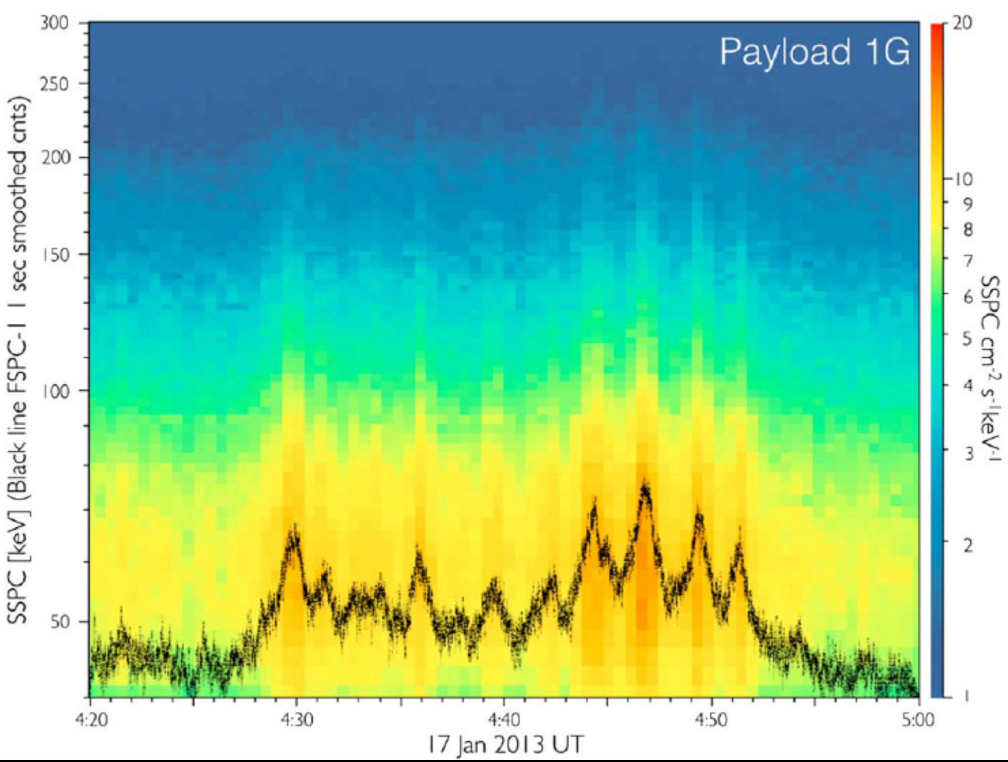


[Hudson+ 2004]



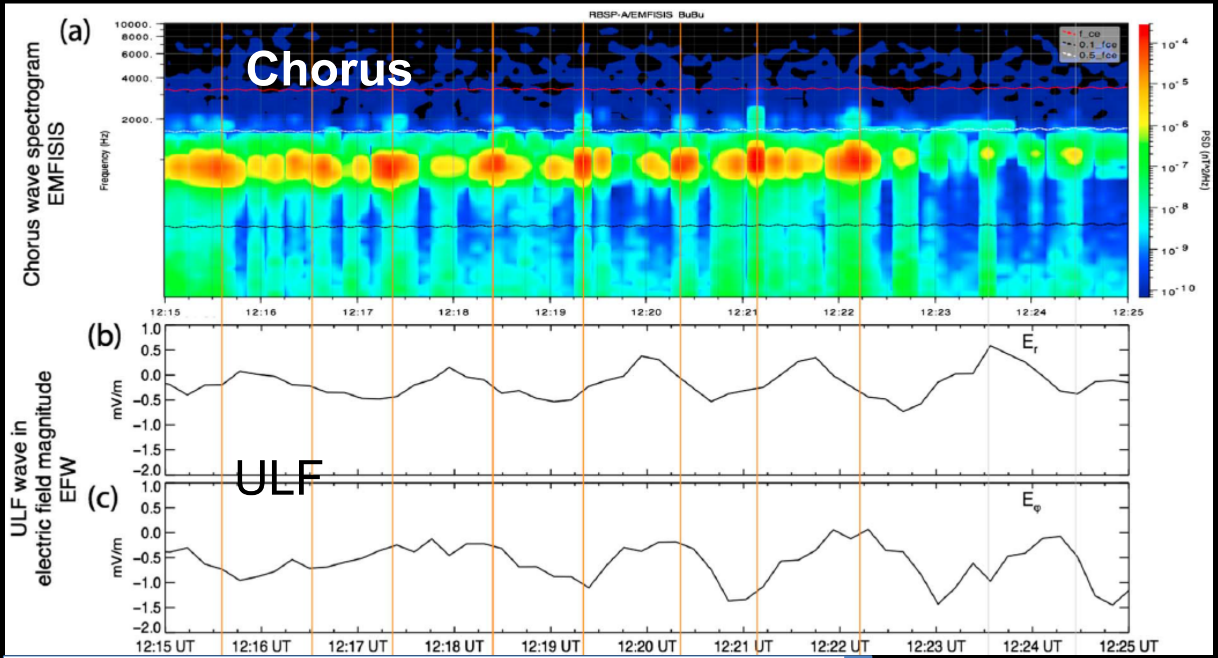
[Liu+ 2016]

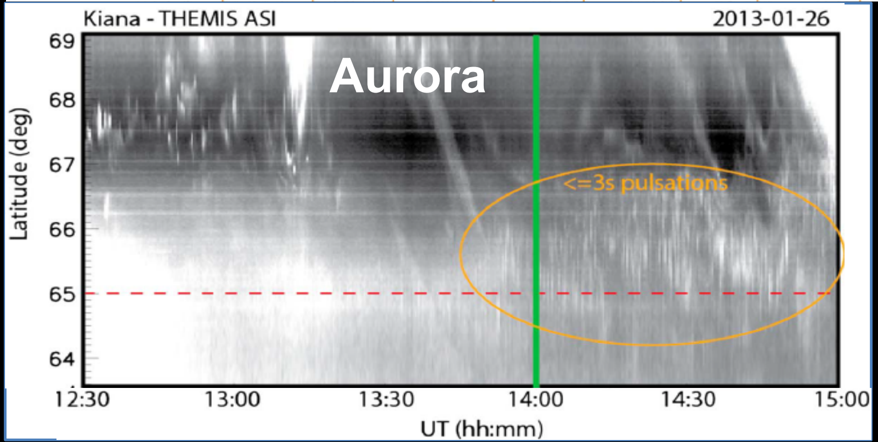
ULF waves: Effects on particle precipitation



[Brito+ 2015]

- ULF waves (<10 mHz) have been linked to relativistic electron precipitation in the absence of VLF/EMIC waves.
- Compressional magnetic field oscillations may directly generate precipitations by lowering the mirror points.





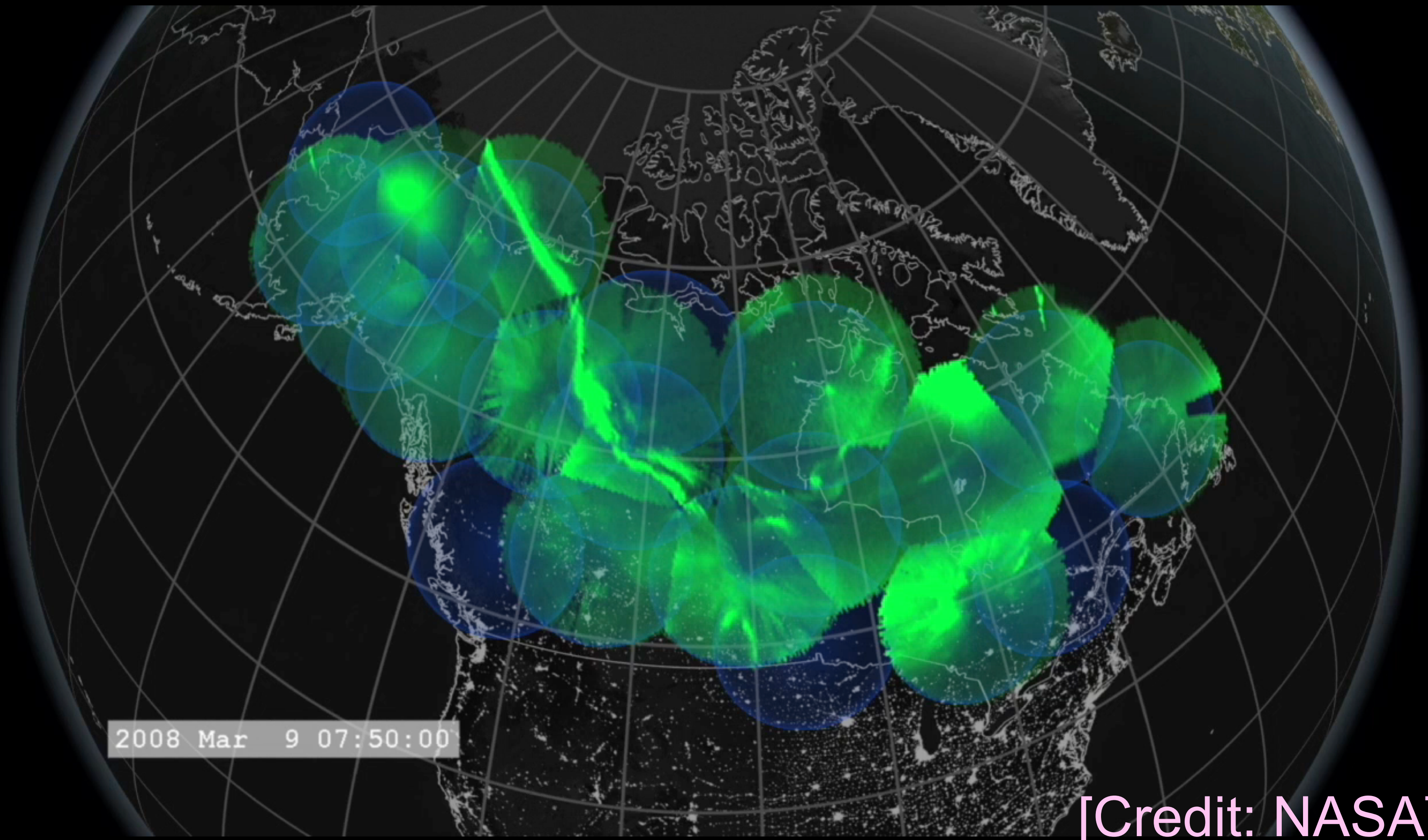
[Jaynes+ 2015]

- Pc4–5 ULF waves modulate chorus waves, leading to pulsating auroral precipitation.

3. Impacts of Inner Magnetospheric Waves on the Ionosphere

1) **Generation of diffuse/pulsating aurora**
   - Provides a major source of energy input (71–84%) into ionosphere [Newell+ 2009]
2) **Changes in ionospheric conductivity**
   - Important for M-I convection [Ridley+ 2004; Wolf+ 2007]
3) **Effects on atmospheric chemistry**
   - Reduce ozone concentration, thus potentially important for Earth's climate. [Thorne 1977; Solomon+ 1982; Randall+ 2005; Turunen+ 2009, 2016]

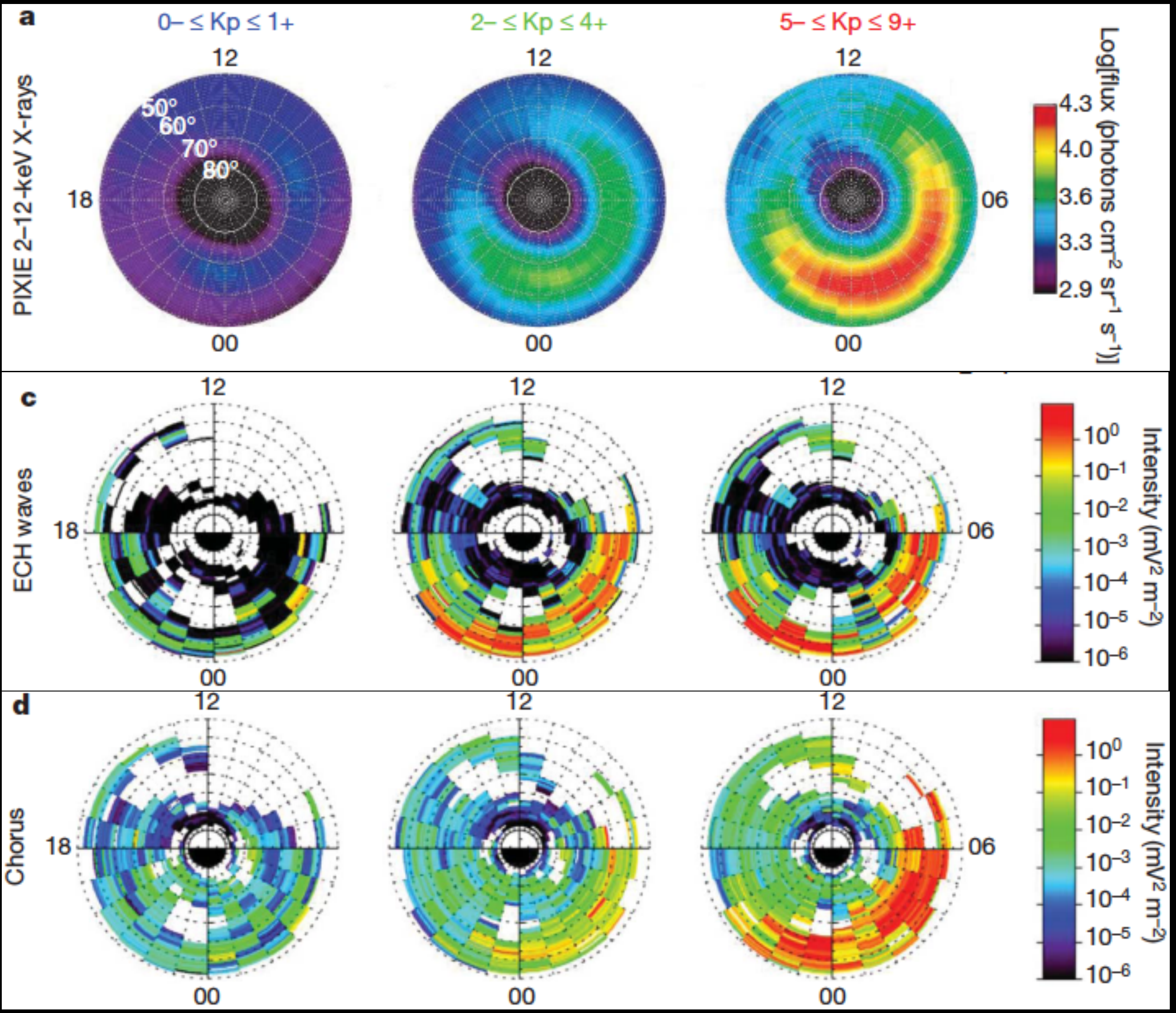
3.1. Wave Impact: Diffuse/Pulsating Aurora

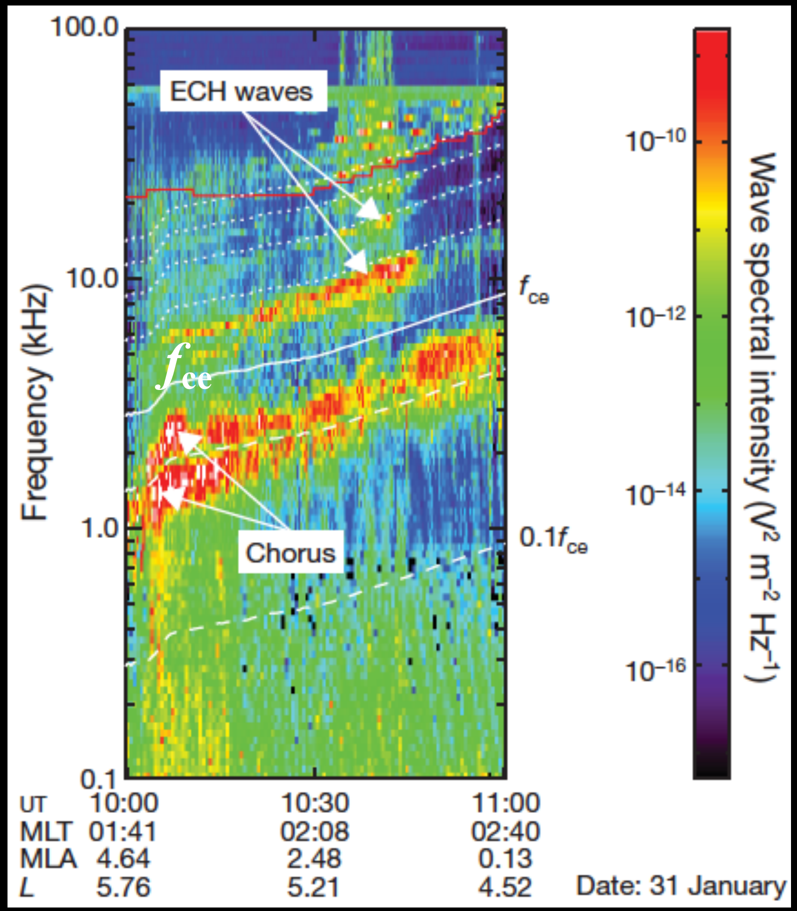


[Credit: NASA]

- **Diffuse aurora**: weak diffusive emissions observed in an extensive region (62º–70º latitude) on the equatorward part of the auroral oval [Lui & Anger 1973; Newell+ 2009]
- **Pulsating aurora**: dynamic auroral structures embedded in the diffuse aurora with 1–10s sec modulation [Johnstone 1978; Davidson 1990; Jones+ 2013]

What is the driver of diffuse aurora?

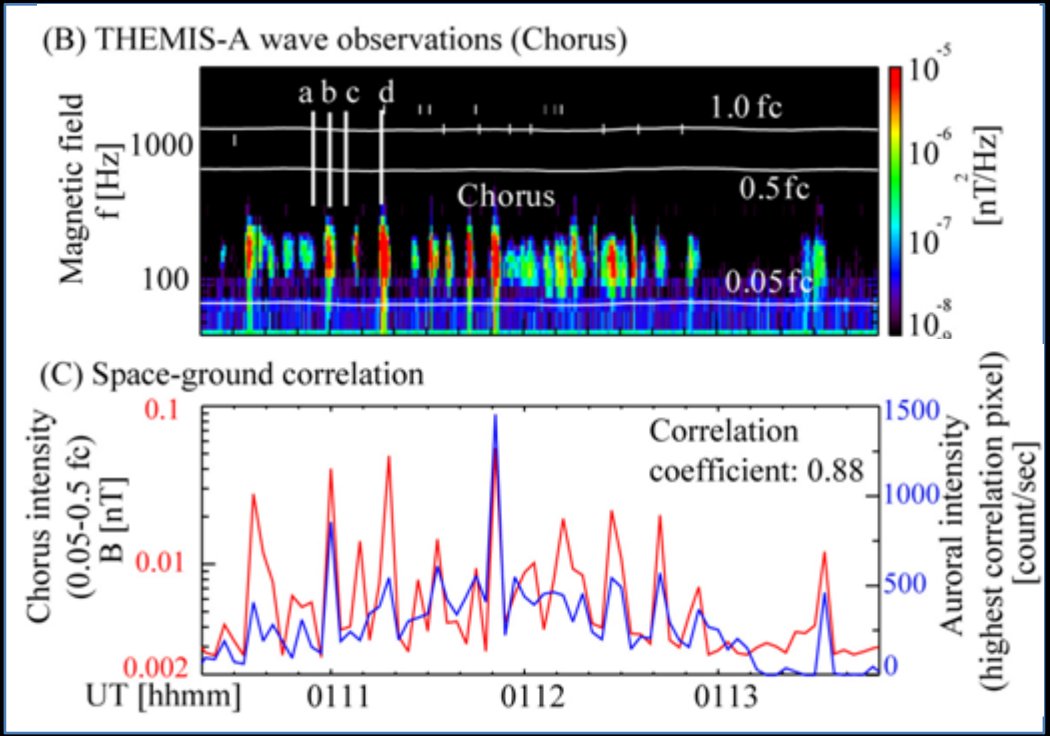




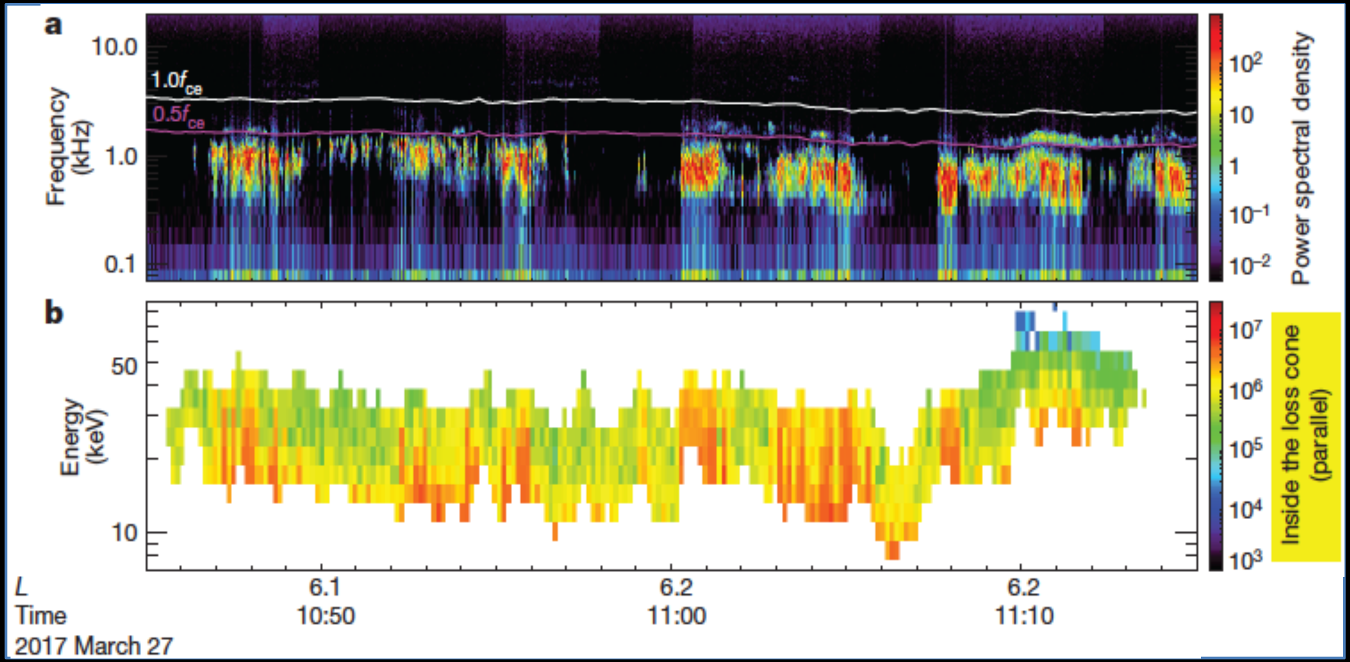
[Petrinec+1999; Thorne+ 2010;
W. Li+ 2012; Meredith+ 2012; Khazanov+ 2015;
Zhang+ 2015; Ni+ 2016]

Earth's diffuse aurora is generated by precipitation of energetic electrons (0.5–10s keV) due to **pitch angle scattering** primarily driven by chorus waves at $L < 8$ and ECH waves at $L > 8$.

What is the driver of pulsating aurora?



[Nishimura+ Science, 2010]

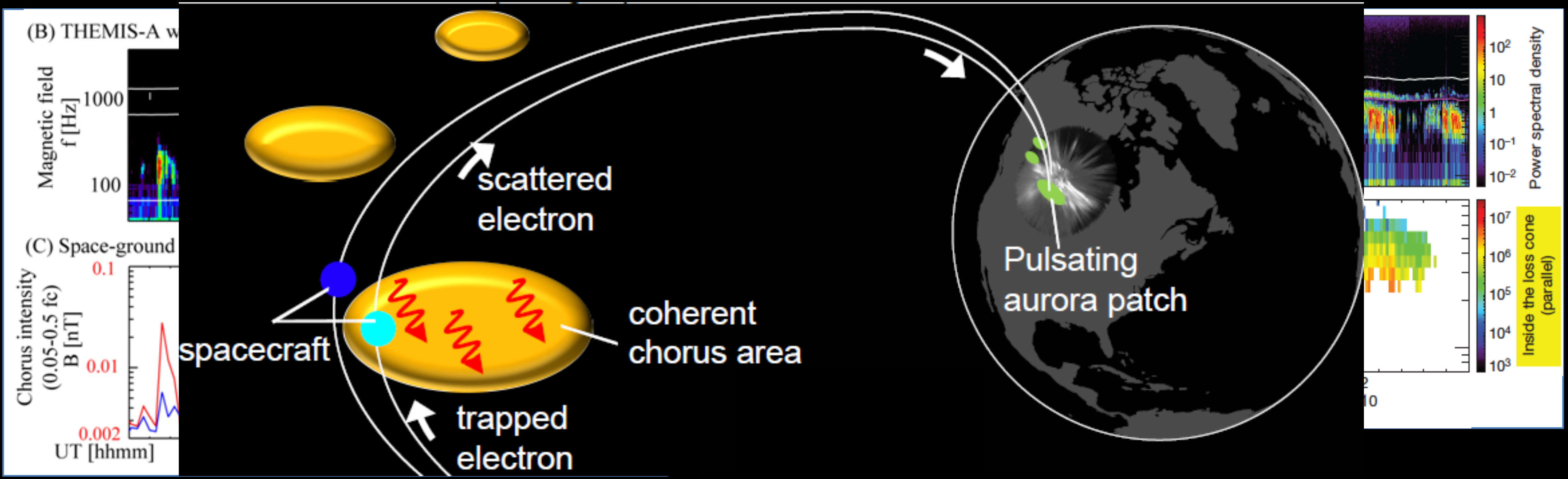


[Kasahara+ Nature, 2018]

One-to-one correlation between chorus wave intensity and PA intensity.

Excellent correlation between chorus wave intensity and loss cone electron flux (10–30 keV).

What is the driver of pulsating aurora?



[Nishimura+ Science, 2010]

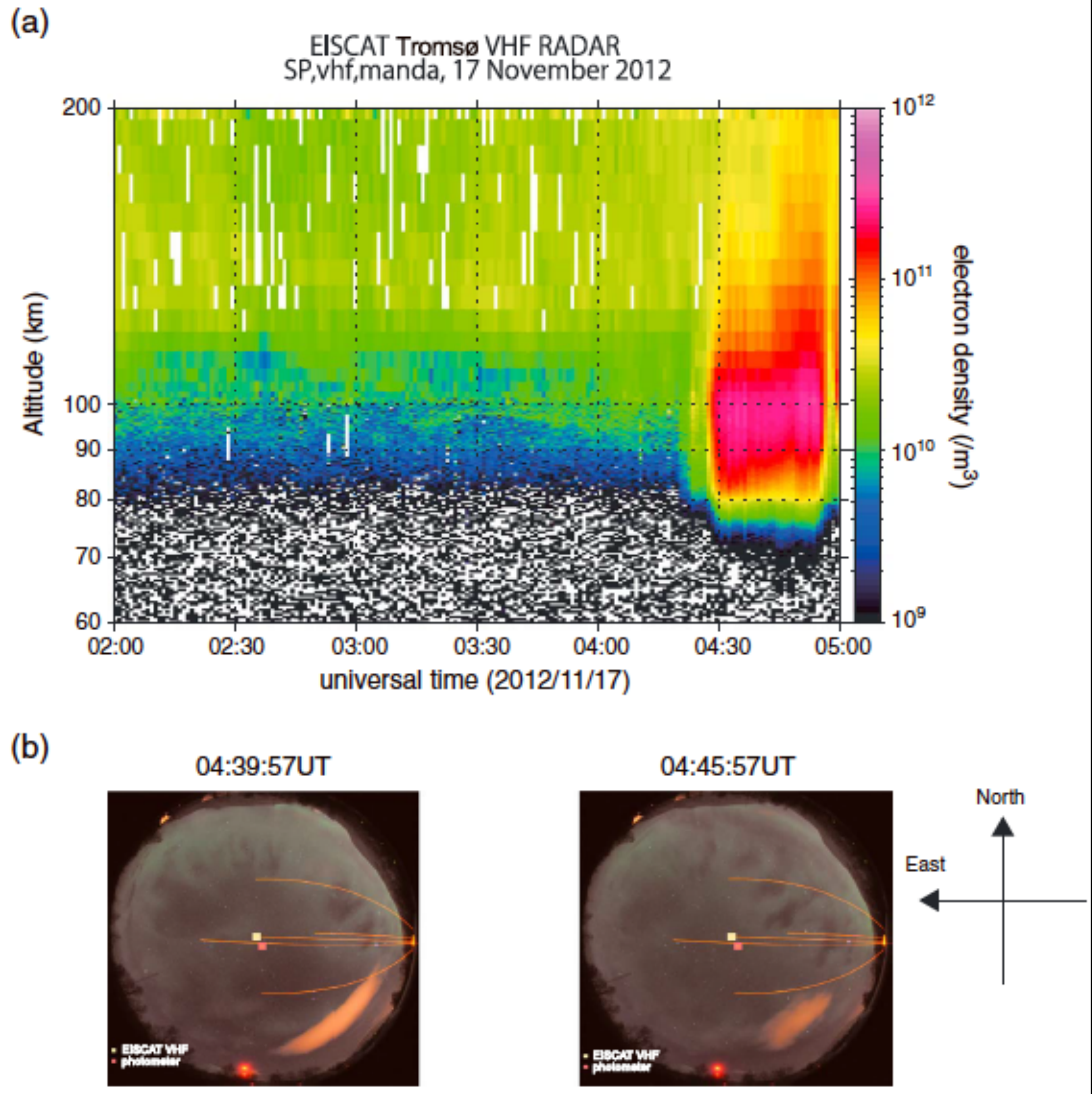
[Kasahara+ Nature, 2018]

One-to-one correlation between chorus wave intensity and PA intensity.

Excellent correlation between chorus wave intensity and loss cone electron flux (10–30 keV).

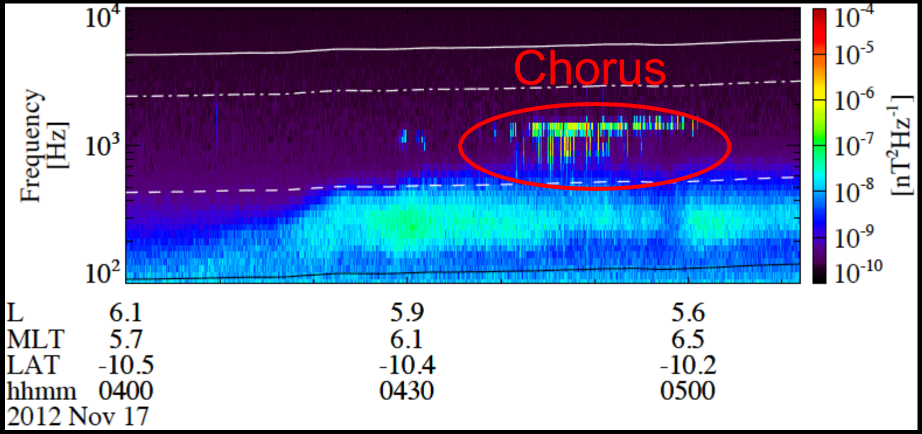
Chorus waves precipitate 10s keV electrons into the loss cone through pitch angle scattering and drive pulsating aurora.

PA causes enhanced electron density in the ionosphere



[Miyoshi+ 2015]

Van Allen Probes



- Electron density enhancements at >68 km in association with pulsating aurora, suggesting a broadband energy range over ~10–200 keV.
- Observed lower band chorus causes the simultaneous precipitations of electrons and produces pulsating aurora.

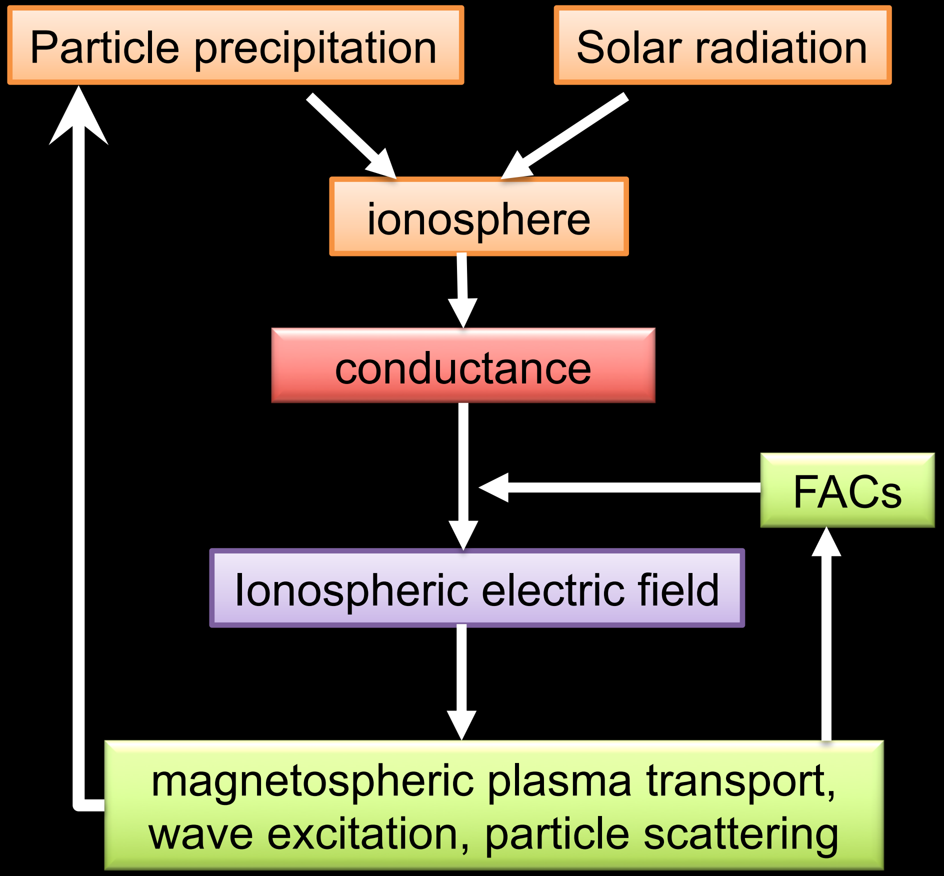
3.2. Wave Impact: Ionospheric Conductivity

- Conductance is a critical element that determines and controls the M-I interactions [Coroniti & Kennel 1973; Hill+ 1976].
- Particle precipitation, particularly diffuse aurora driven by inner magnetospheric waves, is essential for conductance calculation [Newell+ 2009].

How to specify auroral conductance?

- **Empirical formula**: e.g., Robinson
- **Transport code:** e.g., GLOW, B3c
- **Global IT model**: e.g., CTIPe, TIEGCM, GITM

Particle precipitation is a critical input!



[Courtesy of Y. Yu]

How to specify the particle precipitation?

1. Empirical

Auroral particle precipitation → Empirical formula (e.g., Robinson) → Conductance

Precludes specification of small-scale, transient variations in both space and time.

2. MHD parametrization

MHD parameters (T, Ne) → Precipitation number/energy flux → Empirical formula (e.g., Robinson) → Conductance

May not capture auroral precipitation caused by kinetic waves well.

3. Kinetic approach

Wave-induced precipitation → Empirical formula (e.g., Robinson) → Conductance

Needs accurate specifications of waves and plasma on a global scale.

[Courtesy of Y. Yu]

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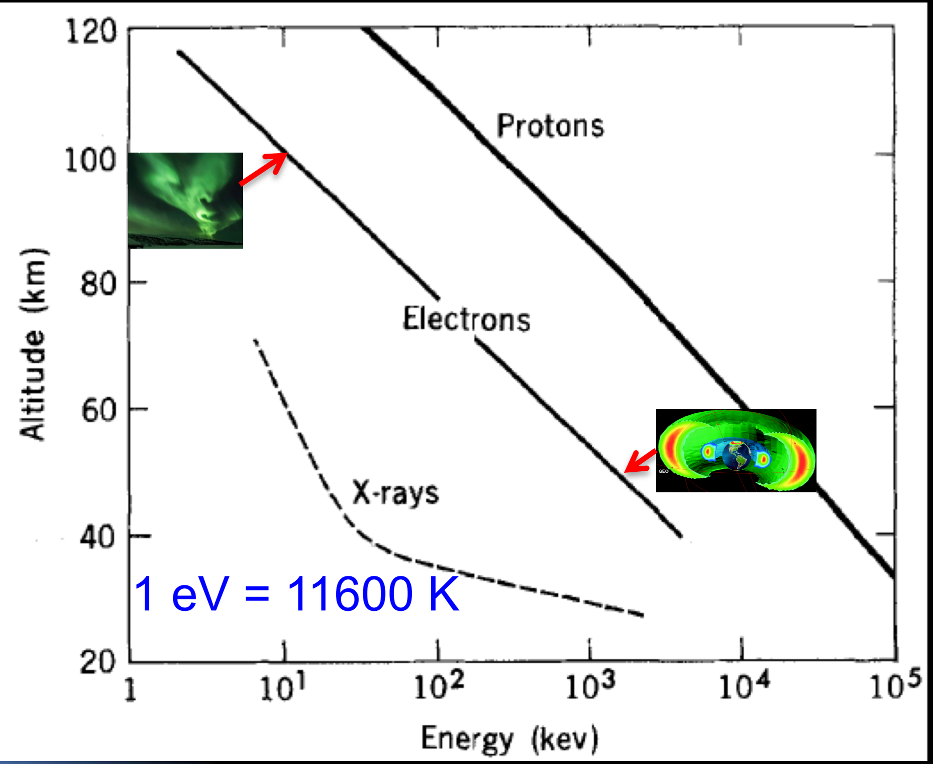
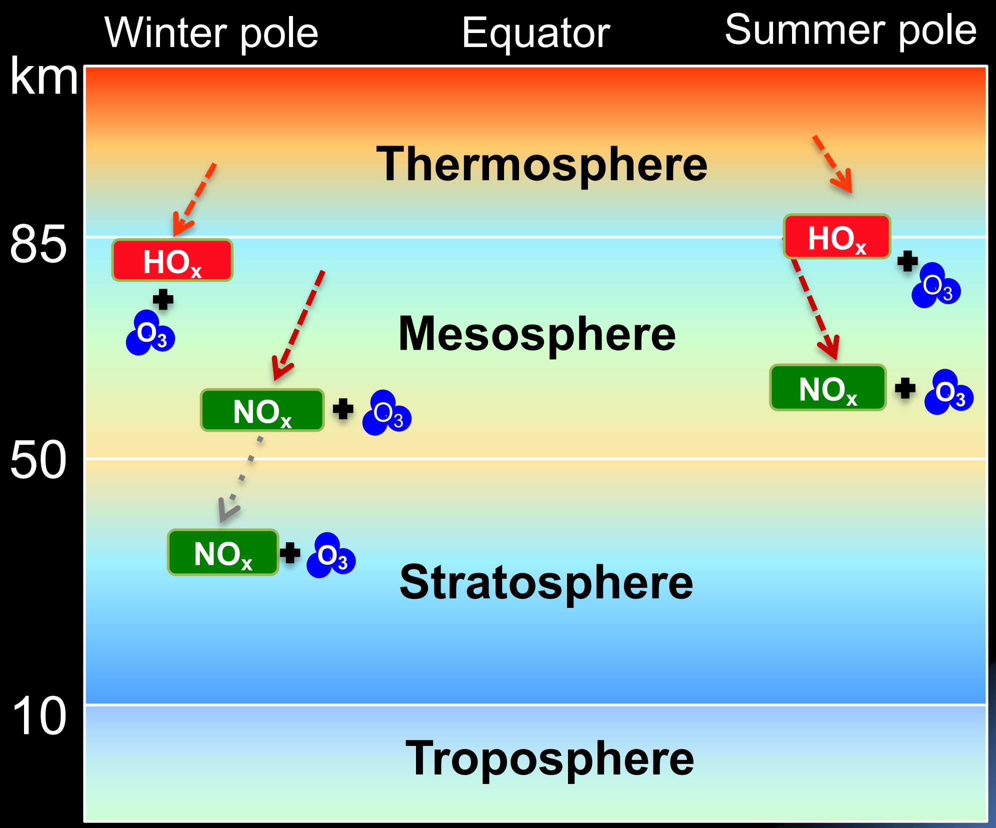
[Courtesy of Y. Yu]

3.3. Wave Impact: Atmospheric Chemistry

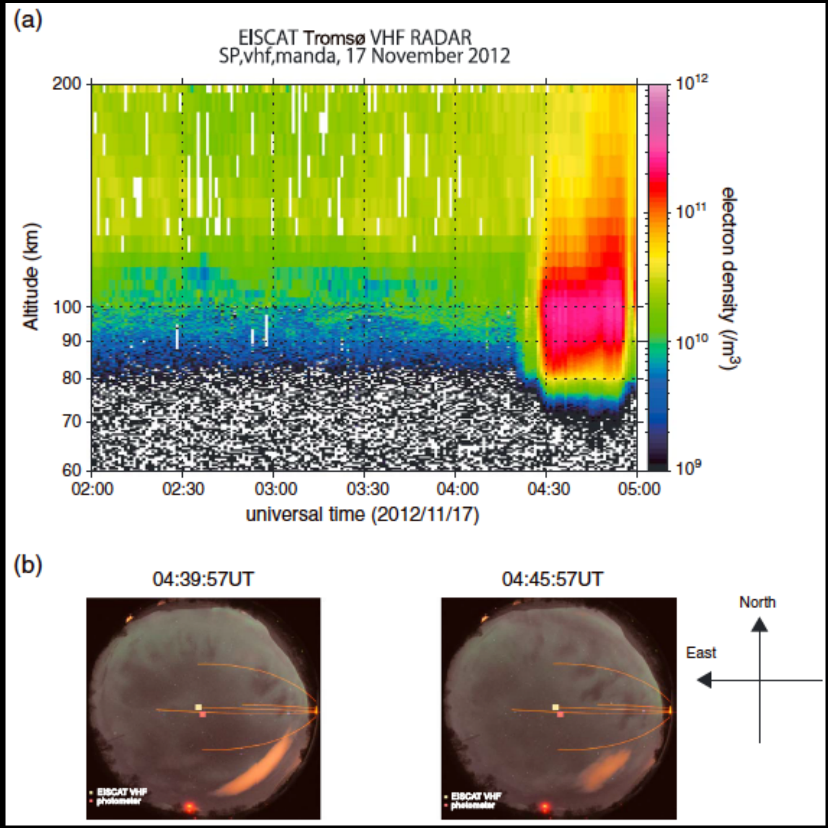


[Thorne 1977]



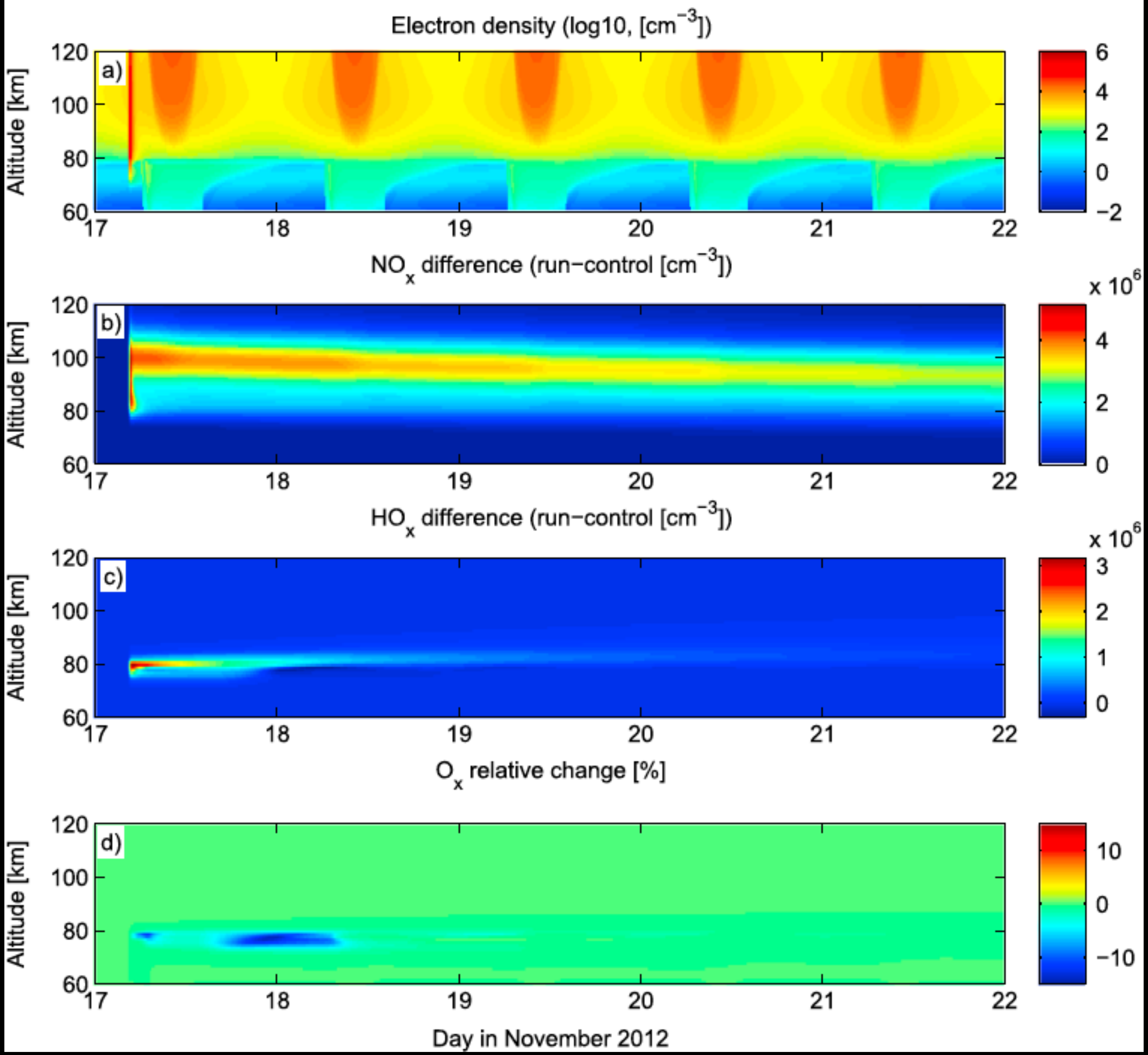
Relativistic electron precipitation ➔ generate NO_x and HO_x in thermosphere, mesosphere, and even in stratosphere ➔ O_3 reduction at > 30 km [Thorne 1977; Solomon+ 1982; Russell+ 1984; Callis+ 1996; Brasseur & Solomon 2005; Randall+ 2005, 2015; Clilverd+ 2006; Seppälä+ 2007; Turunen+ 2009, 2016]

Wave Impact: Atmospheric Chemistry



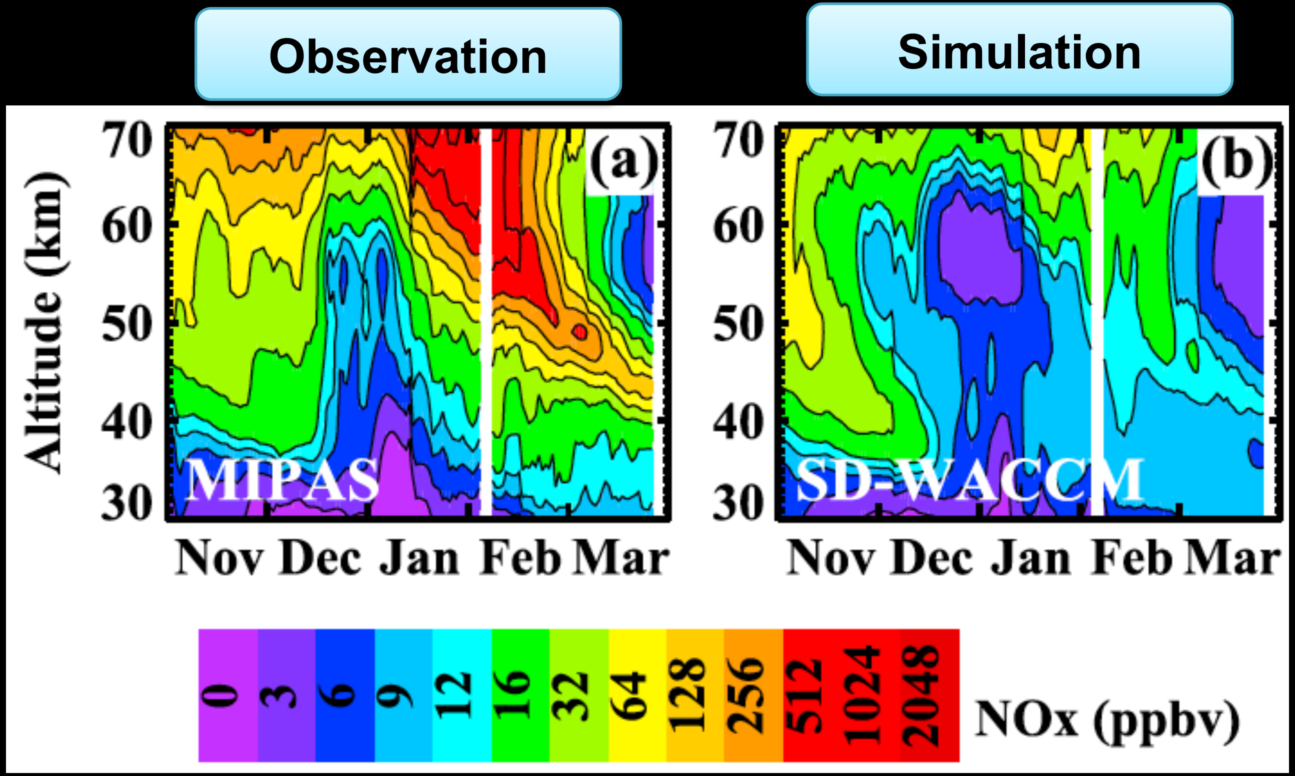
[Miyoshi+ 2015]

- Modeled a single pulsating aurora event using a coupled ion and neutral chemistry model.
- Mesospheric odd oxygen depletion was ~14% at ~75 km.

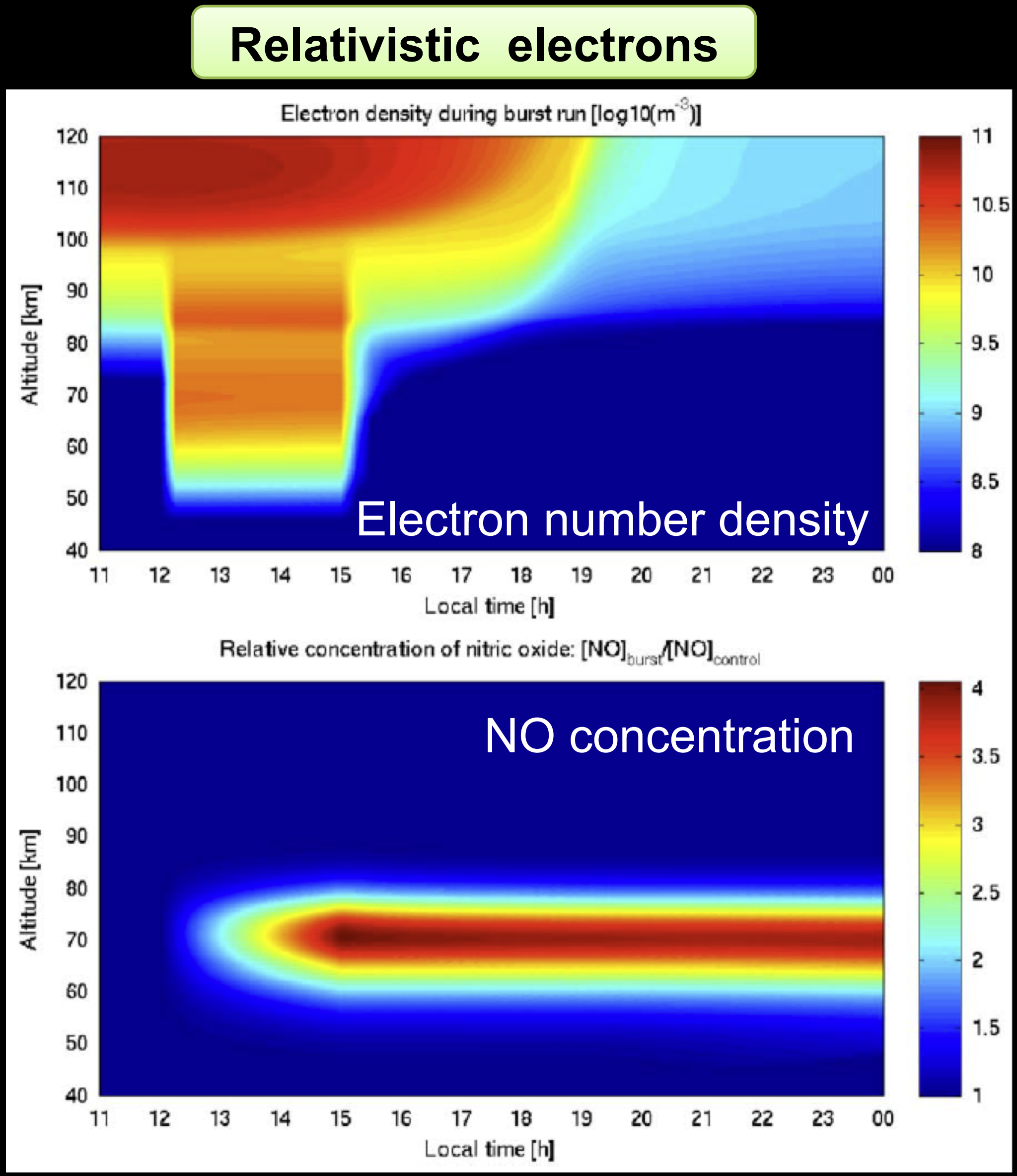


[Turunen+ 2016]

Wave Impact: Atmospheric Chemistry



[Randall+ 2015]



[Turunen+ 2009]

- WACCM simulations considering only solar protons and auroral electrons (<~ 30 keV) underestimate NO_X enhancements observed by MIPAS [Randall+ 2015].
- Full spectrum of precipitating electrons is required to better understand the EPP impact!

Open Questions & Challenges

Inner Magnetospheric Waves & Precipitation

- What are the quantitative roles of various inner magnetospheric waves in energetic particle precipitation? Can we identify the driver of each type of precipitation events?
- How important are the nonlinear effects of waves on energetic particle precipitation?
- How to take full advantage of rapidly growing satellite measurements and state-of-the-art models to specify and predict the global evolution of waves (e.g., machine learning, data assimilation)?

Impacts on the Ionosphere

- How to incorporate the microscale wave dynamics into the macroscale models in a more self-consistent and efficient way to specify and predict particle precipitation?

Open Questions & Challenges

Inner Magnetospheric Waves & Precipitation

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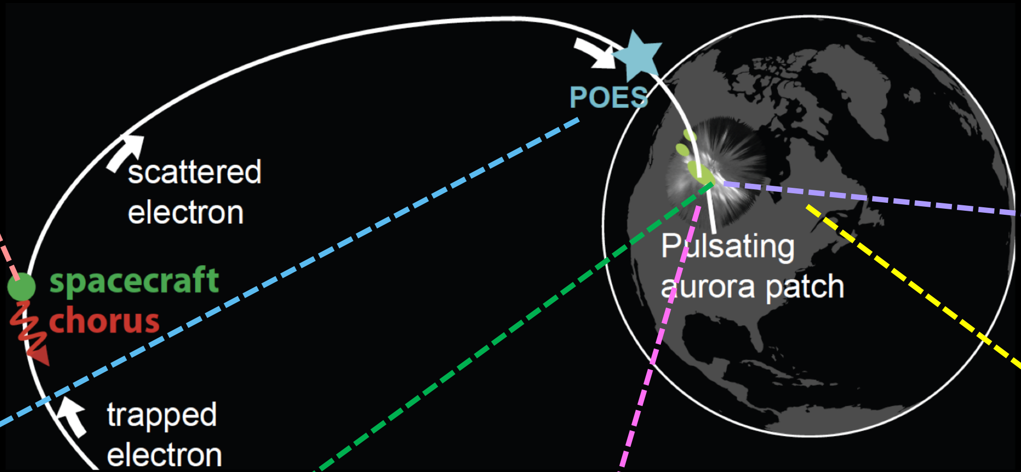
- … of-

GEM Focus Groups

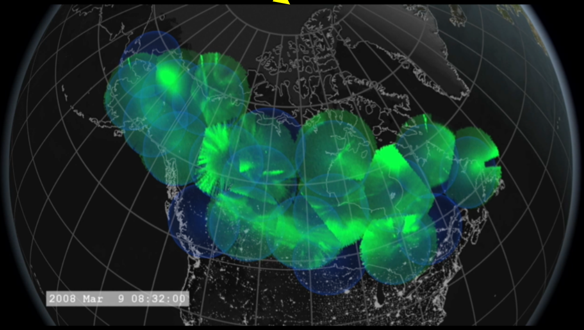
- **3D Ionospheric Electrodynamics and Its Impact on the Magnetosphere-Ionosphere-Thermosphere Coupled System (IEMIT)**
  (2017 – 2021: Hyunju Connor, Haje Korth, Gang Lu, and Bin Zhang; RA: MIC, GSM)
- **System Understanding of Radiation Belt Particle Dynamics through Multi-spacecraft and Ground-based Observations and Modeling**
  (2019 – 2023: Hong Zhao, Lauren Blum, Sasha Ukhorskiy, and Xiangrong Fu; RA: IMAG)
- **ULF wave Modeling, Effects, and Applications**
  (2016 – 2020: Michael Hartinger, Kazue Takahashi, Alexander Drozdov, Maria Usanova, and Brian Kress; RA: GSM)

What can we use to study inner magnetospheric waves and wave-driven particle precipitation?

Equatorial satellites
(Van Allen Probes, THEMIS, MMS, …): magnetospheric waves and particle injection



Magnetometers and VLF receivers
Waves on the ground



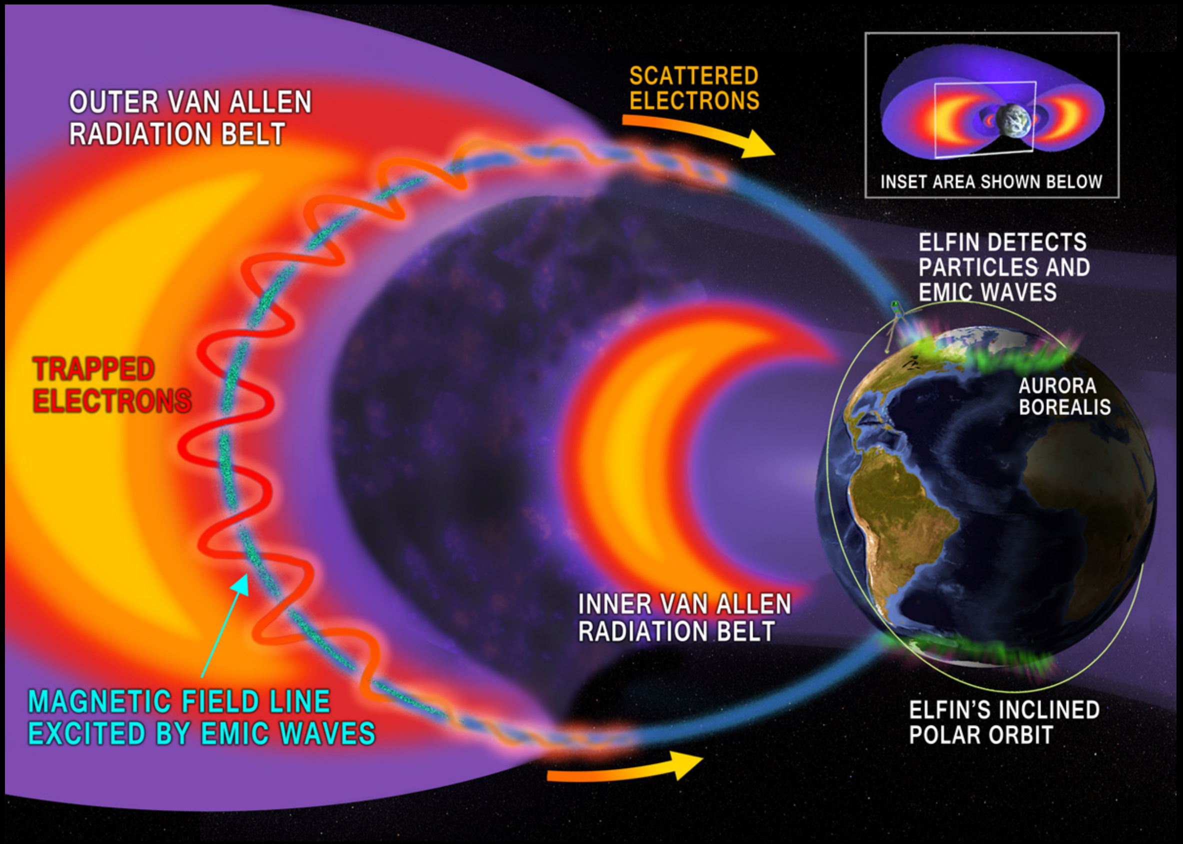
LEO satellites (e.g., POES)
Particle flux at various energies

Radars
Particle density & temperature

Riometers
Auroral particle precipitation

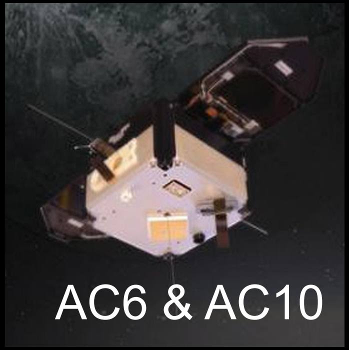
All-sky-imagers
Auroral intensity on a large scale

Future Opportunities: SmallSats and Balloons



http://elfin.igpp.ucla.edu/science/

FIREBIRD
THE AEROSPACE CORPORATION
MONTANA STATE UNIVERSITY
Focused Investigations of Relativistic Electron Burst Intensity, Range, and Dynamics



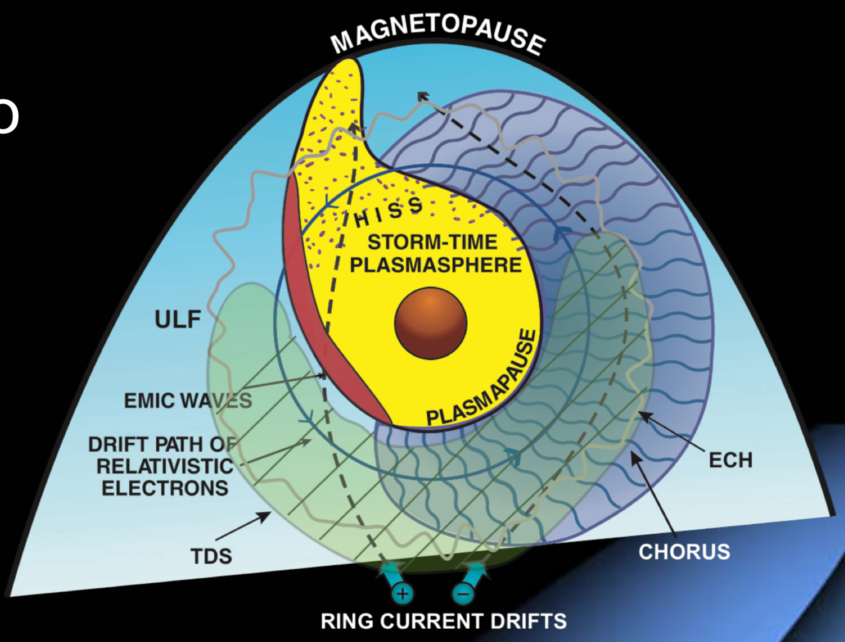
CSSWE
Colorado Student Space Weather Experiment

CeREs
Compact Radiation Belt Explorer
NASA
SwRI

- **Upcoming CubeSat missions: REAL, CIRBE, GTOSat, etc.**
- **SmallSats and Balloons together with the magnetospheric satellites provide an excellent opportunity to understand wave-driven particle precipitation.**

SUMMARY

- Inner magnetospheric waves play an important role in precipitating particles trapped in the magnetosphere into the ionosphere over a broad energy range (100s eV to ~10 MeV).
- Wave-driven precipitating particles
  - ➢ produce spectacular aurora (e.g., diffuse/pulsating)
  - ➢ change ionospheric conductivity
  - ➢ affect atmospheric chemistry to reduce ozone concentration



- Although there are still open questions and challenges in understanding and quantifying wave-driven particle precipitation, future opportunities are available to address some of these challenges.

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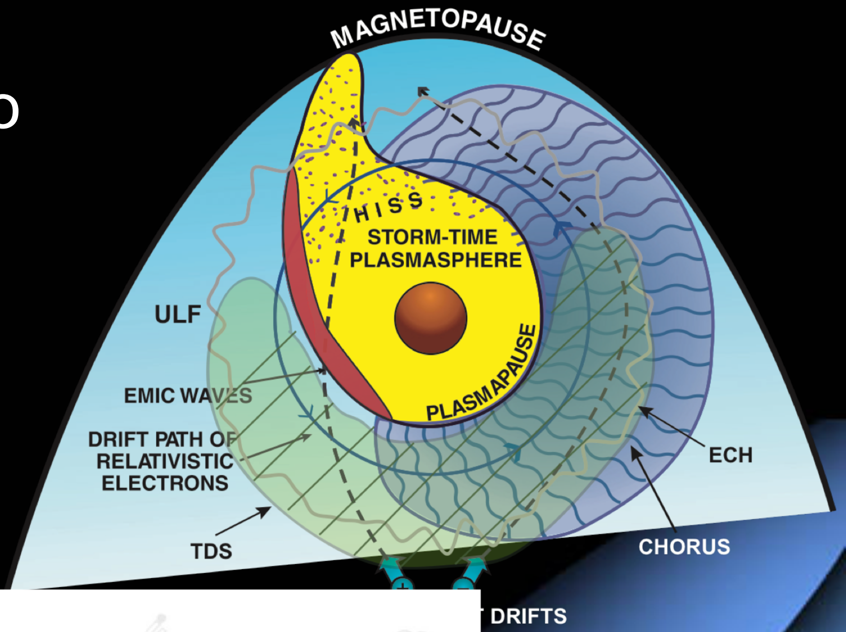

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