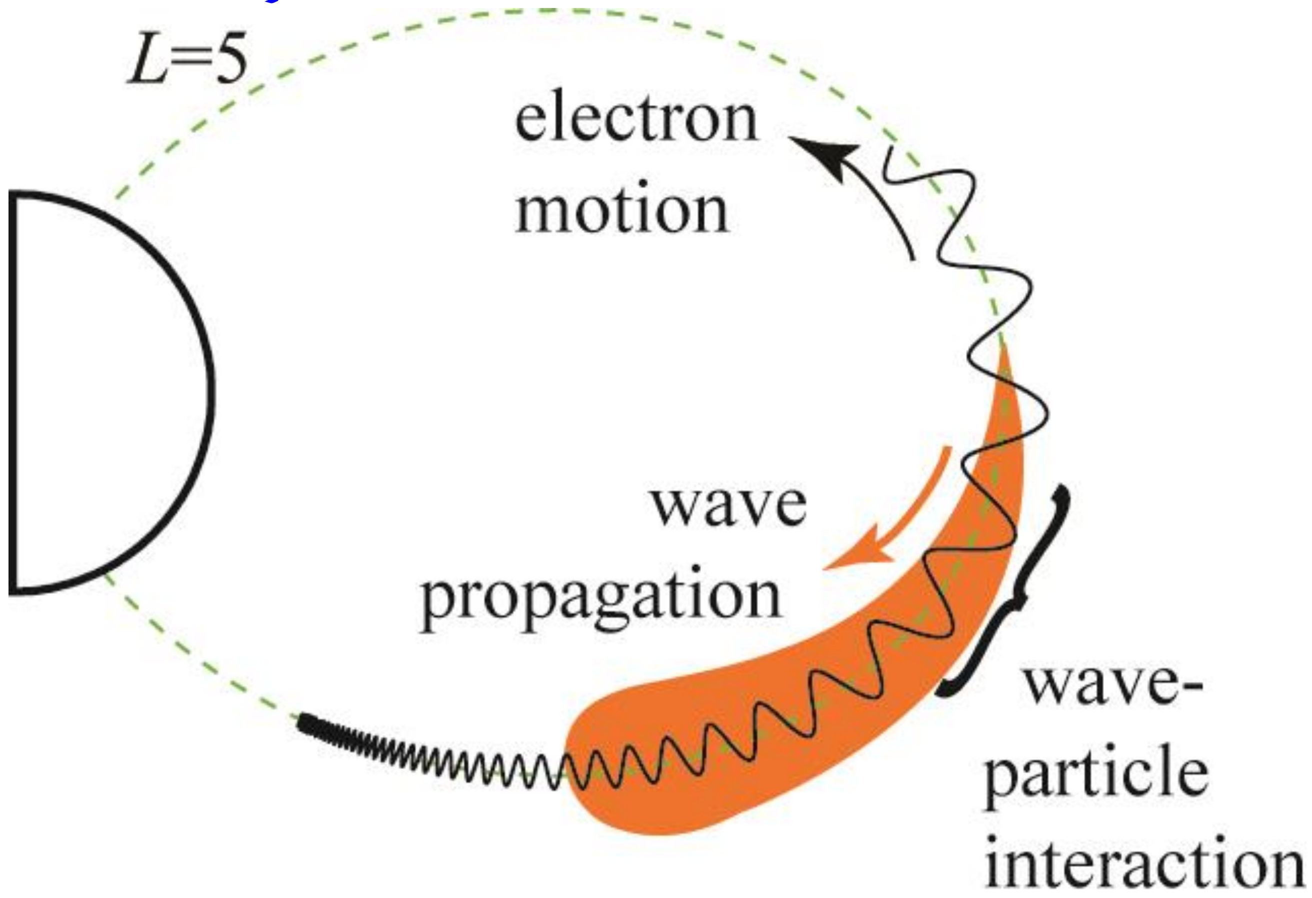
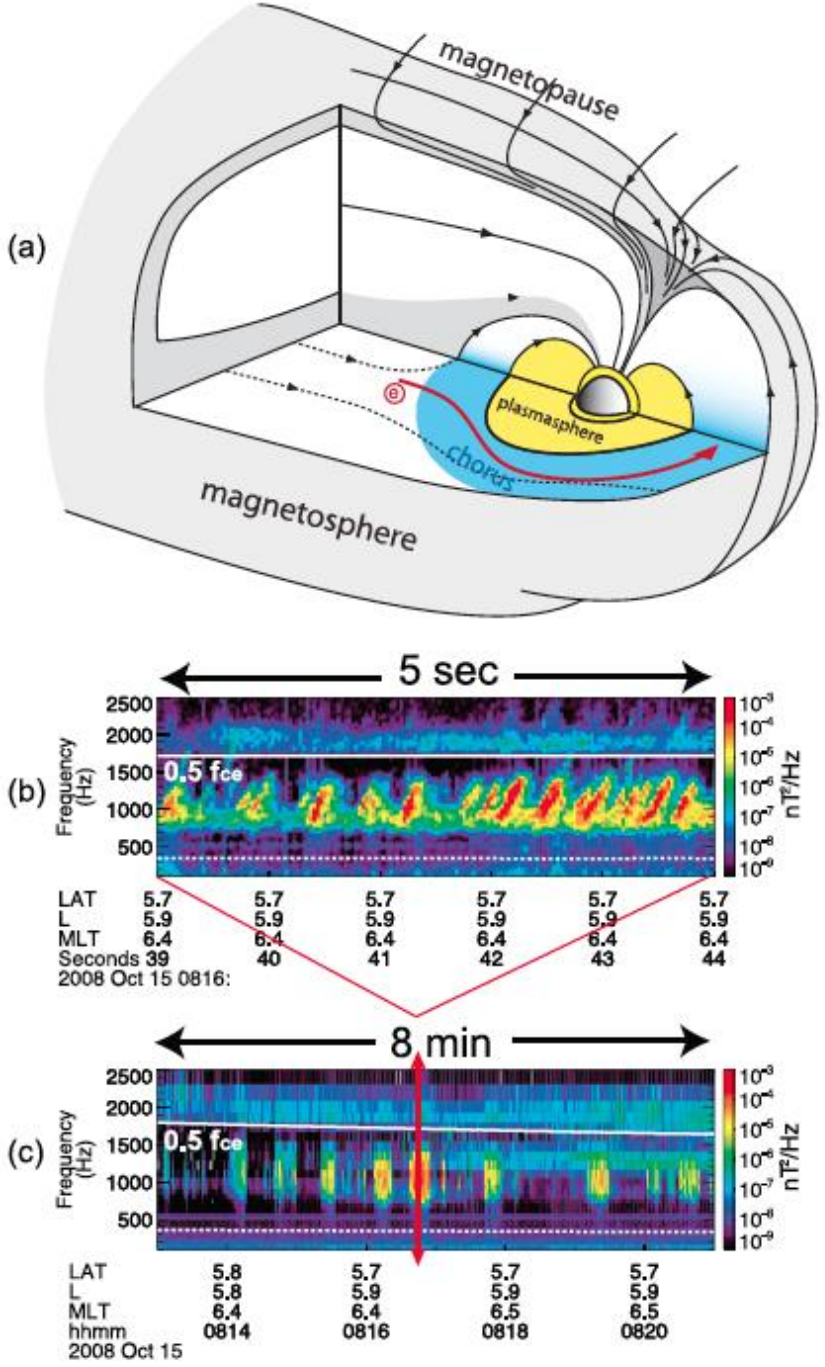
Space Physics Master's Course
Lecture 11
Wave-particle interactions

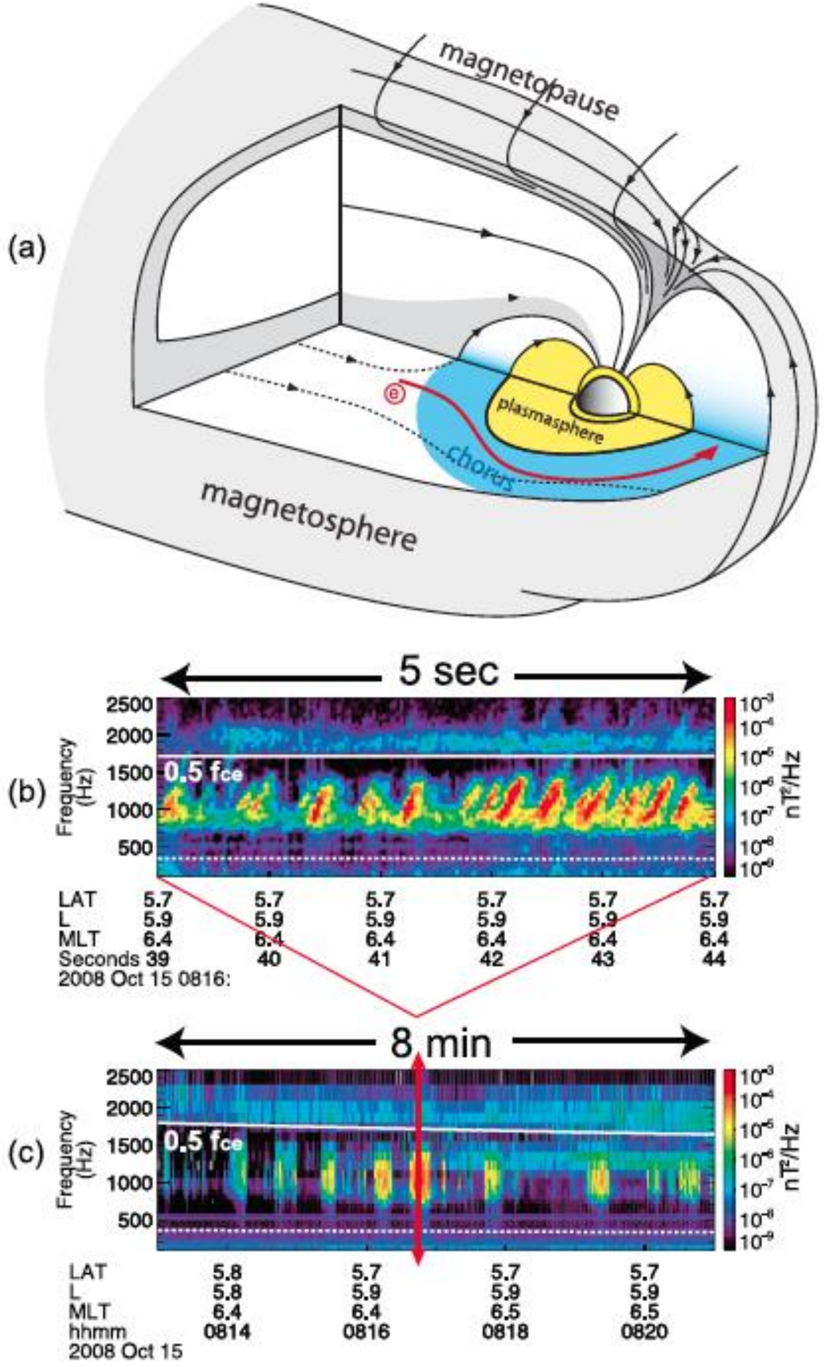


Chorus characteristics



Li et al. [2012], Fig. 1

- Found outside plasmasphere on **dawn-side**
- Due to unstable, drifting plasmasheet electrons
- Multi-scale structure in space and time



Li et al. [2012], Fig. 1

Chorus characteristics

Despite several decades of observational and theoretical investigation of magnetospheric chorus, there remains considerable debate on the precise mechanism of cyclotron resonance that governs the frequency chirp of chorus elements.

https://www.frontiersin.org/journals/astronomy-and-space-sciences/articles/10.3389/fspas.2022.981949/full

Why are the distributions of substorm-injected electrons anisotropic? (“pancake” vs “cigar” desitributions)

Betatron vs Fermi acceleration

Anisotropic electron distributions during substorm dipolarization result primarily from **betatron acceleration**, which operates through **conservation of the first adiabatic invariant** as the magnetic field rapidly increases. While dipolarization does involve strong **time-varying magnetic fields that induce electric fields**, the characteristic perpendicular anisotropy (pancake distributions) arises from the adiabatic response to changing magnetic field strength, not directly from the induced electric fields themselves. These electric fields contribute to other acceleration processes (Fermi acceleration, direct acceleration, convective transport) that operate concurrently with betatron acceleration during dipolarization events.

Anisotropic electron distributions—particularly **perpendicular anisotropy** (where $W_\perp > W_\parallel$, creating pancake distributions)—drive chorus wave growth through the **whistler-mode anisotropy instability**, also called the **cyclotron resonance instability.**

Origin of two-band chorus in the radiation belt of Earth

https://www.nature.com/articles/s41467-019-12561-3

When $T_\perp > T_\parallel$ (perpendicular temperature exceeds parallel temperature), the electron velocity distribution develops excess perpendicular energy. This creates free energy that can be tapped by electromagnetic waves.

Cyclotron Resonance Condition:

Whistler waves preferentially resonate with electrons whose **perpendicular velocity component matches the wave phase velocity.**

Electrons moving perpendicular to the magnetic field (at ~90° pitch angle) have excess perpendicular velocity in a pancake distribution

These electrons extract energy from the wave while simultaneously having the right phase velocity for resonance.

The net result is **positive energy transfer from electrons to the wave**, causing wave growth.

The mechanism full circle:

Dipolarization → Betatron → Anisotropic Electrons → Chorus Waves

Dipolarization injects electrons with perpendicular anisotropy (pancake distributions from betatron acceleration and induced field effects)

These anisotropic electrons enter the inner magnetosphere where they create free energy

Whistler-mode waves are excited via the anisotropy instability

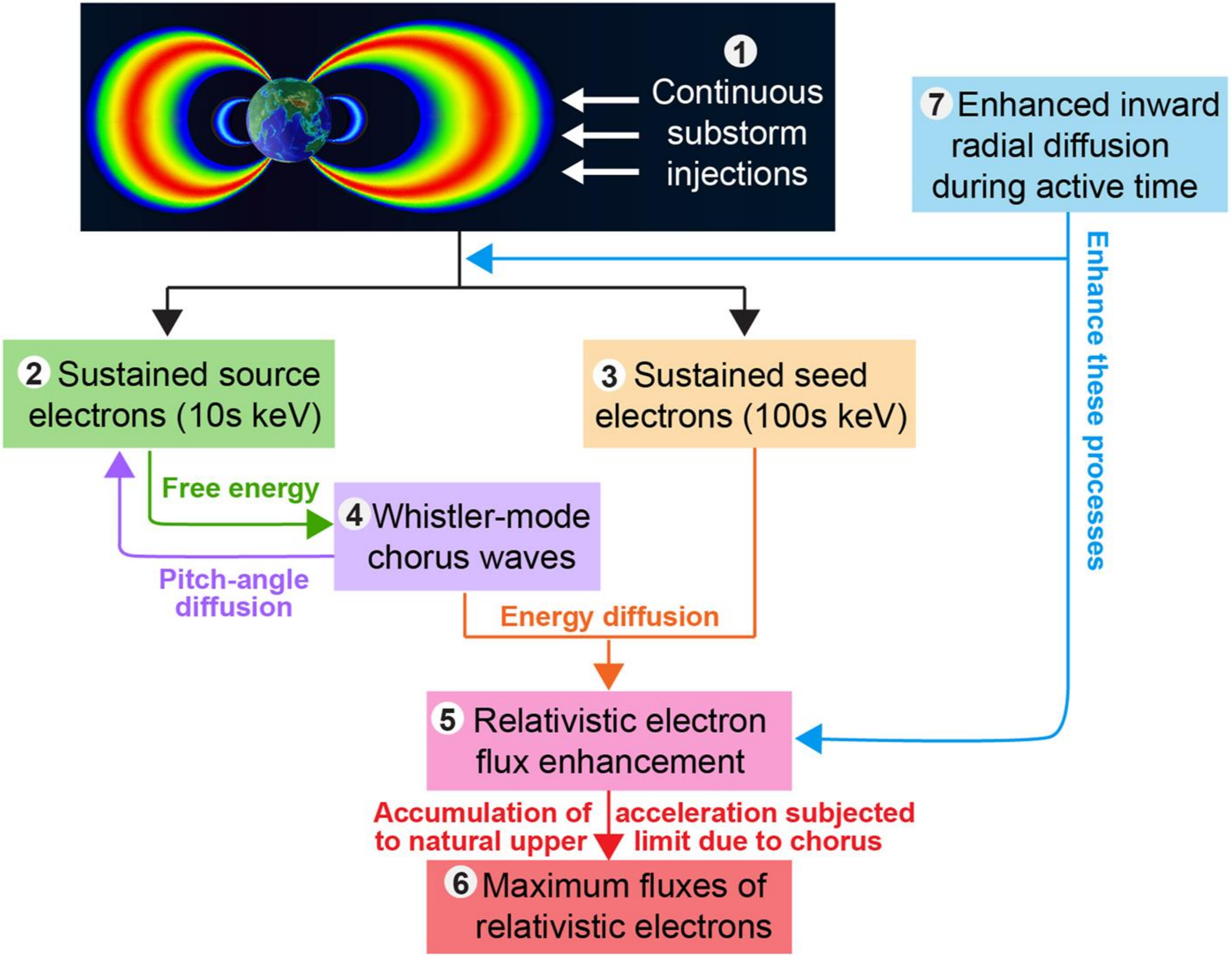
Chorus waves grow to large amplitudes and scatter electrons, causing:

- Pitch angle scattering (causing precipitation)
- Parallel acceleration (via Landau resonance)
- Formation of complex multi-band spectral structures

Dipolarization → Betatron creates pancake distribution ($T_\perp > T_\parallel$) → This creates a population skewed toward high perpendicular velocities → Whistler waves resonate with these fast perpendicular electrons → Fast electrons lose energy to waves → Wave grows

The anisotropic velocity distribution shape itself (not bulk temperature, but the actual **distribution function gradient**) provides the free energy. When $\partial f/\partial v > 0$ at the resonant velocity, the wave feeds on that excess of faster particles.

Chorus waves accelerate electrons to relativistic energies through **resonant wave-particle interactions** that transfer wave energy to electrons. The **quasi-linear diffusive process** dominates for most electrons, providing gradual acceleration from seed energies to MeV over days. **Nonlinear phase trapping** accelerates already-relativistic electrons to ultra-relativistic energies within sub-seconds. The efficiency depends critically on **low plasma density**, **sustained wave activity**, and **continuous seed electron supply** from substorm injections. This mechanism explains why relativistic electron flux enhancements in the outer radiation belt are strongly correlated with chorus wave activity during geomagnetic storms.



1 Continuous substorm injections
7 Enhanced inward radial diffusion during active time
Enhance these processes
2 Sustained source electrons (10s keV)
3 Sustained seed electrons (100s keV)
Free energy
4 Whistler-mode chorus waves
Pitch-angle diffusion
Energy diffusion
5 Relativistic electron flux enhancement
Accumulation of acceleration subjected to natural upper limit due to chorus
6 Maximum fluxes of relativistic electrons

Synergy of waves in acceleration

(i) inward radial diffusion by Pc5 waves

plus subsequent

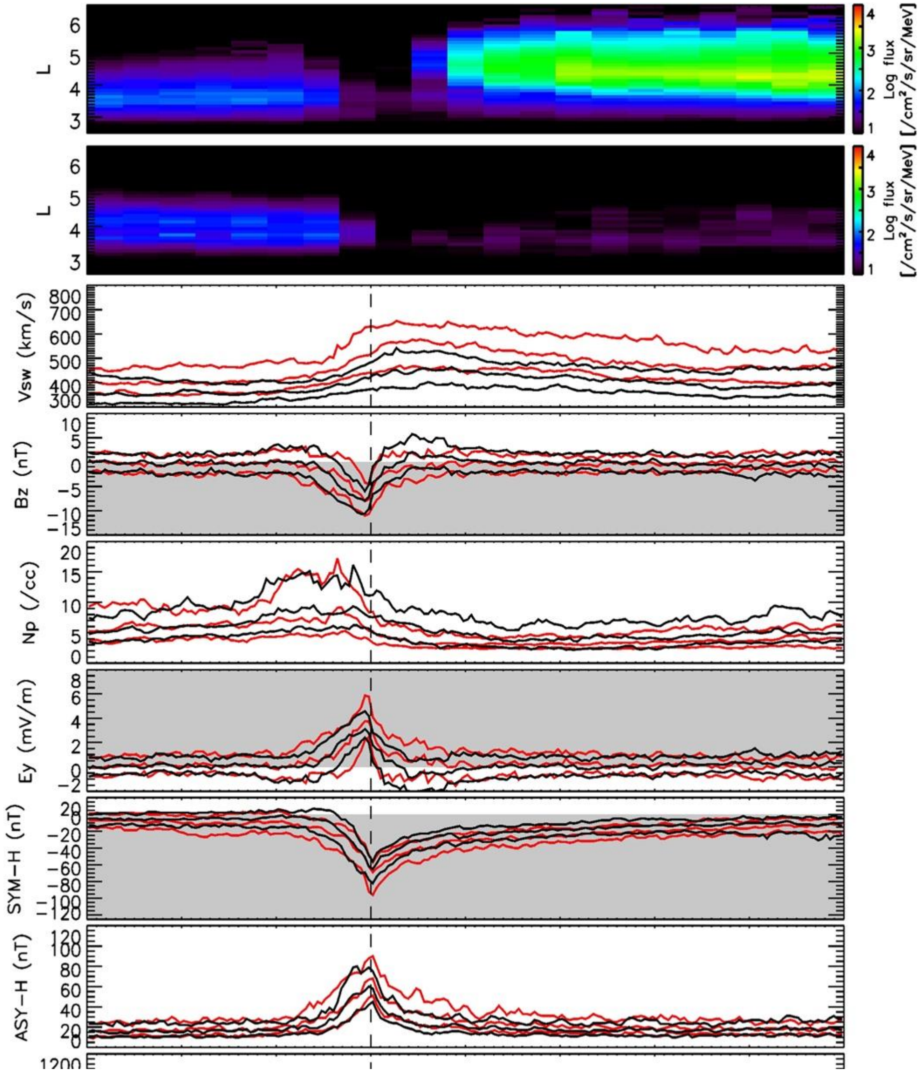
(ii) local acceleration by lower band chorus

Zhao, H., Baker, D. N., Li, X., Jaynes, A. N., & Kanekal, S.
*The effects of geomagnetic storms and solar wind conditions on the **ultrarelativistic** electron flux enhancements. JGR 2019*

SEA of 87 storms
Sept. 2012 – Apr. 2018
49 (38) enhancement (no)
of 5.2 MeV e^-

Storms with **Enhancement**

- ◇ High solar wind speed (ULF wave generation)
- ◇ Sustained IMF Bs (storms)
- ◇ Higher AE (substorms - chorus, seed electrons)
- ◇ Higher ASY-H (ULF wave generation)



Synergy of waves in acceleration

(i) inward radial diffusion by Pc5 waves

driven by solar wind speed/pressure and/or ring current

(ii) local acceleration by lower band chorus

driven by substorm-injected electrons

Substorm influence on RBs

Frequent and intense **substorms**

not capable of massively accelerating electrons to relativistic energies

but play a crucial role through the supply of **seed electrons** and their role in **chorus wave growth**.

Synergy of waves in acceleration

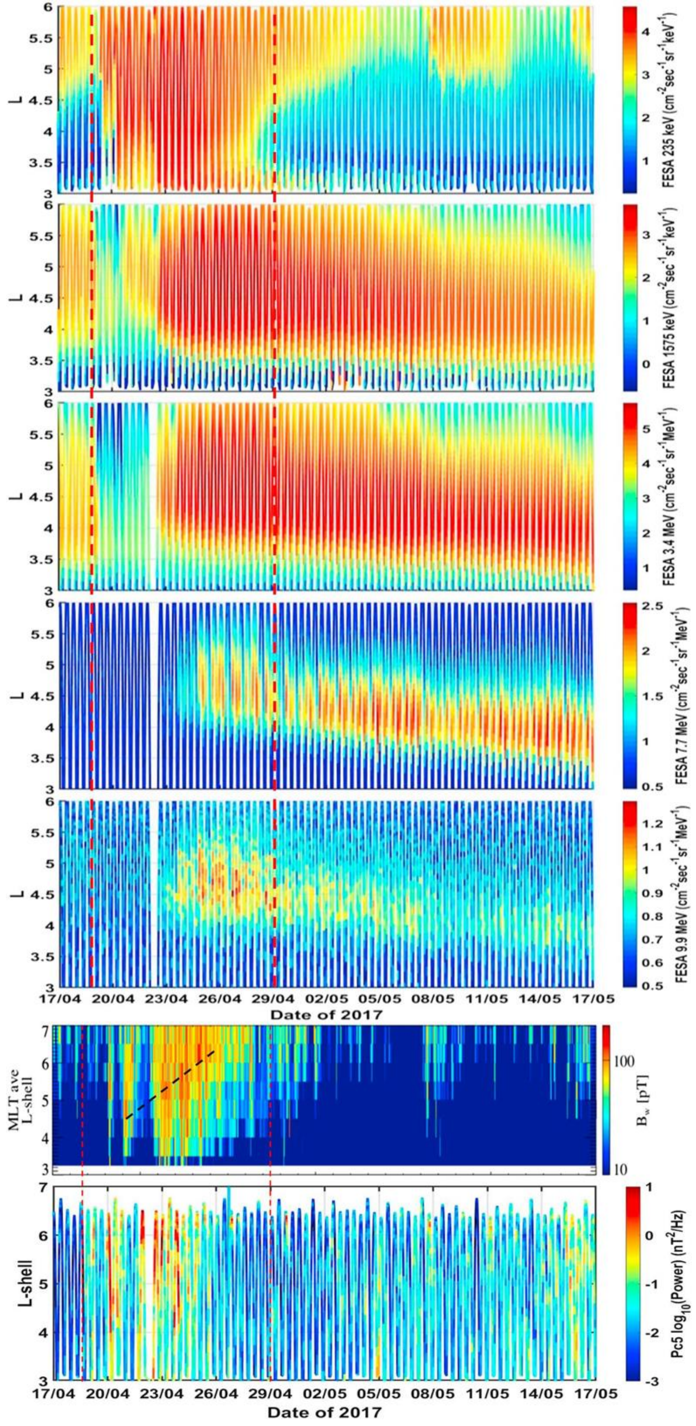
(i) inward radial diffusion by Pc5 waves

driven by solar wind speed/pressure and/or ring current

(ii) local acceleration by lower band chorus

driven by substorm-injected electrons

(iii) further acceleration by Pc5



Waves synergy and RB acceleration

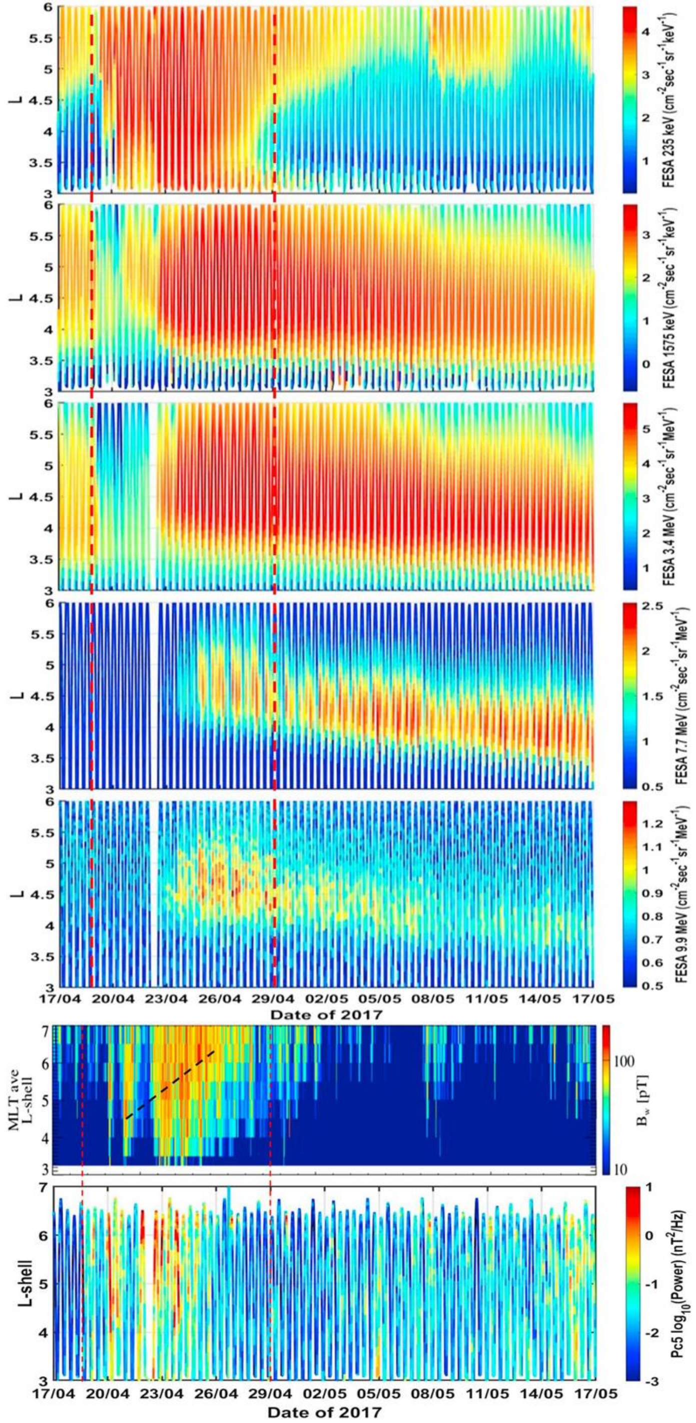
SYM-H$_{min}$ = -50 nT

Substorm seed e^- enhancement

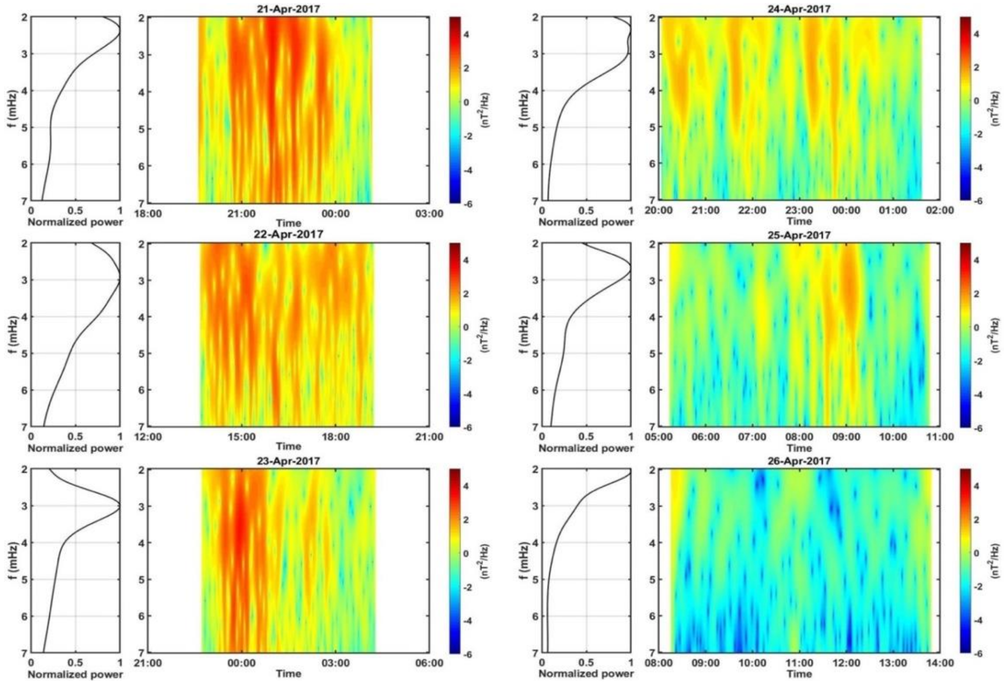
Relativistic e^- increase

Later: enhancement of 10 MeV electrons – **NOT recorded by GEO sats**

Highly Relativistic Electron Flux Enhancement During the Weak Geomagnetic Storm of April–May 2017, Katsavrias+ JGR2019



Waves synergy and RB acceleration

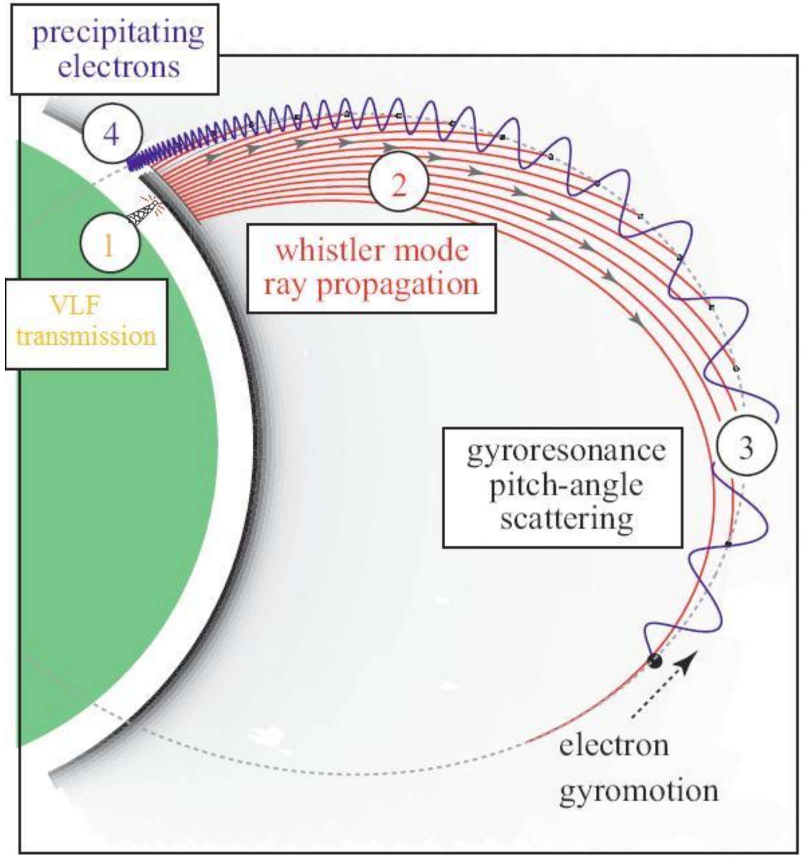


Peak in power spectral density is in the 2–3.5 mHz frequency range – very close to the drift frequency (2.3–3 mHz) of relativistic e⁻

Highly Relativistic Electron Flux Enhancement During the Weak Geomagnetic Storm of April–May 2017, Katsavrias+ JGR2019

Loss of Radiation Belt electrons

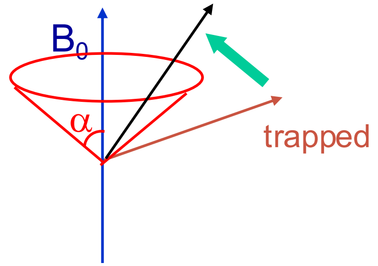
VLF electromagnetic waves, created by lightning, transmitters, or otherwise, can induce precipitation of energetic electrons by altering the pitch angle of their motion

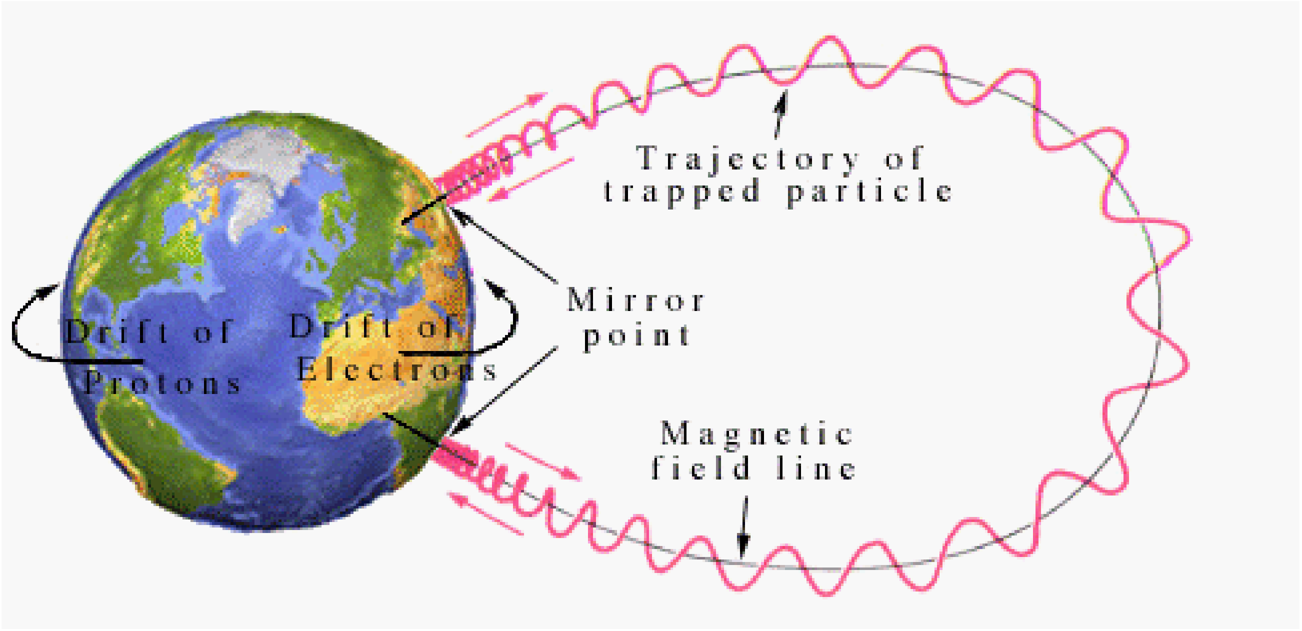


Loss of Radiation Belt electrons

WPI-PAD CONTROL OF LOSS RATE

ULF/ELF/VLF waves resonate with trapped particles in the magnetosphere causing **pitch angle scattering** and precipitation.





Controlling radiation belts: HAARP

Controlling radiation belts: HAARP

The Greek connection: Dennis Papadopoulos

Electron precipitation into the atmosphere

>100 keV electrons

trapped

precipitating