ESS 265
Instrumentation, Data Processing and Data Analysis in Space Physics

Lecture 10: AC Magnetometers and Plasma Wave Detectors

C.T. Russell

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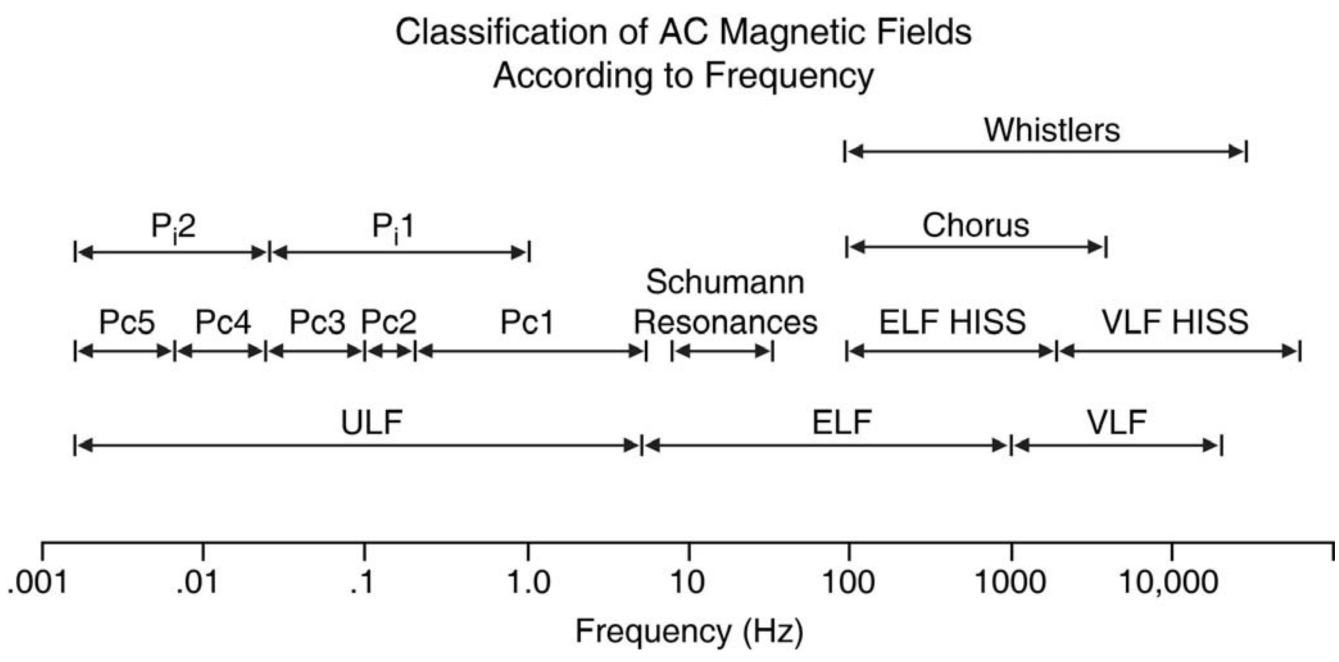
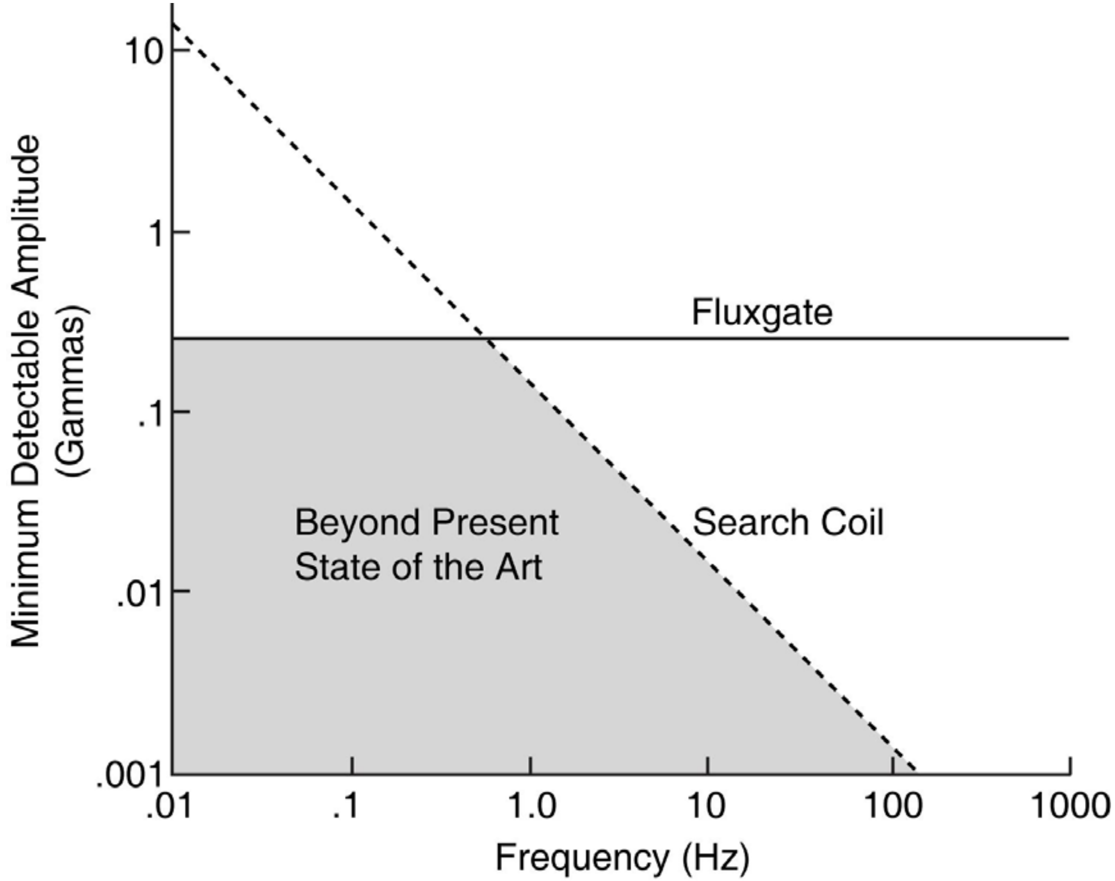
AC Magnetometers

Frequency Range	Phenomena	Magnetometer Type
ULF 5 – 600s	Pc2, 3, 4, 5, Pi 1, 2	Fluxgate, Rapid-run quartz fiber
ULF 5 – 0.2 s	Pc1	Search coils
ELF 5 – 3000 Hz	Schumann resonances	Search coils
VLF 3000 – 30,000 Hz	Whistlers, chorus, hiss	Air core/search coils



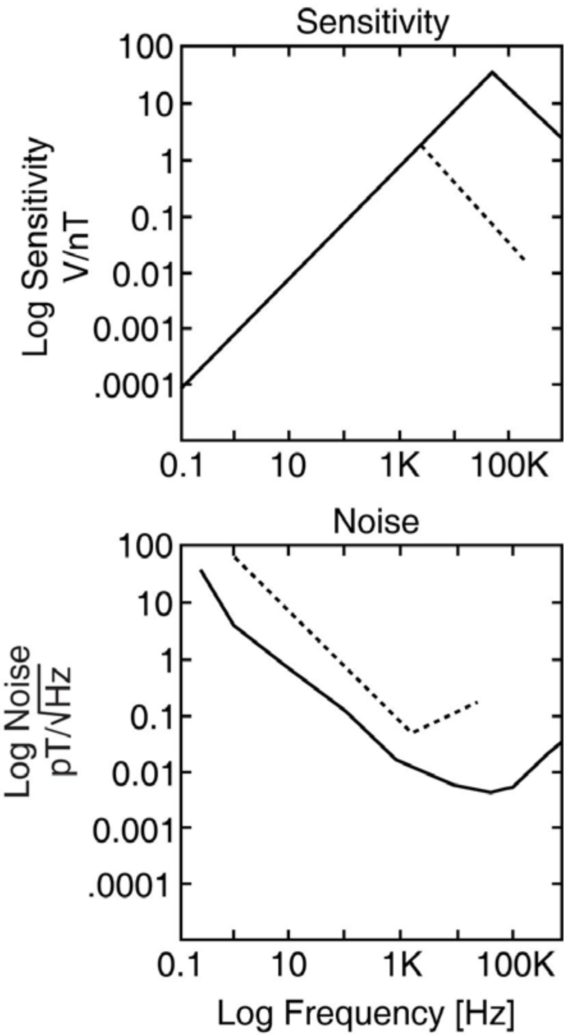
Which Magnetometers to Use?



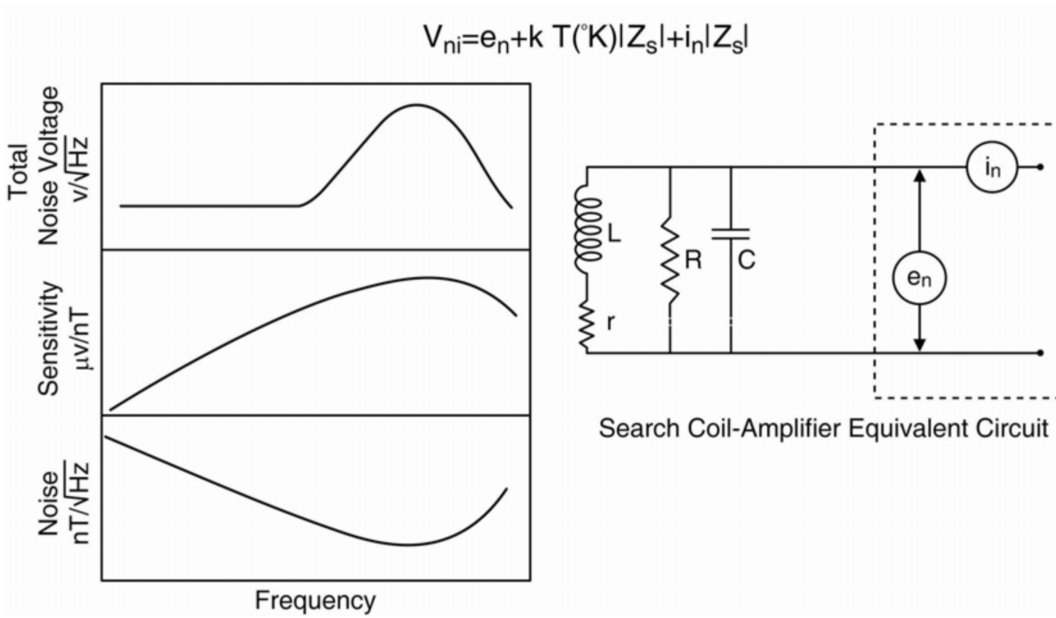
- Because it measures the derivatives of the signal, the search coil is more sensitive than the fluxgate at high frequencies.
- The search coil does not measure the zero-frequency field so that it is less useful.

Search Coil: Magnetometer Design

- Core
  - Permeable mu metal
  - Metglass (125 layers, 1/8” square)
  - Ferrite (AM radio antenna)
  - Permeability ~2700
  - Permeability limited by geometry
- Windings
  - 6000 to 10,000 turns (affects frequency response)
  - Resistance low (<2000 Ohms) to keep thermal noise low
  - Wire cannot be too thin
  - Coils cover middle third of core
- Preamplifier
  - Must be at sensor or cable capacitance is dominant
  - Sensor and preamp capacitance ~3pF
  - Cable capacitance is ~15pF per meter
  - Gain ~1000
  - Sensitive to noise; use common mode rejection



Search Coil Design



Sensitivity	$S = \mu_e NAK,\ \mu V/nT\text{-}Hz$
Effective Permeability	$\mu_e = 1.6(l/d)^{1.6}$
Inductance	$L = \mu_e N^2 A/l$, Henries
Resonant Frequency	$f = (2\ \ )^{-1}(LC)^{-1/2}$, Hz
Impedance	$R = (L/C)^{1/2}$, Ohms
Voltage noise	$V_{ni} = e_n + kT\lvert Z_s\rvert + i_n\lvert z_s\rvert$

= *voltage noise +thermal noise + current noise*

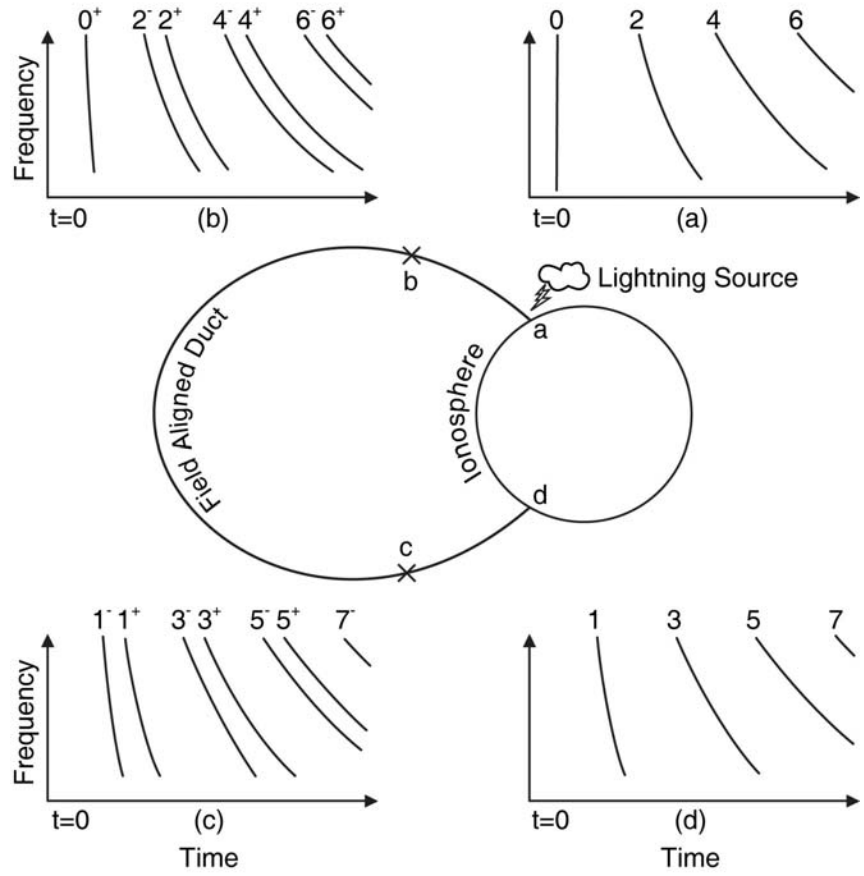
N = number of turns; A = area in cm^2, K = 2π x 10^{-7}

Sensor Output

- Direct FM telemetry link (ISEE-1)
- Digital snapshots (Galileo)
- Swept frequency analysis (ISEE-1, Galileo)
- Fixed frequency channels (OGO, ISEE 1, 2)

Whistlers

- Natural waves at ELF/VLF frequencies can be created in the atmosphere and in the plasma.
- Lightning creates electromagnetic waves over a broad frequency range.
- It is particularly intense over VLF frequencies (3-30k Hz) because of the duration of the discharge.
- Whistler waves bounce back and forth in the magnetosphere guided by the field and density enhancements.
- Unducted (magnetospherically reflected whistlers) can also occur.
- Dispersion is the variation in speed with frequency. The dispersion of a whistler can be used to determine the path of the whistler and the electron density.
- Whistlers were instrumental in the discovery of the plasmapause.

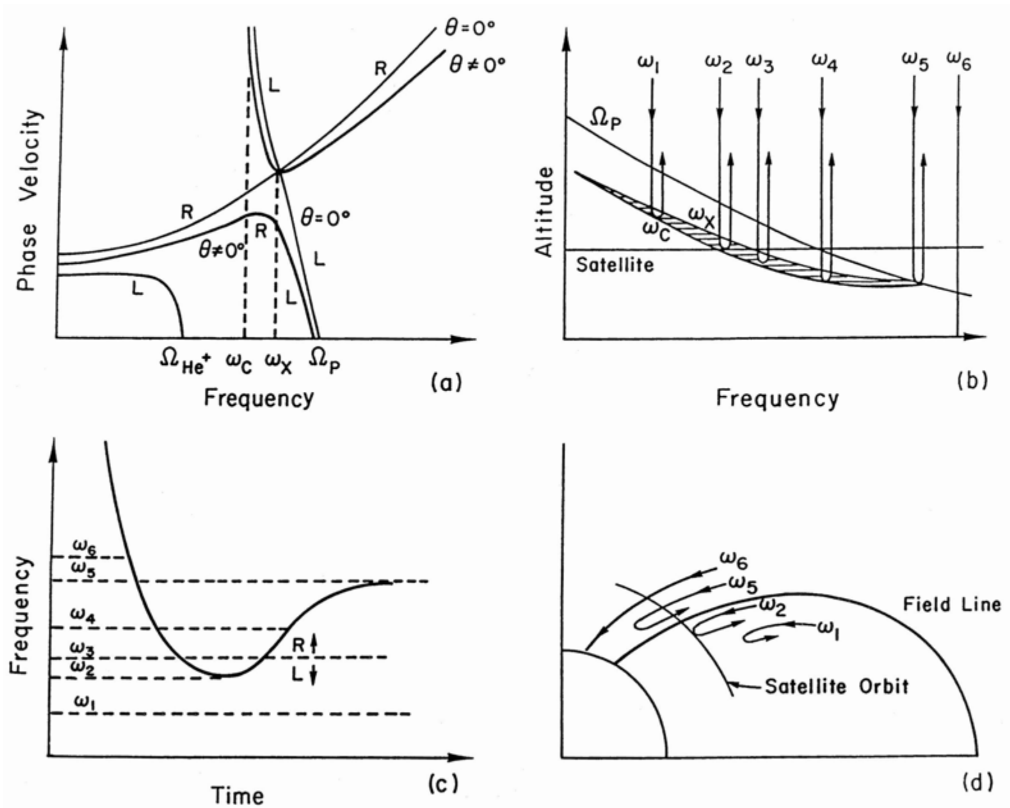


Whistler Phenomena

- Ducted Multiple Hop Whistlers
  - Ion Cutoff Whistlers
- Fractional Hop Whistlers
  - Ion Whistlers
    - Proton
    - Helium
    - Other (He_2^+ or 0^{++})
  - Subprotonospheric Whistlers
    - Reflects before leaving ionosphere
- Unducted Whistlers
  - Magnetospherically Reflected Whistlers
  - Nu Whistlers
  - Walking Trace Whistlers

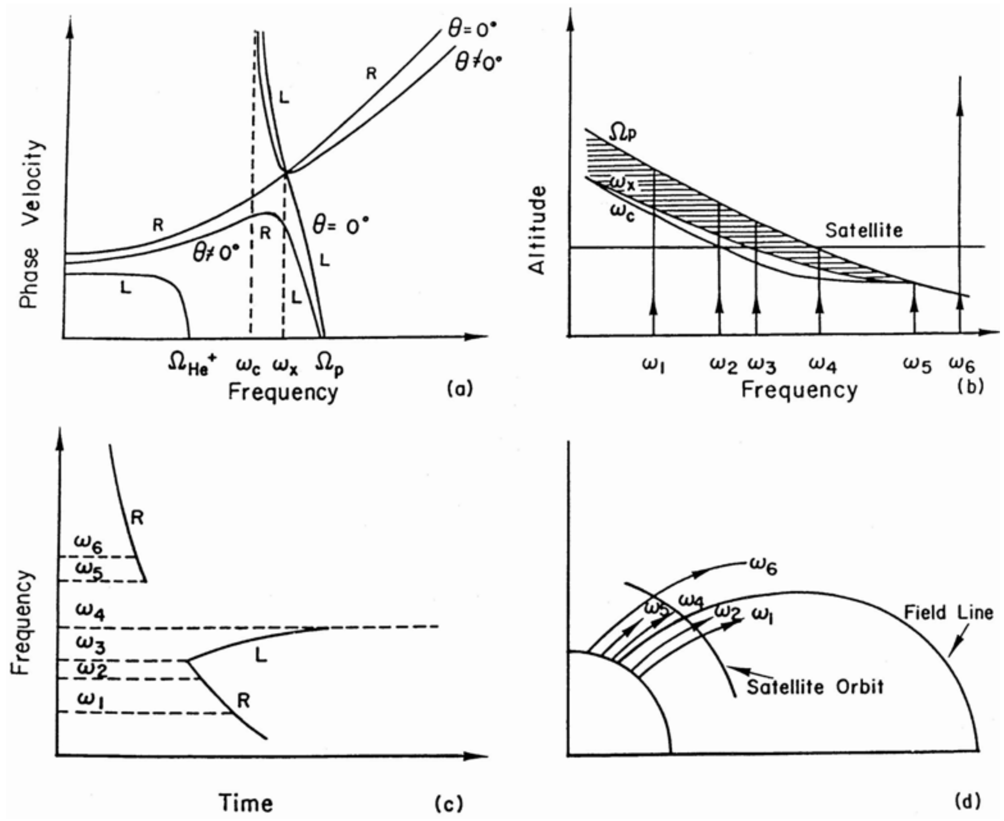
Ion Cutoff Whistler

- Wave energy is coming down field line, presumably generated in the other hemisphere.
- Multi-component ion composition creates a crossover frequency and a cutoff frequency.
- Downcoming wave is reflected when it reaches the cutoff frequency.



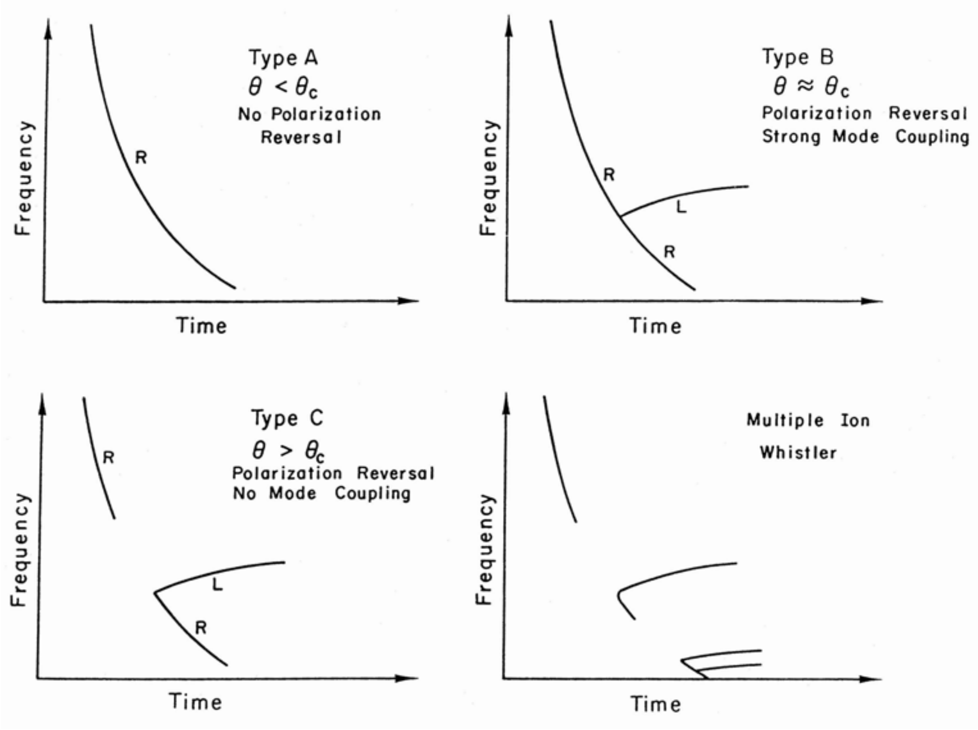
Ion Whistlers

- Whistler-mode energy from lightning moving upwards to the spacecraft moves higher in normalized (to the local gyro) frequency.
- The ionospheric plasma has multiple ionic species. This complicates the dispersive properties of waves near the ion gyro frequency, producing a crossover frequency and a cutoff frequency between the helium and proton gyrofrequencies.
- We note that waves refract vertically as they enter the high refractive index ionosphere.
- For non-parallel propagating waves, two branches separate at the crossover frequency, allowing conversion of right-handed waves to left-handed.



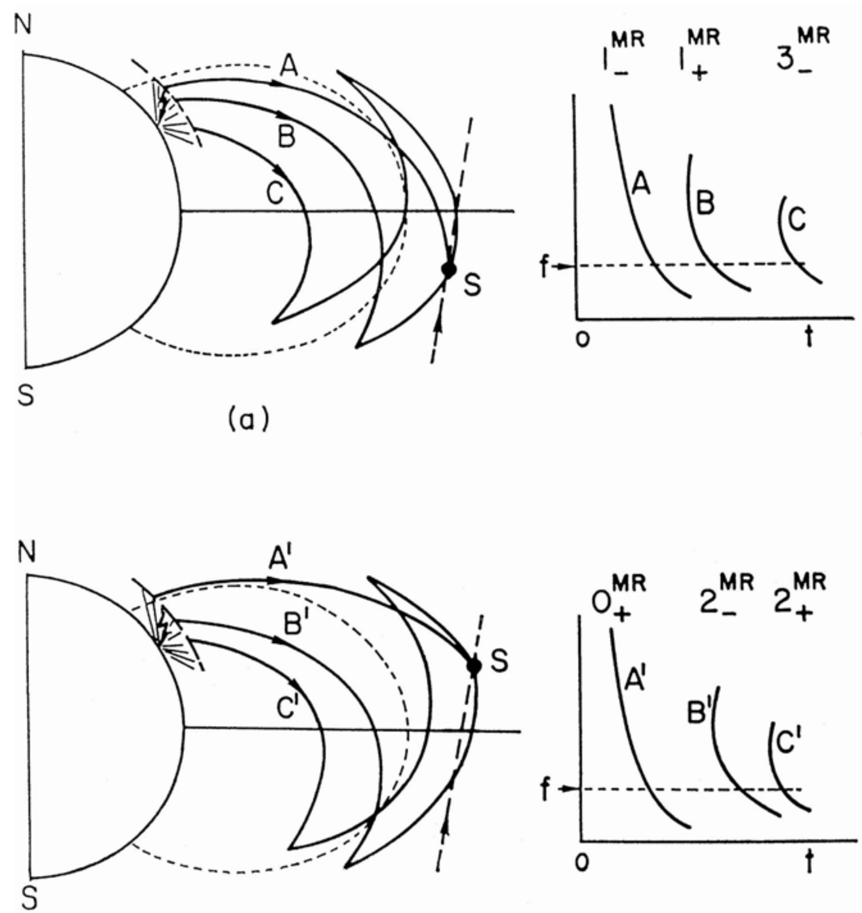
Types of Ion Whistlers

- If the wave travels nearly parallel to the magnetic field, the wave remains right-handed.
- If the wave propagates at a large angle to the field, the wave switches from right-handed to left-handed at the crossover frequency and the left-handed waves are absorbed at the local ion gyrofrequency causing a gap in the spectrum as they move upward.
- If there is strong coupling at the crossover frequency, both polarizations exist filling in the gap.
- Multiple ions can cause multiple ion resonances.



Magnetospherically Reflected Whistlers

- Waves that are not ducted by density enhancements along the field line may reach the spacecraft by very different paths.



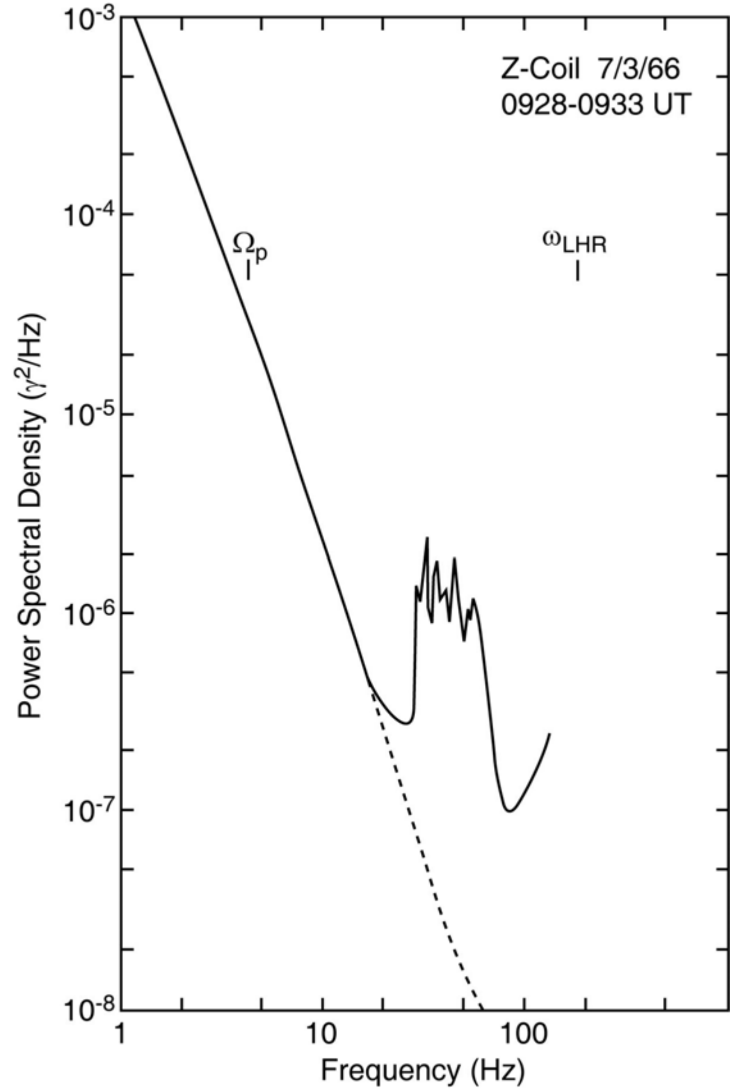
Low Altitude Emissions

- ELF Hiss
  - Featureless broad-band spectrum in the plasmasphere
- Chorus
  - Structural emission with rising tones, outside the plasmasphere
- VLF Hiss
  - Auroral Hiss
  - Mid-Latitude Hiss
  - Low-Latitude Hiss
- LHR Noise
  - Strong band of noise narrowly confined to the equatorial plane
- Discrete Emissions
- Quasi-Periodic Emissions
  - Controlled by ULF waves?

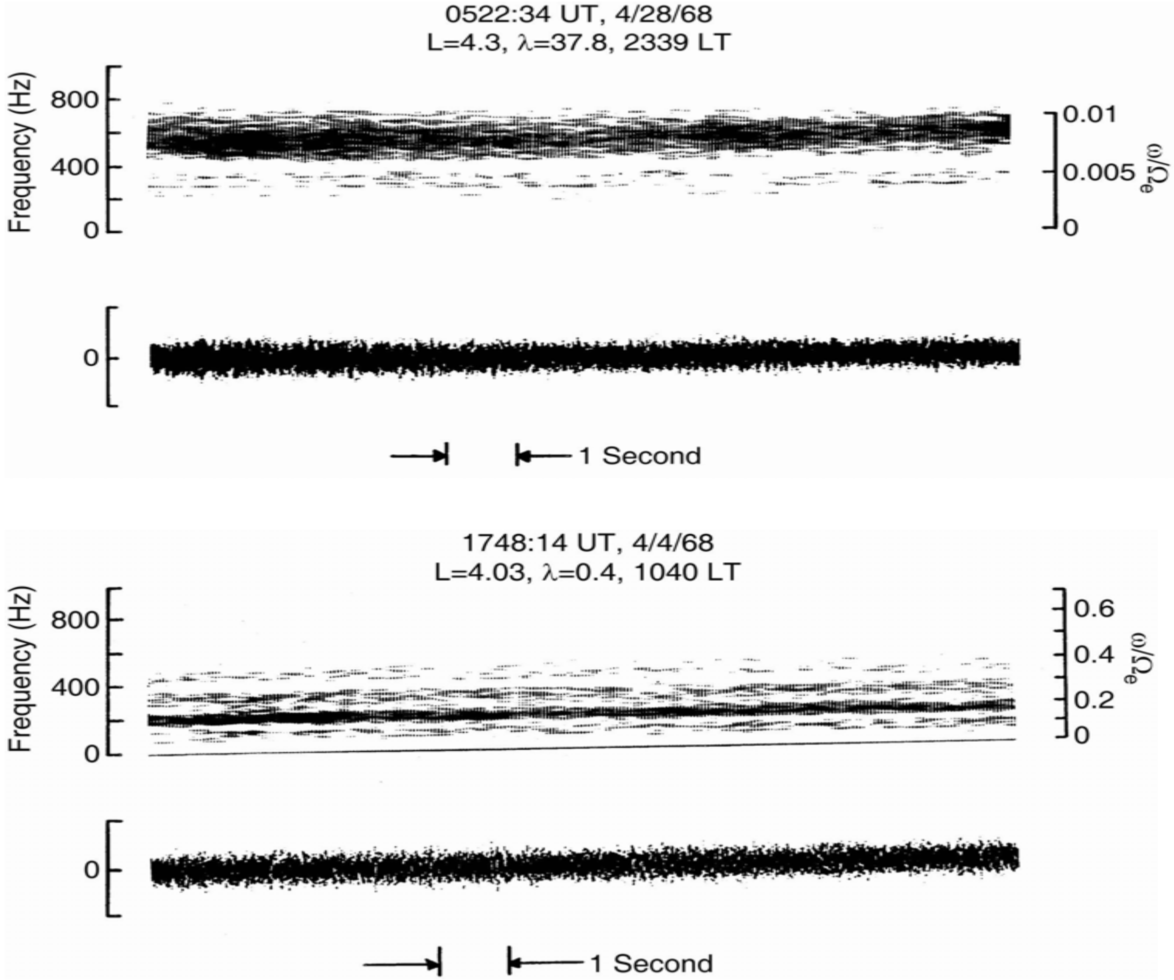
Magnetospheric Emissions

- Plasmasphere
  - Plasmapheric Hiss
  - Sub LHR Hiss

- Outer Magnetosphere
  - Chorus
  - High Latitude ELF Hiss
  - Highpass Noise
  - Broadband Noise

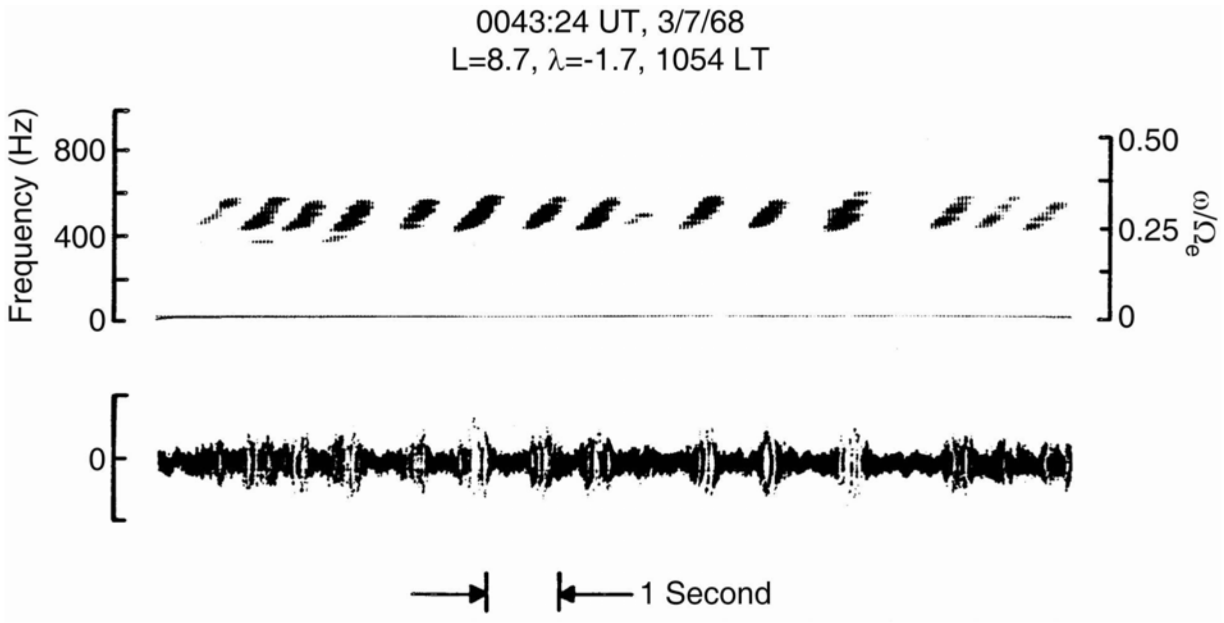


Plasmapheric Hiss



- Plasmapheric hiss is found throughout the plasmasphere. It resonates with energetic electrons causing pitch angle diffusion and loss.

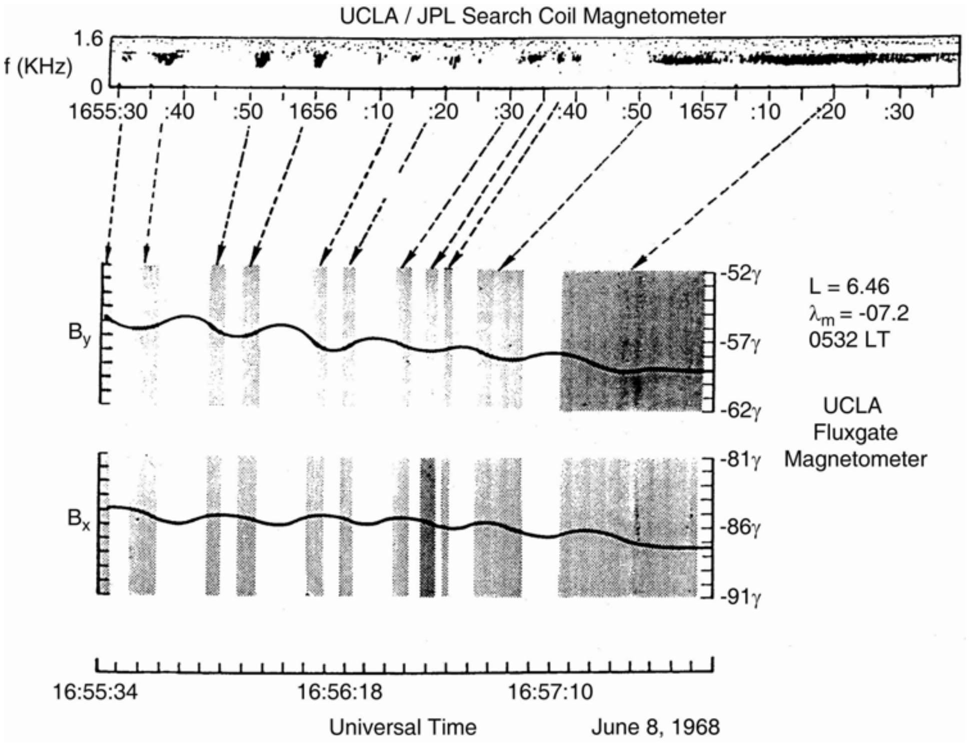
Chorus



- Outside the plasmasphere, the spectral forms become dynamic rising in frequency. These waves help scatter the energetic electrons and lead to their eventual loss.

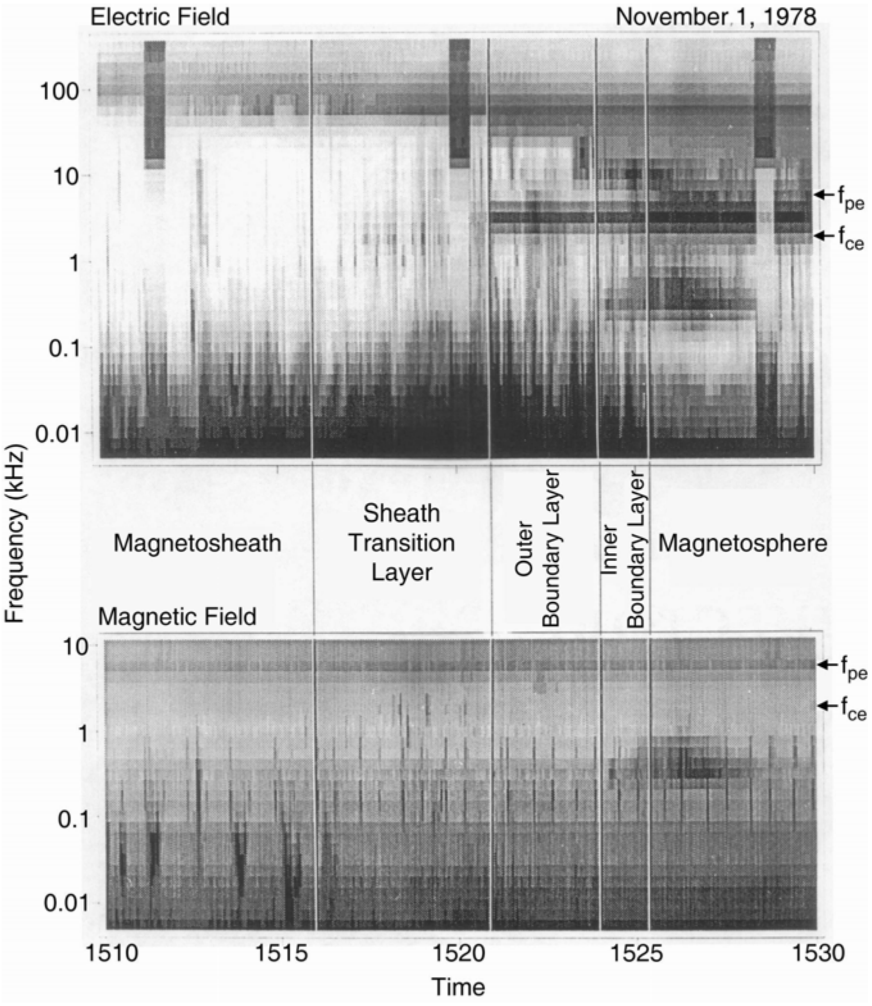
Coupled Emissions

- Whistler mode waves grow when there is a pressure anisotropy with $P_\perp > P_\parallel$
- We expect that if a particle population were nearly unstable, it could be made unstable by a compressional wave that changed the pressure anisotropy.
- In this example, we see a correlated low-frequency wave and ELF wave growth, but the authors did not prove the wave was compressional.



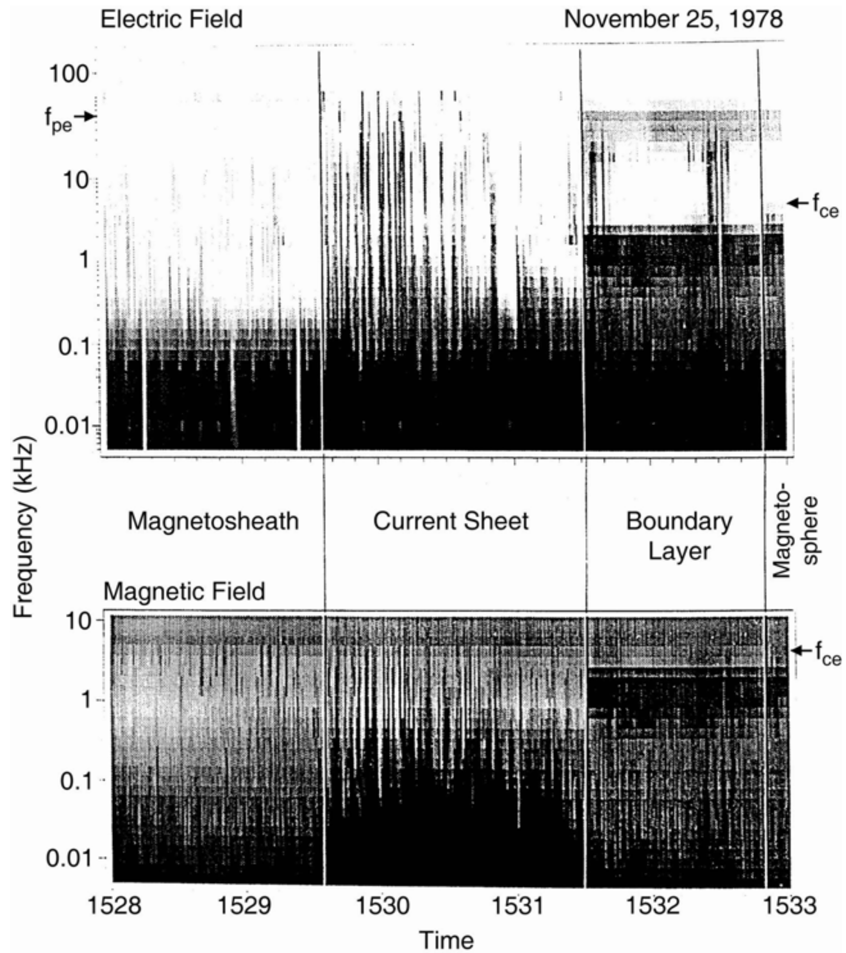
Electrostatic vs. Electromagnetic Waves: Northward IMF

- Use of electric (dipole) and magnetic (search coil) antennas simultaneously can help identify wave types.
- At this magnetopause crossing, electromagnetic waves are seen well below the electron gyrofrequency on both the dipole and search coil antennas.
- Above the electron gyrofrequency where electromagnetic waves cannot propagate, there are no magnetic signals, but there are signals seen on the electric antenna.
- Note that they extend from the independently identified boundary between the magnetosheath and the boundary layer inward into the magnetosphere. They are marking field lines attached to the ionosphere.



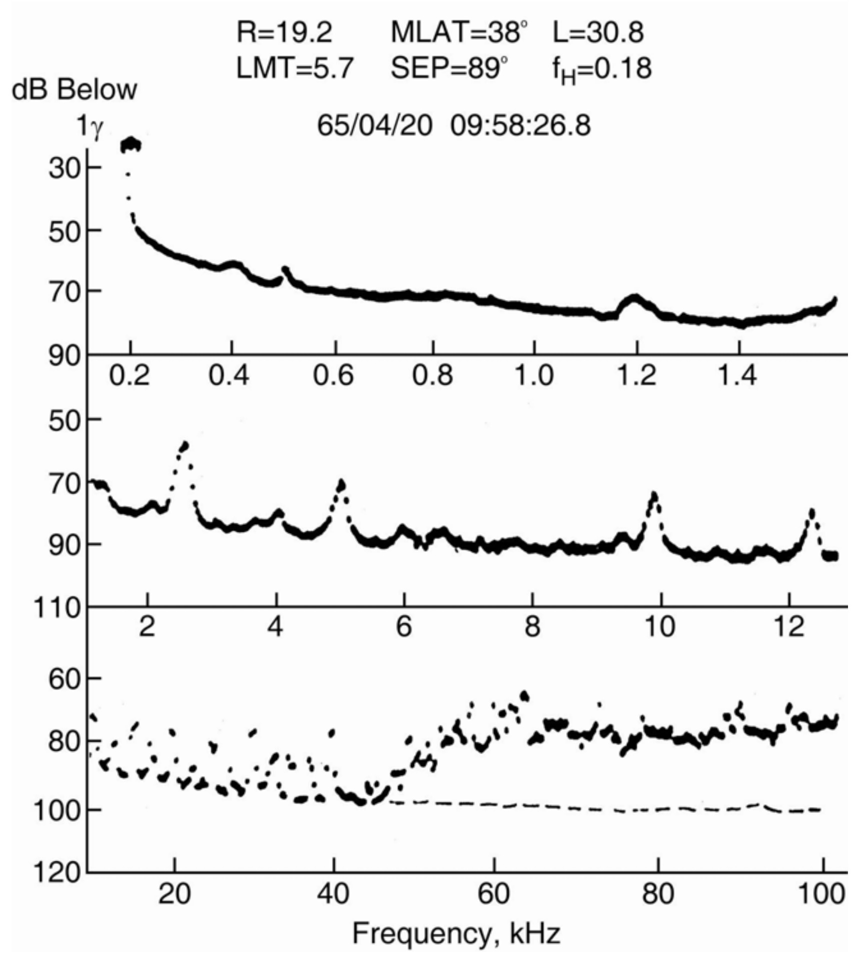
Electrostatic vs. Electromagnetic Waves: Southward IMF

- In this example of a magnetopause, crossing the IMF is southward.
- Here there is a thick current sheet region filled with electromagnetic waves at low frequencies (below the electron gyrofrequency) and electrostatic waves at high frequencies.
- At the point where the magnetosphere is entered, both the magnetospheric electrostatic waves and the electromagnetic waves turn on. This helps us understand the particle populations even though not well measured by the spacecraft.



Highpass Noise

- Seldom are magnetic signals examined at radio wave frequencies, i.e. above the electron plasma frequency.
- On the OGO spacecraft, a loop or “air core” antenna was flown extending in frequency to above 100 kHz.
- Here is an example of the electromagnetic highpass noise they saw.



Summary

- Search coil magnetometers, air core magnetometers and loops measure the electromagnetic spectrum above the range of fluxgate magnetometers.
- They are essential for studies in the ELF and VLF ranges.
- There are many different phenomena consisting of whistler-mode waves.
- These waves help precipitate electrons from the radiation belts.
- They also help us remotely sense processes occurring in the magnetosphere.
- Not all waves near these frequencies are electromagnetic; some of the waves are electrostatic. These waves are not seen on the search coil magnetometers, but must be studied with electric antennas.

Backup Slide: Plasma and Magnetic Field at Magnetopause