# Wave-particle interactions in the radiation belts

## GEM tutorial

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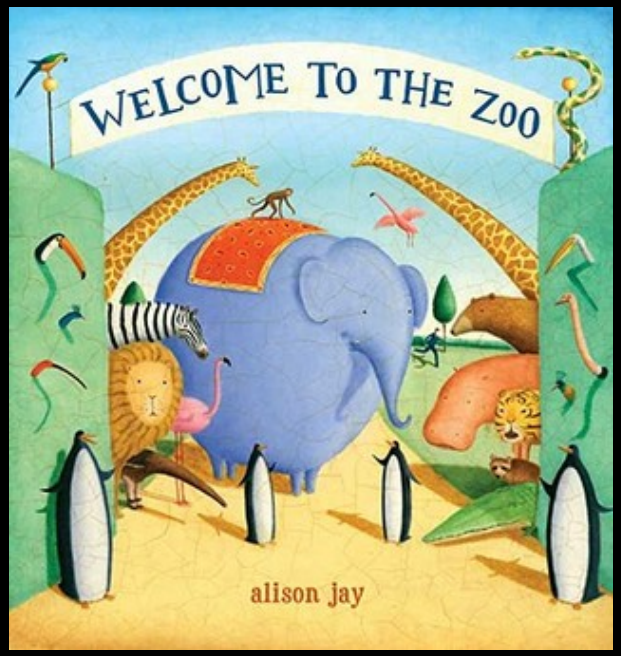
Thanks to I. Mann, M. Hartinger, A. Jaynes, A. Kellerman, D. Malaspina, A. Drozdov

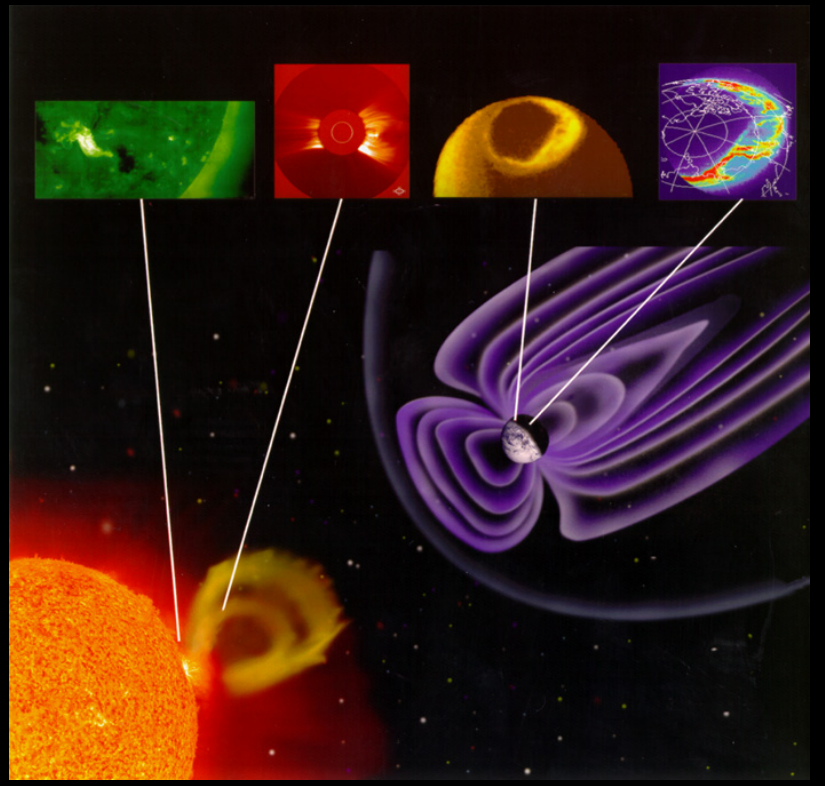
# Outline

- Solar-terrestrial environment
- Single particle motion and adiabatic invariants
- Wave-particle interactions
  - ULF waves
  - EMIC waves
  - Ion cyclotron harmonic waves
  - Magnetosonic waves
  - VLF waves (chorus and hiss)
  - Broad-band kinetic Alfven waves
  - Time-domain structures
- Summary



# Introduction: solar-terrestrial environment

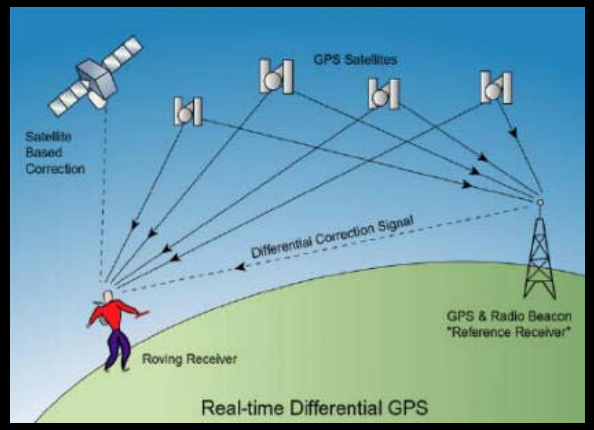
- The Sun constantly emits radiation (the solar wind).
- The Earth's magnetic field deflects it.
- Periodically, energetic particles coming from the Sun get trapped by the Earth's magnetic field, get energized and form the radiation belts.



# Geomagnetic storm effects

Generation of intense electrical currents and energetic particle fluxes…

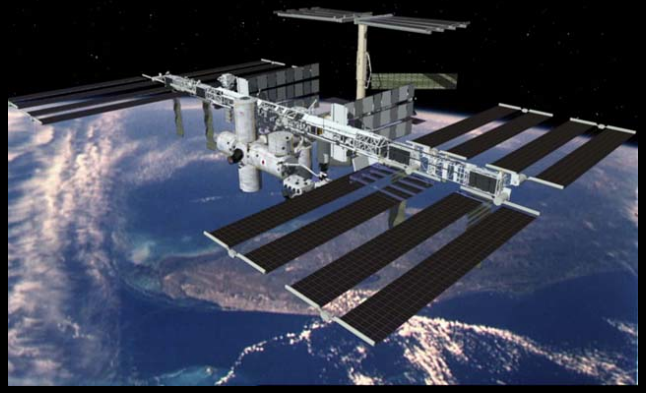
Generation of the aurorae borealis and australis. "Thanksgiving" aurora above Edmonton downtown.




Disruption of HF communications, distortion of radio signals, GPS location errors.

Inductive generation of unwanted currents in transformer networks, pipelines etc.

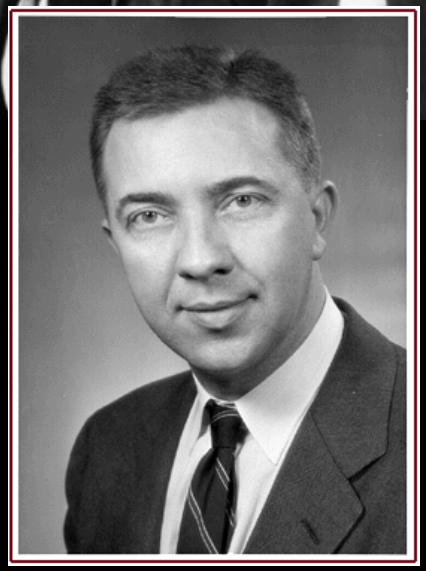
Radiation dose: damage to satellites, space-station, polar aircraft flights…



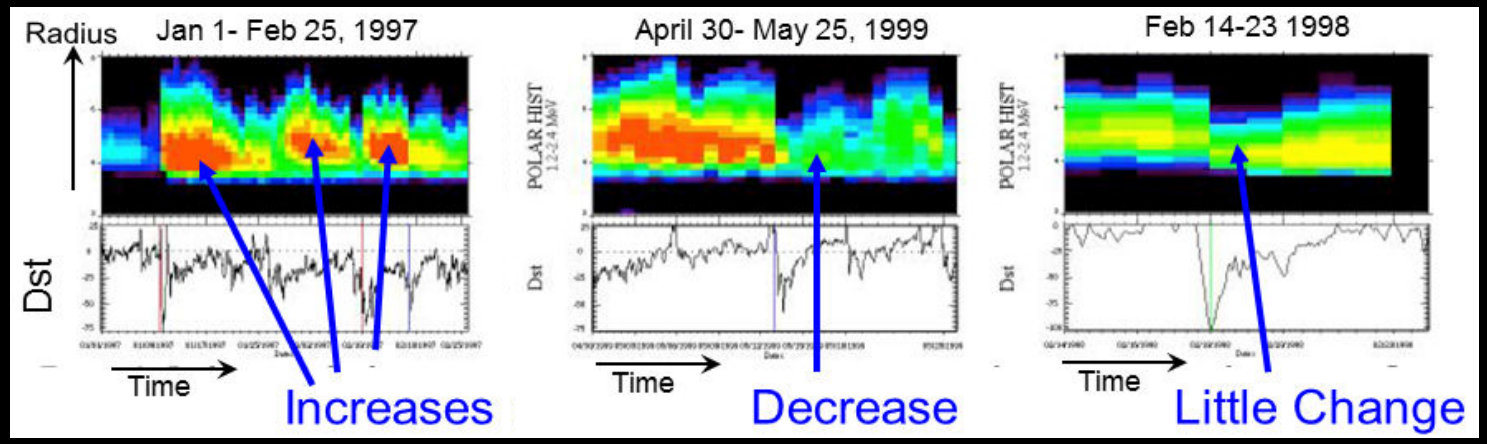
# Unexpected radiation belts

- Radiation Belts discovered unexpectedly by James Van Allen.
- Explorer 1 spacecraft, launched on Redstone rocket on 31st Jan. 1958.
- Cover of Time magazine in 1959 ("Man of the Year").
- Comprise trapped electrons and protons.
- 50+ years later, Van Allen radiation belts still a mystery.

From left: William H. Pickering, James Van Allen and Wernher von Braun

# Radiation belt dynamics:
# 50+ years later, we still don't fully understand it!

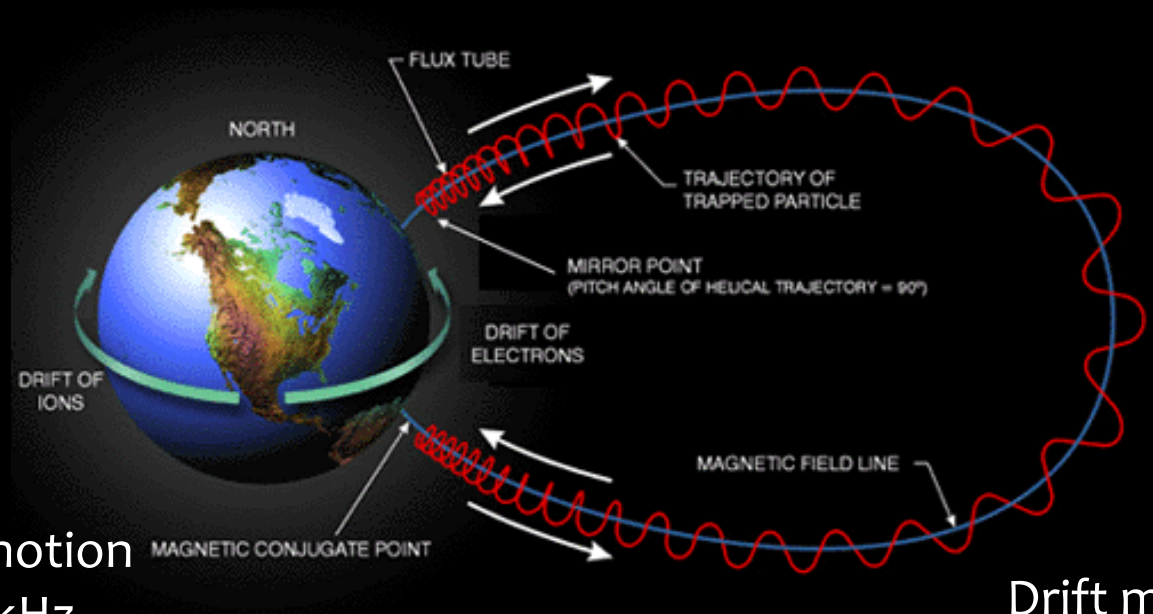



Reeves et al., 2003

Response of radiation belt electrons to geomagnetic storms is determined by a balance between energization and loss and cannot be predicted (so far).

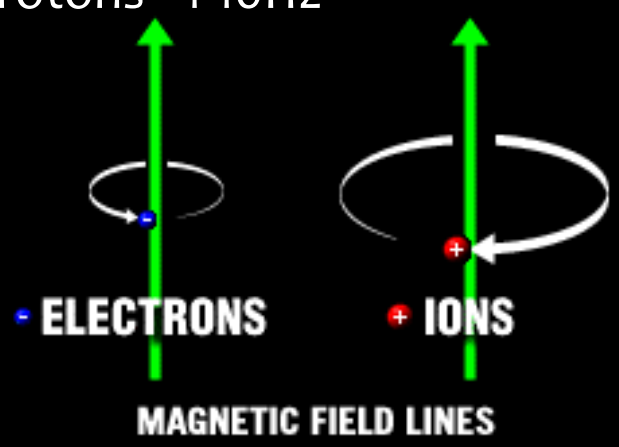
However, we do know that wave-particle interactions are important for radiation belts!

# Periodic charged particle motion

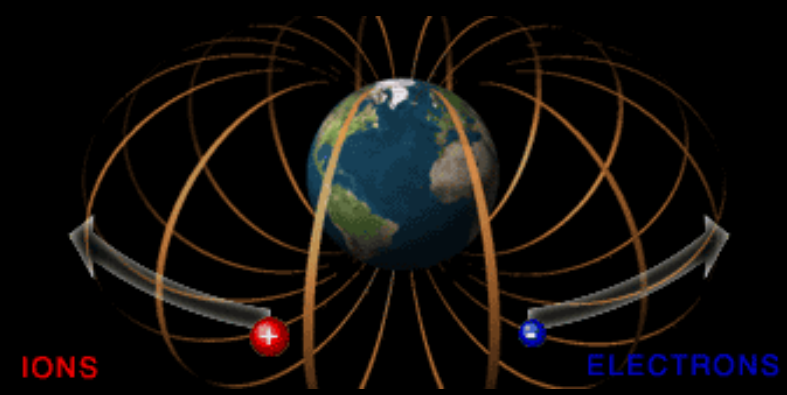



Bounce motion
1MeV electrons
@ GEO~1Hz

Cyclotron motion
electrons ~kHz
protons ~1-10Hz




Drift motion
electrons ~mHz



# Adiabatic invariants

- Invariants associated with periodic cyclotron, bounce and drift motion.
- Violation of either of the adiabatic invariants may result in irreversible changes in electron phase-space density (PSD) aka distribution function.

First invariant

$$\mu = \frac{m v_{\perp}^{2}}{2B}$$

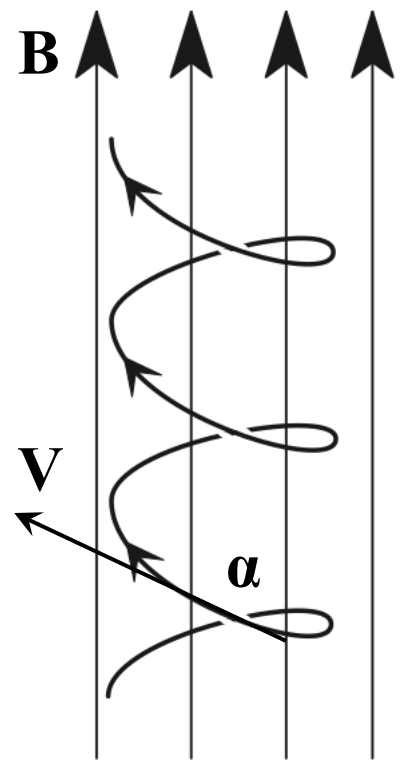
Second invariant

$$J = \int m v_{par} ds$$

Third invariant

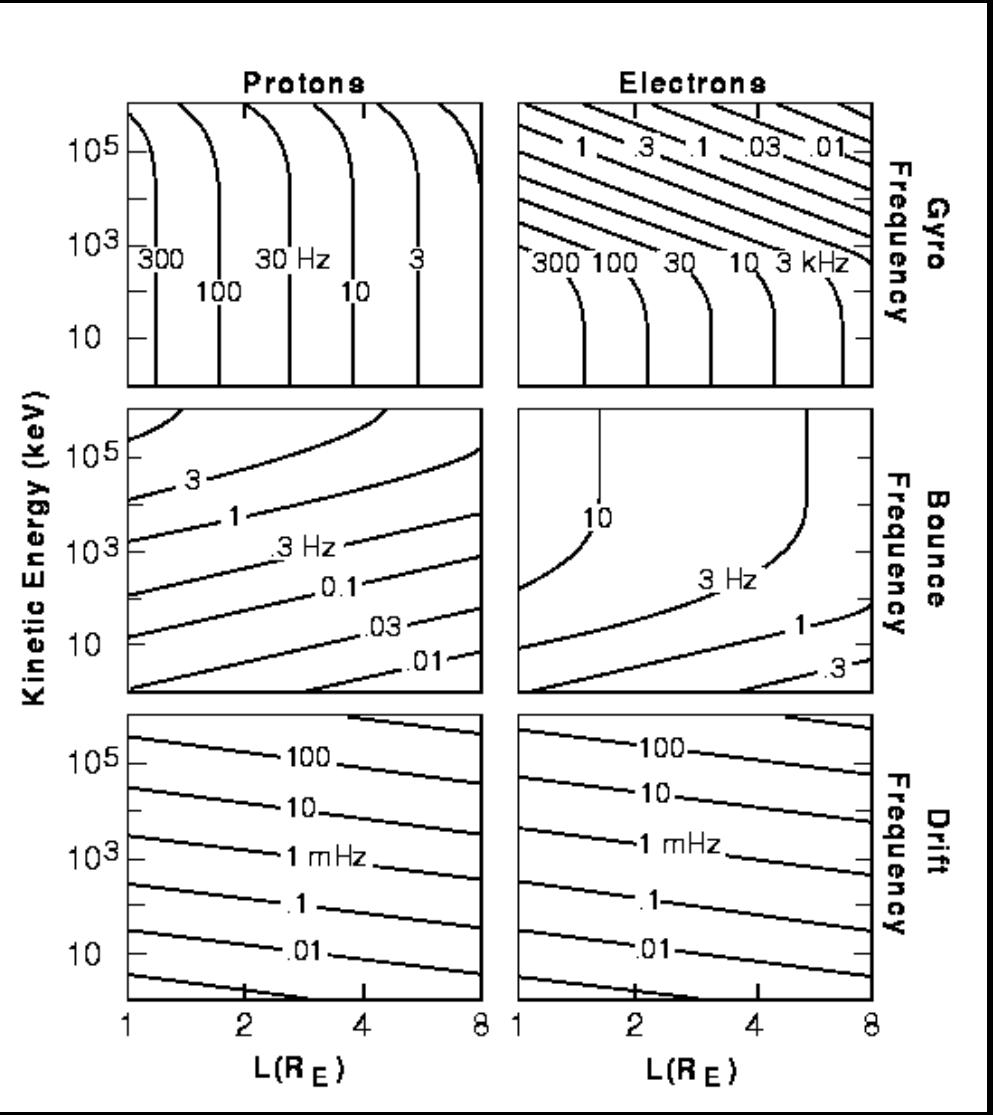
$$\Theta = \int B dS$$

Helical trajectory
Pitch angle, **α**

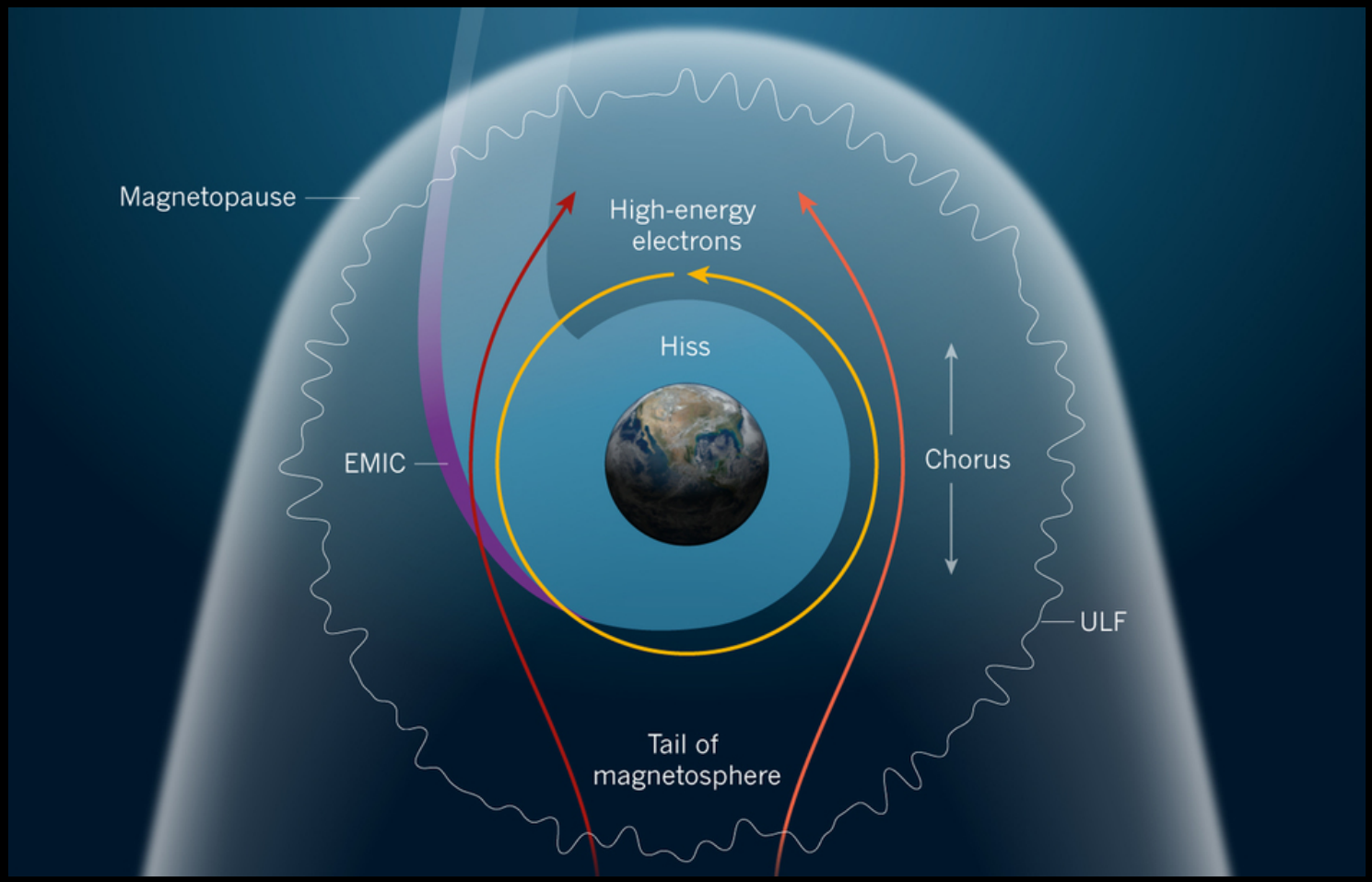


# Characteristic timescales

Wave-particle interactions are associated with violation of adiabatic invariants – see the timescales as a function of L and energy on the right.



# Locations of different wave modes




Locations of different wave types that may interact with radiation belt electrons as they drift around the Earth. Hudson (2013).

# ULF waves

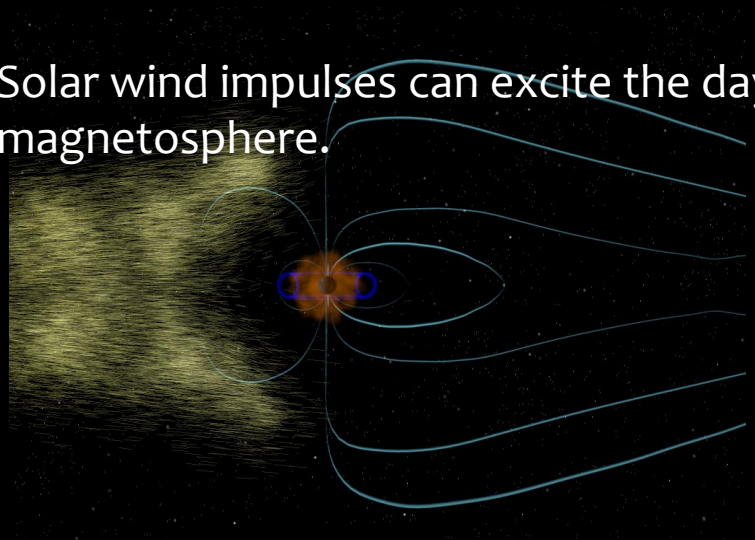
- Geomagnetic pulsations or ultra-low-frequency (ULF) waves cover roughly the frequency range from 1 mHz to 1 Hz.
- Largest wavelengths and lowest frequencies in system.
- Amplitudes ~a few nT in B, and ~ a few mV/m in E.

| Pulsation classes | | | | | | |
|---|---|---|---|---|---|---|
| Continuous | | | | | Irregular | |
| Pc1 | Pc2 | Pc3 | Pc4 | Pc5 | Pi1 | Pi2 |
| 0.2-5s | 5-10s | 10-45s | 45-150s | 150-600s | 1-40s | 40-150s |
| 0.2-5Hz | 0.1-0.2Hz | 22-100mHz | 7-22mHz | 2-7mHz | 0.025-1Hz | 2-25mHz |

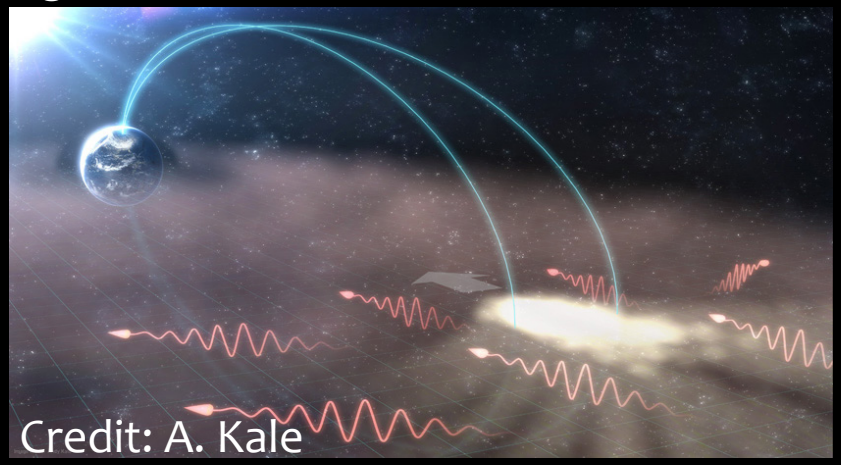
ULF wave classification according to type and period (Jacobs, et al., 1964).

# ULF wave excitation

Solar wind impulses can excite the dayside magnetosphere.



Instabilities and bursty bulk flows, or reconnection, may excite ULF waves on the night side.




Kelvin-Helmholtz "wind-over-water" instability on the flanks can excite ULF waves.

More about ULF waves: Mike Hartinger's tutorial on Friday.

# Pc5 waves: effect on radiation belts

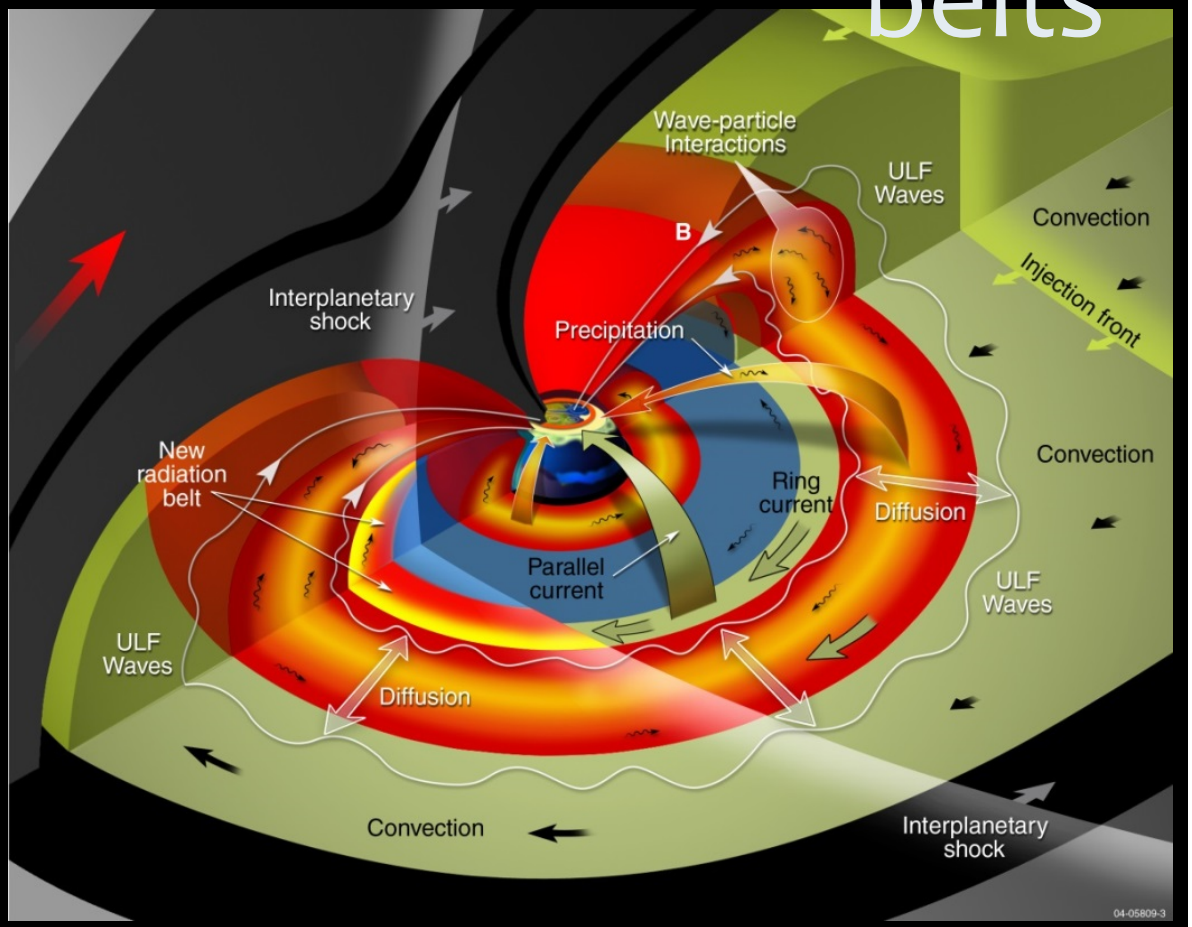
Inward radial transport and first-invariant conserving acceleration (Elkington et al., 2006).

Loss due to outward radial diffusion (Turner et al., 2011).

Precipitation due to altering pitch-angles (Brito et al., 2015).

Modulation of higher-frequency wave growth (Loto'aniu et al., 2009; Li et al., 2011; Breneman et al., 2015; Nemec et al., 2015).

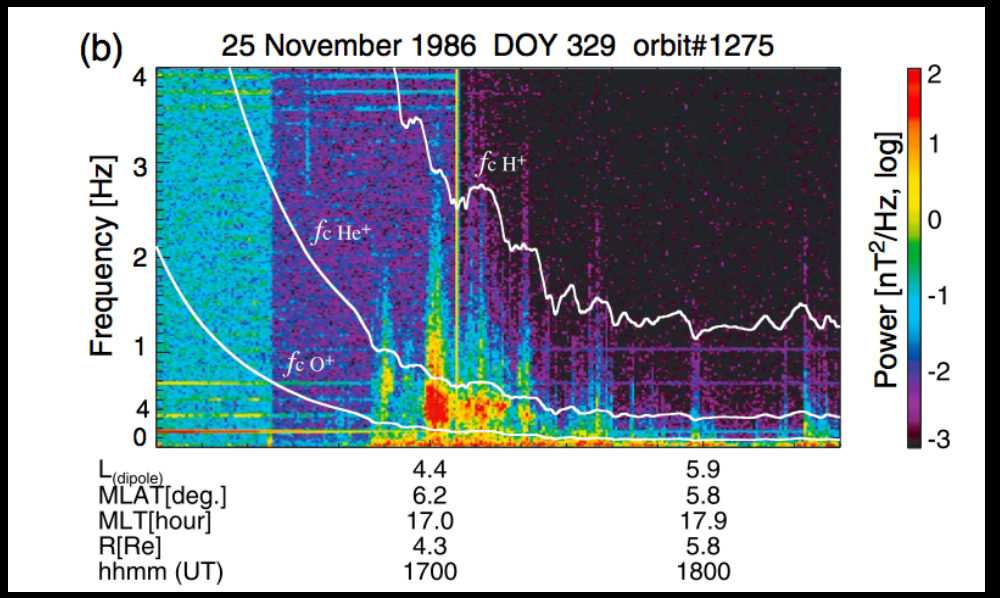
Drift resonance leads to more rapid transport at selected energies (Mann et al., 2013).




Mauk et al., 2012

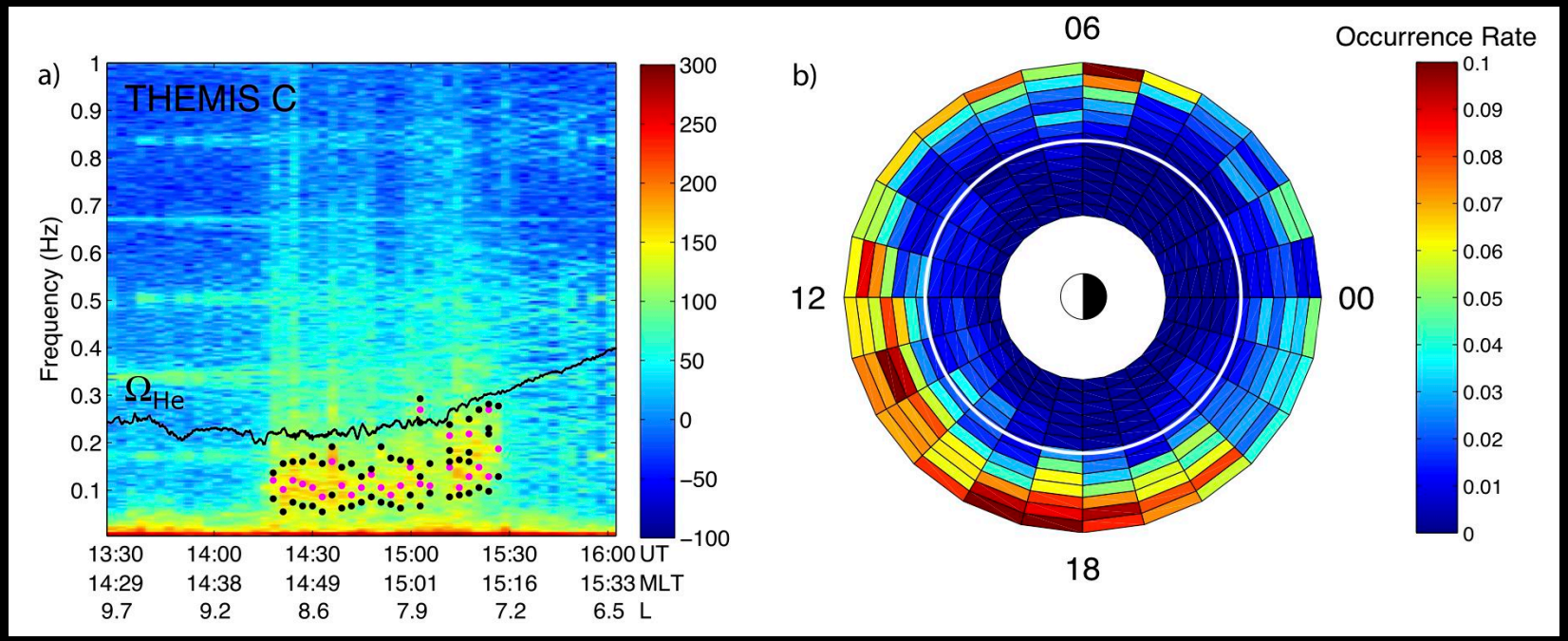
# EMIC (electromagnetic ion cyclotron) waves

- Transverse plasma waves generated by wave-particle interaction (ion cyclotron instability).
- Energy source: 10 - 100 keV protons with $T_{perp} > T_{para}$.
- Typical amplitudes in space: ~1 - 10 nT in B, ~1 mV/m in E.
- Three bands below $H^+$, $He^+$, $O^+$
- Typical frequencies: 0.1 - 5 Hz (Pc 1 range) – technically still ULF waves…
- Can cause precipitation of both ~10-100 keV protons and ~MeV electrons (Miyoshi et al., 2008).




Keika et al., 2013

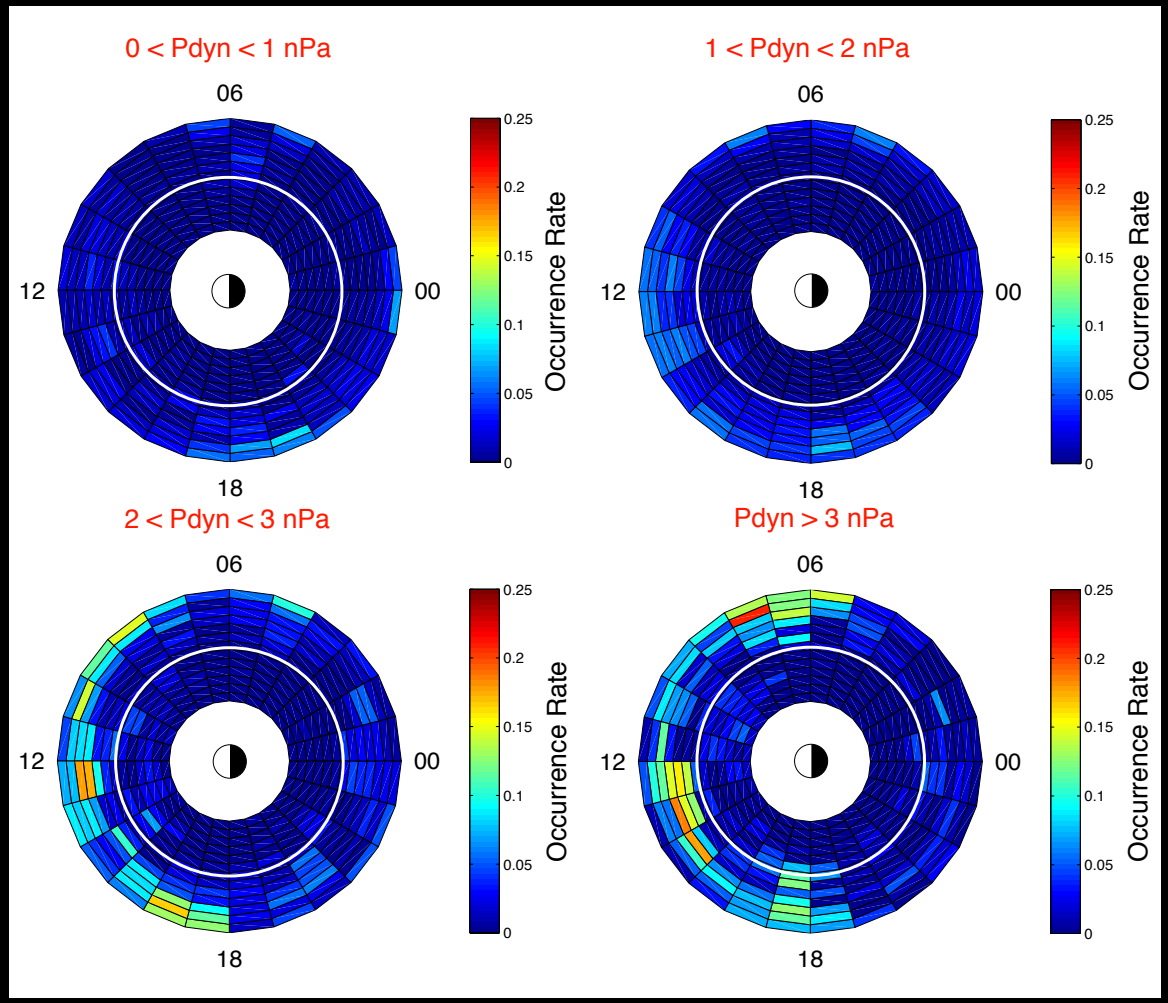
# EMIC occurrence




Usanova et al., 2012
THEMIS statistics 2007-2011.

EMIC occurrence in the inner magnetosphere is low.
Most wave events observed beyond GEO orbit on the dayside.

# EMIC occurrence vs. solar wind $P_{dyn}$

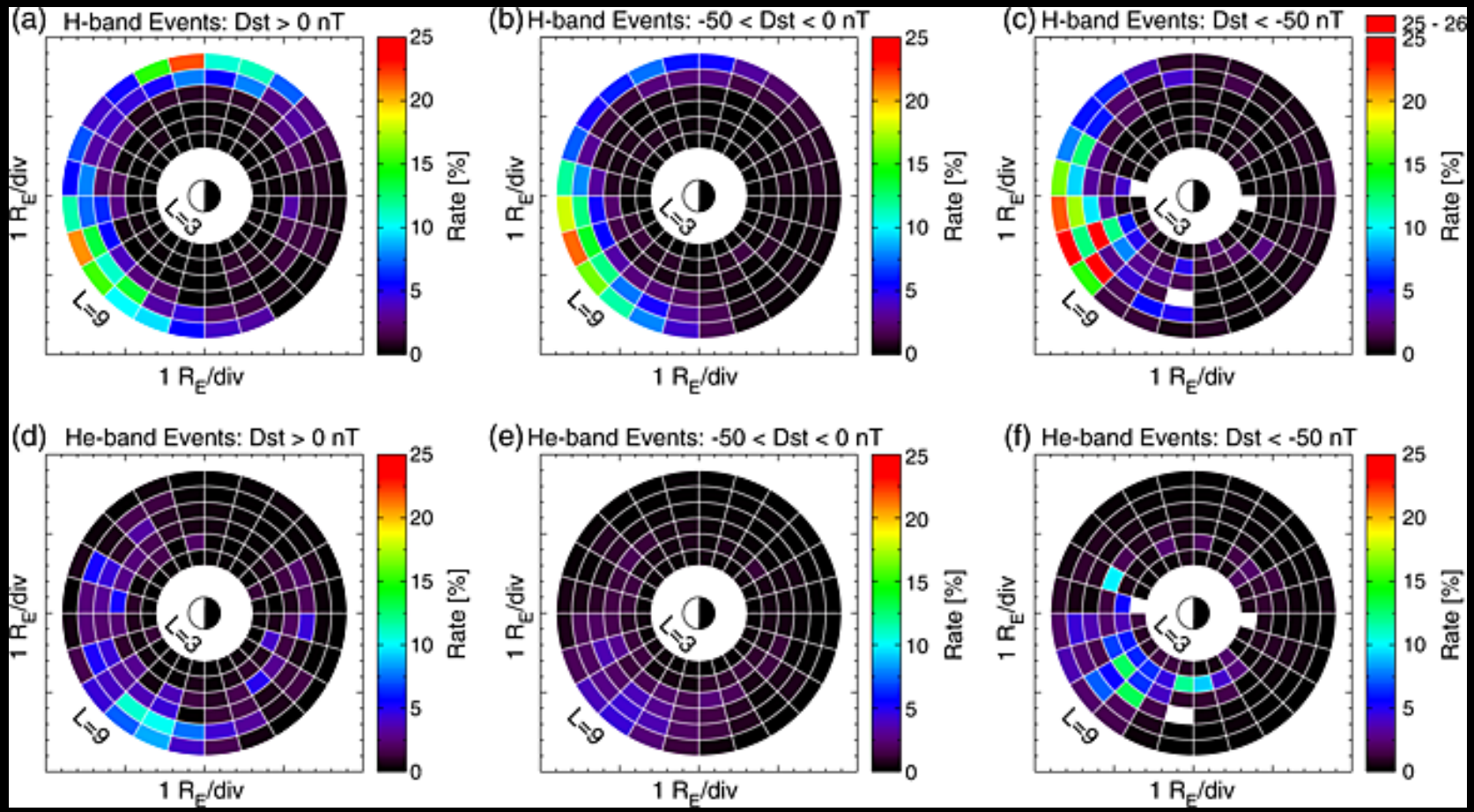



Probability increases with L-shell and solar wind dynamic pressure.

THEMIS statistics 2007-2011

Usanova et al., 2012

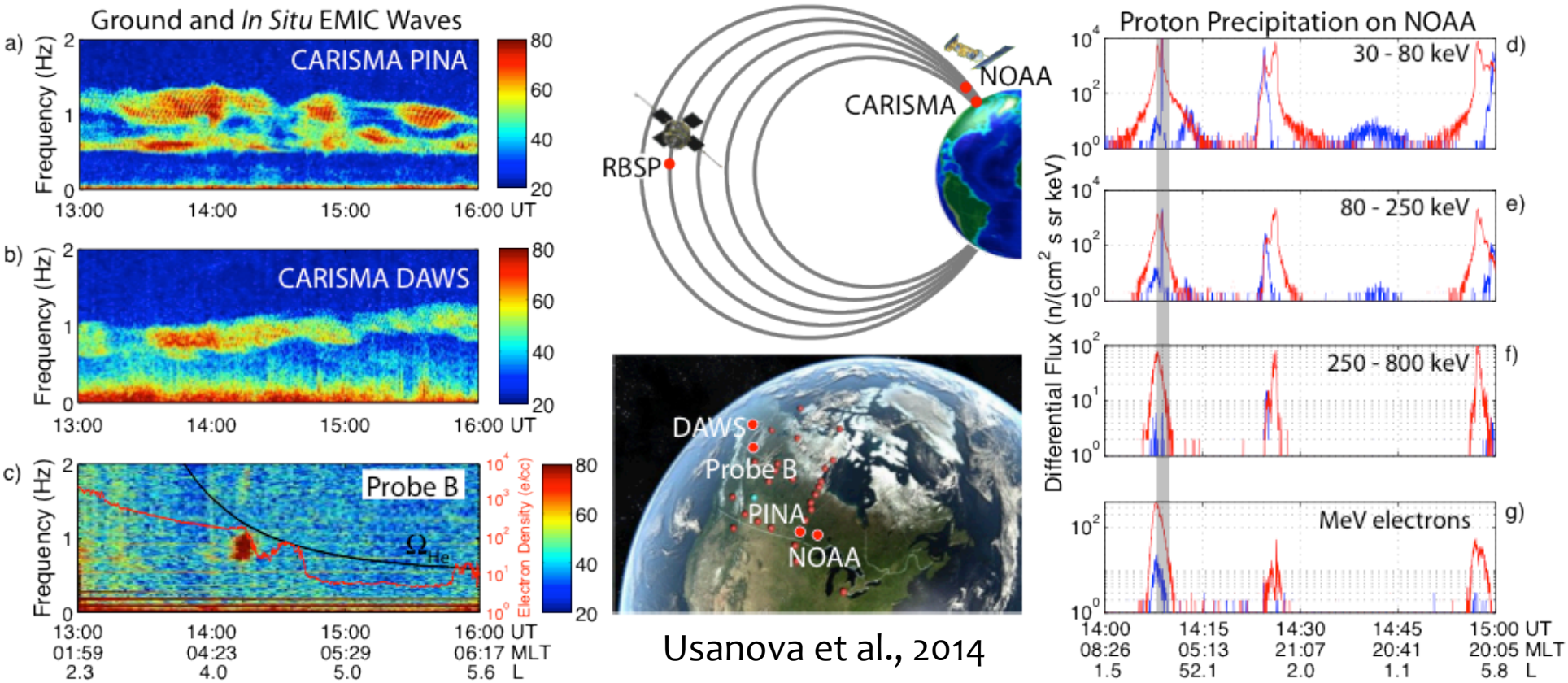
# EMIC wave occurrence




4.5 years of AMPTE/CCE data. Probability increases during compressions (positive Dst) and disturbed conditions (negative Dst). Keika et al., 2013

He band is often excited in the inner duskside magnetosphere during storms.

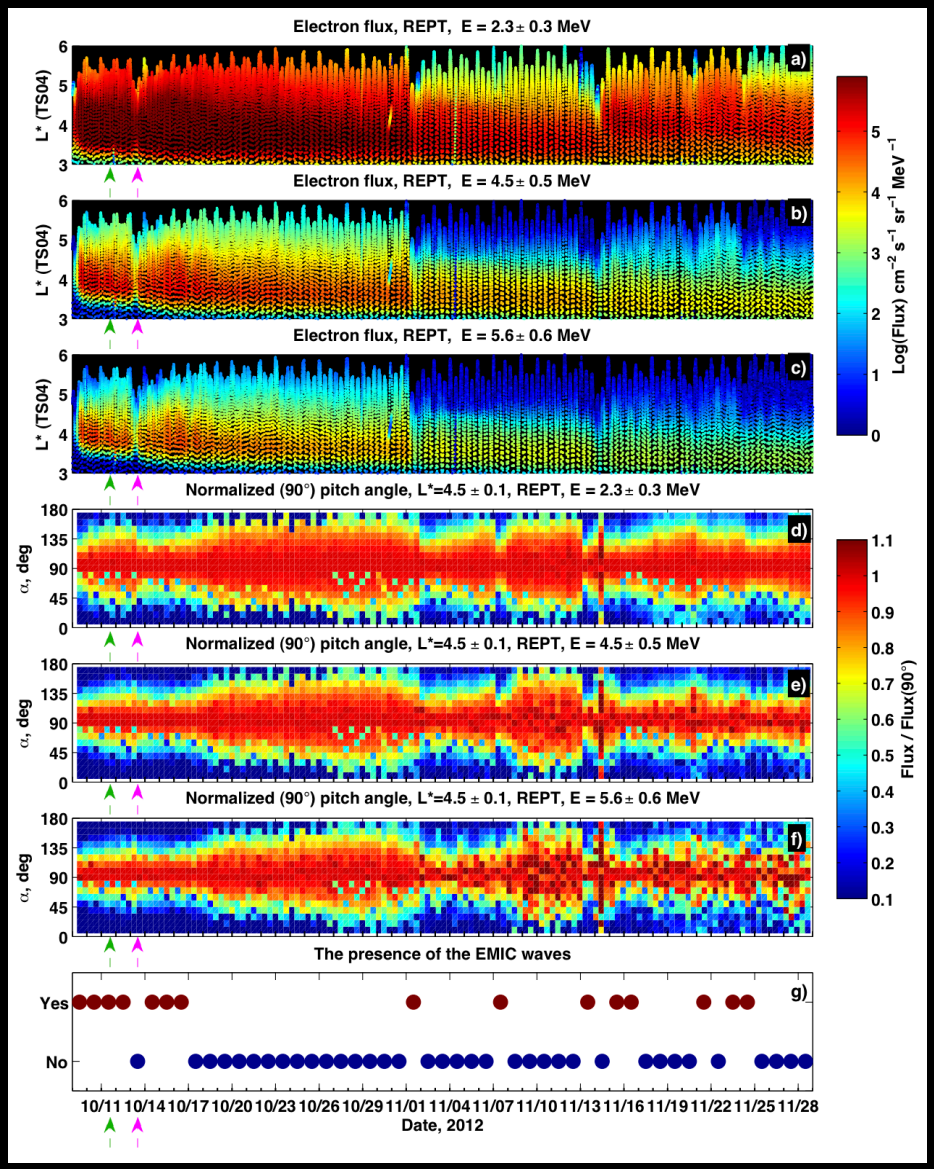
# EMIC waves and proton loss




Usanova et al., 2014

Conjugate EMIC wave observations from the CARISMA magnetometers and the Van Allen Probes together with proton loss on the LEO-orbit NOAA POES satellite on October 11, 2012. No MeV electron loss observed.

# Electron pitch-angle scattering by EMIC waves

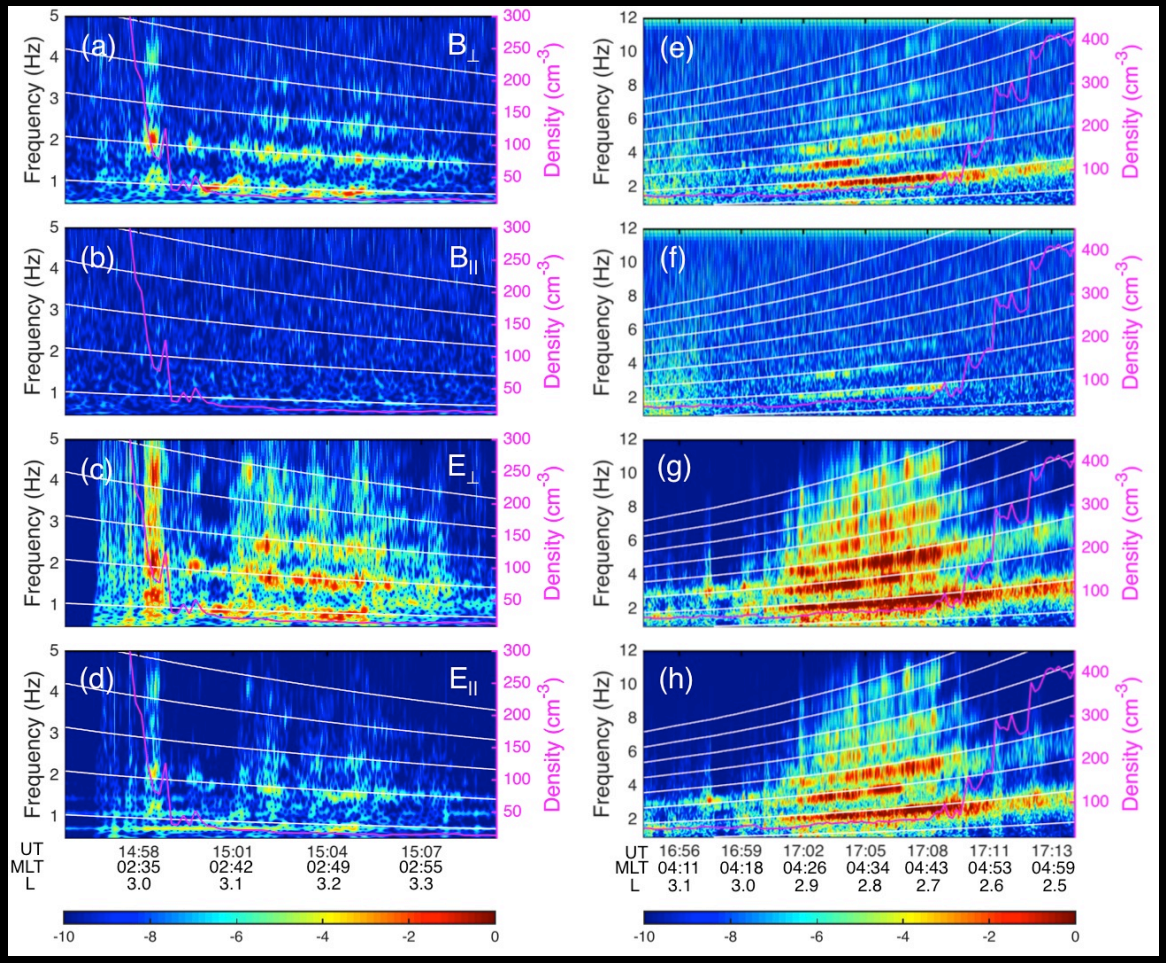



- Differential electron flux as a function of L* (a-c), and normalized differential flux as a function of PA L*=4.5 (d-f) in the 2.3, 4.5, and 5.6 MeV energy channels,, and EMIC wave occurrence from L~4-4.5 on the ground from October 9 to November 29, 2012.
- EMIC waves scatter low-pitch angle particles but cannot interact with > ~45 degree pitch-angle electrons.
- Other waves modes are required to act simultaneously with EMICs to remove the core 90-degree population.

Usanova et al., 2014

# Oxygen ion cyclotron harmonic waves

Nov 11, 2012 March 17, 2013

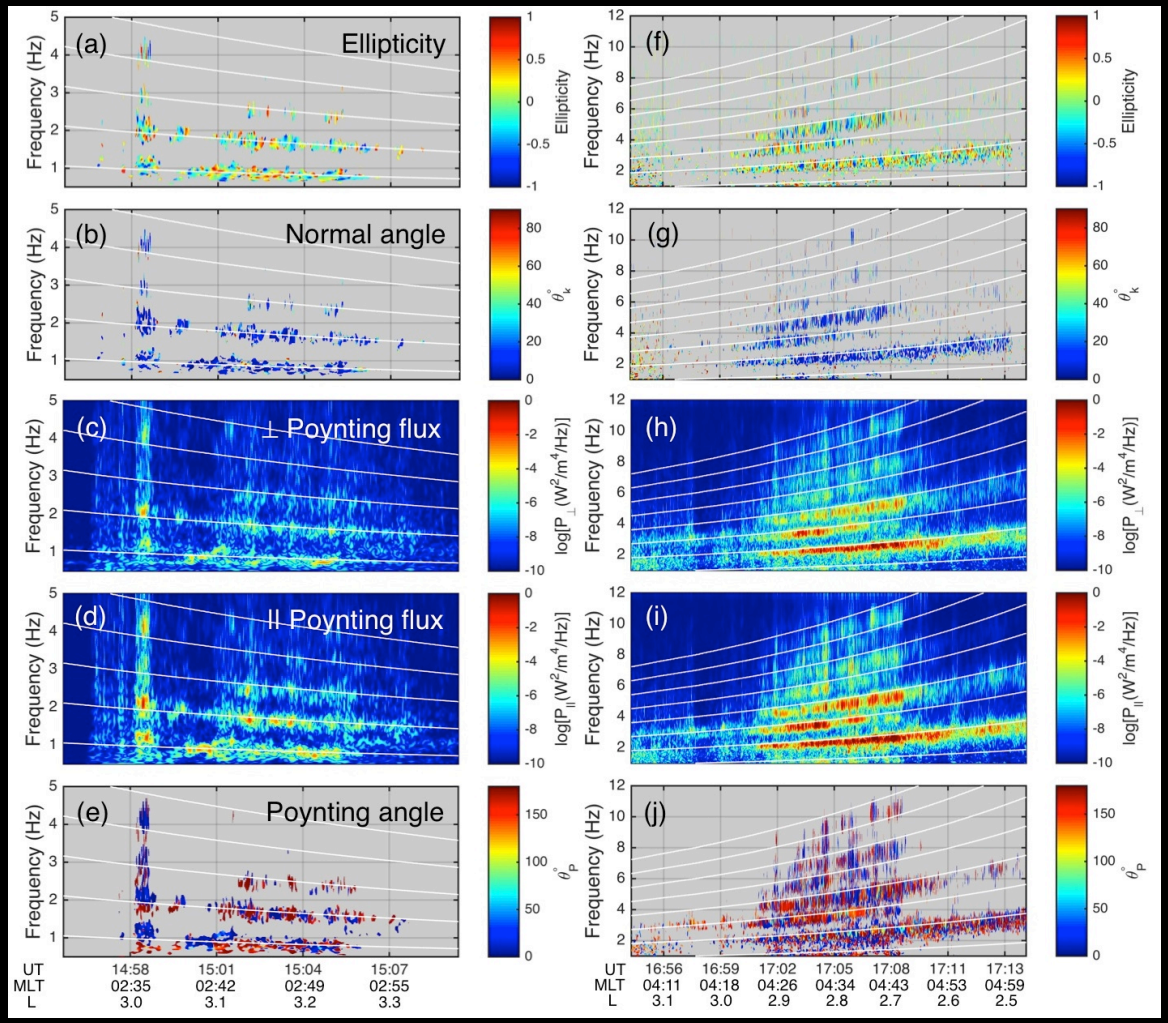



Usanova et al., submitted to GRL

- Waves at oxygen cyclotron frequency and its harmonics.
- Frequency: ~a few-several Hz.
- Transverse electromagnetic: a few nT in B, ~a few mV/m in E.
- Propagate almost parallel to the background magnetic field.
- Observed mostly outside the plasmapause (magenta curve).

# Oxygen ion cyclotron harmonic waves

Nov 11, 2012 March 17, 2013



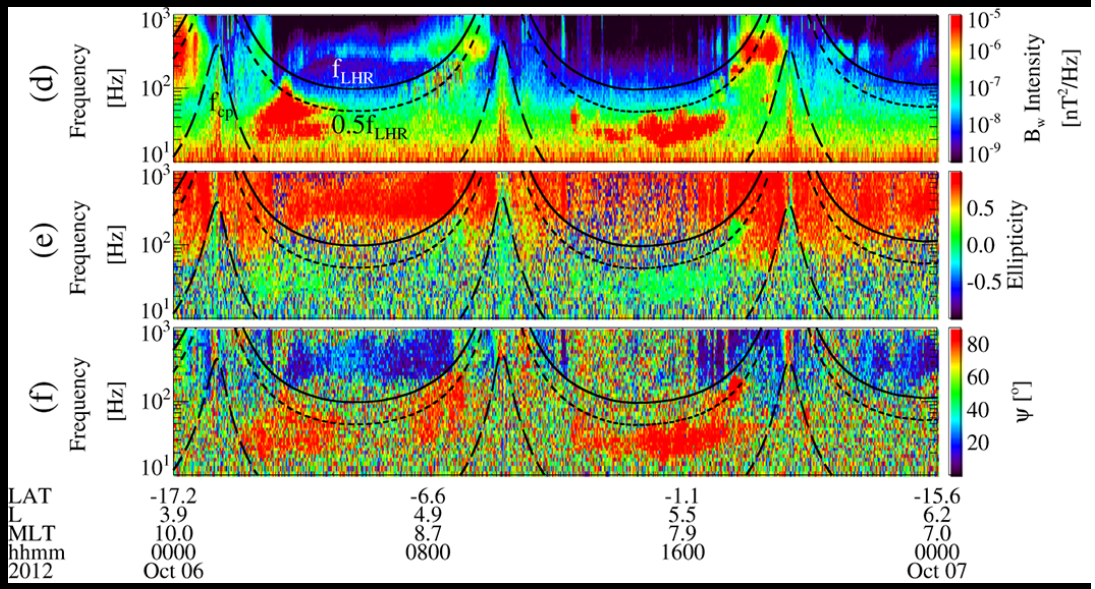

Usanova et al., submitted to GRL

- Mixed ellipticity.
- Normal angle <20 degrees.
- Dominant parallel energy flux.
- Bi-directional propagation – waves in the source region.

- Both events observed during a drop-out of ~ a few MeV electrons – may contribute to loss.

# Magnetosonic waves (aka equatorial noise)

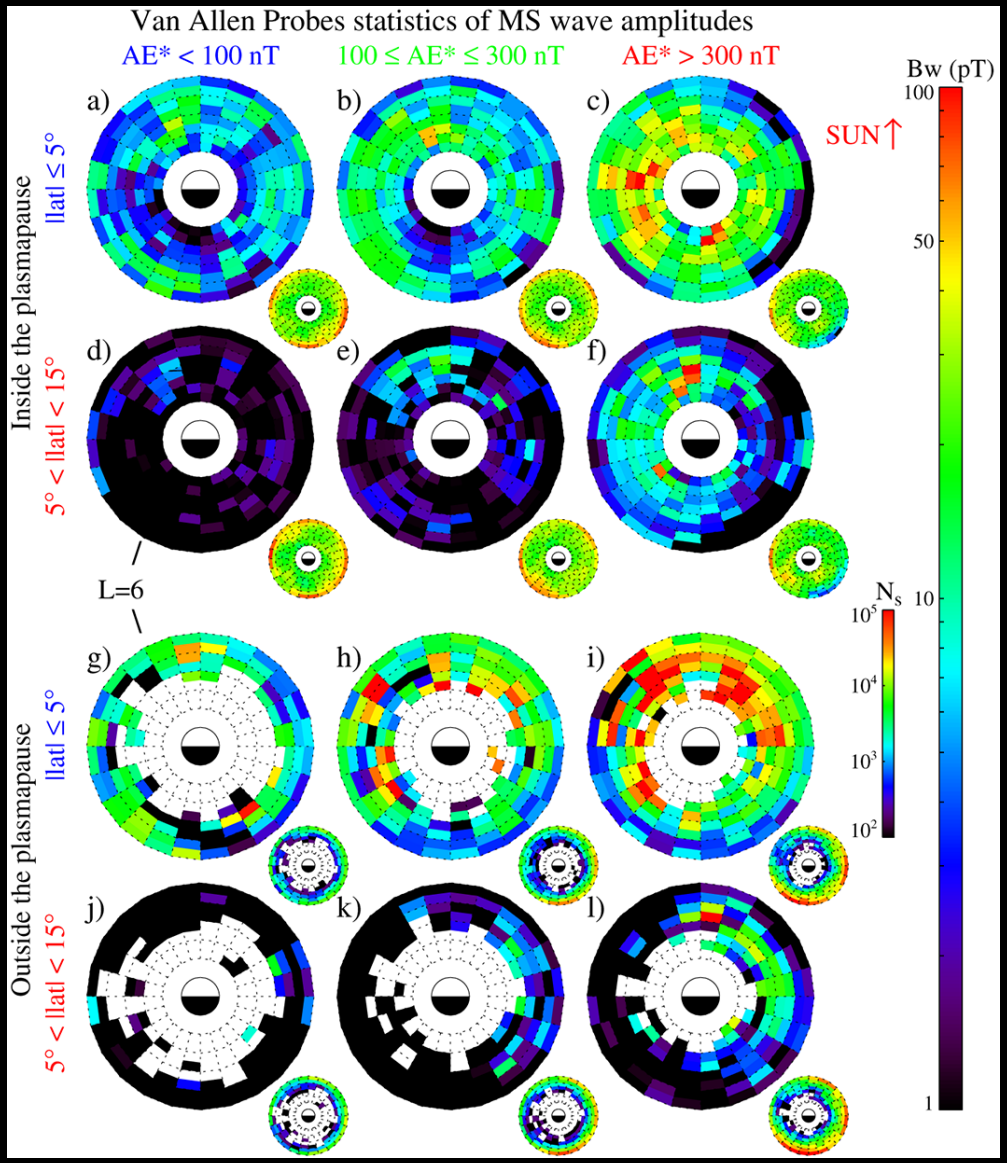
- Longitudinal electromagnetic waves.
- Frequency: a few-100 Hz
- Amplitudes ~1-50 pT.
- Frequencies between the proton gyrofrequency ($f_{cp}$) and the lower hybrid resonance frequency ($f_{LHR}$).
- Generated near the magnetic equator.
- Propagate perpendicular to the background magnetic field.
- Energy source: ~10 keV protons with positive gradients in the perpendicular velocity distribution.
- Can accelerate energetic electrons via Landau resonance from ~100 keV to ~MeV on a timescale of several days outside the plasmapause (Ma et al., 2016).
- Can scatter 90-degree pitch angle electrons due to bounce resonance (Shprits 2009).




Ma et al., 2016

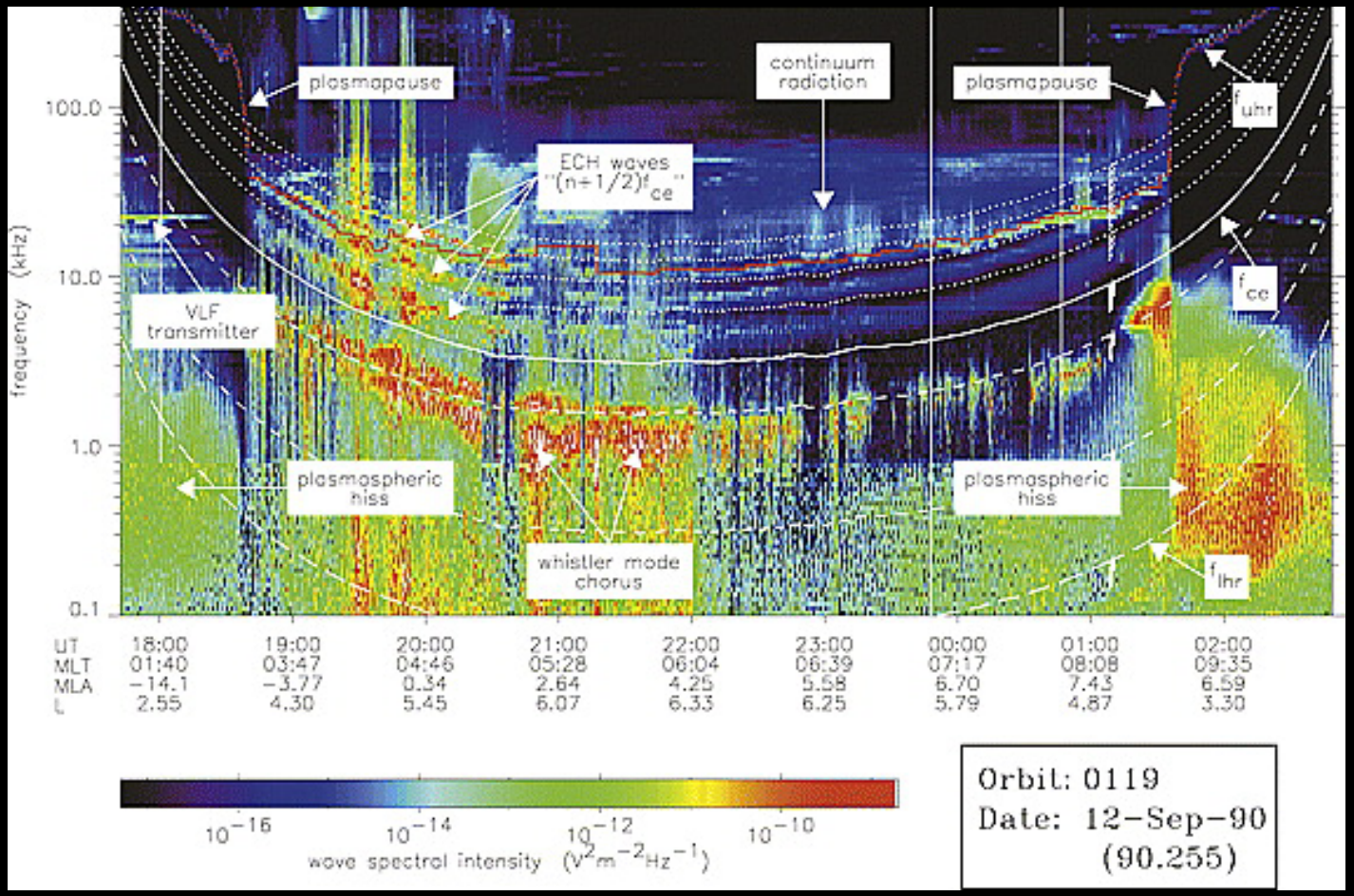
# Magnetosonic wave distribution

Strongest MS waves (~50 pT and occurrence rate of ~20%) near the magnetic equator, in the dawn sector outside the plasmapause, under disturbed conditions.




Van Allen Probes statistics
Oct 2012-Apr 2015
Ma et al., 2016

# Whistler-mode waves: chorus and hiss

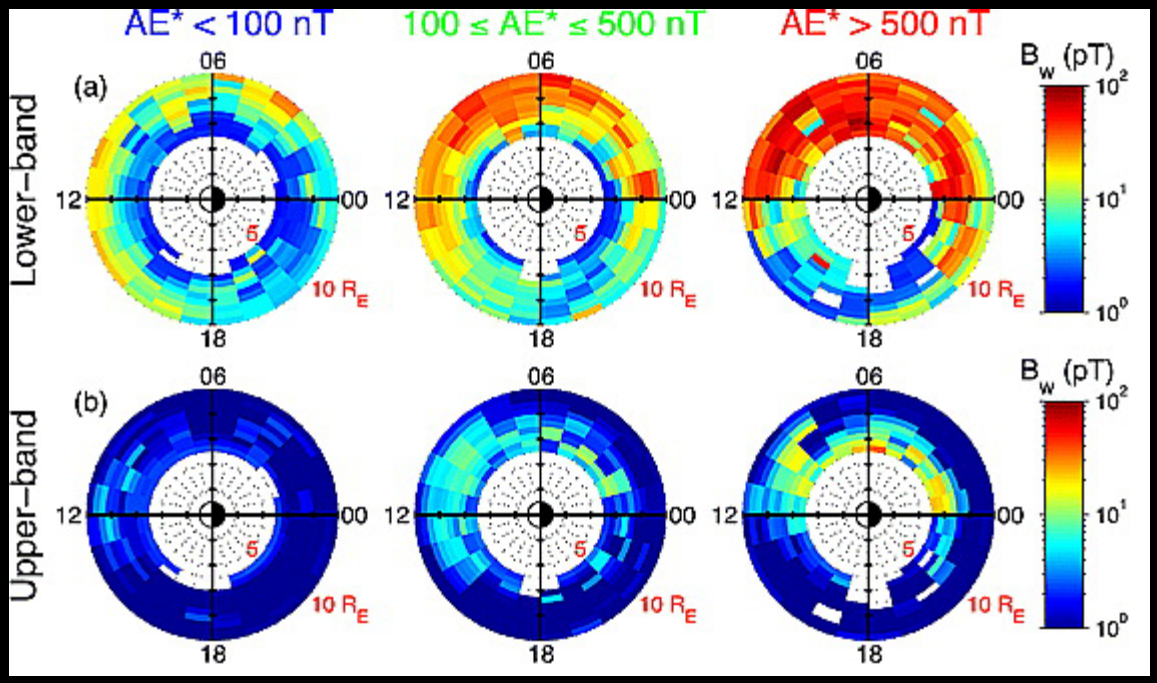



CRRES observations: hiss inside the plasmapshere, chorus outside
Meredith et al., 2004

# Whistler-mode waves: chorus

- Electromagnetic plasma waves.
- Frequency 0.1-0.8 $f_{ce}$, with a gap near 0.5 $f_{ce}$, where $f_{ce}$ is the equatorial electron cyclotron frequency that splits the spectra into lower and upper-band chorus.
- Amplitude: 10-100 pT in B, 1-10 mV/m in E.
- Large amplitude and short-living (.1s) chorus with E>100 mV/m (e.g. Cully et al., 2008) – see non-linear waves and time-domain structures below.
- Source: anisotropic ~tens keV electron distributions with $T_{perp}>T_{para}$ injected from the plasma sheet during geomagnetically active times.
- Source region is generally believed to be near the equator.
- Important role in both acceleration and loss processes of energetic electrons in the inner magnetosphere:
  - Lower-band chorus loss of 10-100 keV electrons;
  - Upper-band chorus loss of a ~few keV electrons.

# Chorus distribution




Chorus waves are usually observed in the low-density region, outside the plasmapause from midnight through dawn to the afternoon sector.

Global distribution of (a) lower-band chorus and (b) upper-band chorus on THEMIS.

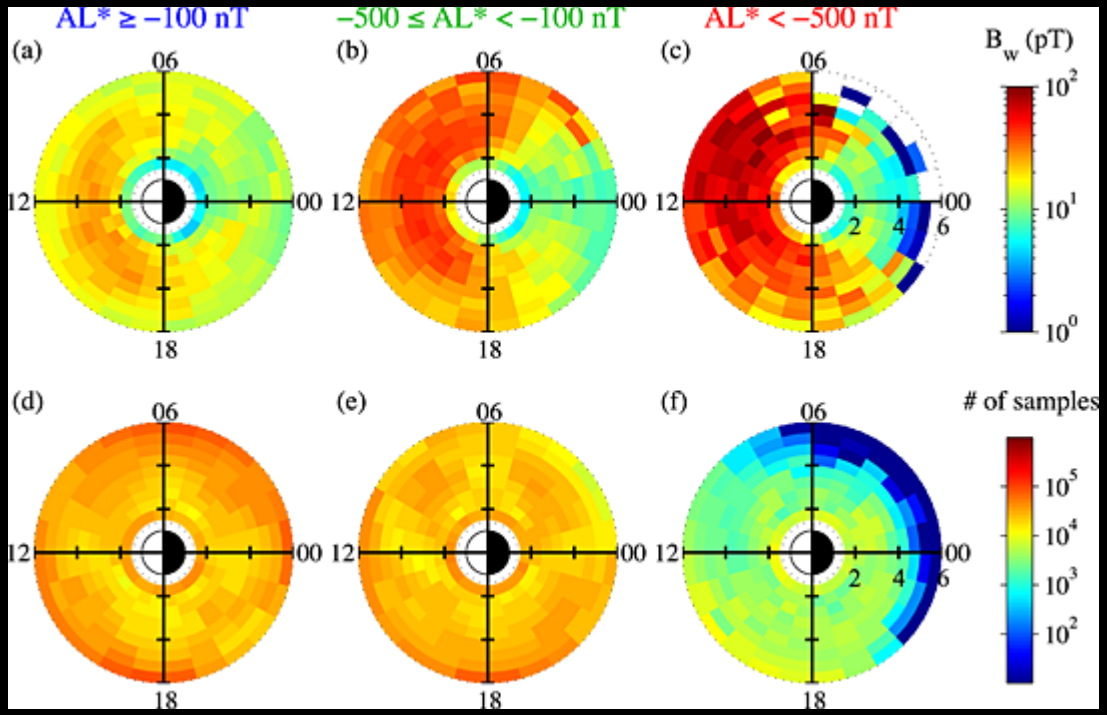
More intense waves are observed during geomagnetically active times.

Lower band chorus has higher amplitudes.
Li et al., 2011

# Whistler-mode waves: hiss

- Hiss: mostly incoherent, whistler-mode plasma waves.
- Observed inside the plasmapause.
- Broadband emissions in 100 Hz – 2 kHz range, peak freq. of 550 Hz (some unusual >20 Hz hiss observed on Van Allen Probes, *Li et al.* 2013).
- Amplitude 10-100 pT.
- Parallel propagating in generation region.
- Chorus may provide the source – propagates through plasmapause to evolve into hiss (Bortnik et al., 2008).
- Most efficient for lower energy electrons.
- Mainly causes pitch-angle scattering and precipitation into the atmosphere:
  - <1 MeV electrons: timescales of days (or less).
  - 1-10 MeV electrons: timescales of 10's-100's of days.

# Hiss distribution

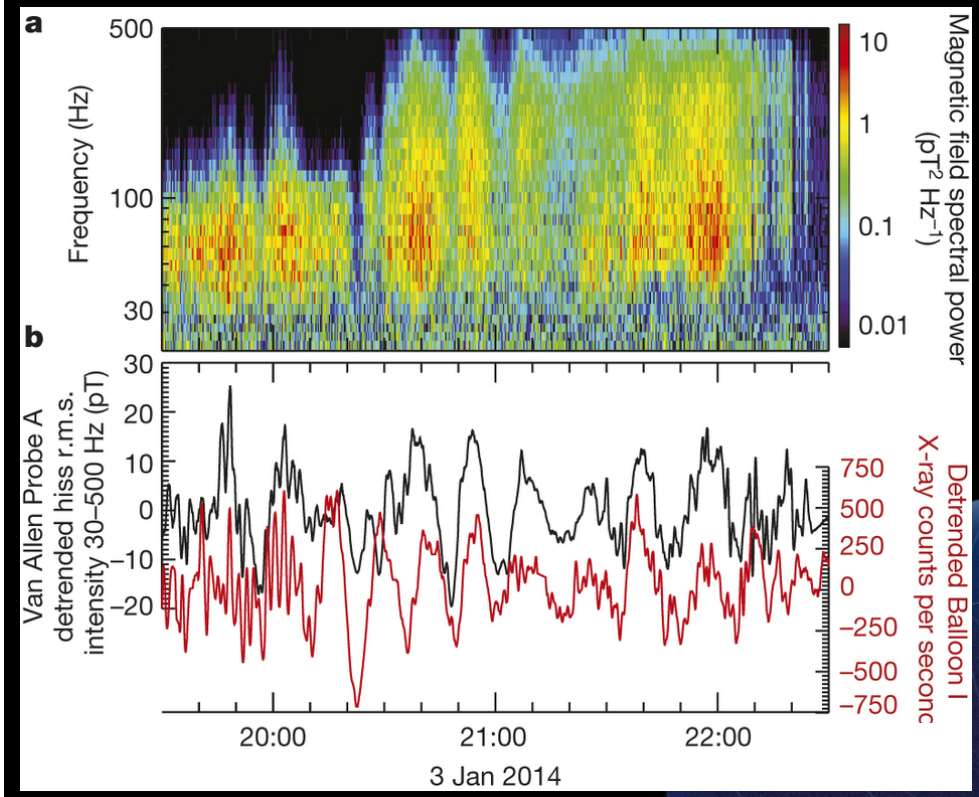



Global distribution from Van Allen Probes; October 2012-2014. The equatorial hiss amplitudes exhibit pronounced increase with substorm activity and also show a substantial day-night asymmetry.

Li et al., 2015

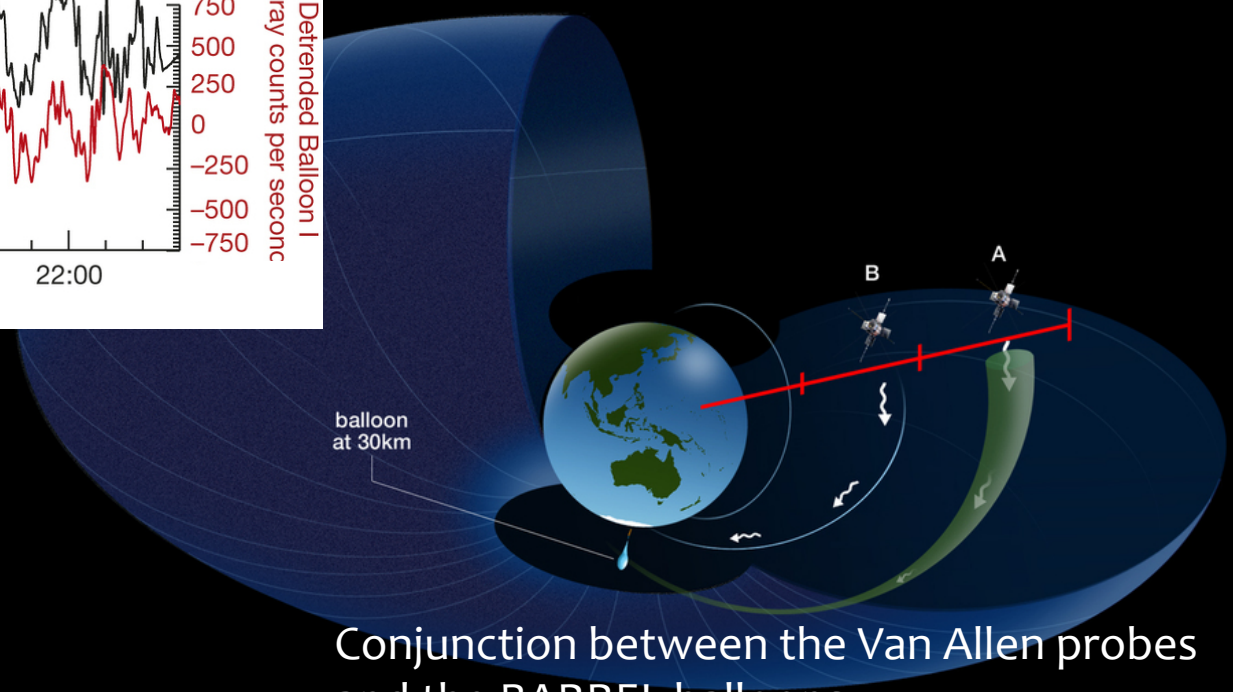
Consistent with CRRES statistics by Meredith et al., 2004.

# Hiss-induced 10-200 keV electron precipitation



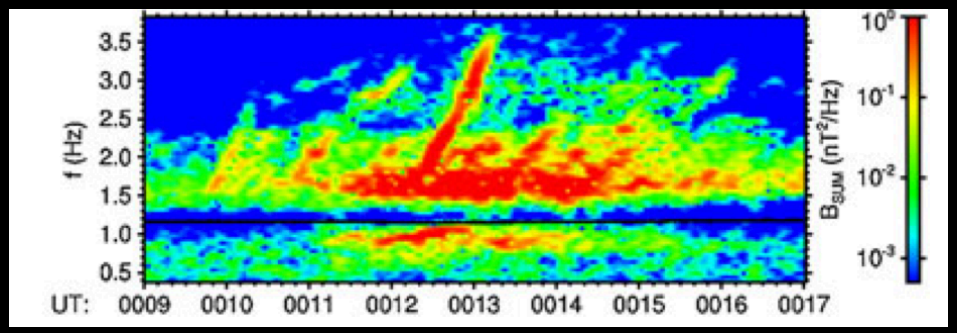

Breneman et al., 2015

- Hiss intensities are coherent with X-ray counts on the BARREL balloon (Millan et al., 2013) due to energetic electron precipitation.
- ULF wave modulation of hiss growth and precipitation.

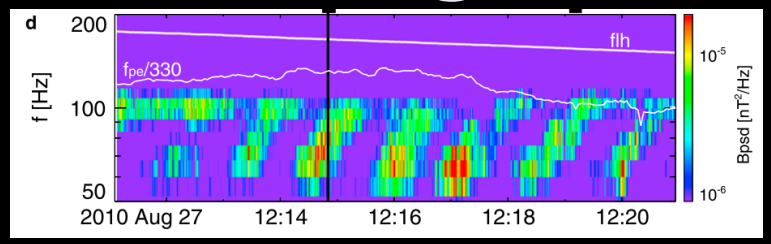



Conjunction between the Van Allen probes and the BARREL balloons.

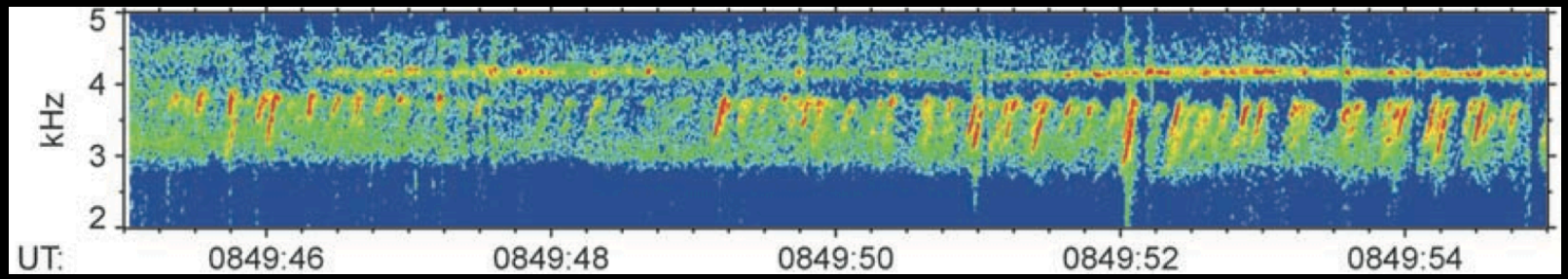
# Non-linear EMIC, magnetosonic, whistler waves: rising tones




Cluster EMIC waves: Grison, 2013



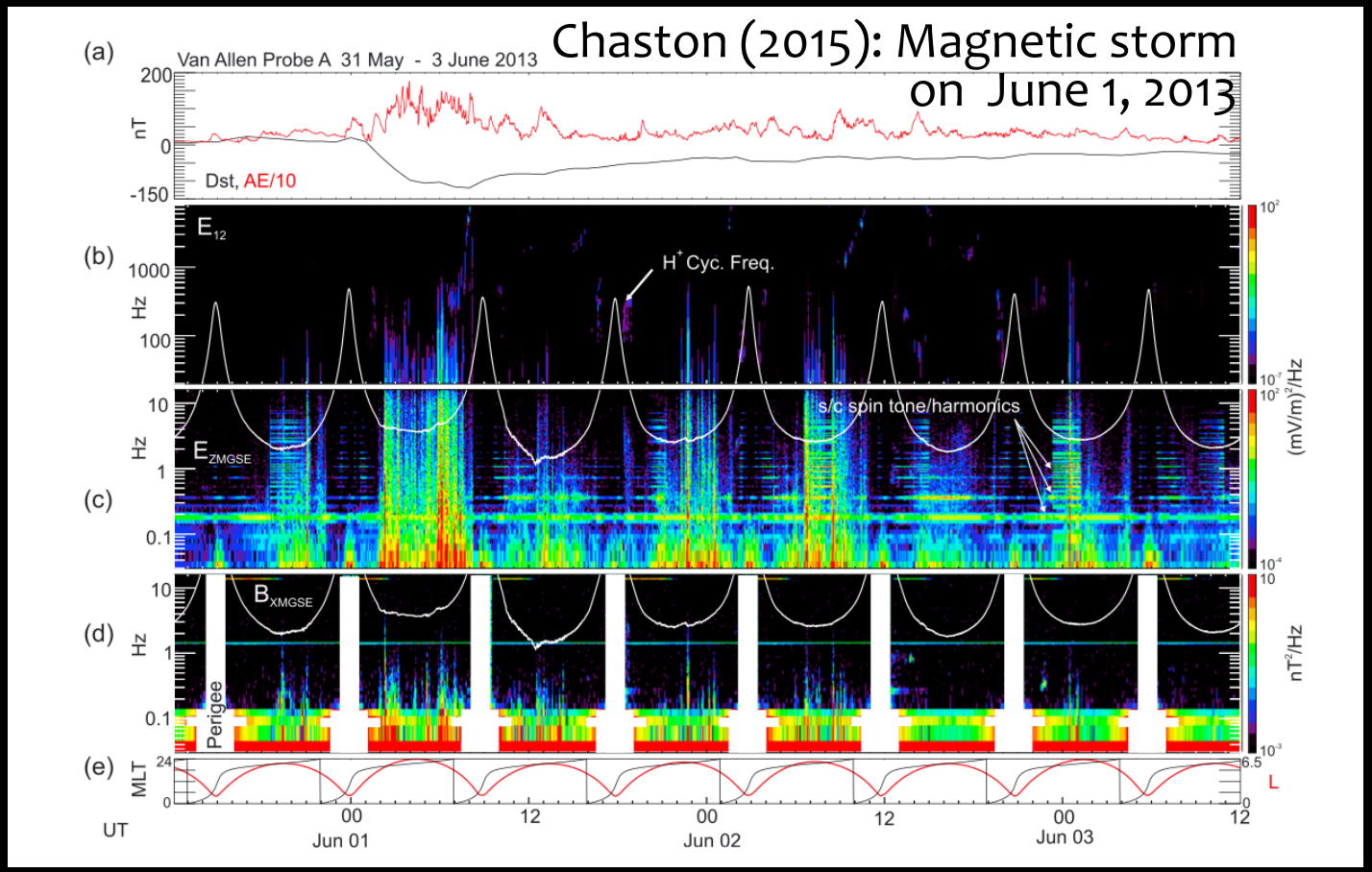

THEMIS magnetosonic waves: Fu et al., 2014




Cluster chorus waves: Santolik and Gurnett, 2003

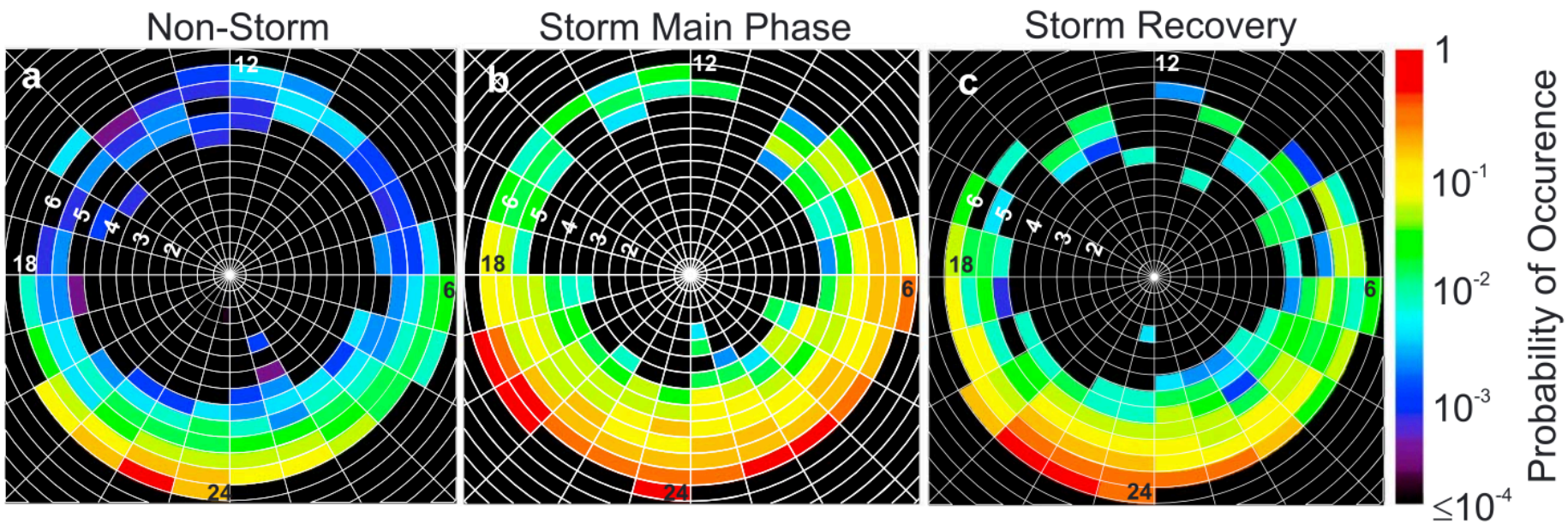
Non-linear wave particle-interaction causes effective pitch angle scattering and can induce relativistic electron microbursts (Omura et al., 2008; Omura and Zhao, 2013).

# Broad-band electromagnetic waves




- Kinetic Alfvén waves are extension of MHD Alfvén waves to the range of short (kinetic) cross-field scales comparable to the ion gyroradius and to the electron inertial length.
- Can cause acceleration and heating of ions and electrons.
- Interact non-linearly with each other and form a power-law turbulent spectrum.
- Often correlated with time domain structures – see next slide.

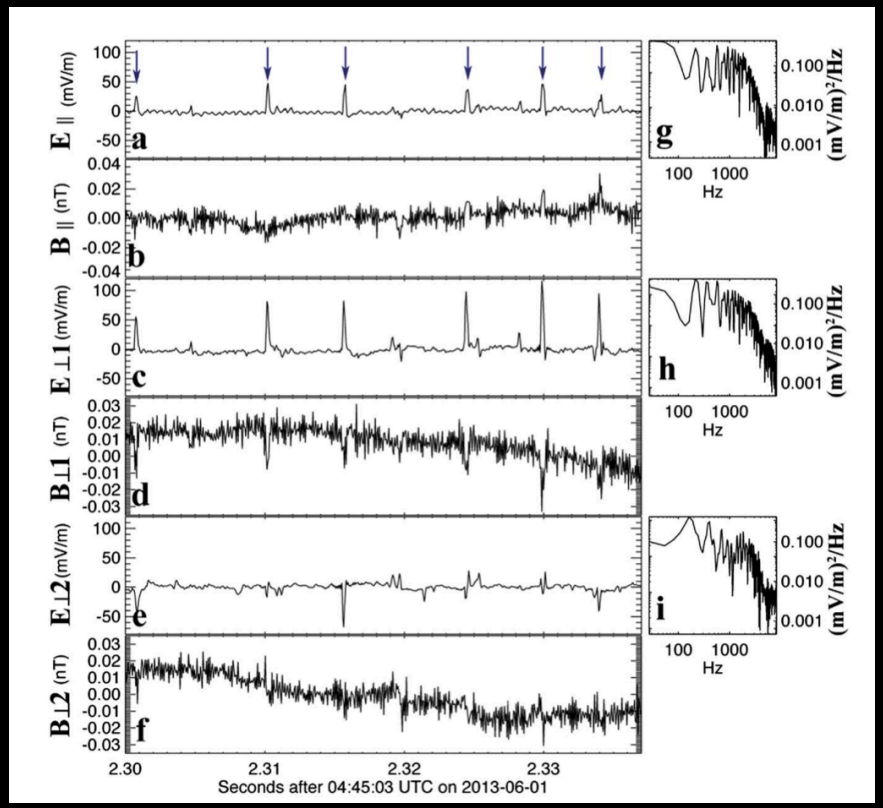
# Broad-band electromagnetic waves: occurrence




Chaston et al. (2015 ): Very common!
Most commonly occur on the nightside at L>4;
occasionally at L~2.5.

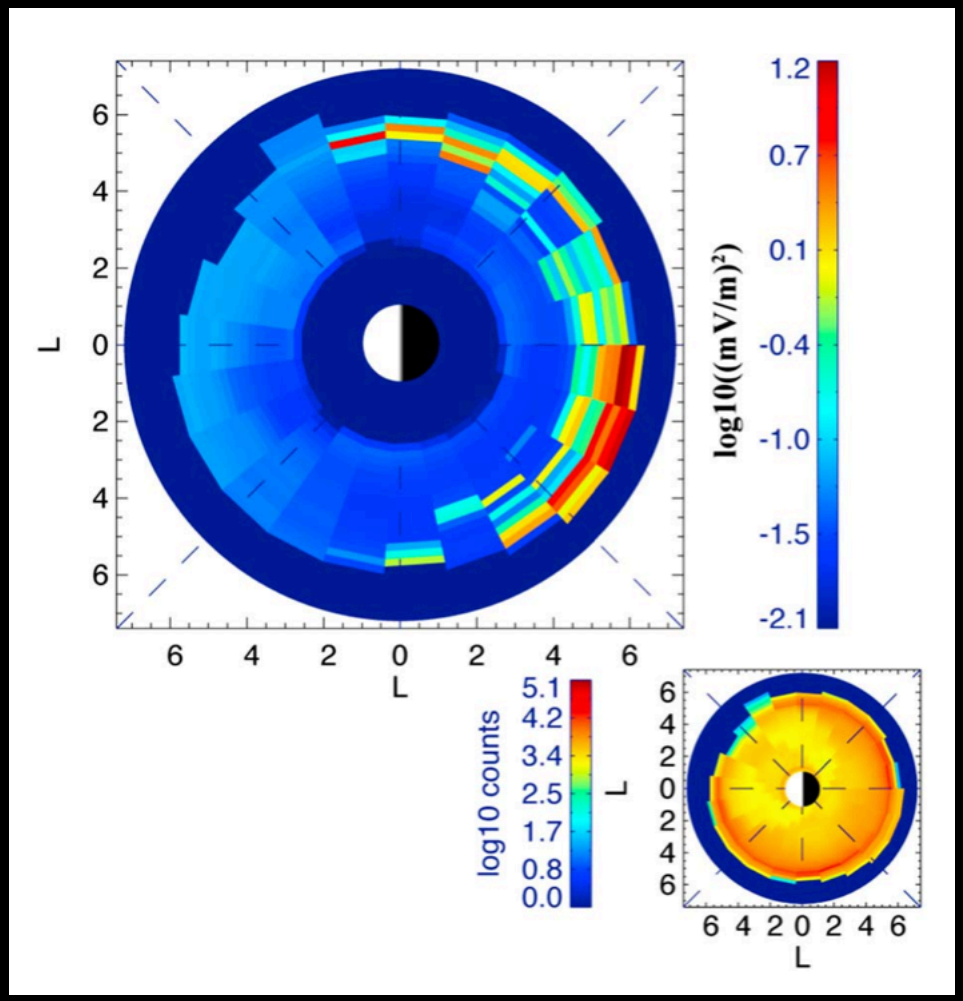
# Time-domain structures (TDS)

- TDS are packets of E-field spikes.
- Spikes last for a few 100ms.
- Contain a local parallel electric field (Mozer et al., 2013, 2015; Malaspina et al., 2014) up to ~100 mV/m.
- Mechanism for producing the ~100 keV electrons further accelerated to ~MeV energies by whistler waves (Mozer et al., 2014).




Malaspina et al., 2014

# TDS distribution




Malaspina et al., 2014

- Strongest at high *L* and weaken closer to Earth.
- A concentration of high amplitudes is observed premidnight.
- Dawn-dusk symmetry.

# Summary

- Radiation belt dynamics is affected by the interaction with different wave modes.
- ULF waves: high-amplitude and long-lasting, cause radial transport, energization and loss.
- EMIC waves: pitch-angle scattering and loss close to loss cone; most efficient for multi-MeV electrons, don't interact with 90-degree pitch-angle electrons.
- Ion harmonic waves: may contribute to loss.
- Chorus: both acceleration and loss.
- Hiss: slow loss over a large range of energies.
- Magnetosonic waves: energization from ~10 keV to ~MeV, less efficient than chorus and hiss.
- Kinetic Alfven waves: may provide seed population for further energization by chorus.
- Time-domain structures: seed population for further energization by chorus. Large electric fields but very short living.

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