

# ULF\* waves and related phenomena

\*ultra-low frequency

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- Many, many different waves!
- $\nu < 1\text{-}5\text{ Hz}$ , period  $T > 0.2\text{-}1\text{ s}$
- $\nu \sim$  cyclotron frequency of proton  $\sim$  an ability to influence and accelerate/decelerate plasma
- Geomagnetic Pc and Pi pulsations
  - Pc, continuous pulsations
  - Pi, irregular pulsations

**TABLE 1**

Notation	Period Range, sec
Pc 1	0.2– 5
Pc 2	5 – 10
Pc 3	10 – 45
Pc 4	45 –150
Pc 5	150 –600

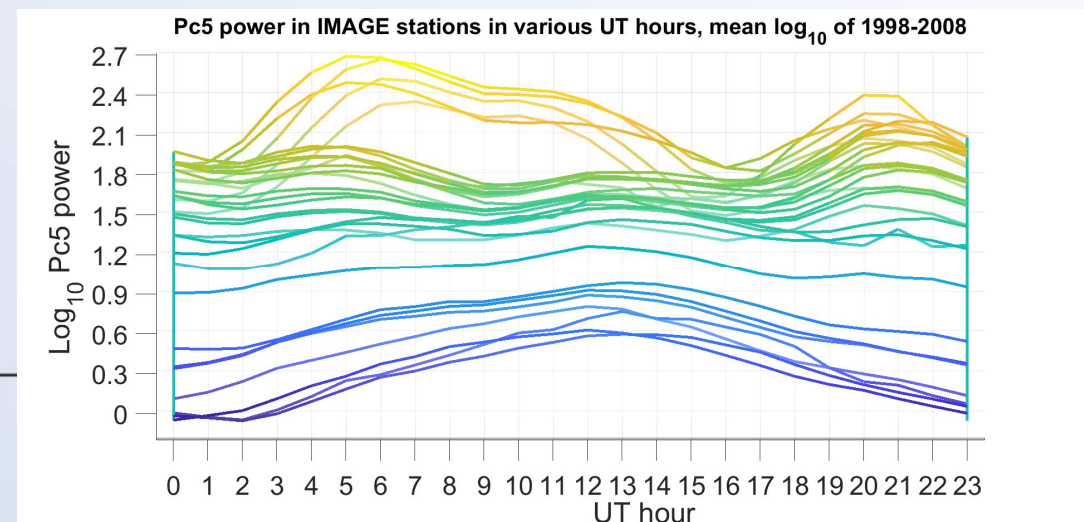
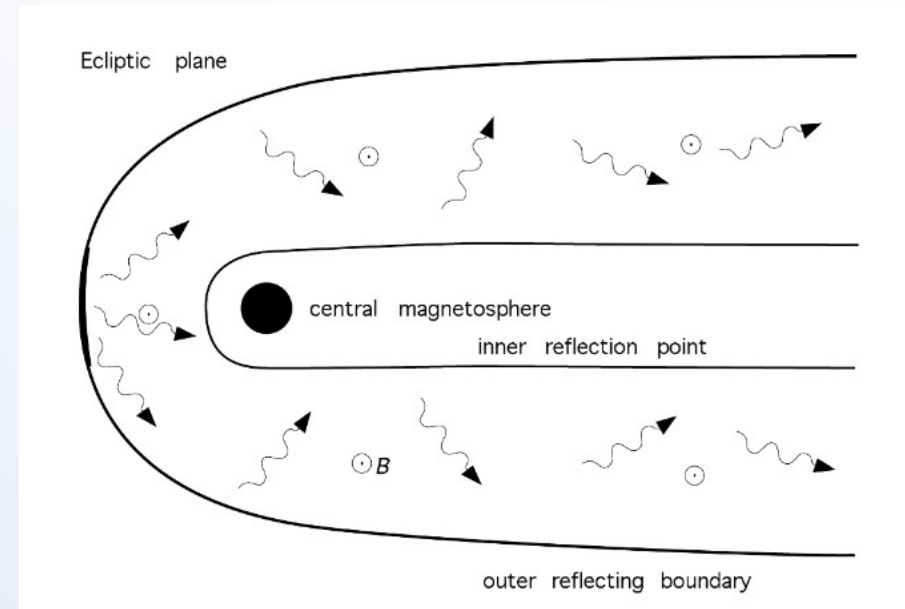
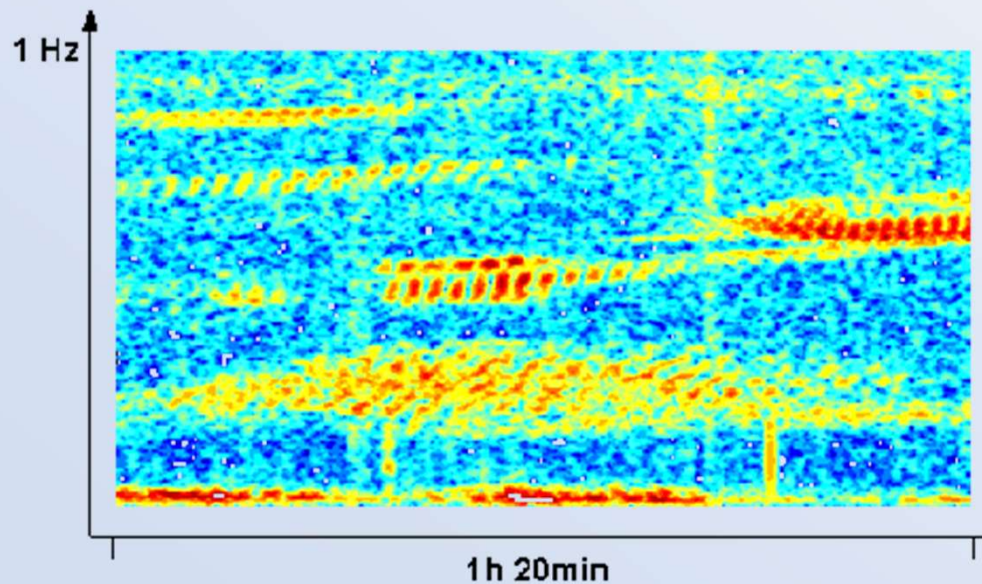
**TABLE 2**

Notation	Period Range, sec
Pi 1	1– 40
Pi 2	40–150

From Jacobs (1964)

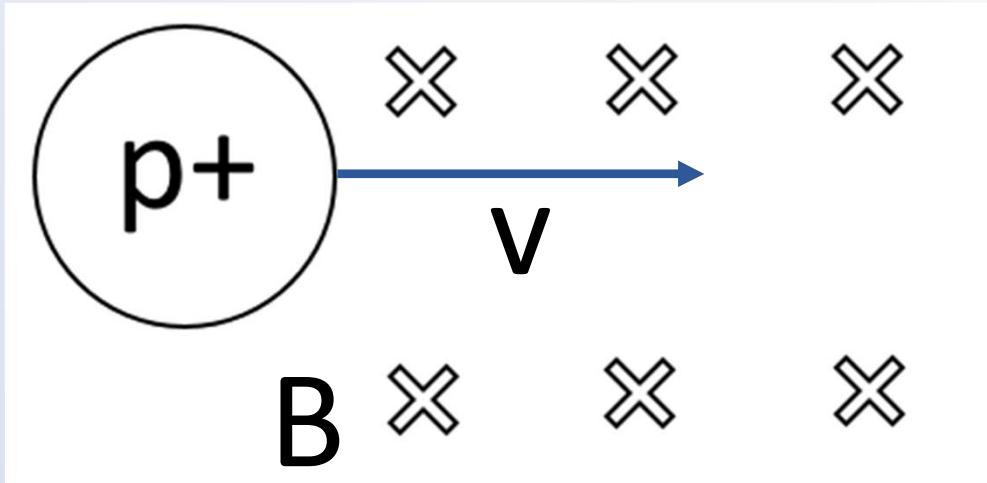
<https://doi.org/10.1029/JZ069i001p00180>

- Some waves in plasmas
- Magnetospheric and ionospheric structures and phenomena
- Statistical features

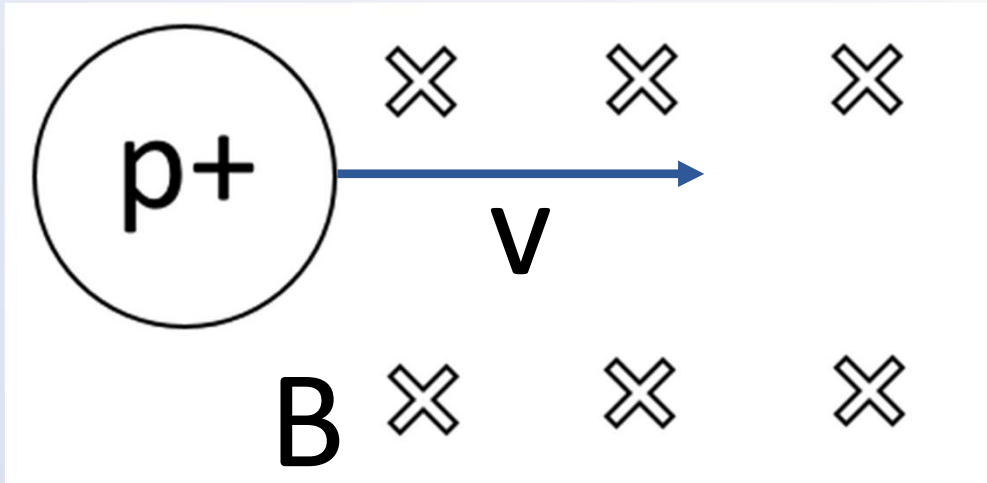


- Characteristic frequencies of plasmas
- Alfvén waves – ion oscillation waves
- Sound waves and magnetosonic waves
- Plasma instabilities:
  - Kelvin-Helmholtz waves

- Charged particle in an magnetic field



- Charged particle in an magnetic field



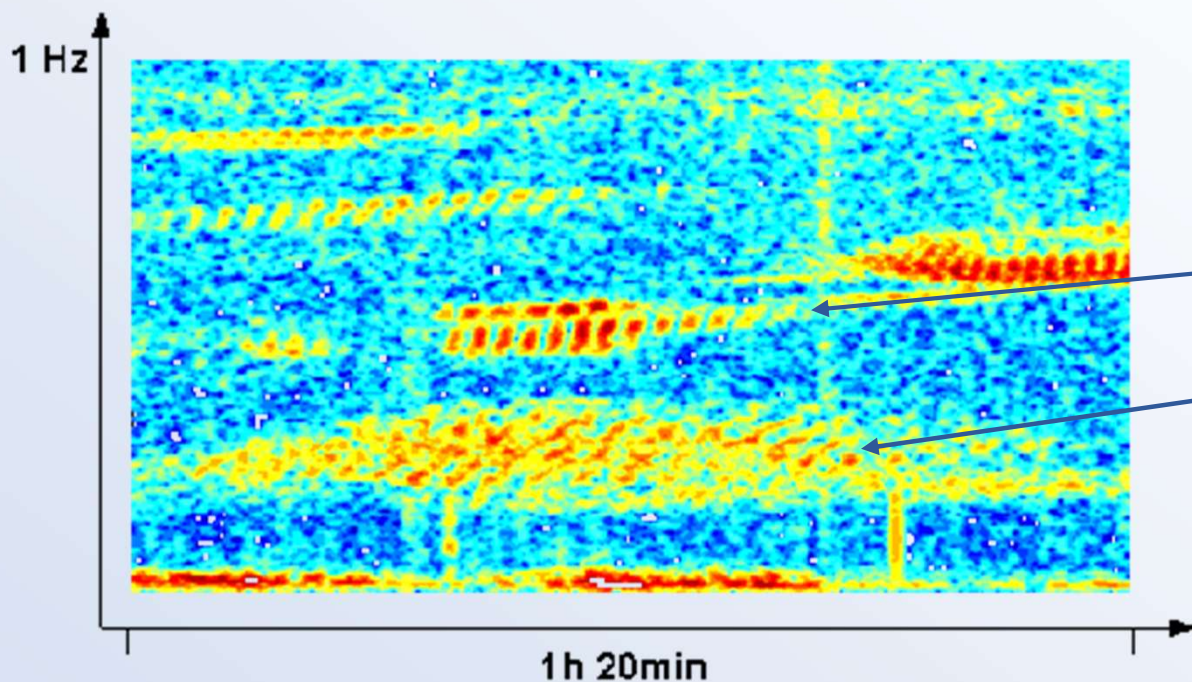
→ Undergoes cyclic motion at cyclotron frequency

$$\omega = 2\pi f = \frac{zeB}{m},$$

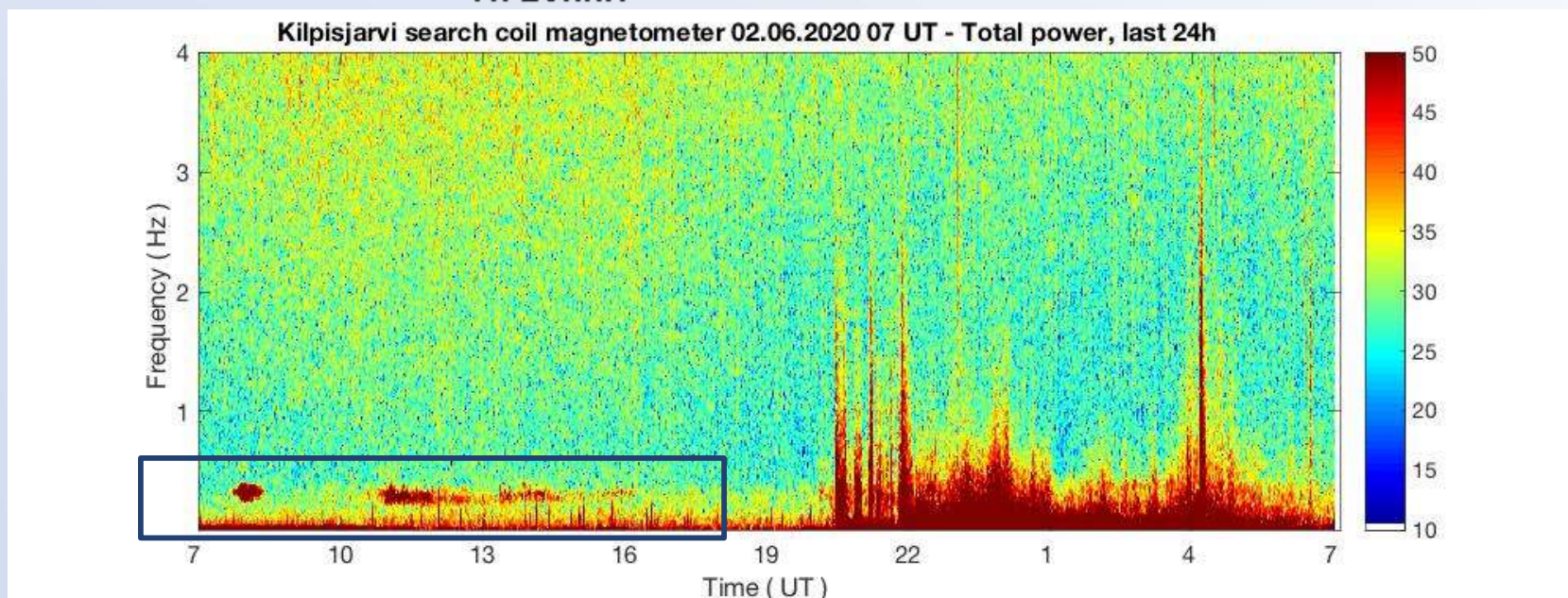
- In magnetosphere:  $f \sim 0.1 - 5$  Hz,  
known as EMIC\* waves, or Pc1 and Pc2 pulsations

\*Electromagnetic ion cyclotron <sup>6</sup>





Pulsations:  
 Pc1, 200-1000 mHz  
 Pc2, 100-200 mHz



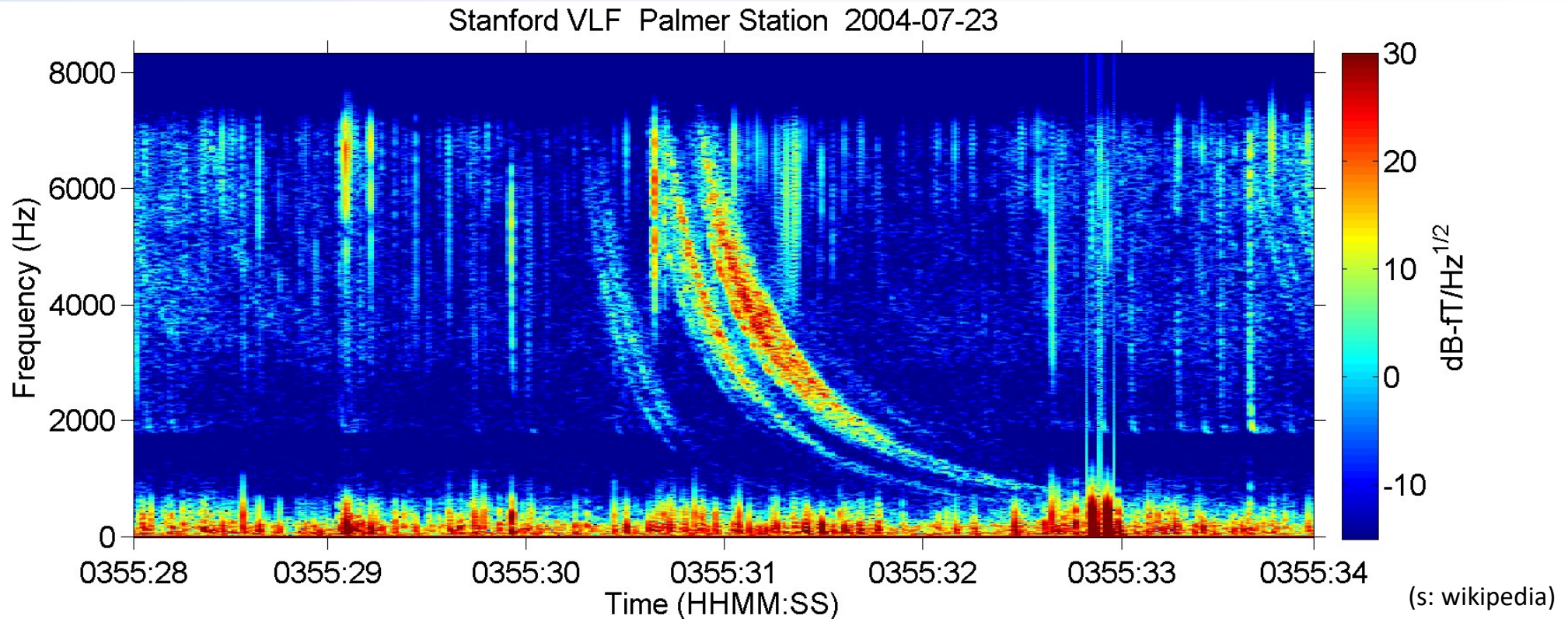
- Theorized by Hannes Alfvén in 1942
- Oscillation of ions and magnetic field,  
 **$\mathbf{B} \rightarrow \mathbf{B} + d\mathbf{B}$**
- Low frequency (less than ion cyclotron frequency)
- Alfvén velocity depends on *magnetic field* and *plasma density*.

$$v_A = \frac{B}{\sqrt{\mu_0 \rho}}$$



- Pressure and magnetic compression waves
- In magnetosphere: whistler waves

It's actually a VLF wave



- Fast magnetosonic wave speed  $v^2 = v_s^2 + v_a^2$
- Slow magnetosonic wave speed  $v^2 = v_s^2 - v_a^2$

ULF wave frequencies  $\sim$  ion cyclotron frequencies  
 $\rightarrow$  One can "tap" into another

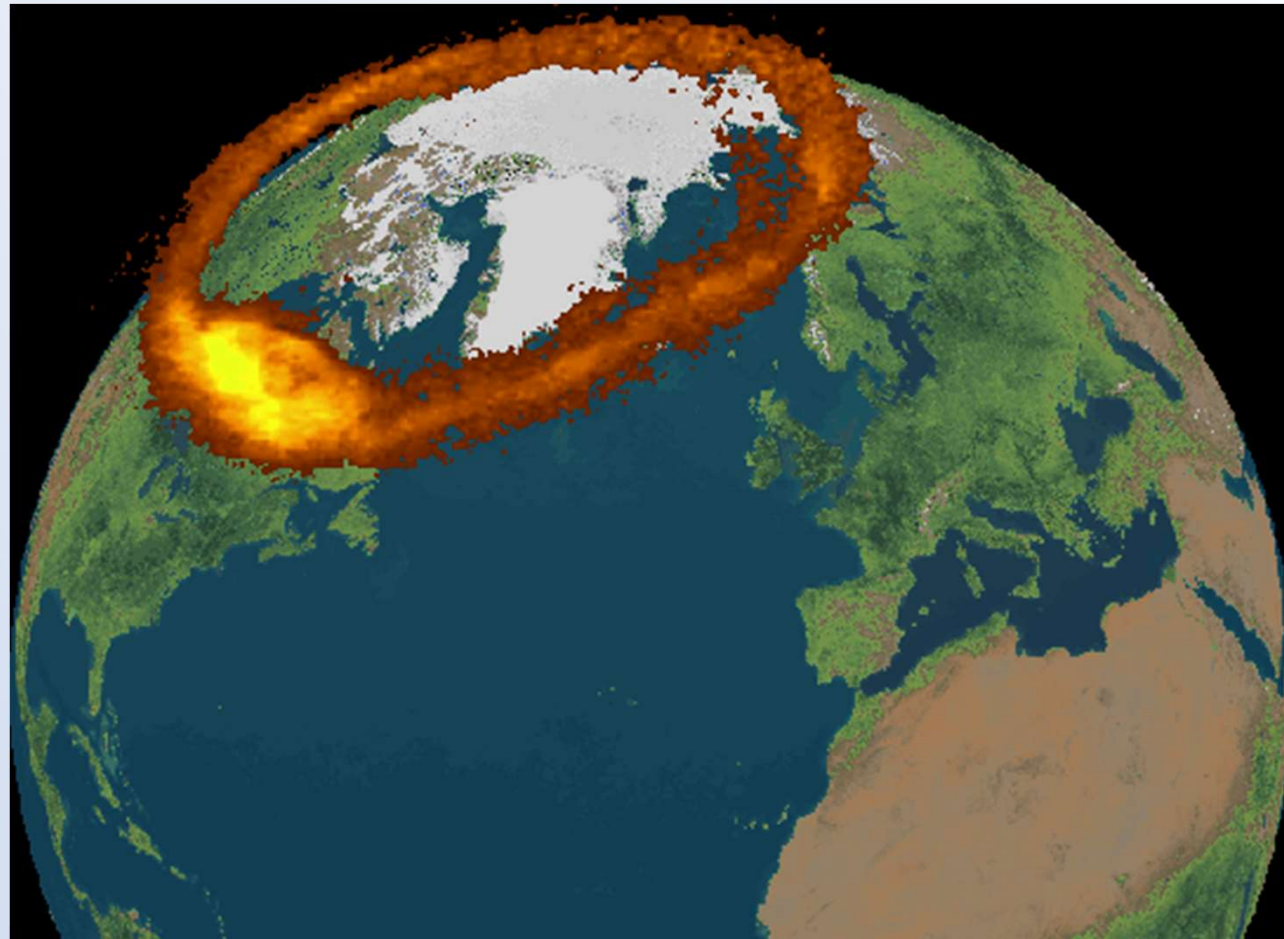


Image credit: NASA

# Kelvin-Helmholtz waves

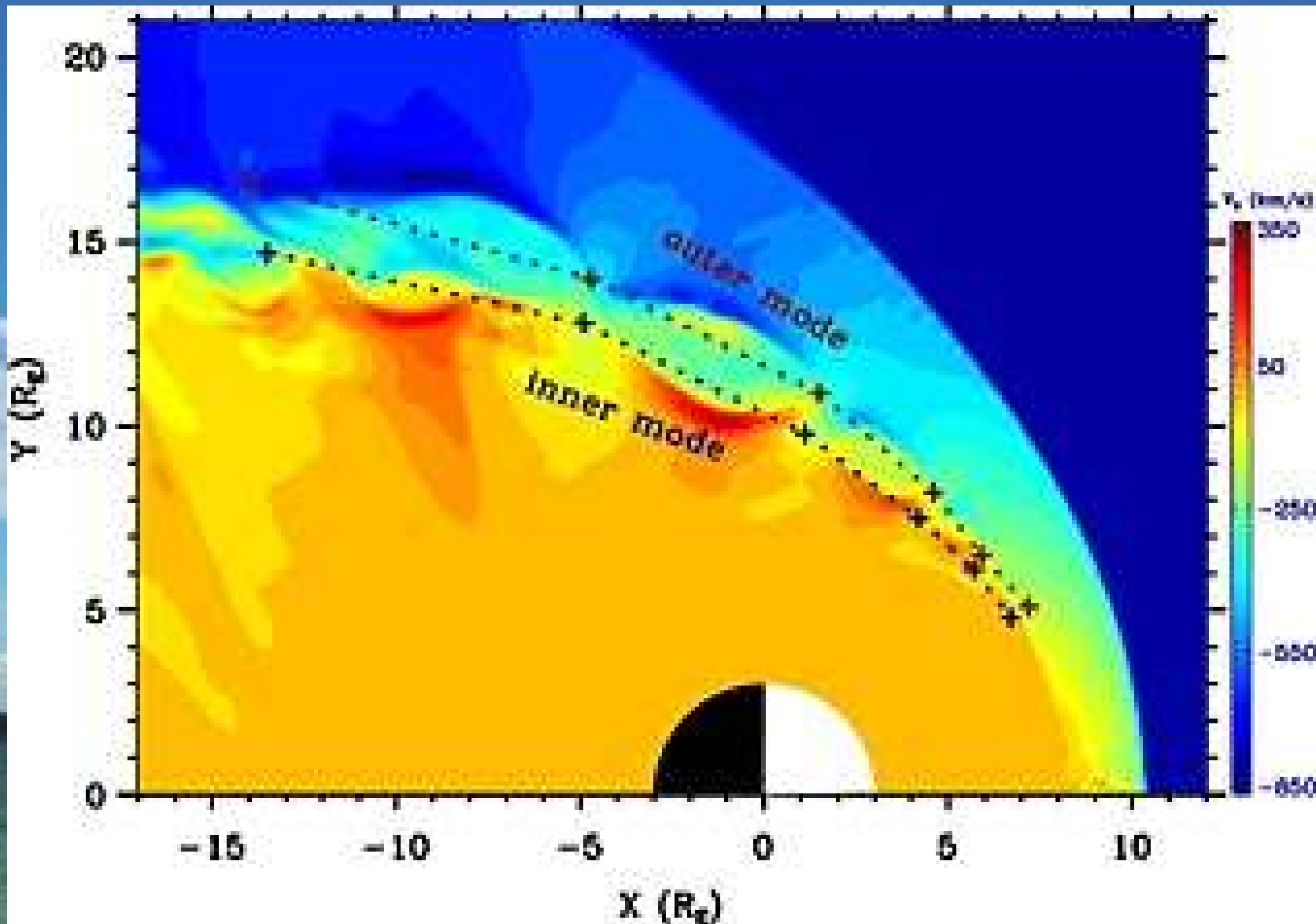


# Kelvin-Helmholtz waves

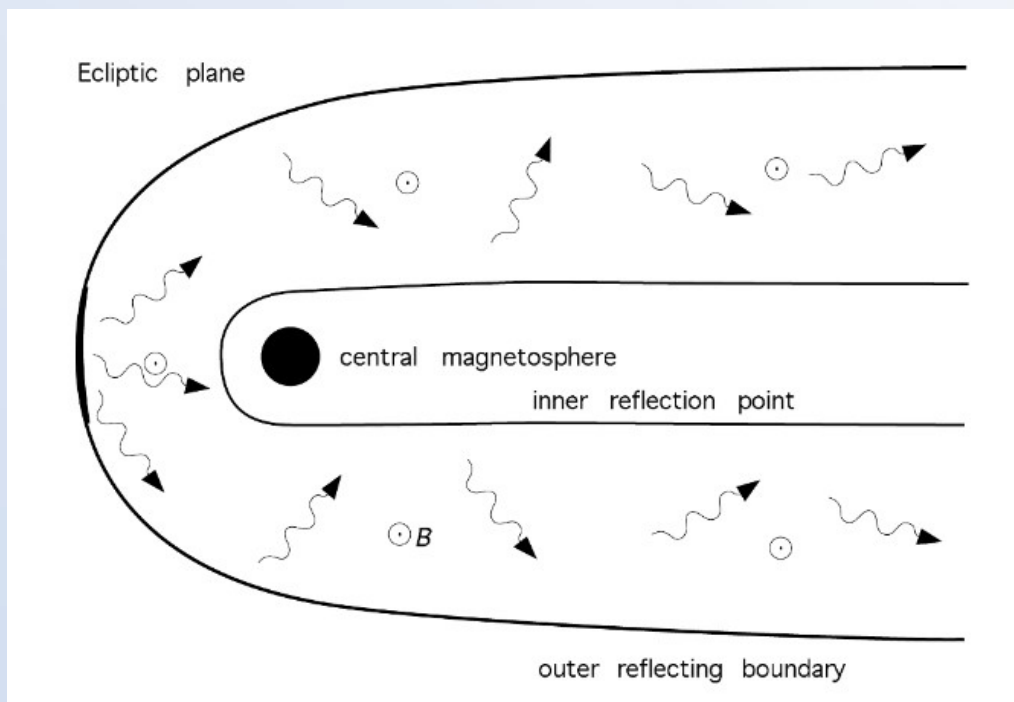
- Instability caused by velocity shear between two fluids
- Greater the speed difference between the fluids, the faster and greater the instability



# Kelvin-Helmholtz waves

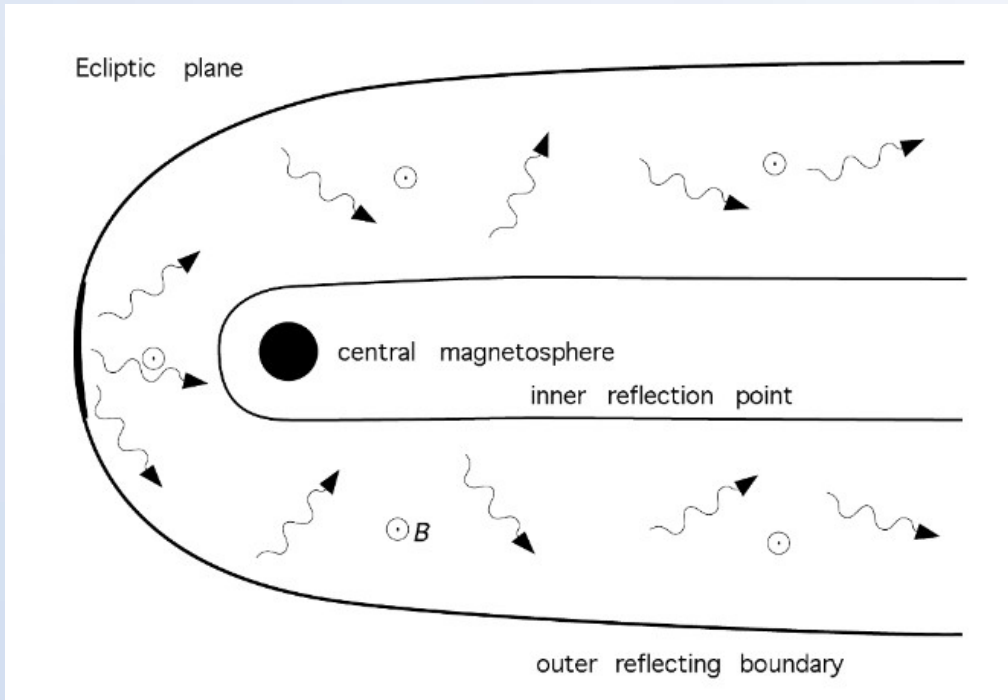




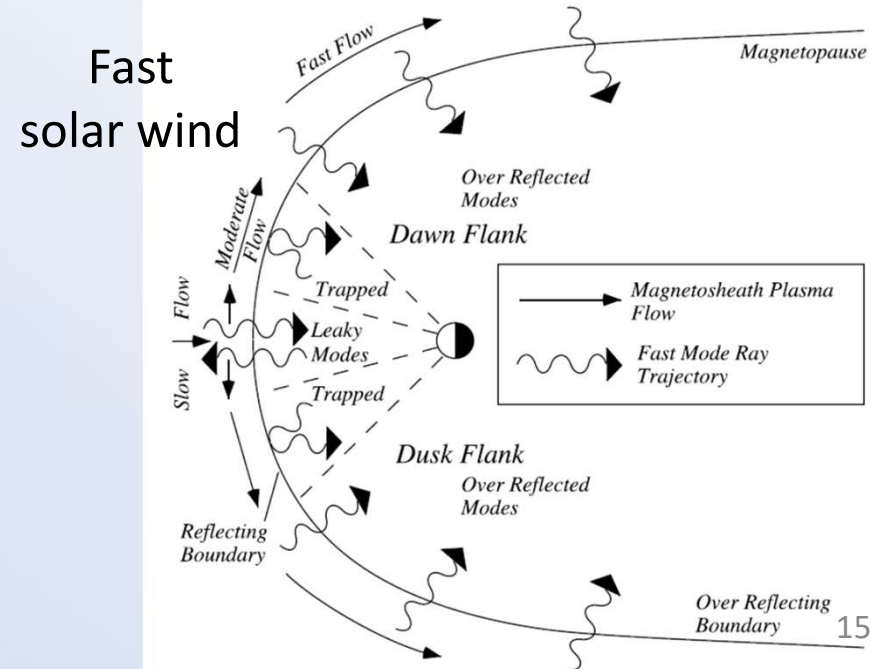
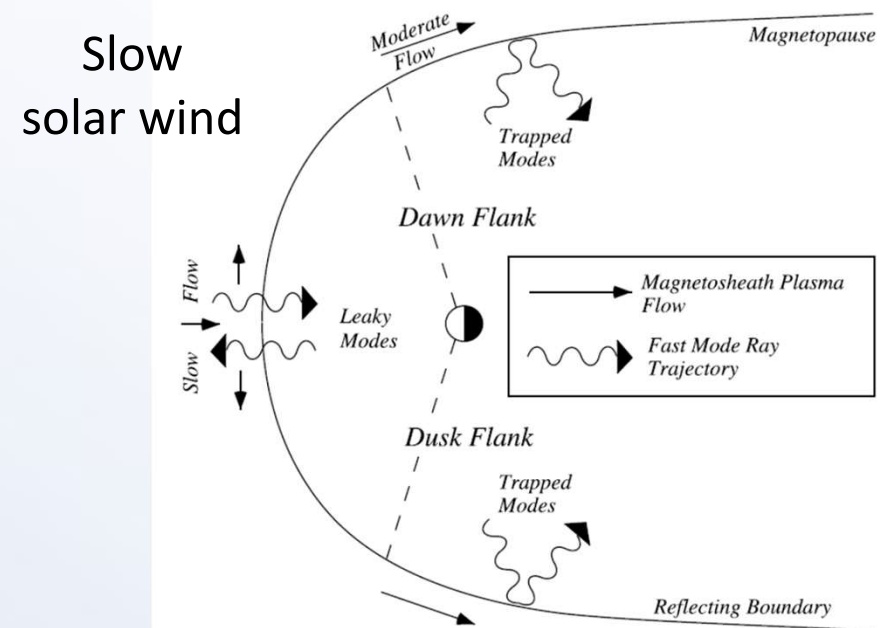


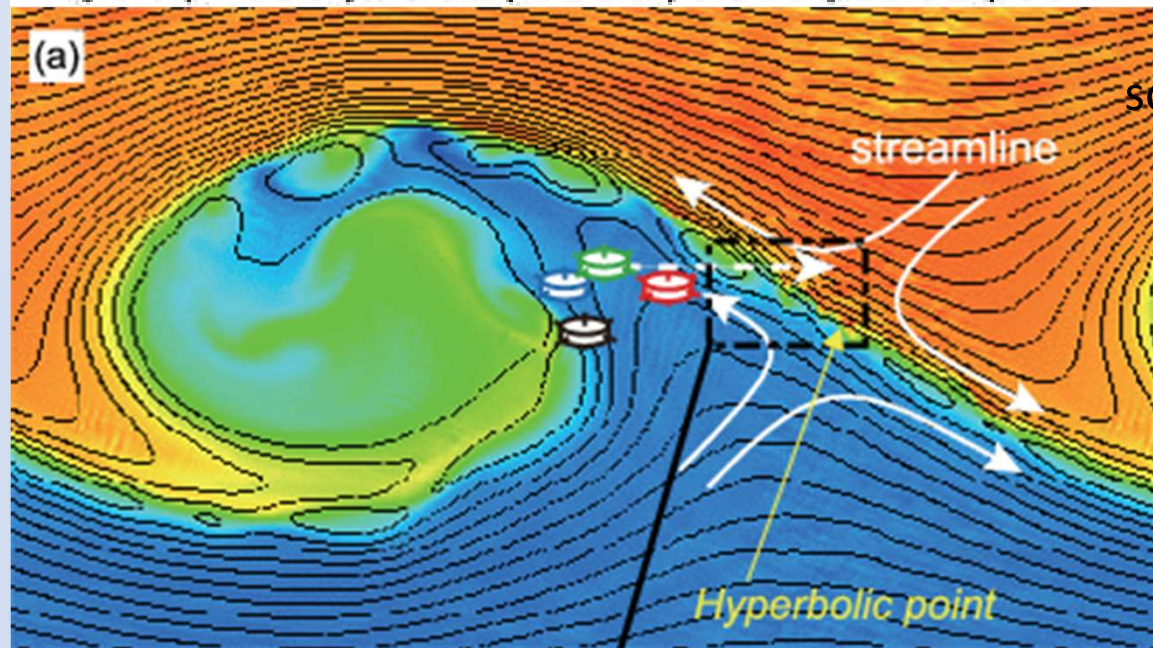
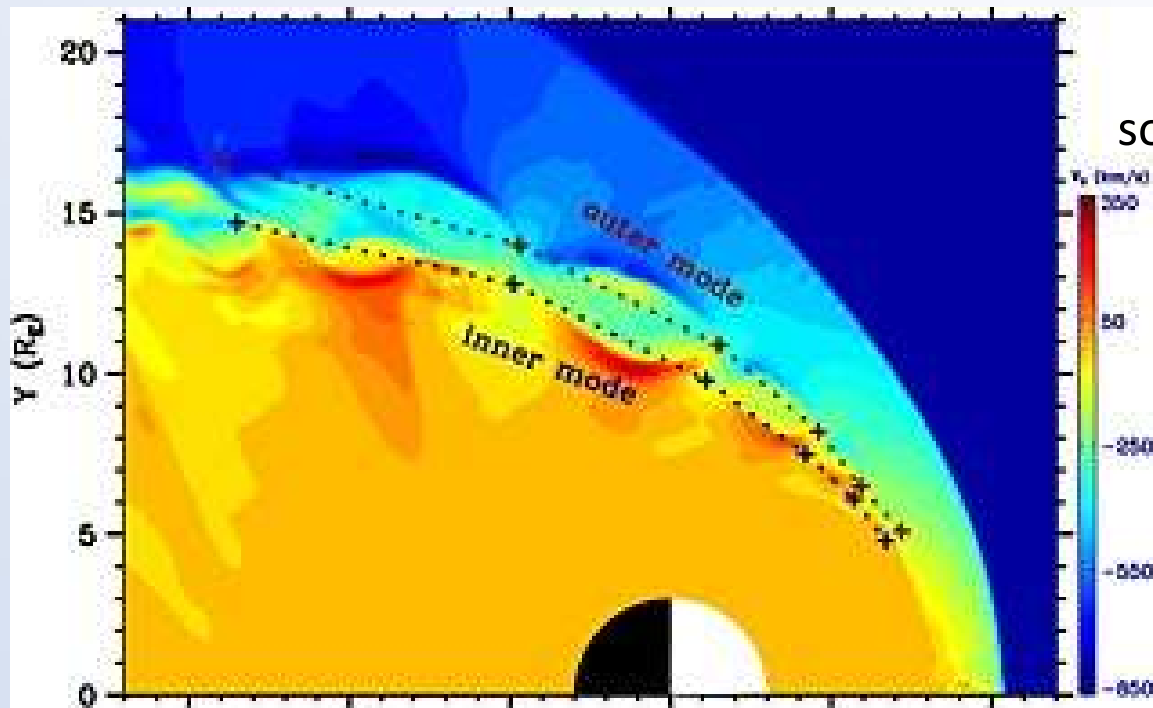
Fast-mode waves bouncing between magnetospheric outer and inner boundaries

## Magnetospheric waveguide

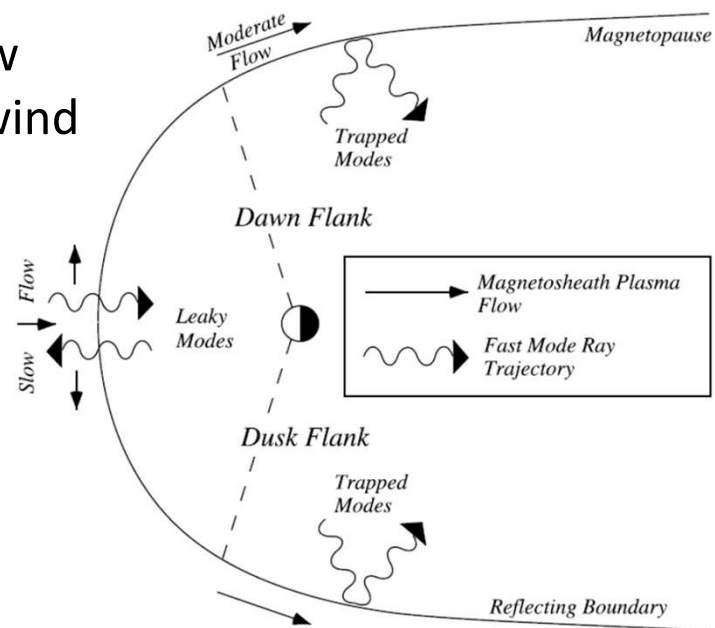


Fast-mode waves bouncing between magnetospheric outer and inner boundaries

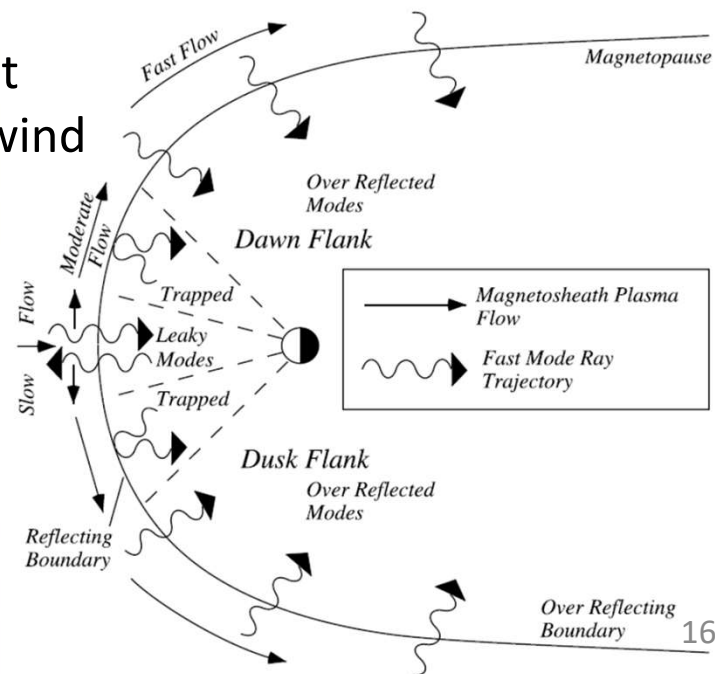




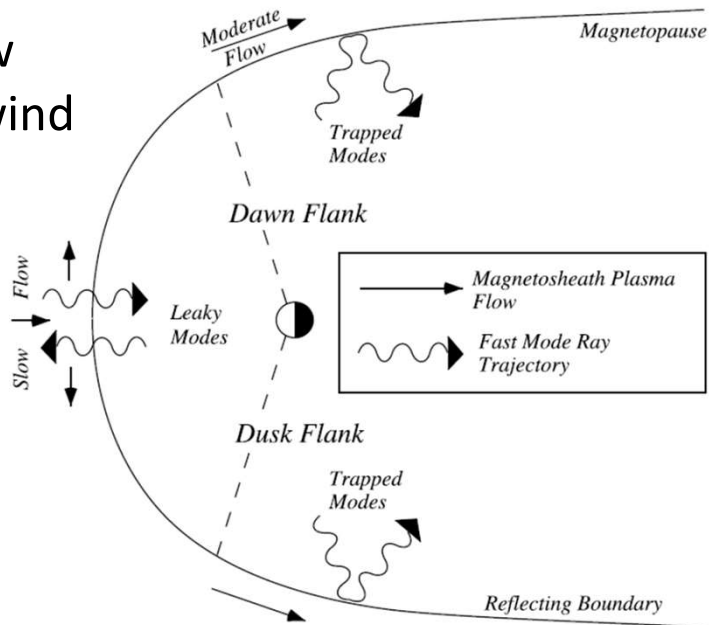
Slow solar wind



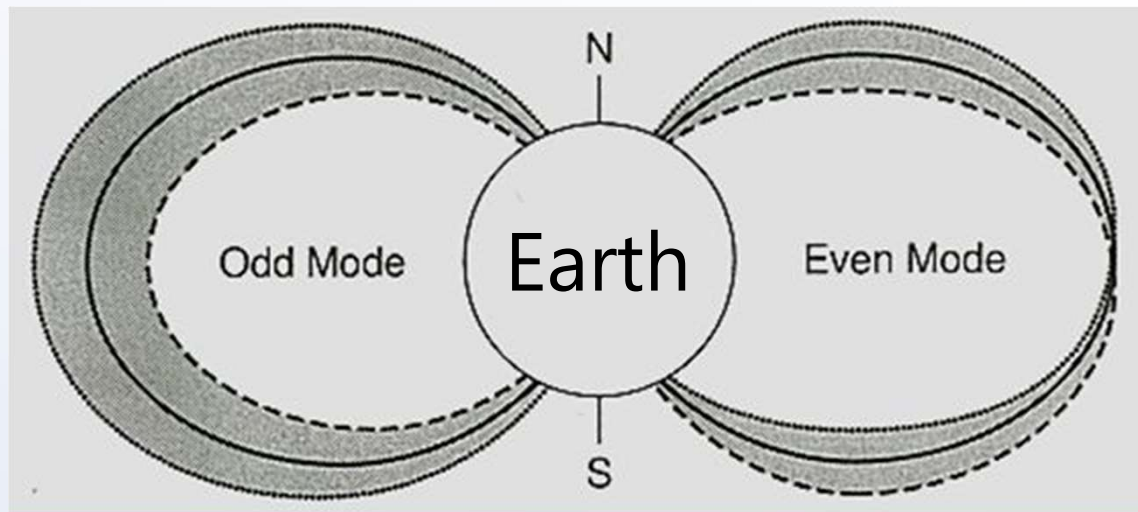
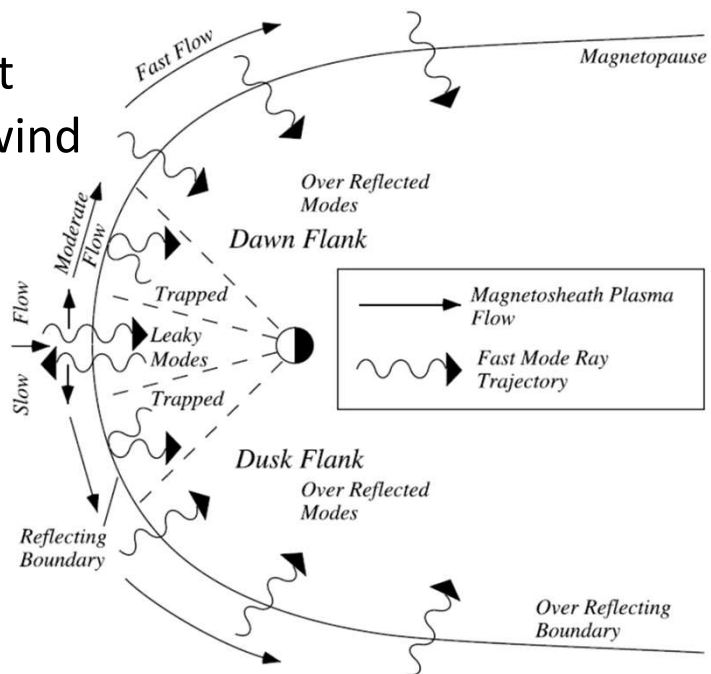
Fast solar wind



Slow solar wind



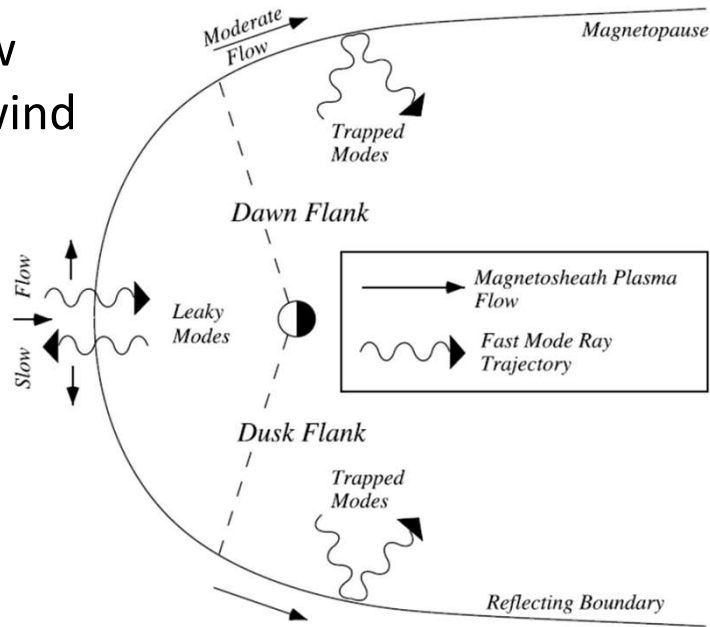
Fast solar wind



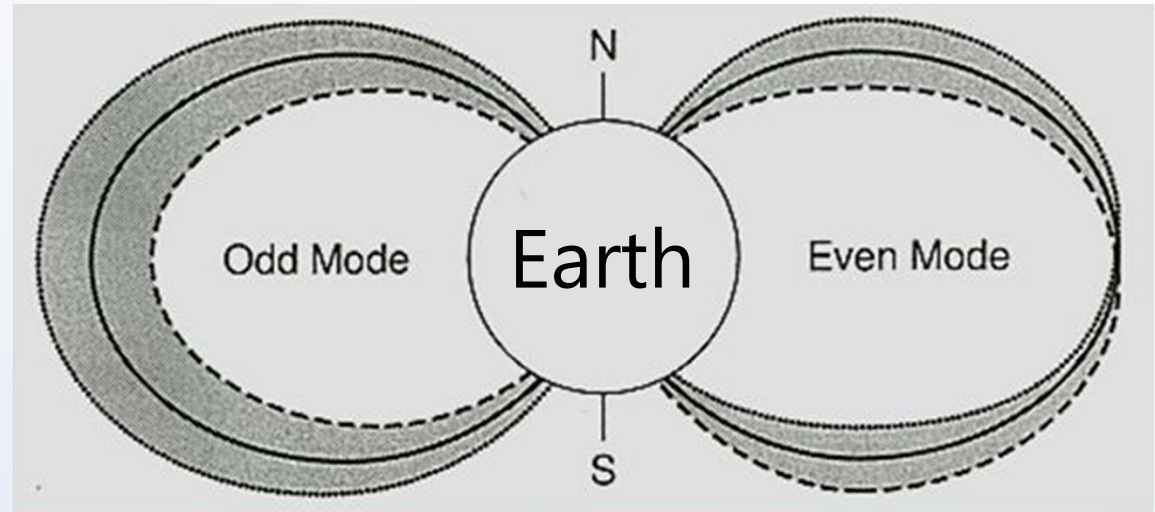
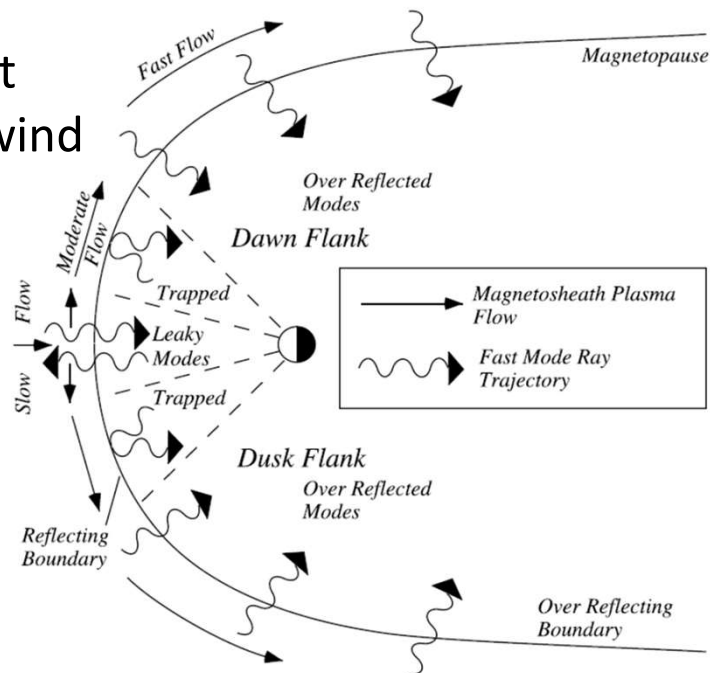
Shear Alfvén waves



Slow solar wind



Fast solar wind



Shear Alfvén waves

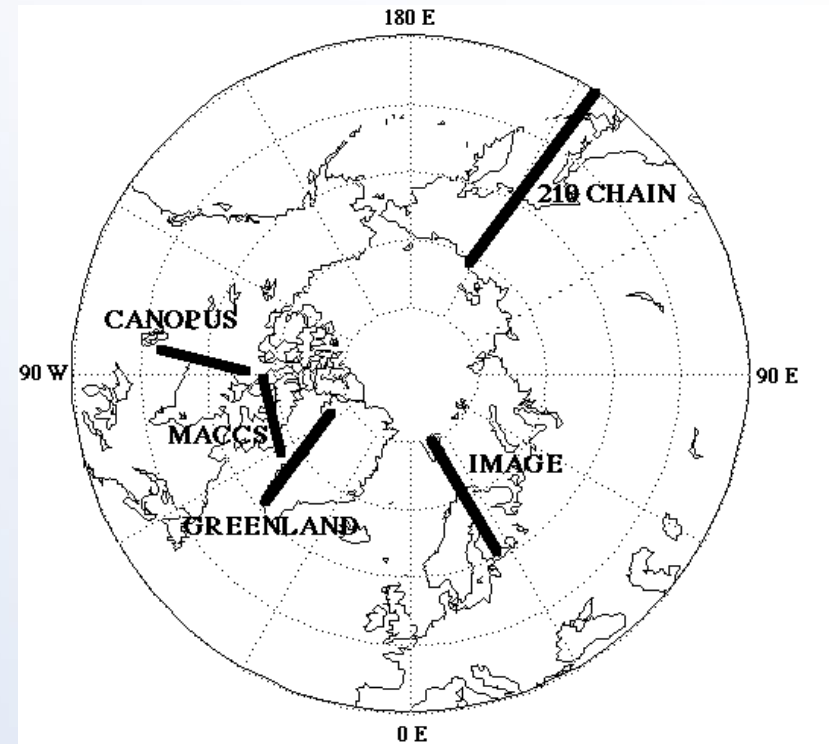
→ Fast mode magnetosonic wave transforms into shear Alfvén wave traversing the magnetic field lines



# Ground measurements

## Magnetometer chains

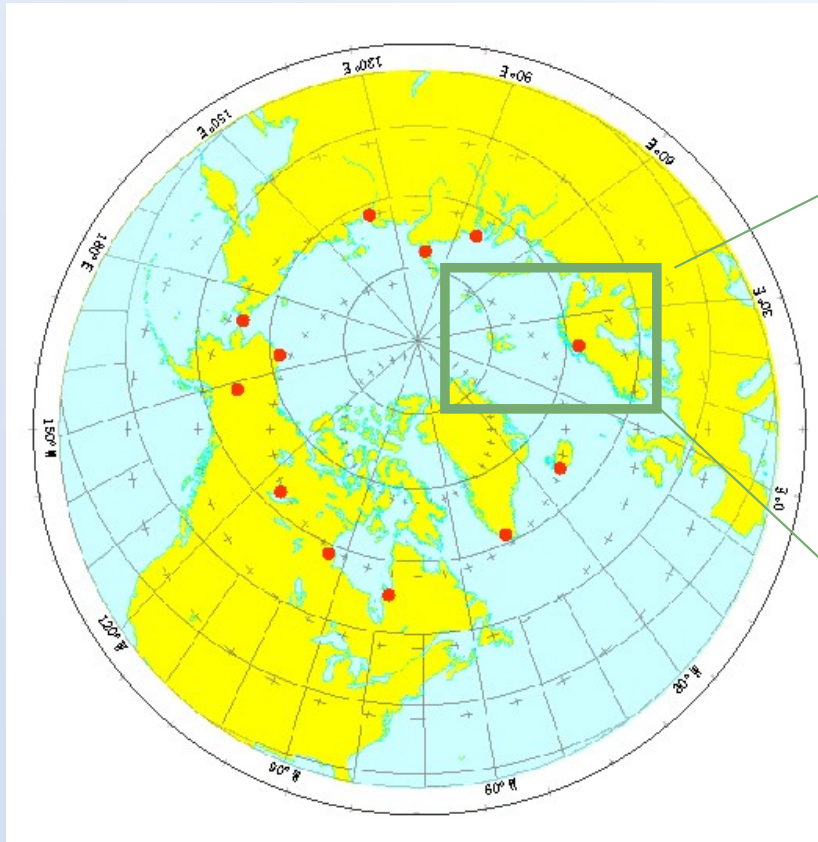
- IMAGE network
- CARISMA (earlier CANOPUS) and MACCS
- MAGDAS / 210 CHAIN
- Greenland Coastal Array
- Scandinavian SME (only historical data).



# Magnetometer networks

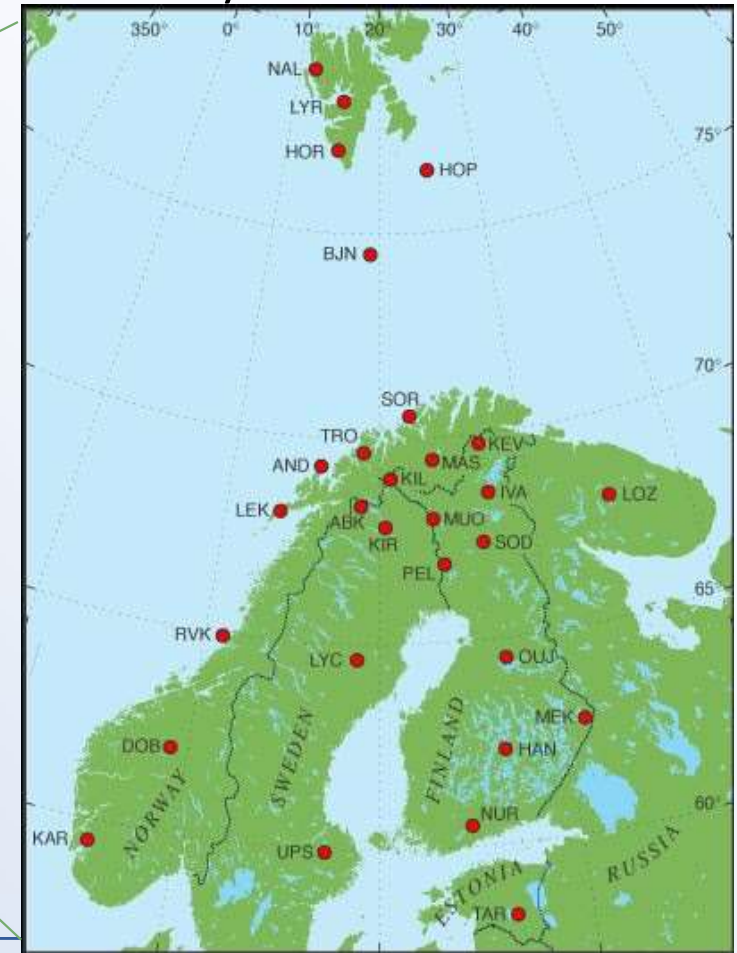
\* 3 decommissioned;  
4 more upcoming in 2024

12 Kyoto AL observatories



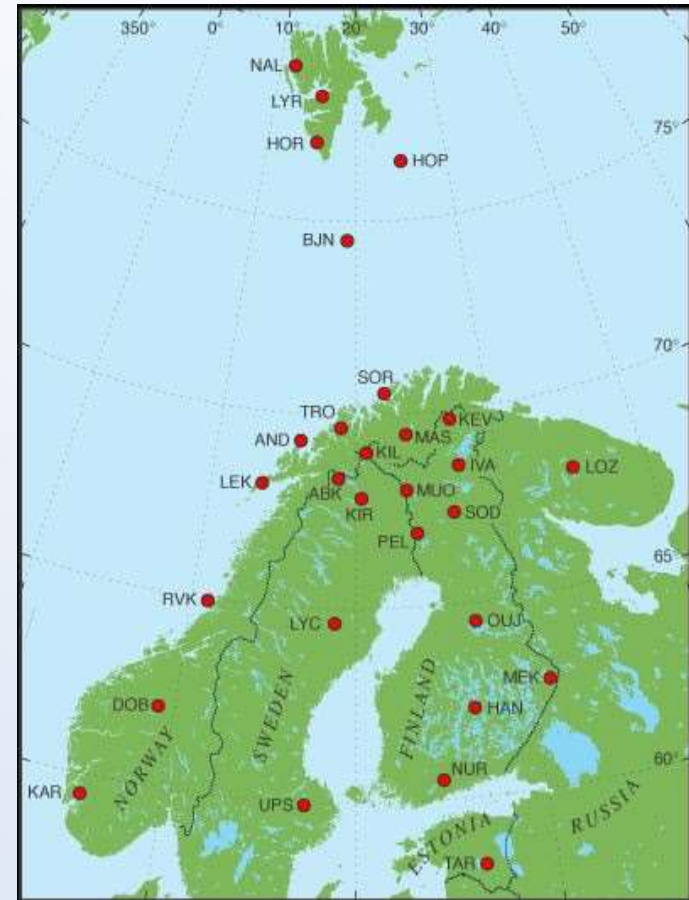
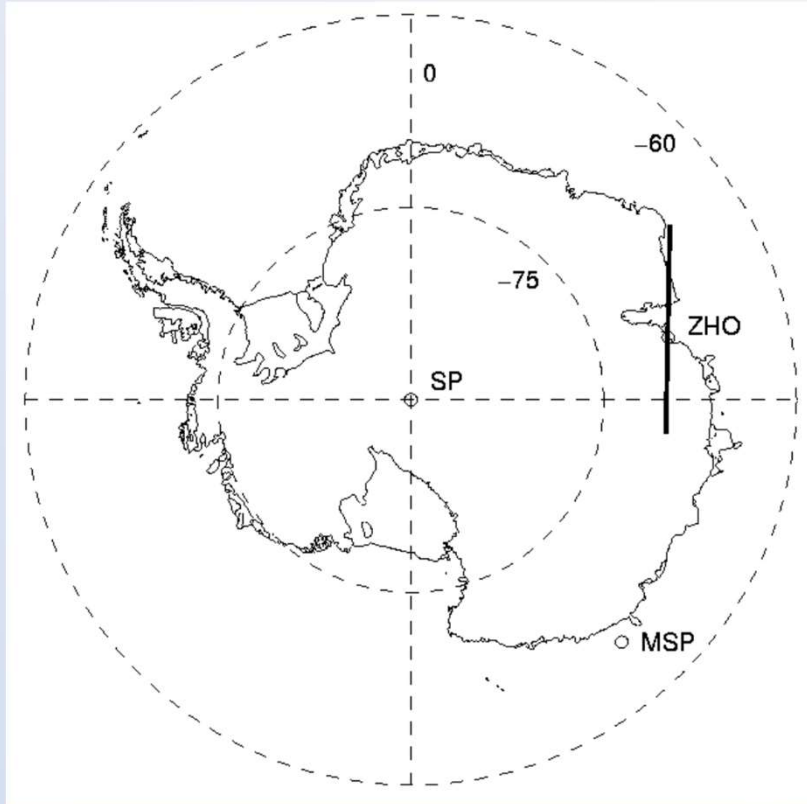
Fluxgate magnetometers

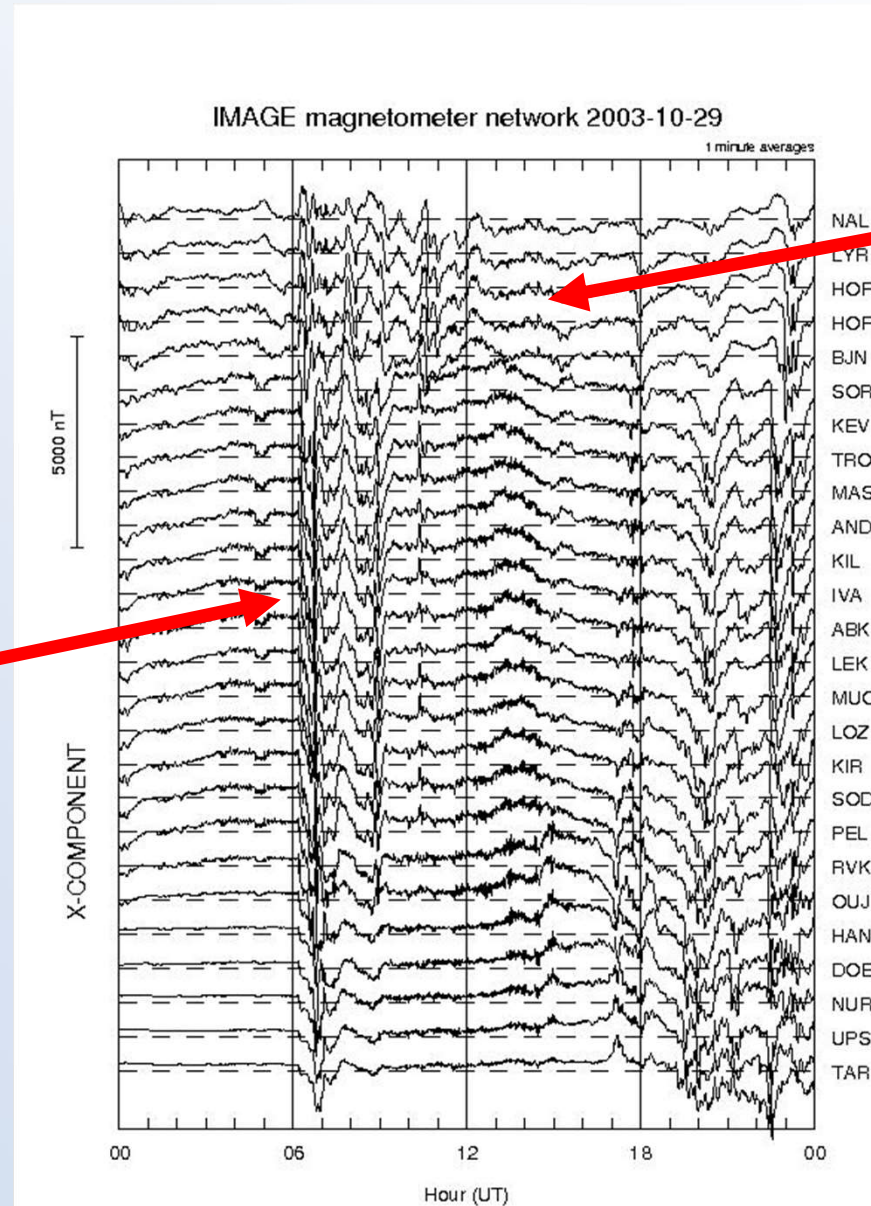
Currently\* 52 IMAGE observatories



Courtesy of Häkkinen

# Conjugate magnetic measurements

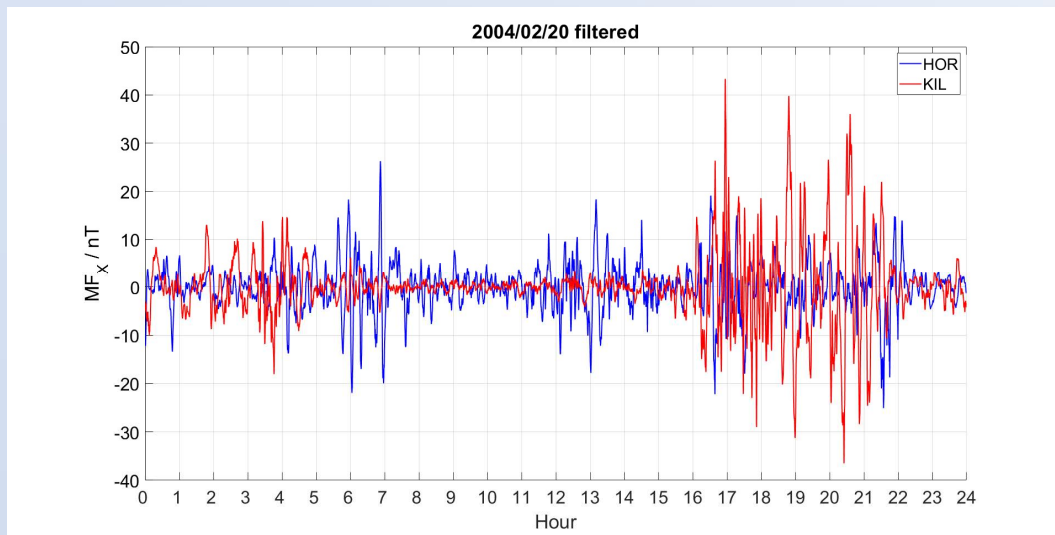
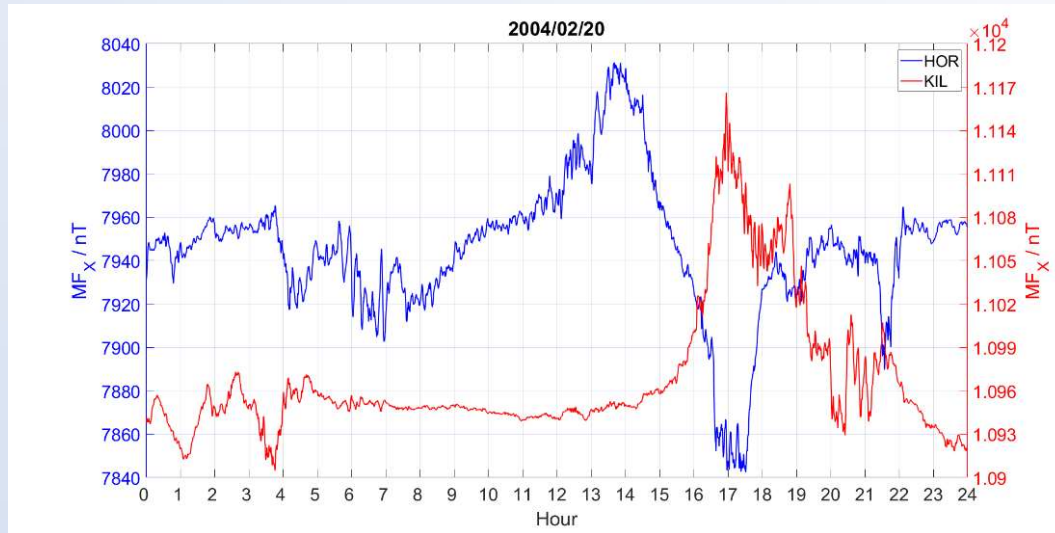




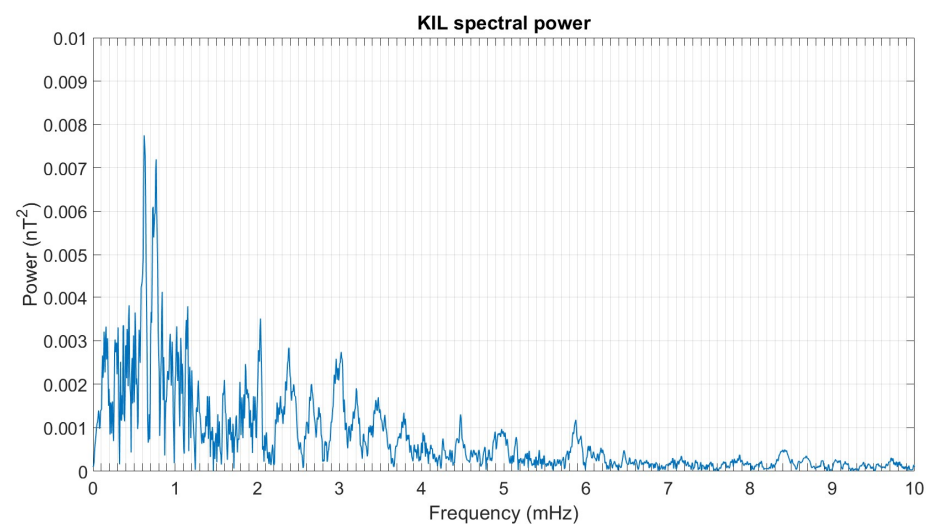
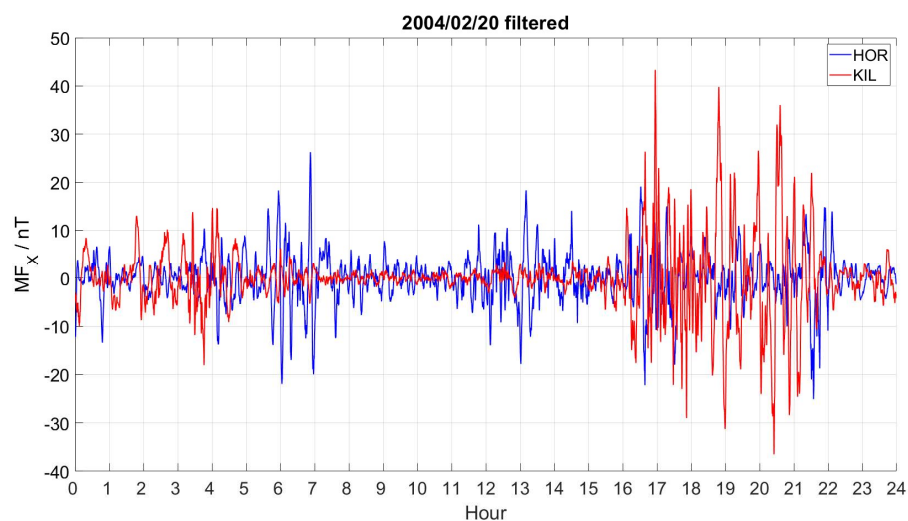
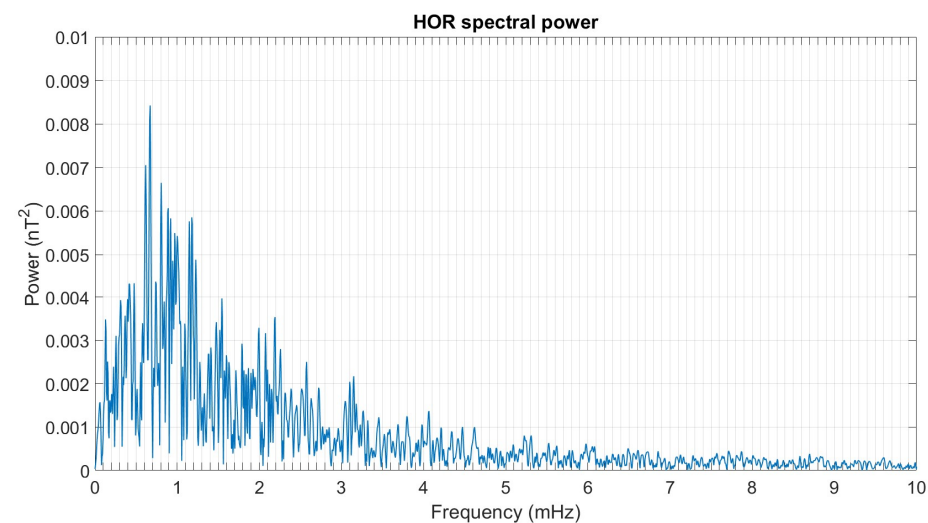
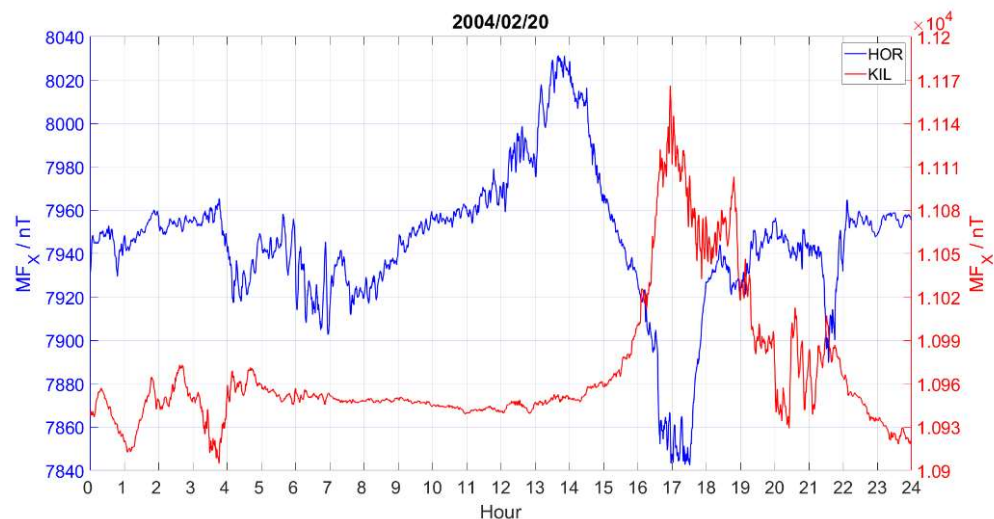
Pc5 pulsations

Storm-time substorms

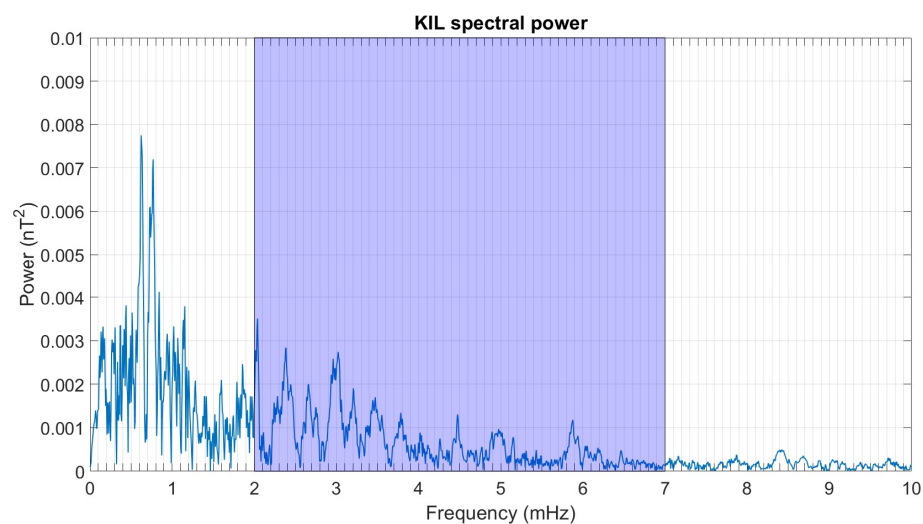
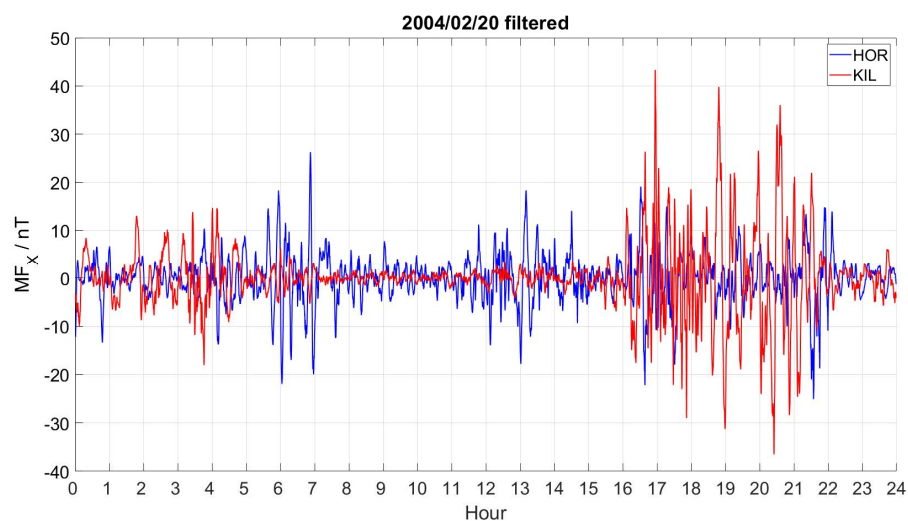
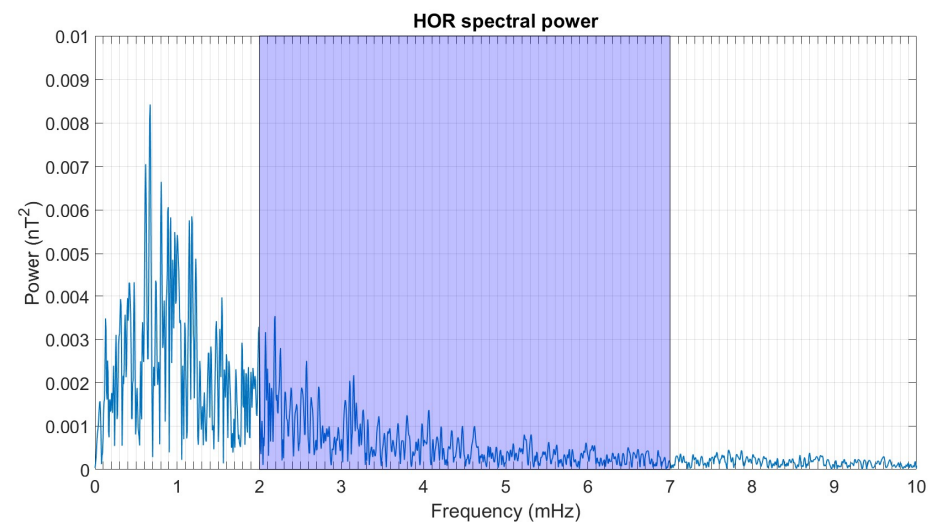
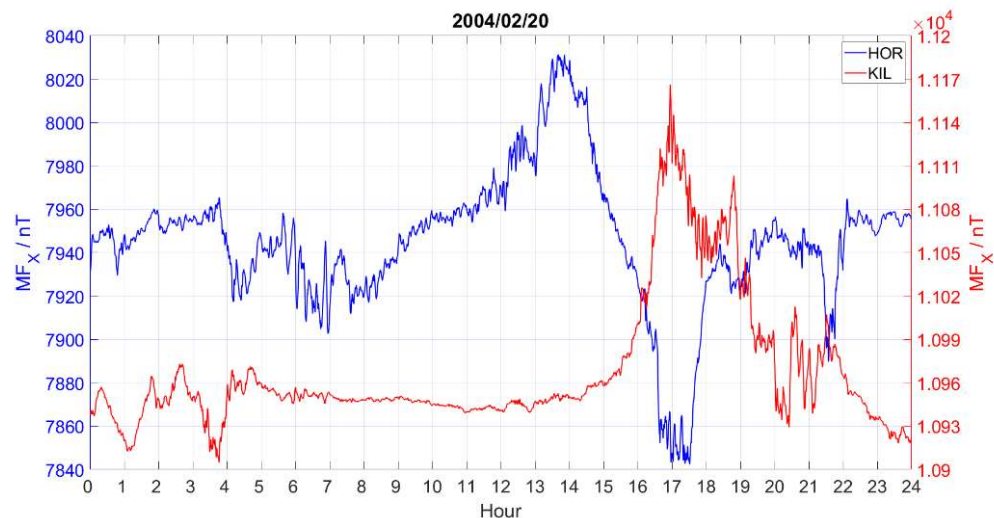






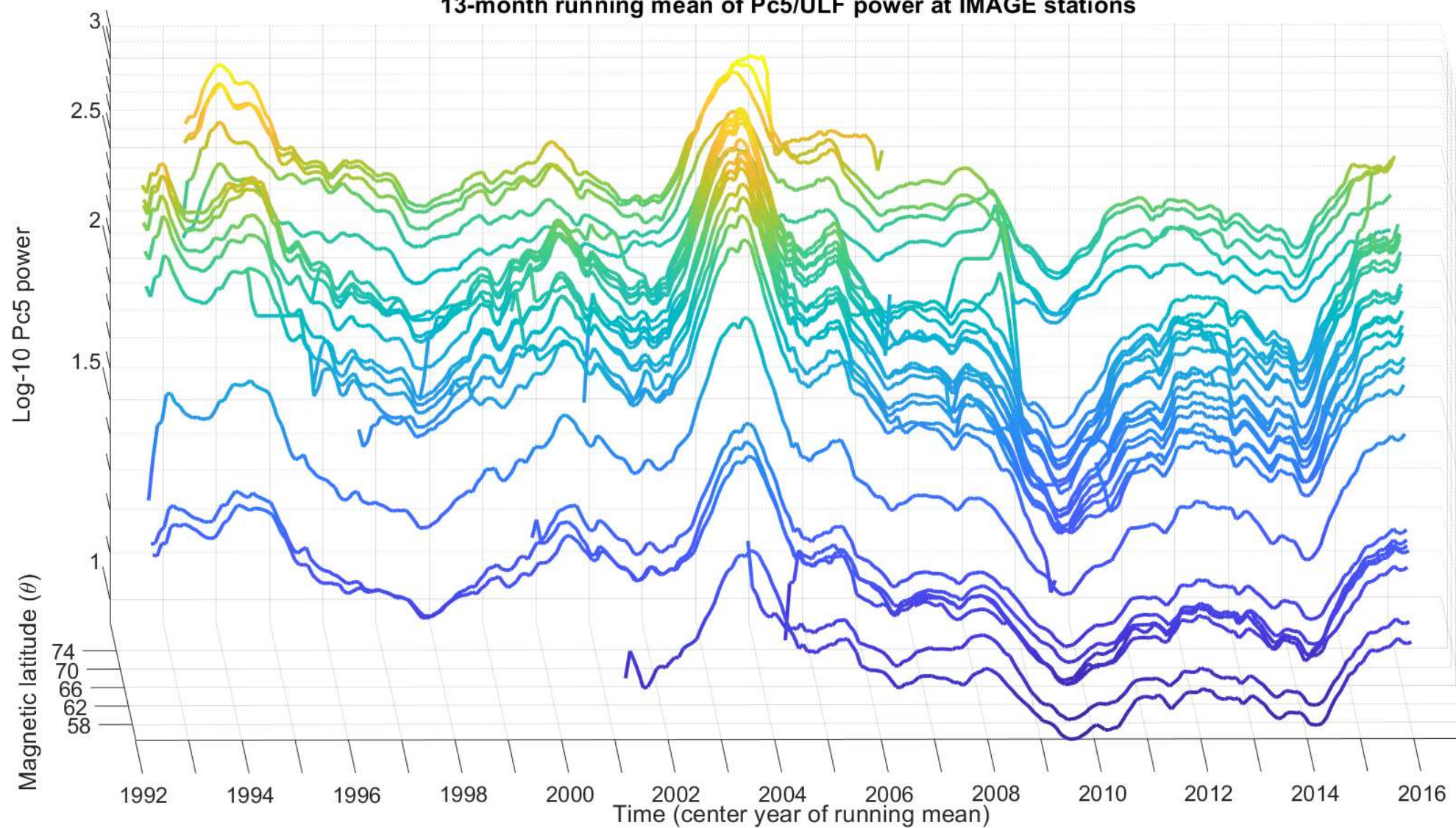


\* Fast Fourier Transform



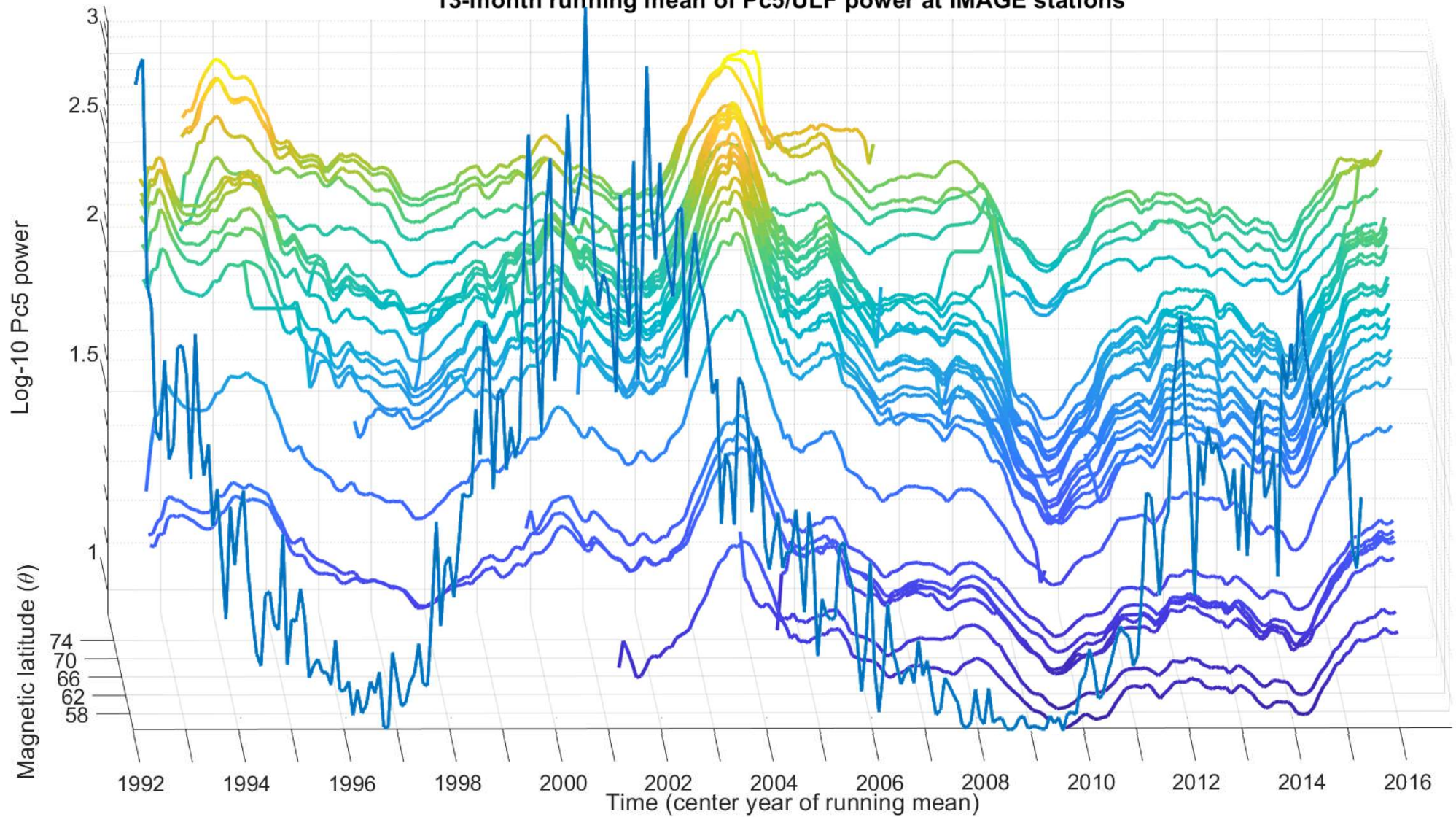
Pc5 waves

13-month running mean of Pc5/ULF power at IMAGE stations



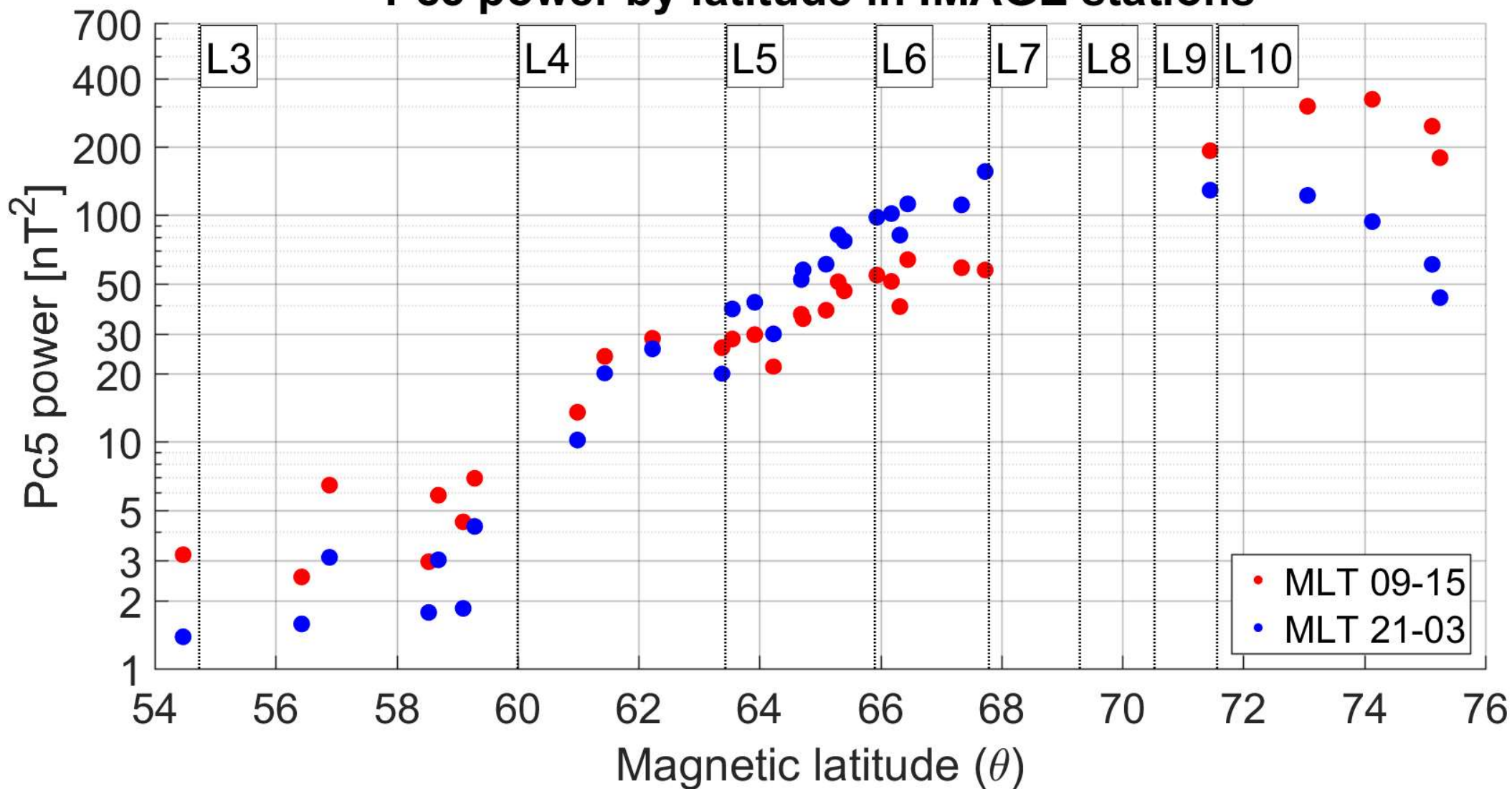


13-month running mean of Pc5/ULF power at IMAGE stations





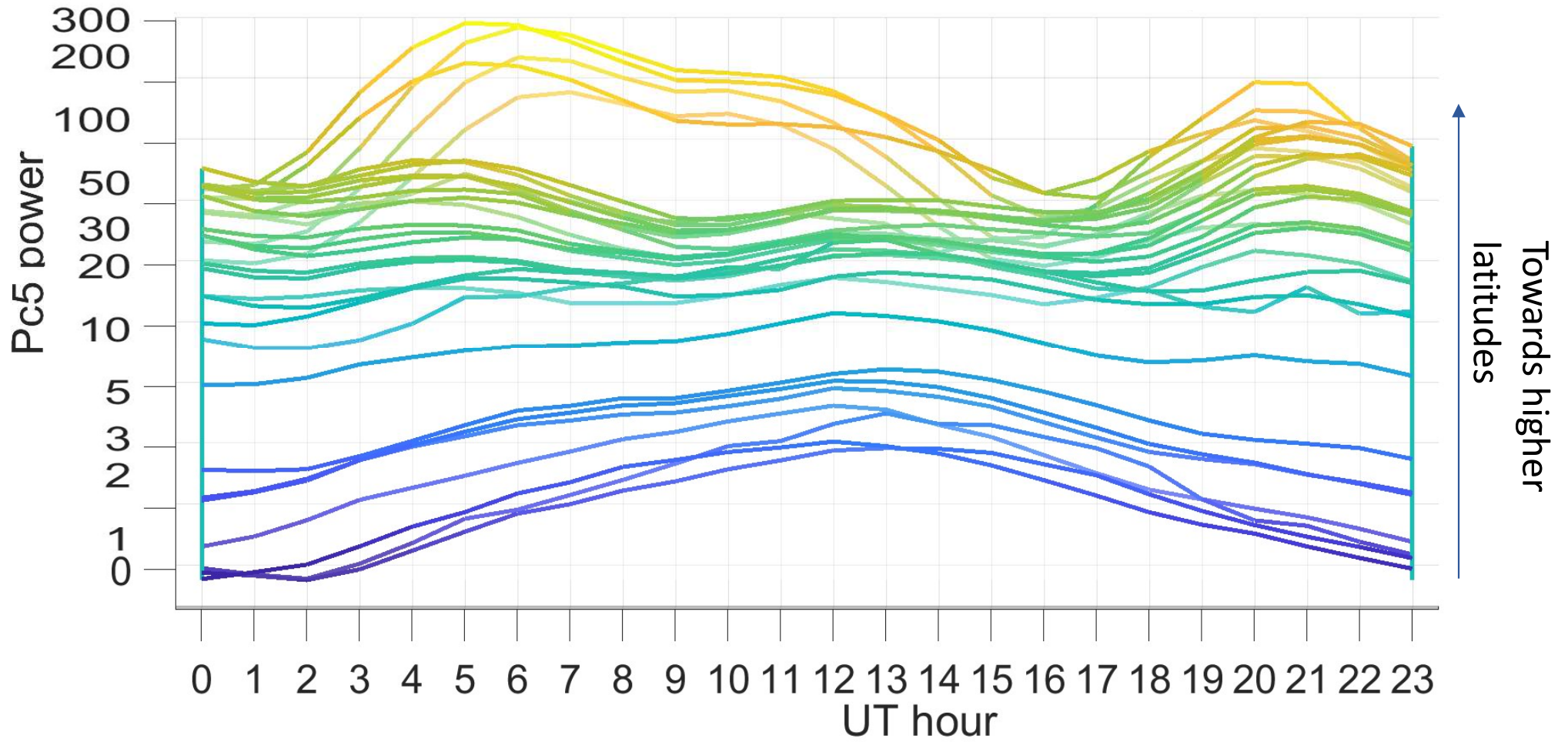
## Pc5 power by latitude in IMAGE stations



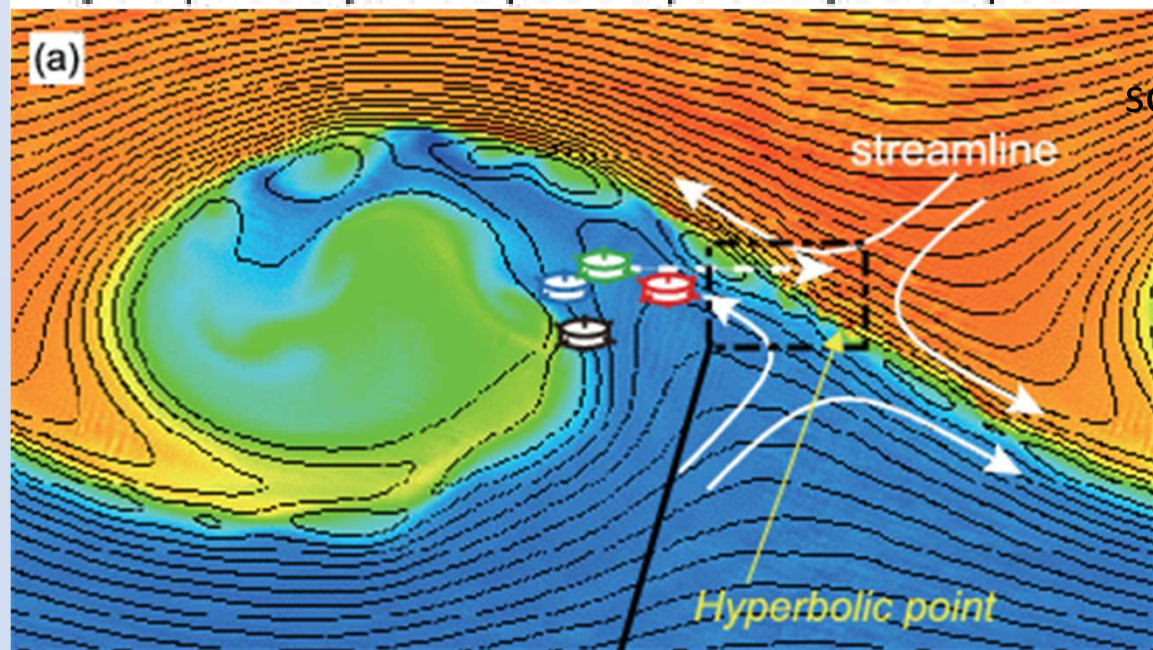
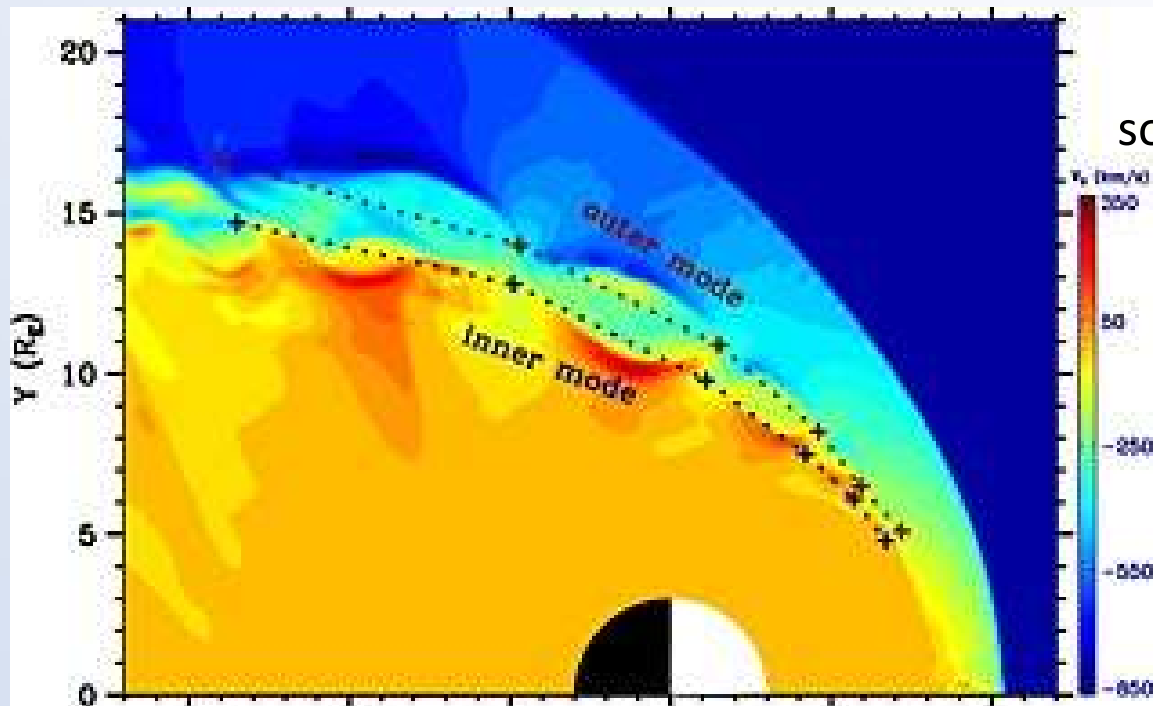
\*  $L = 1/\cos^2 \theta$



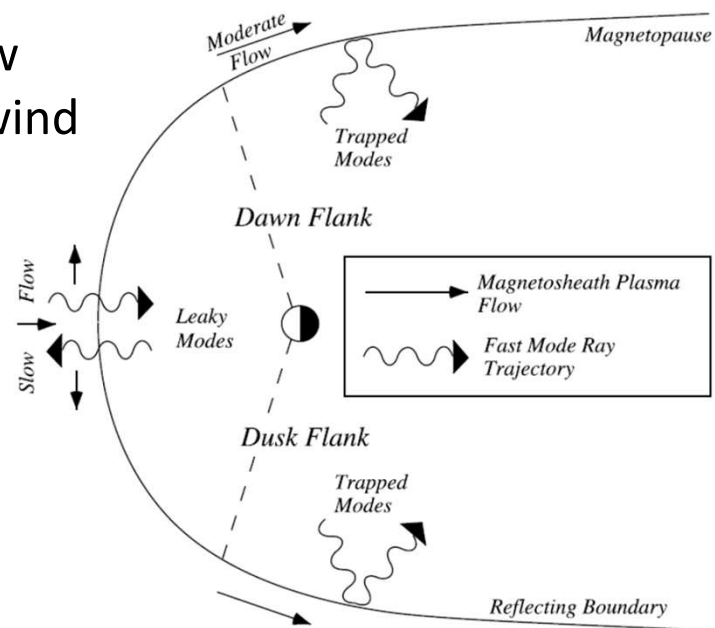
# Sampling by the hour



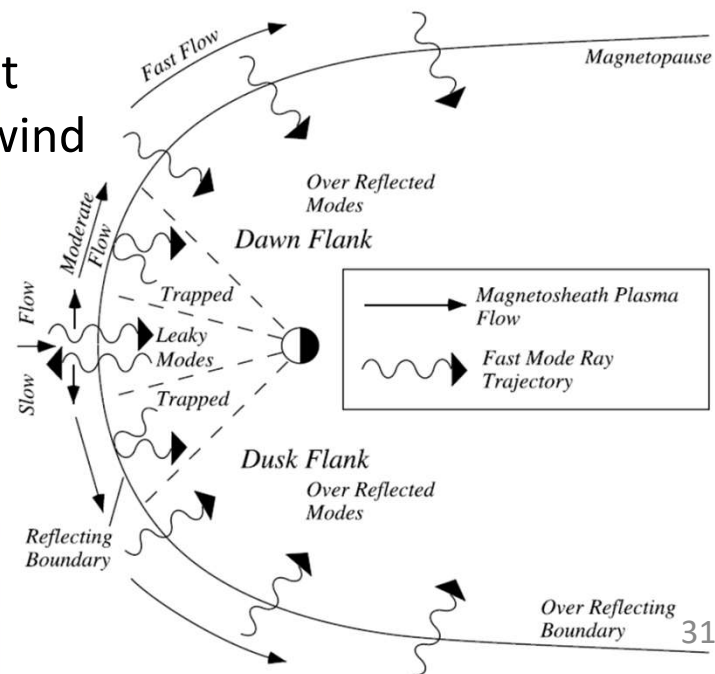




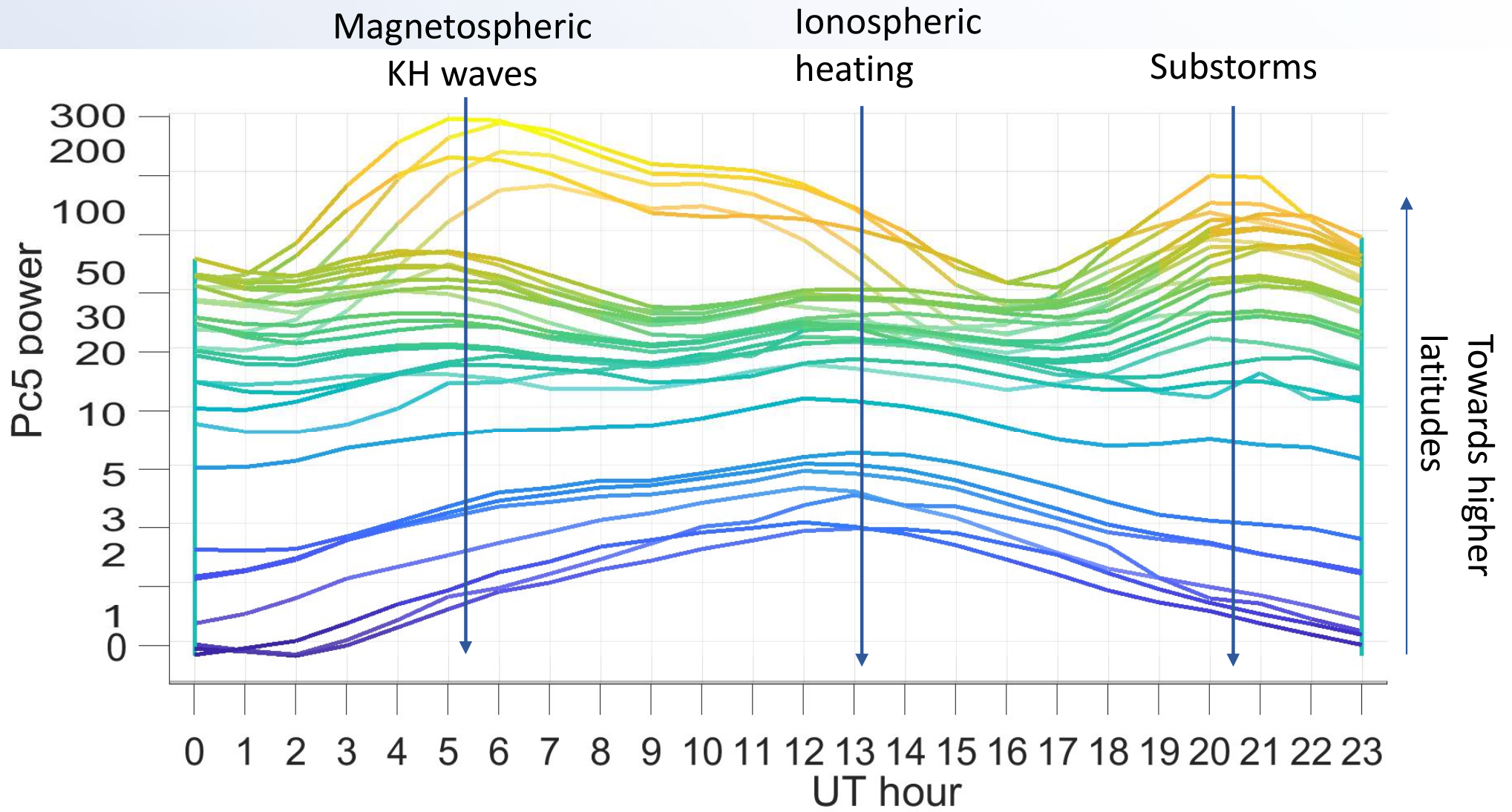
Slow solar wind

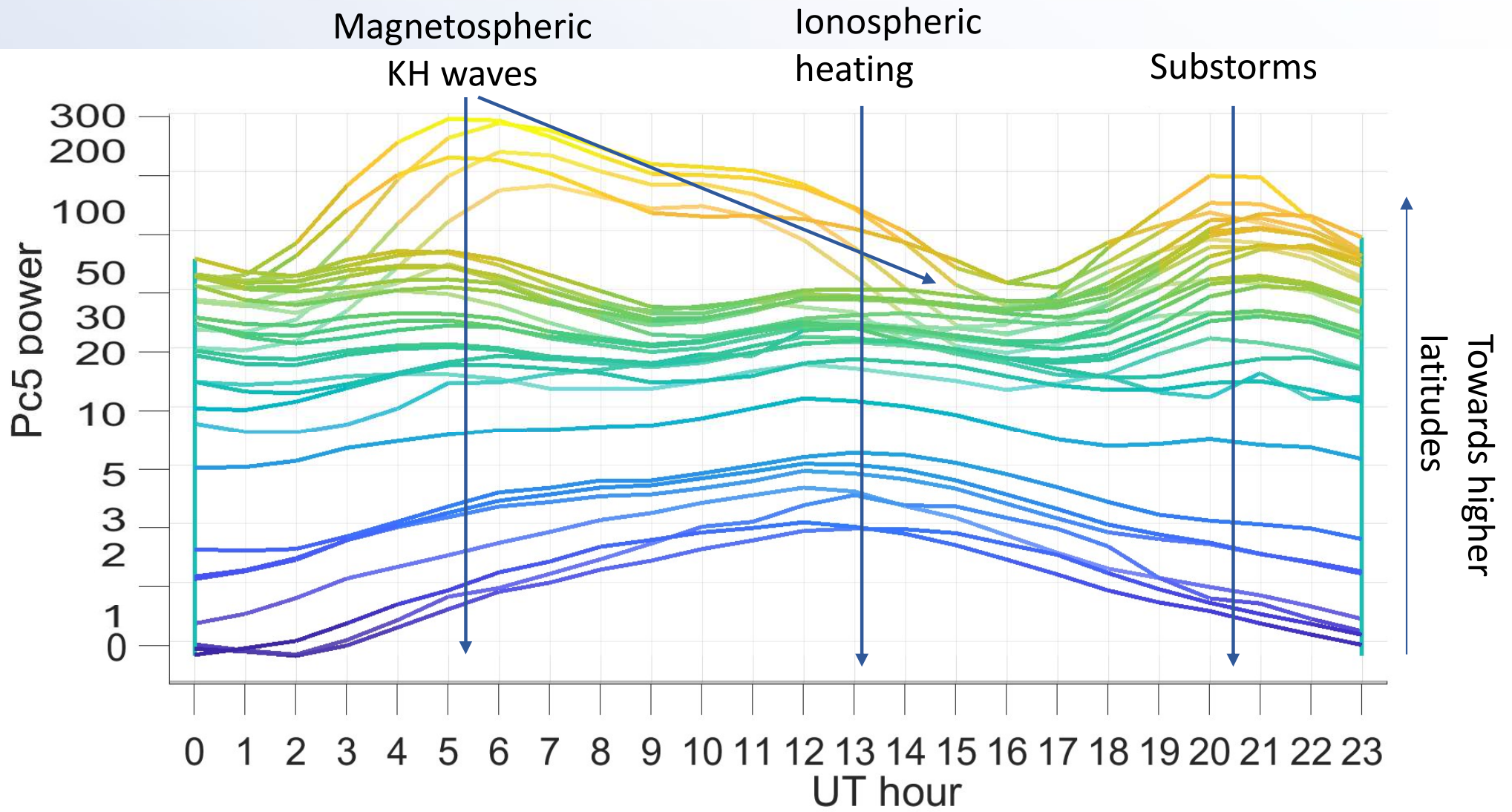


Fast solar wind

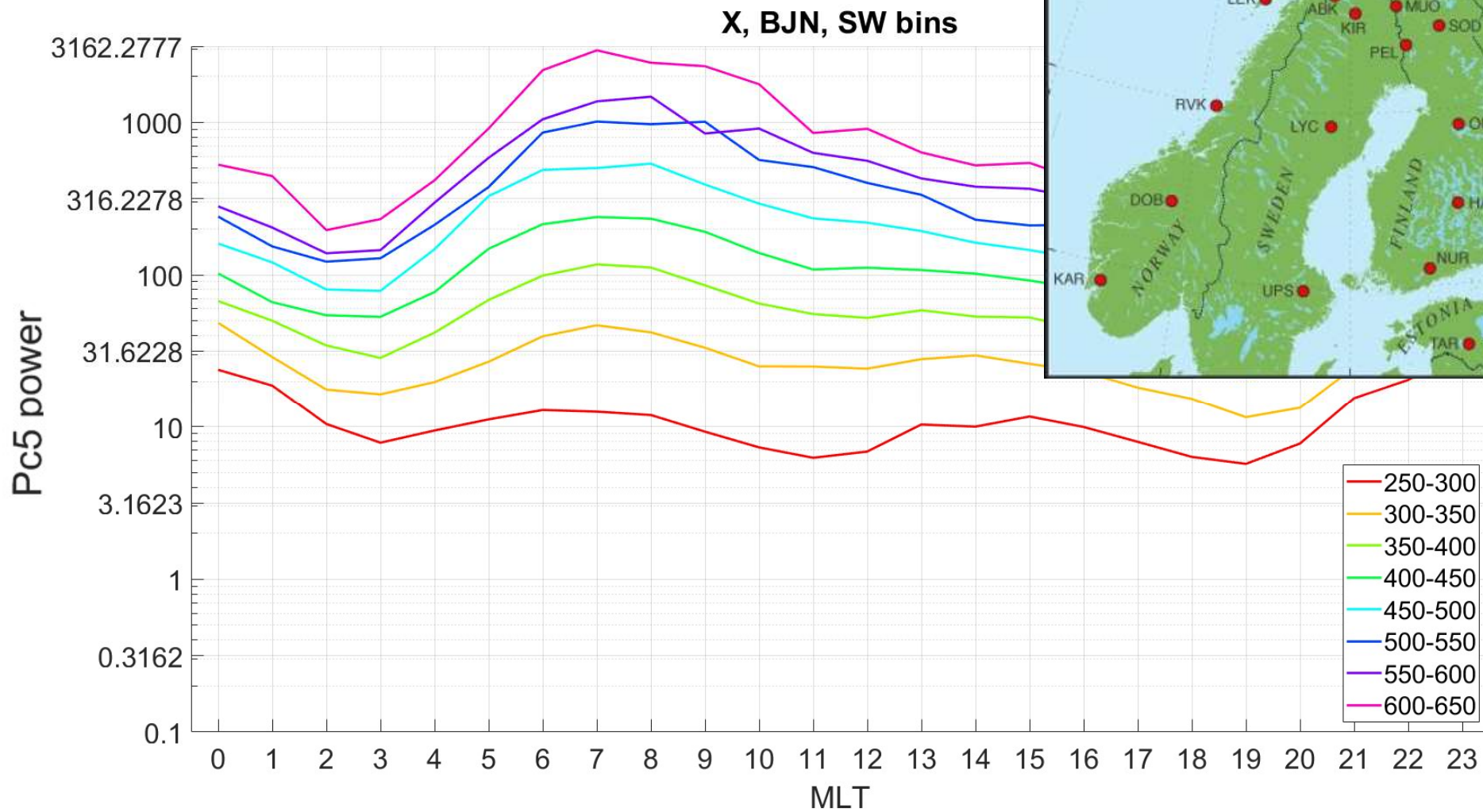
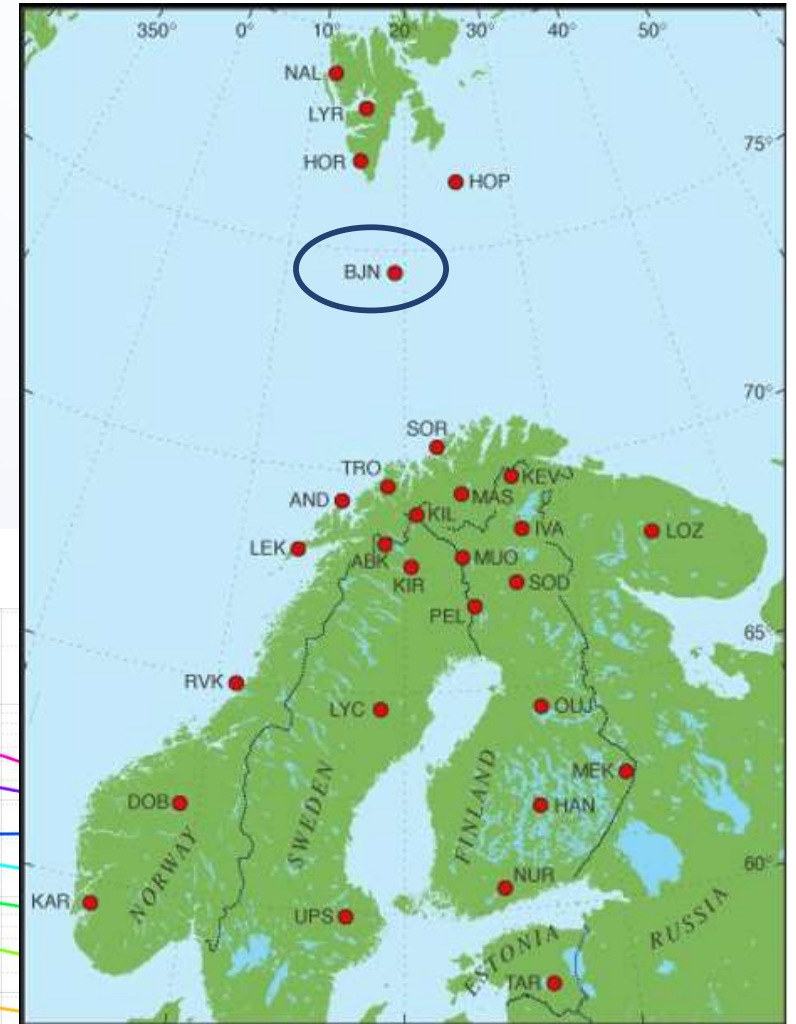






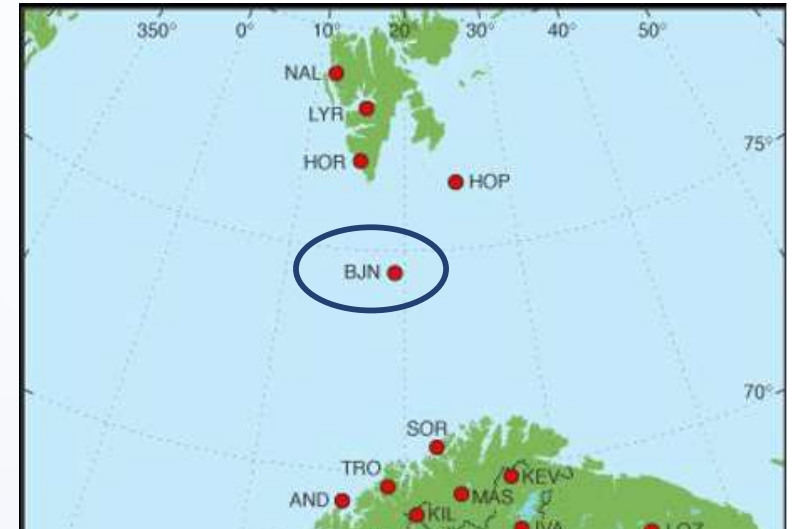


# Effect of solar wind speed





# Effect of solar wind speed



X, BBN, SW bins

