ACADEMY OF FINLAND

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ULF* waves and related phenomena

*ultra-low frequency

Magnetism & Applications 2023

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ULF waves

- Many, many different waves!
- ν < 1-5 Hz, period T > 0.2-1 s
- ν ~ cyclotron frequency of proton ~ 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

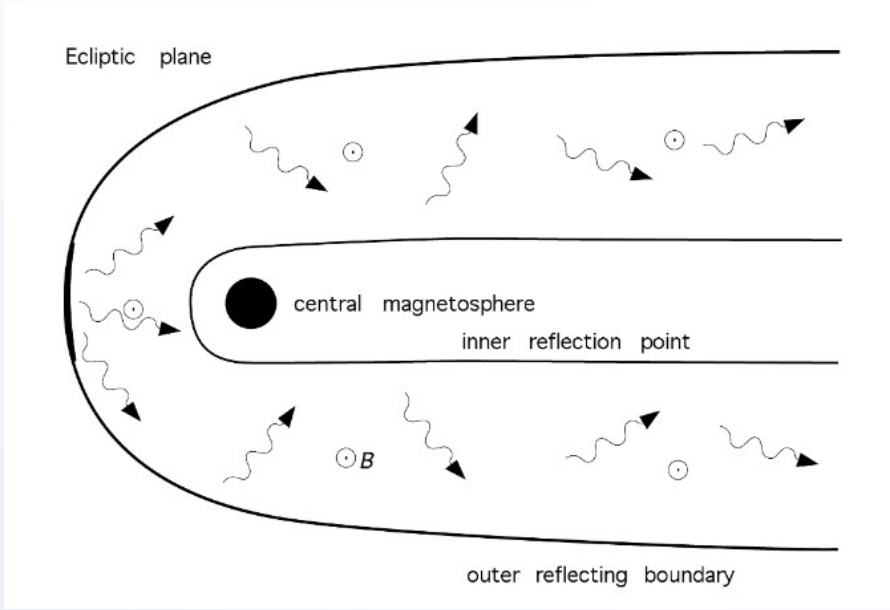
TABLE 2

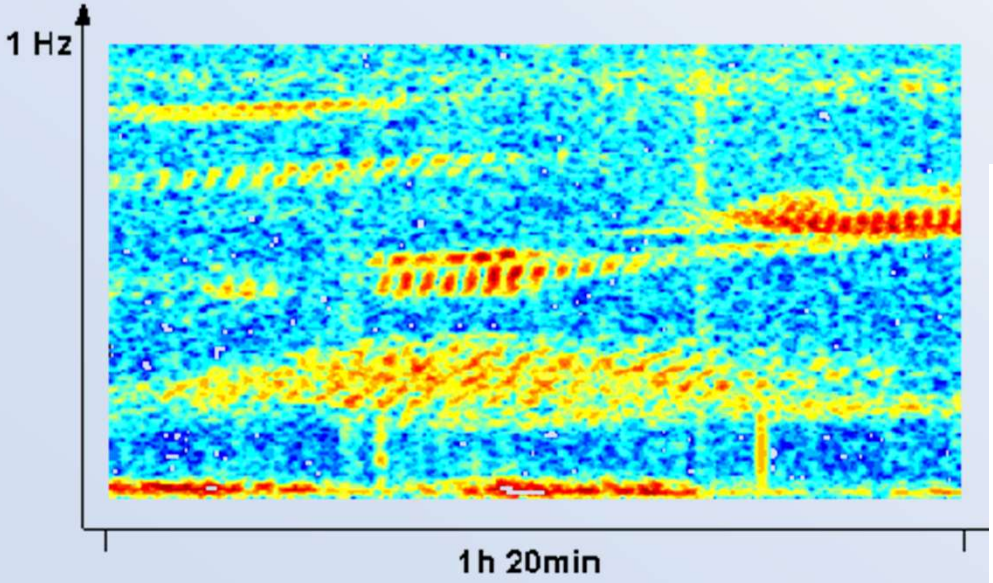
Notation	Period Range, sec
Pi 1	1– 40
Pi 2	40–150

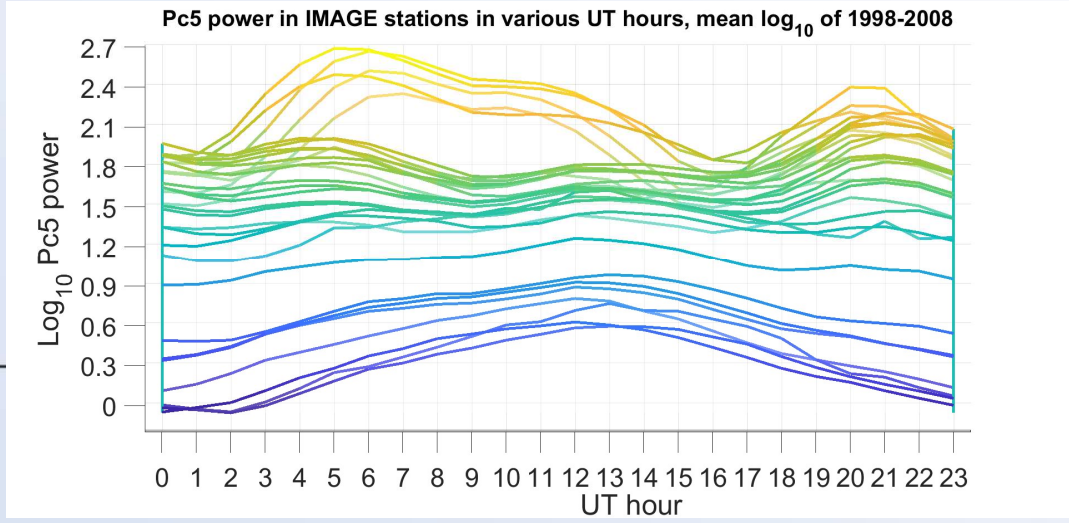
From Jacobs (1964)
https://doi.org/10.1029/JZ069i001p00180

Content

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

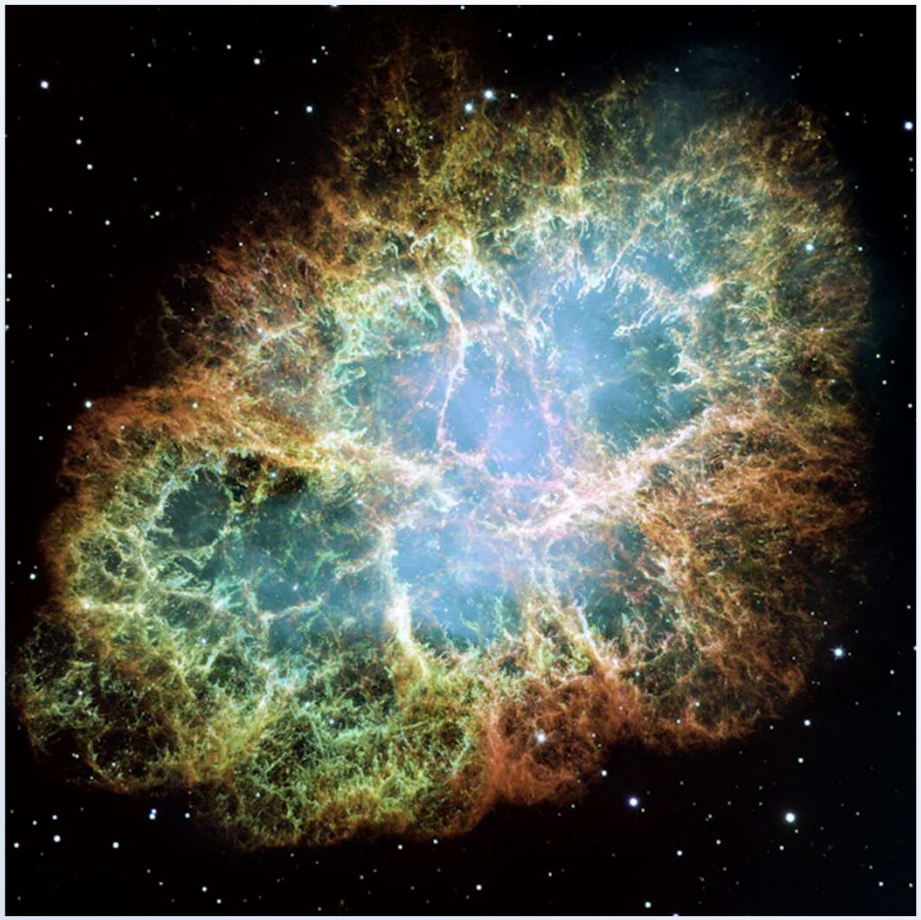






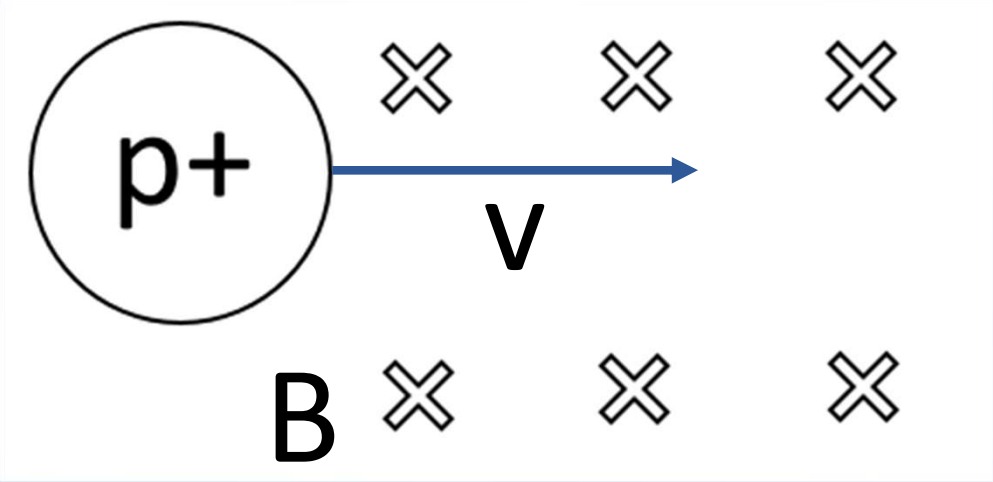
About waves and frequency

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



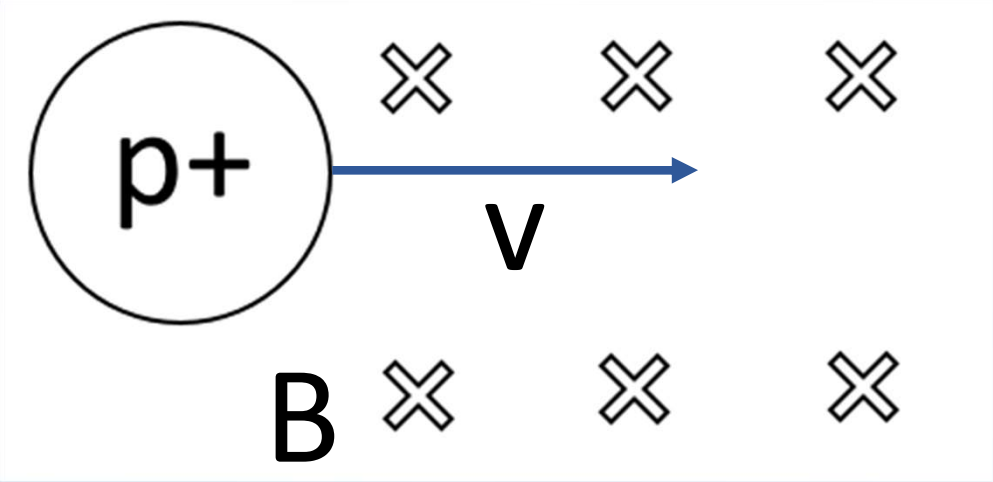
Cyclotron frequency

- Charged particle in an magnetic field



Cyclotron frequency

- Charged particle in an magnetic field



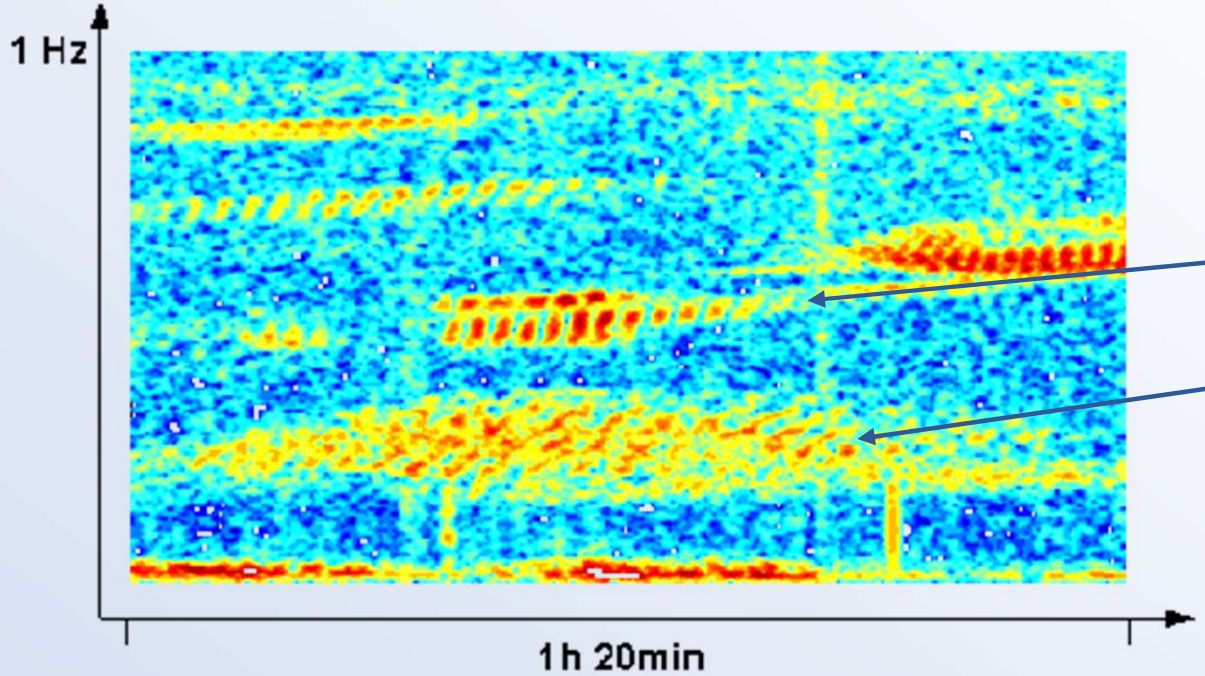
→ Undergoes cyclic motion at cyclotron frequency

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

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

*Electromagnetic ion cyclotron

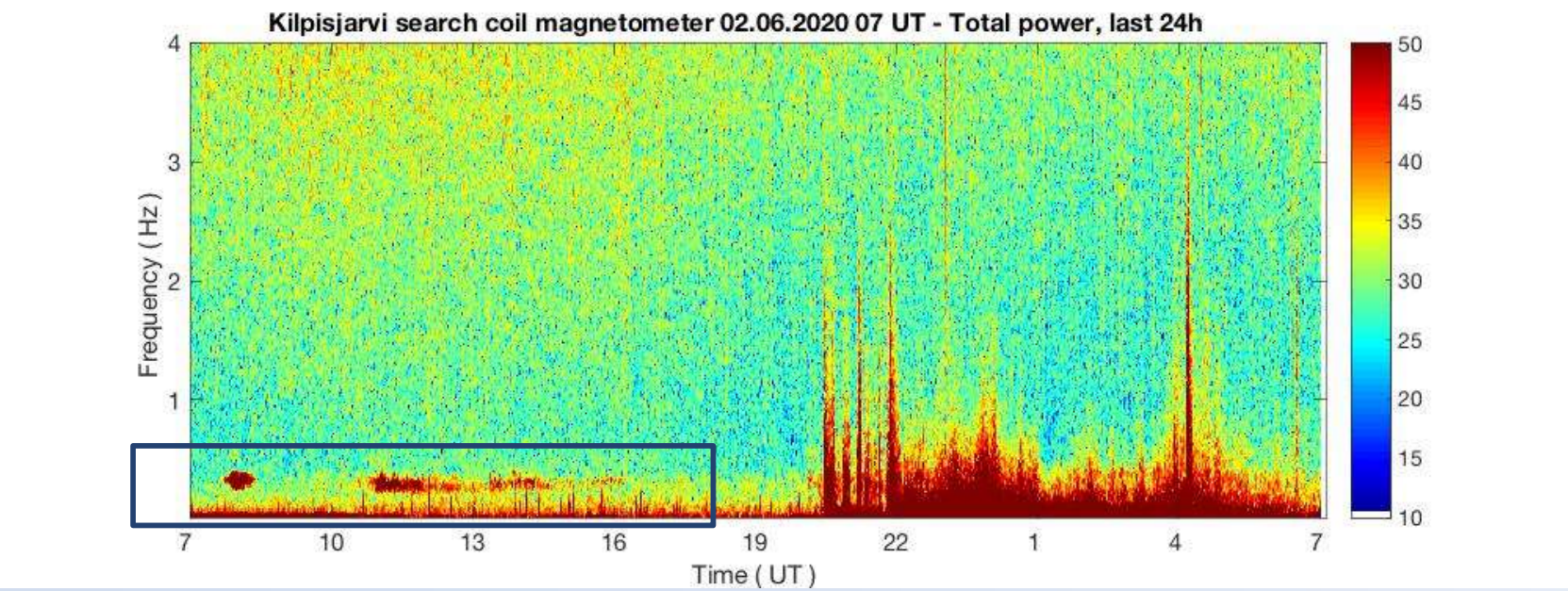
Ion cyclotron waves



Pulsations:

Pc1, 200-1000 mHz

Pc2, 100-200 mHz



Oscillating magnetic field: Alfvén waves

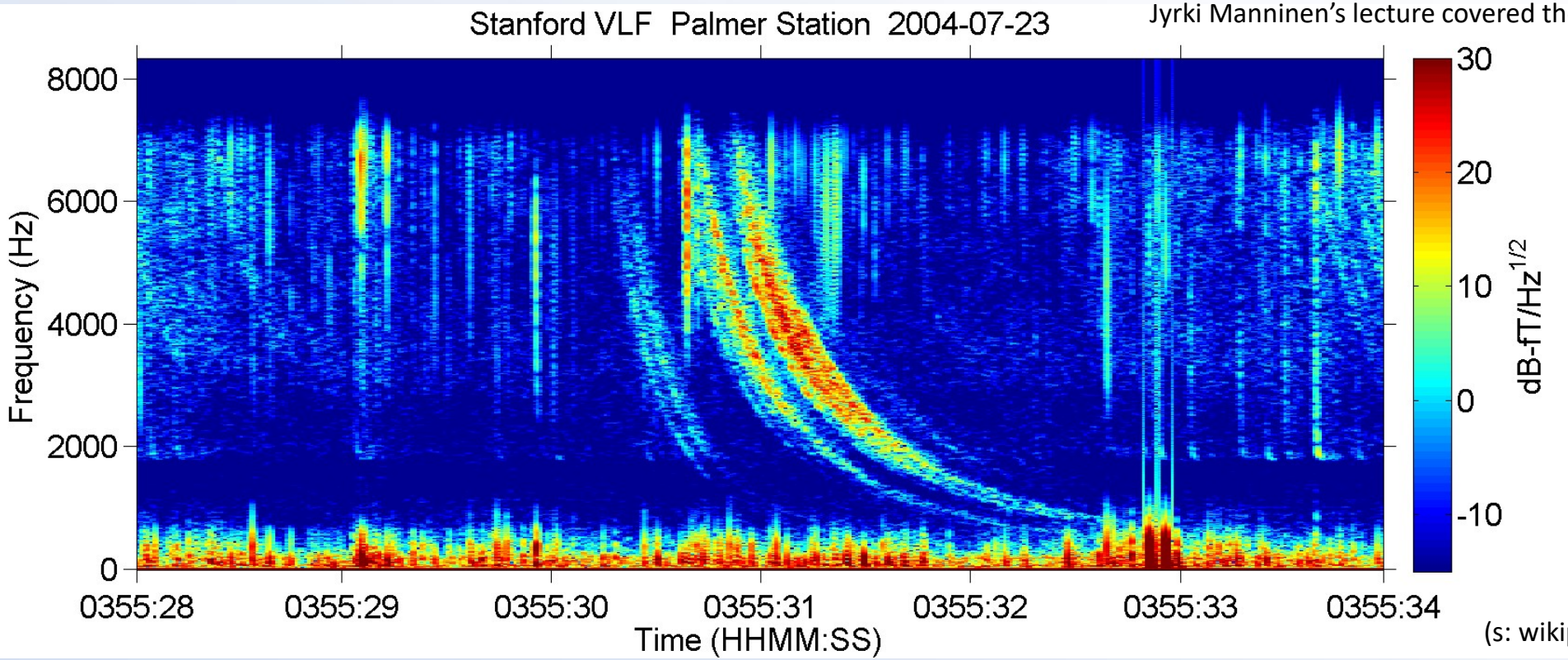
- Theorized by Hannes Alfvén in 1942
- Oscillation of ions and magnetic field, **B** → **B** + d**B**
- Low frequency (less than ion cyclotron frequency)
- Alfvén velocity depends on *magnetic field* and *plasma density*.

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

Sonic and magnetosonic waves

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

It's actually a VLF wave
Jyrki Manninen's lecture covered these



(s: wikipedia)

- 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 waves as precursors of "killer electrons"

ULF wave frequencies ~ ion cyclotron frequencies
→ One can “tap” into another

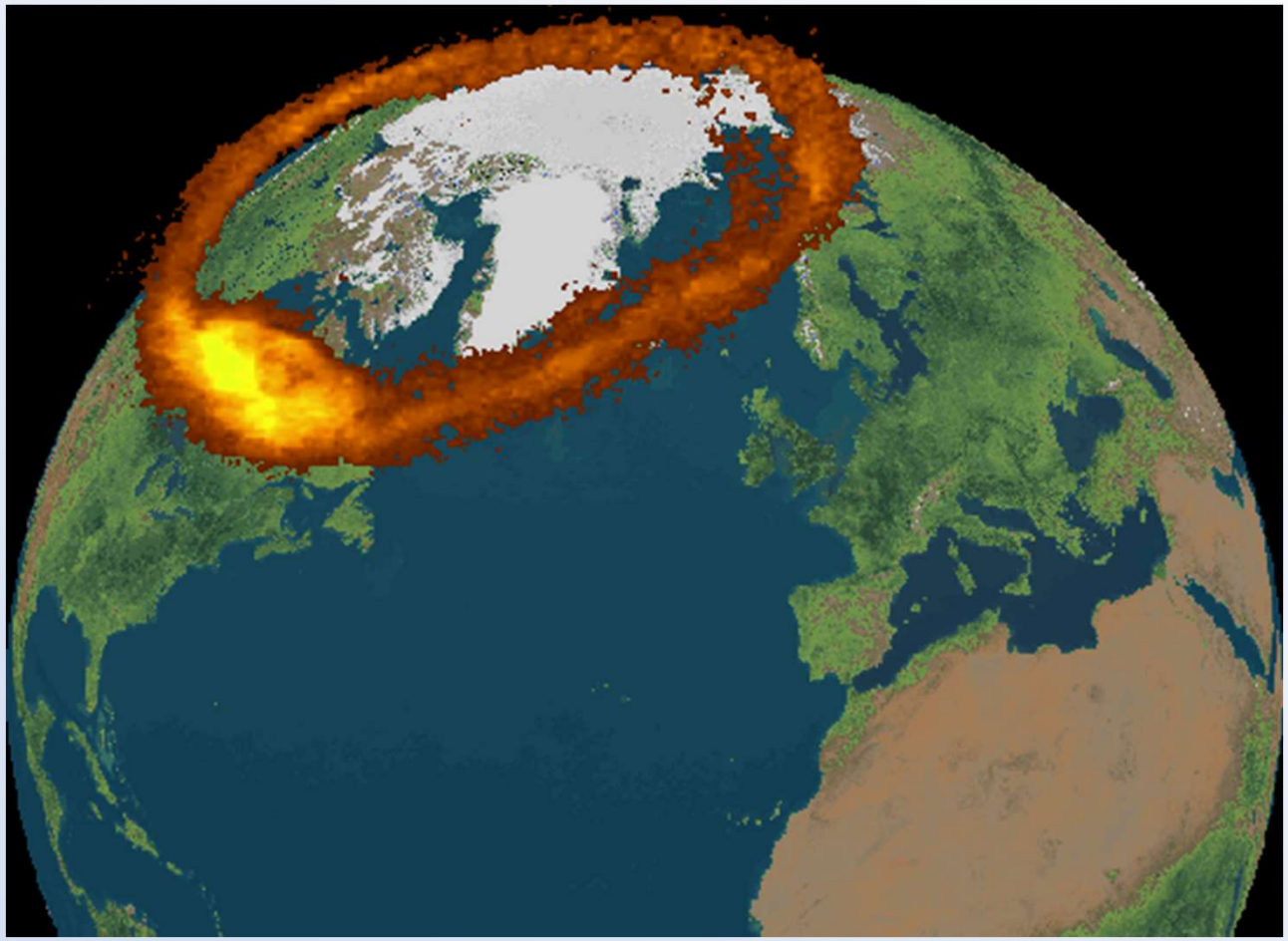
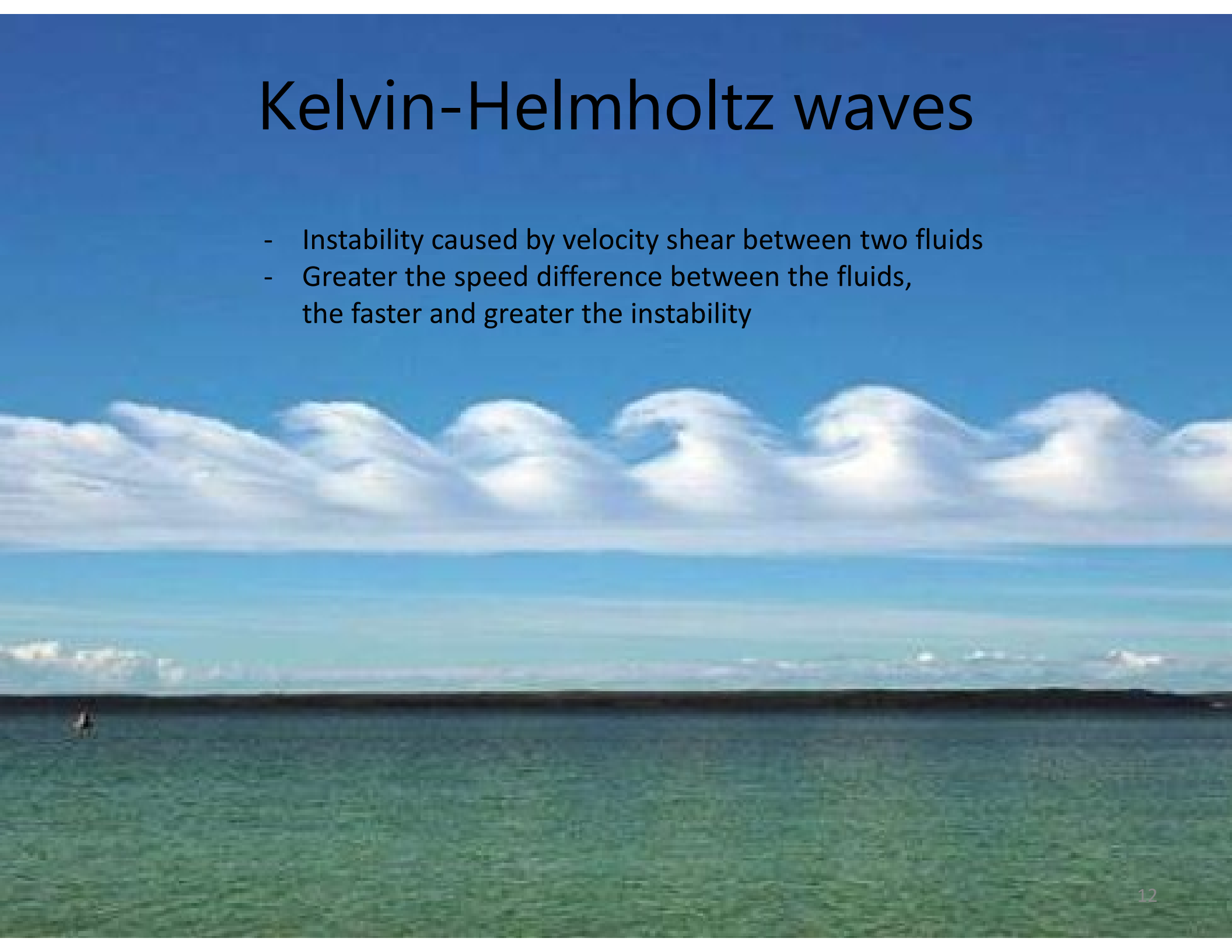


Image credit: NASA

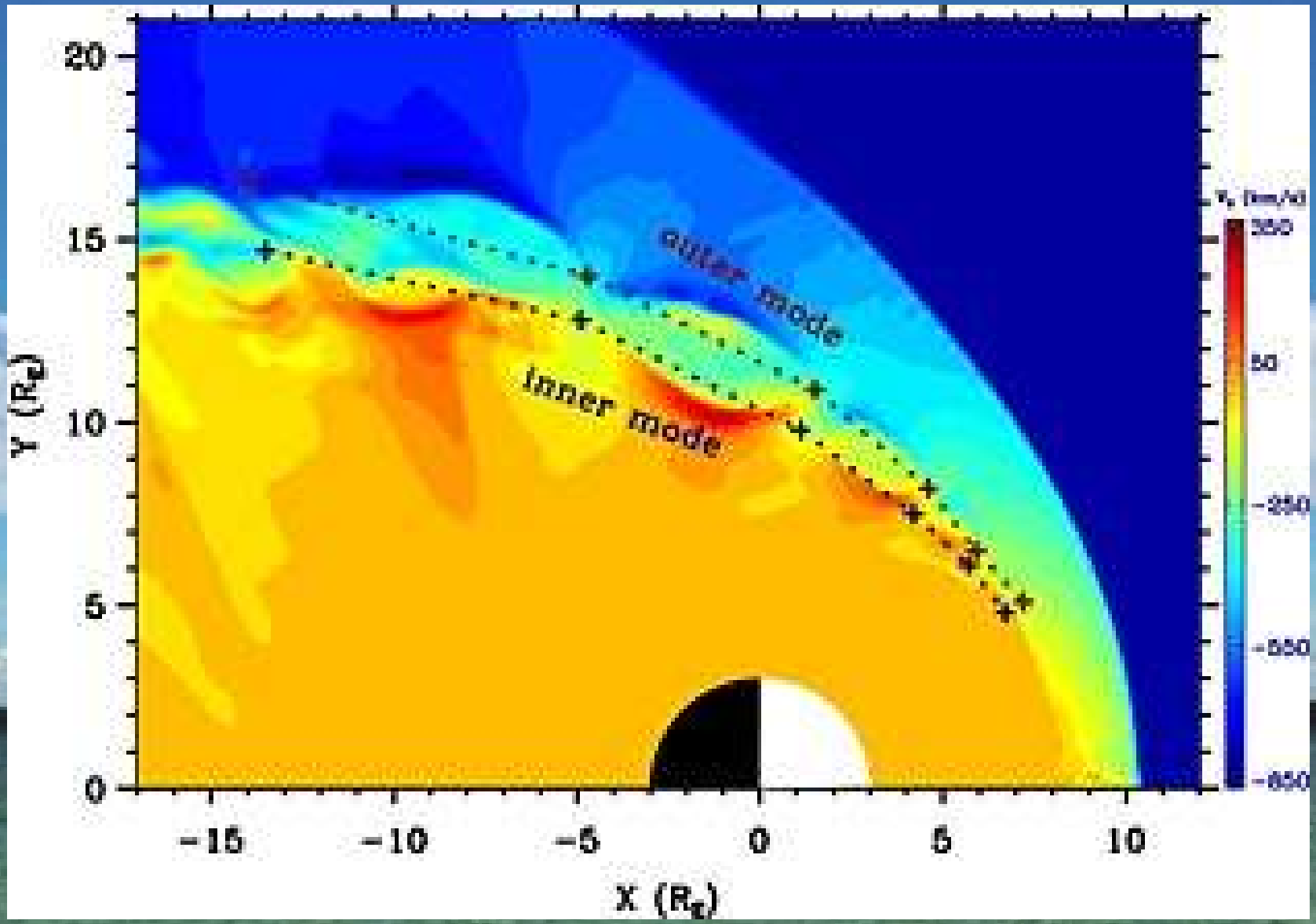
Kelvin-Helmholtz waves

Kelvin-Helmholtz waves

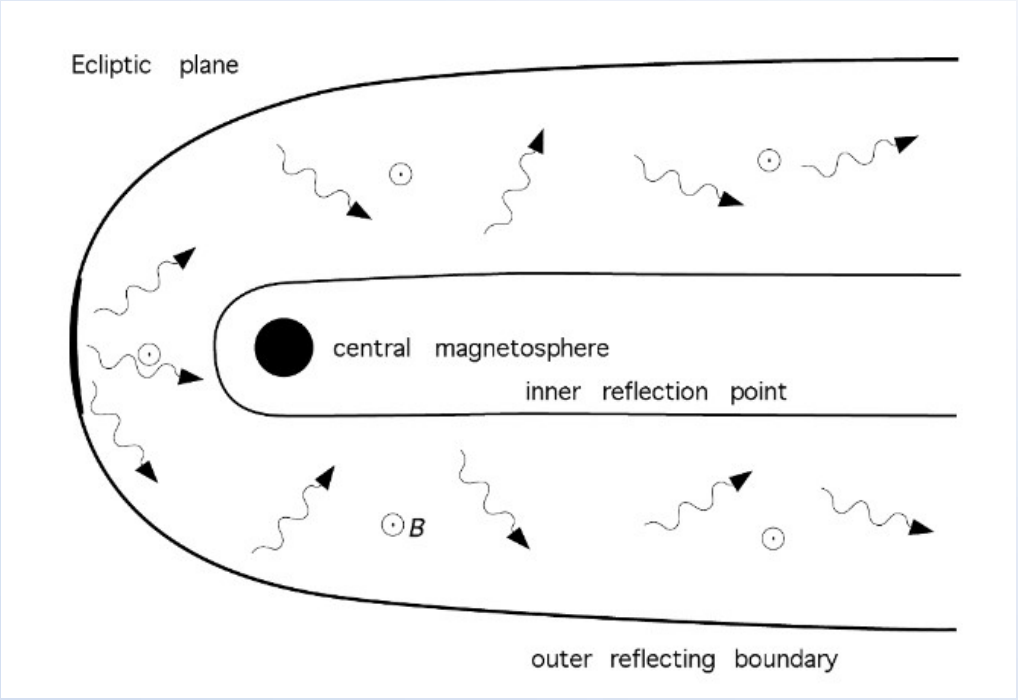
- Instability caused by velocity shear between two fluids
- Greater the speed difference between the fluids, the faster and greater the instability



Kelvin-Helmholtz waves



Magnetospheric waveguide



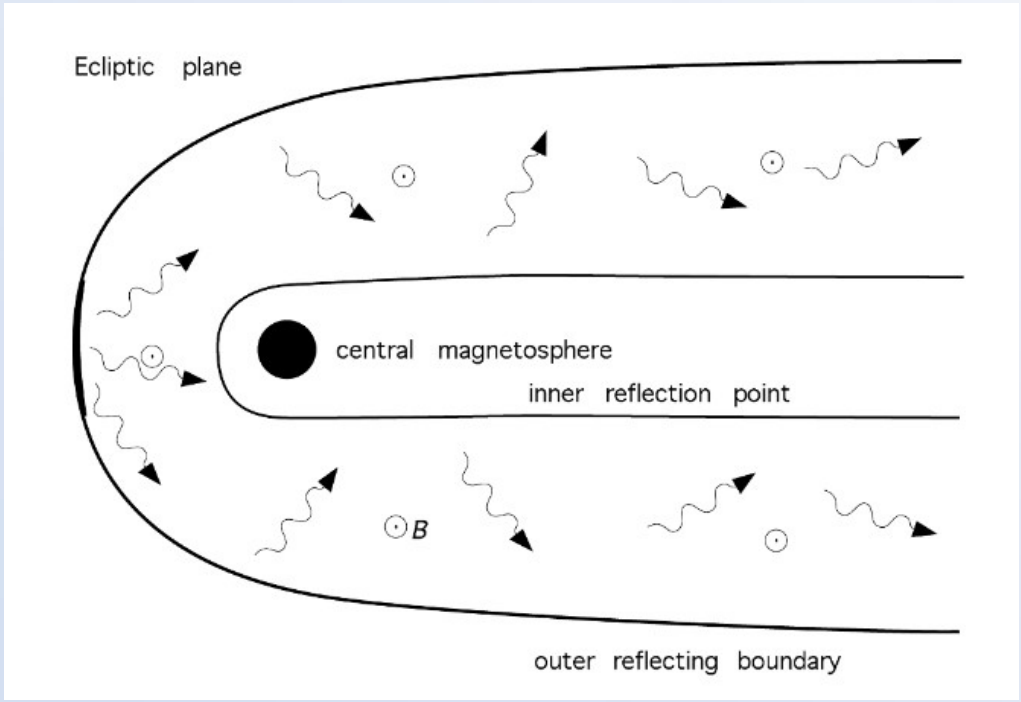
Fast-mode waves bouncing between magnetospheric outer and inner boundaries

Magnetospheric waveguide

Slow solar wind

Fast solar wind

Magnetospheric waveguide



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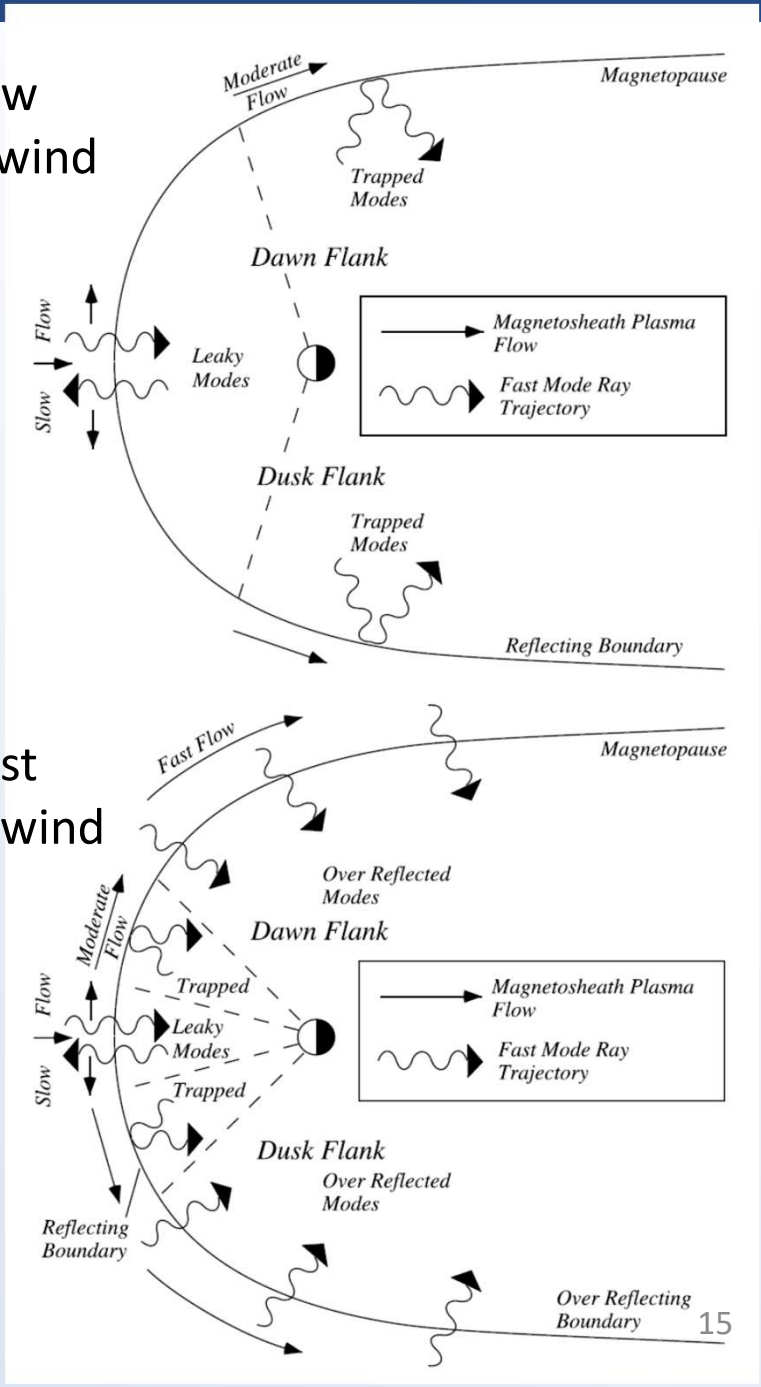
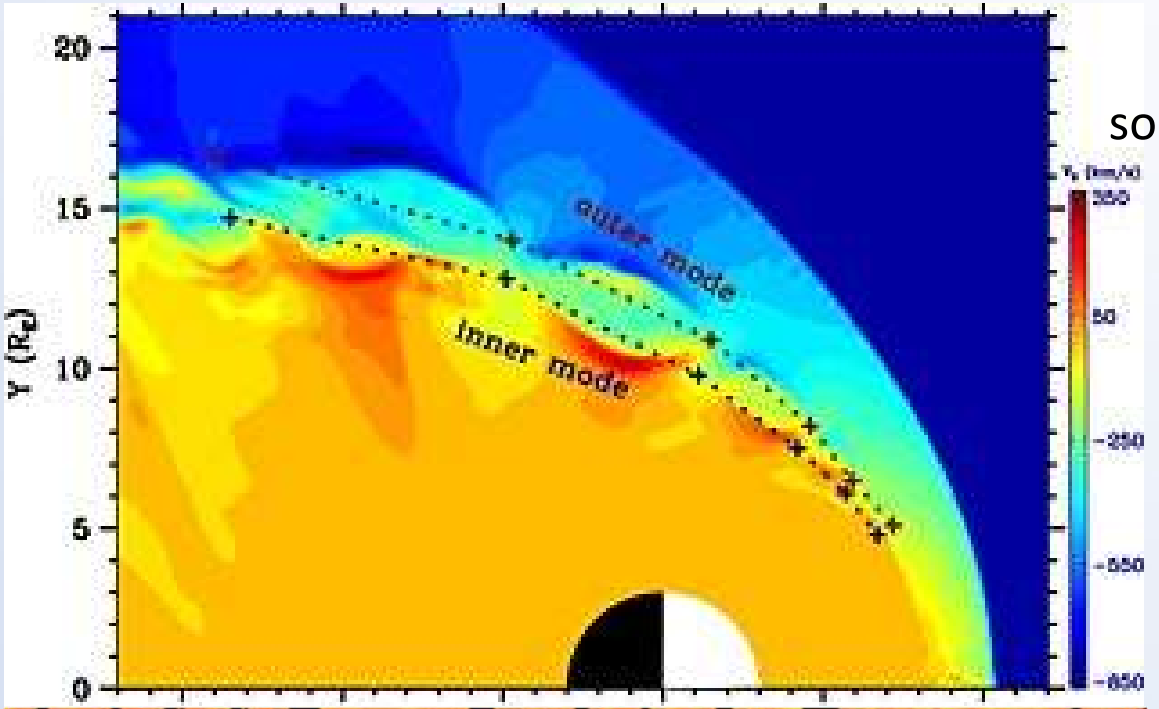
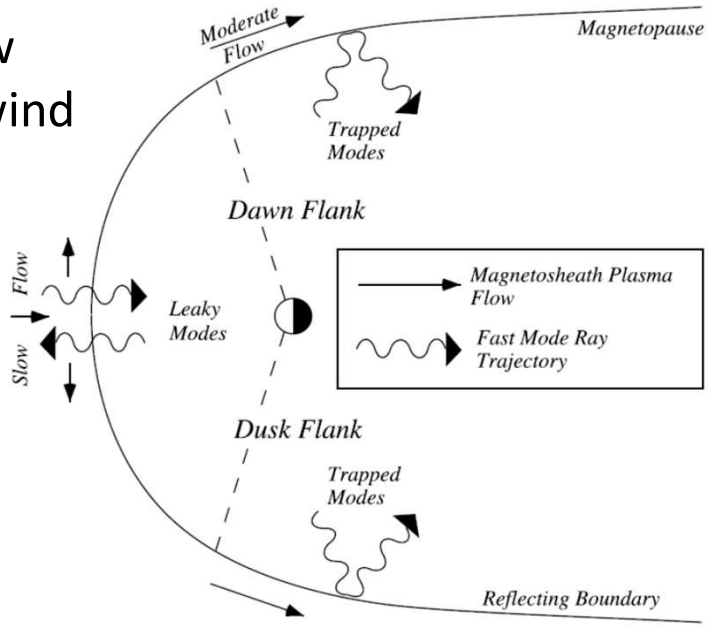
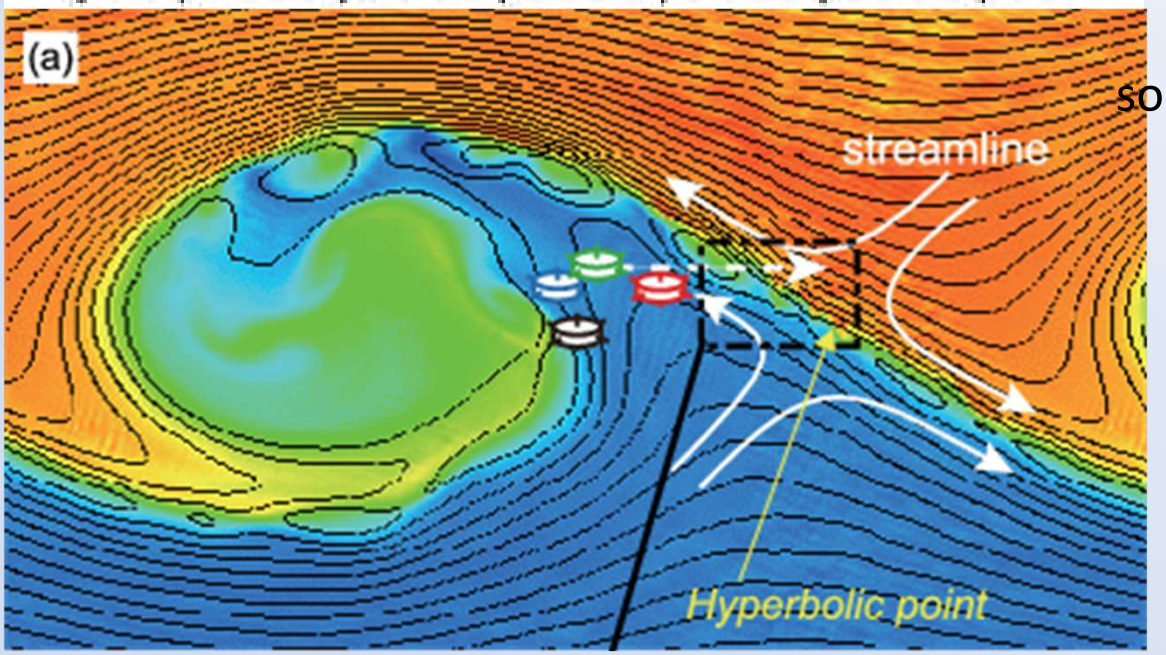


Magnetospheric waveguide



Slow solar wind





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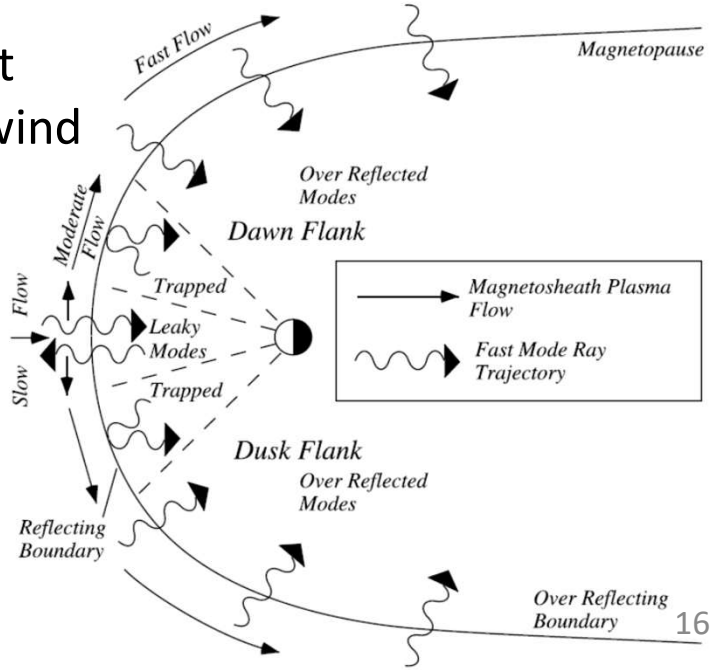
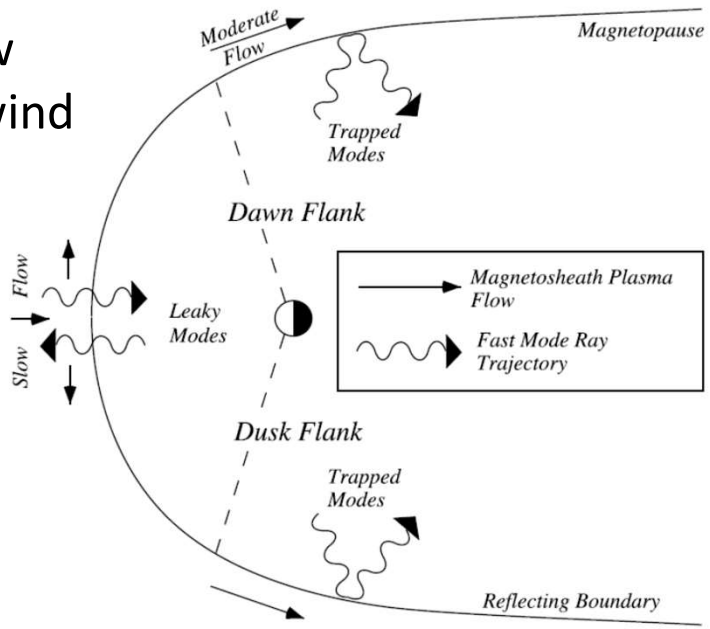
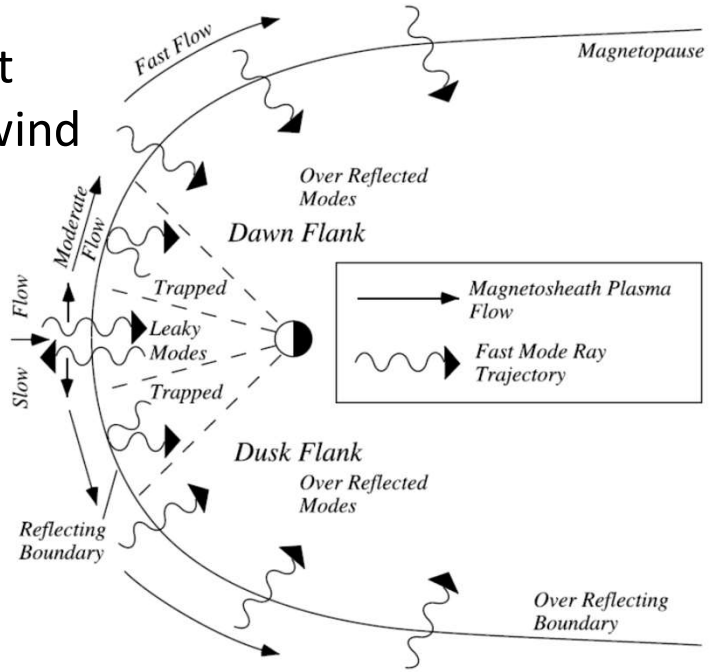


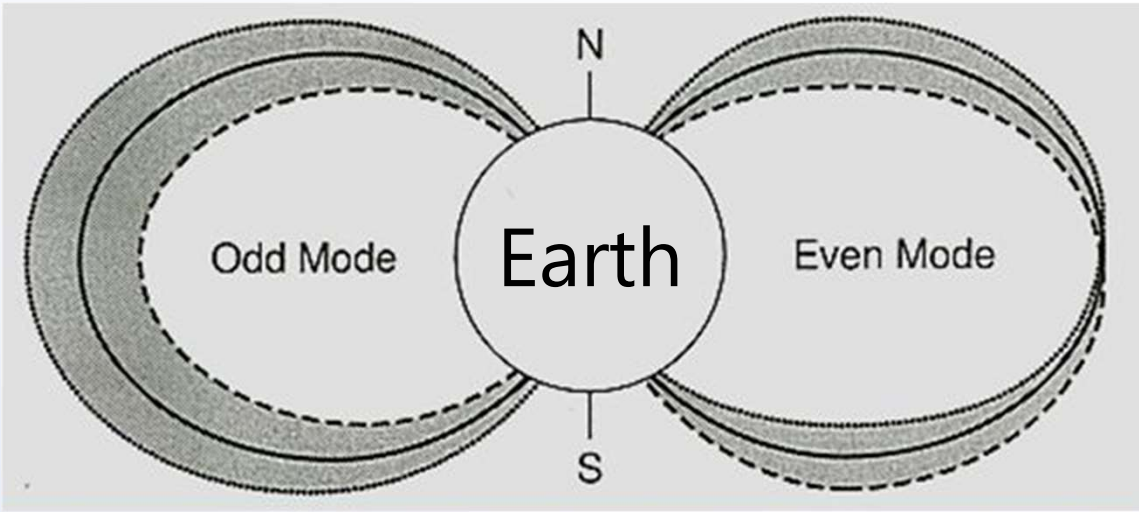
Field line resonance

Slow solar wind



Fast solar wind

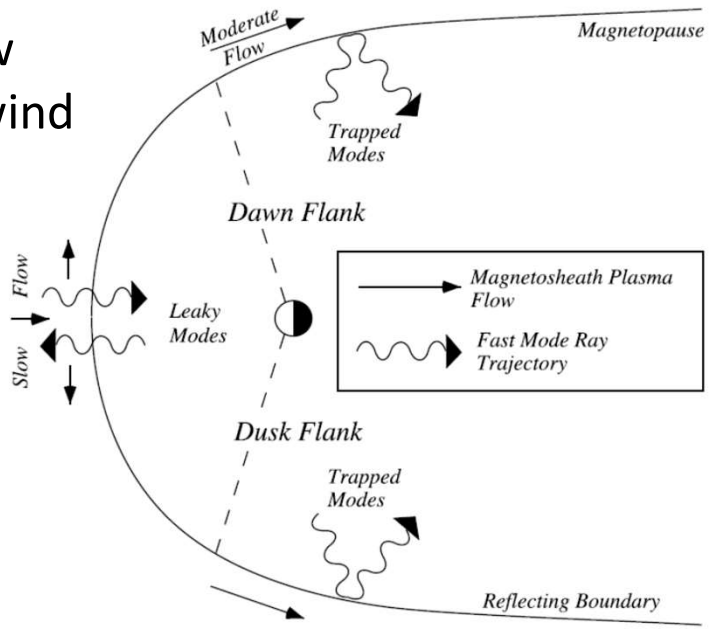




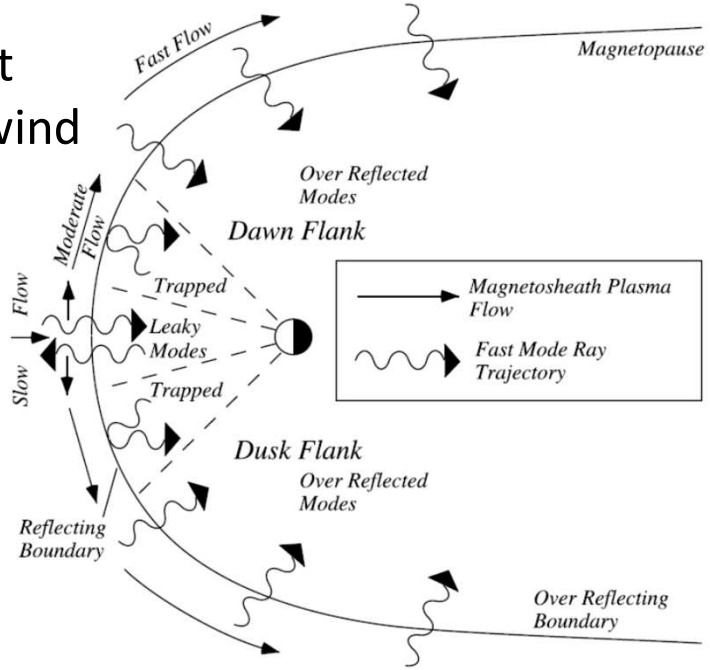
Shear Alfvén waves

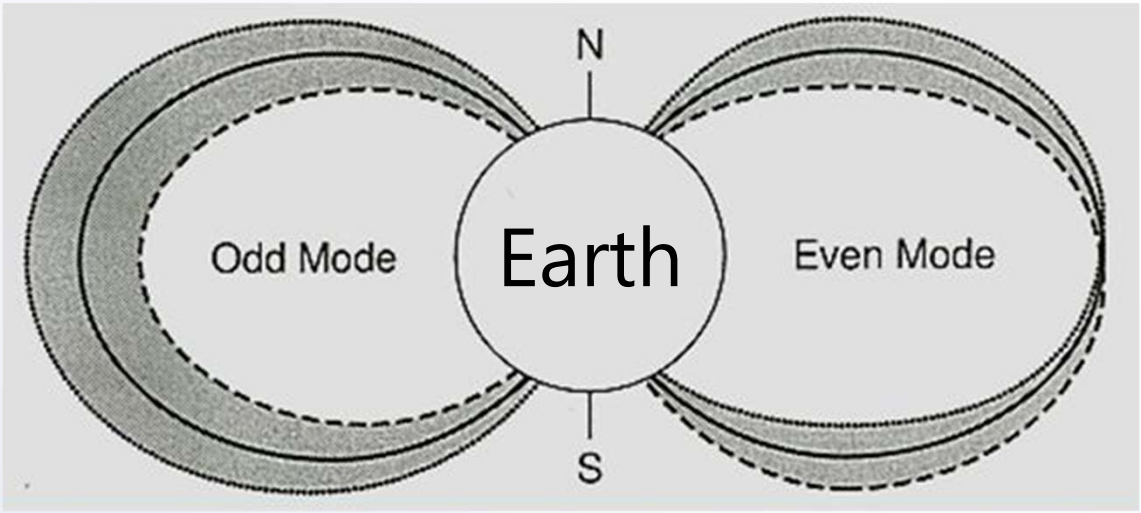
Field line resonance

Slow solar wind



Fast solar wind



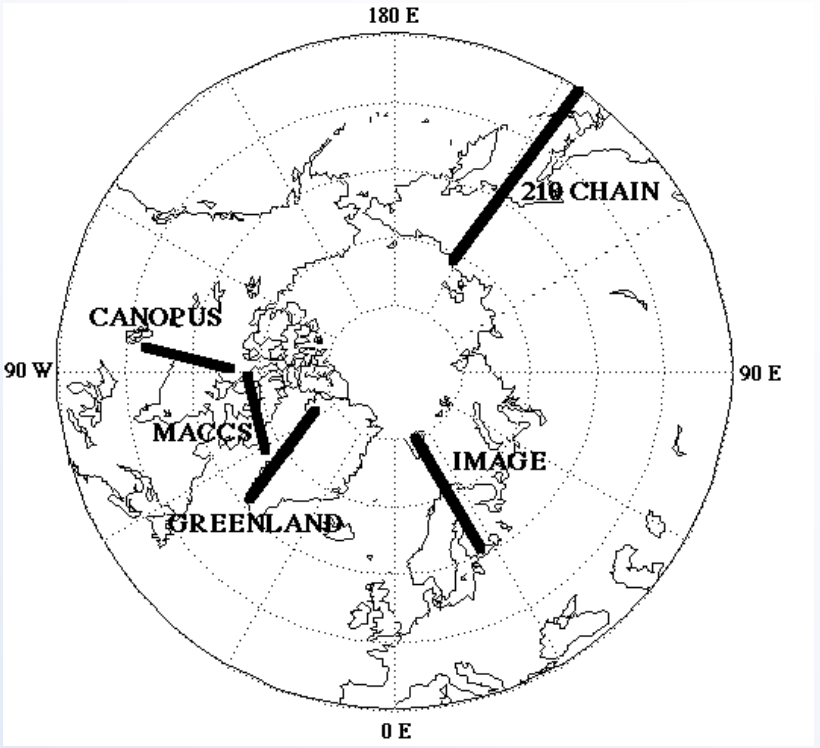


Shear Alfvén waves

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

Ground measurements
Magnetometer chains

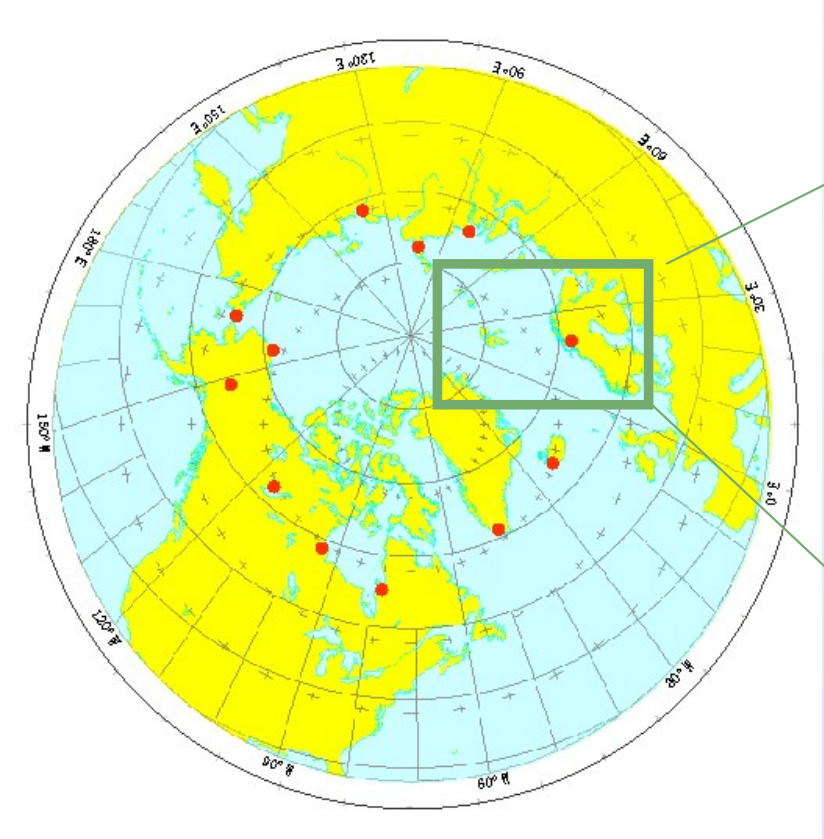
- IMAGE network
- CARISMA (earlier CANOPUS) and MACCS
- MAGDAS / 210 CHAIN
- Greenland Coastal Array
- Scandinavian SME (only historical data).



Magnetometer networks

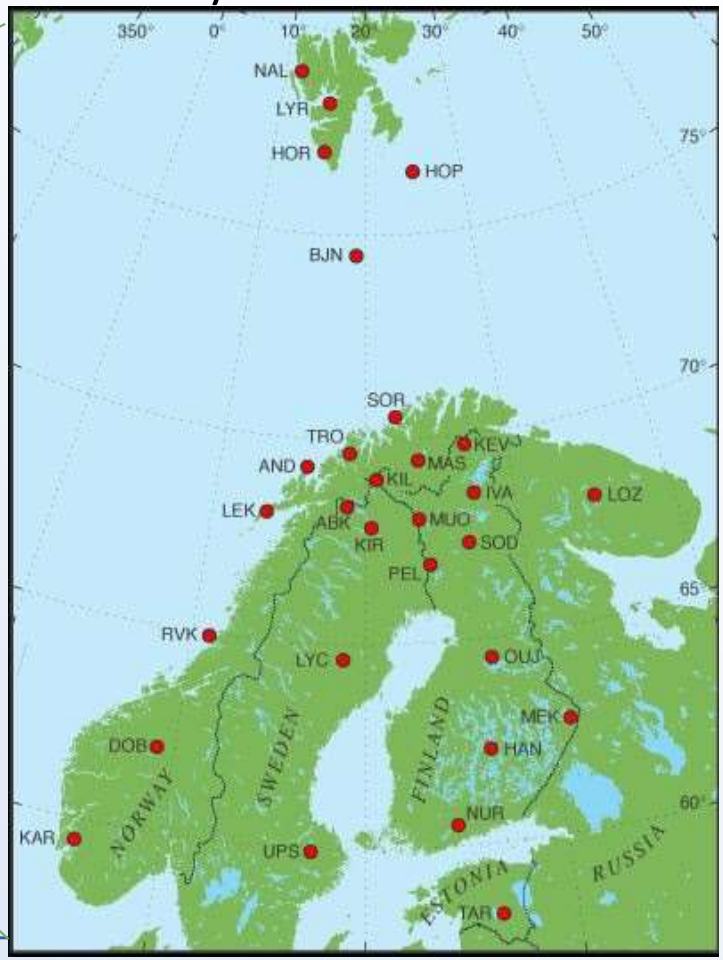
* 3 decommissioned;
4 more upcoming in 2024

12 Kyoto AL observatories



Fluxgate magnetometers

Currently* 52 IMAGE observatories



Courtesy of Häkkinen

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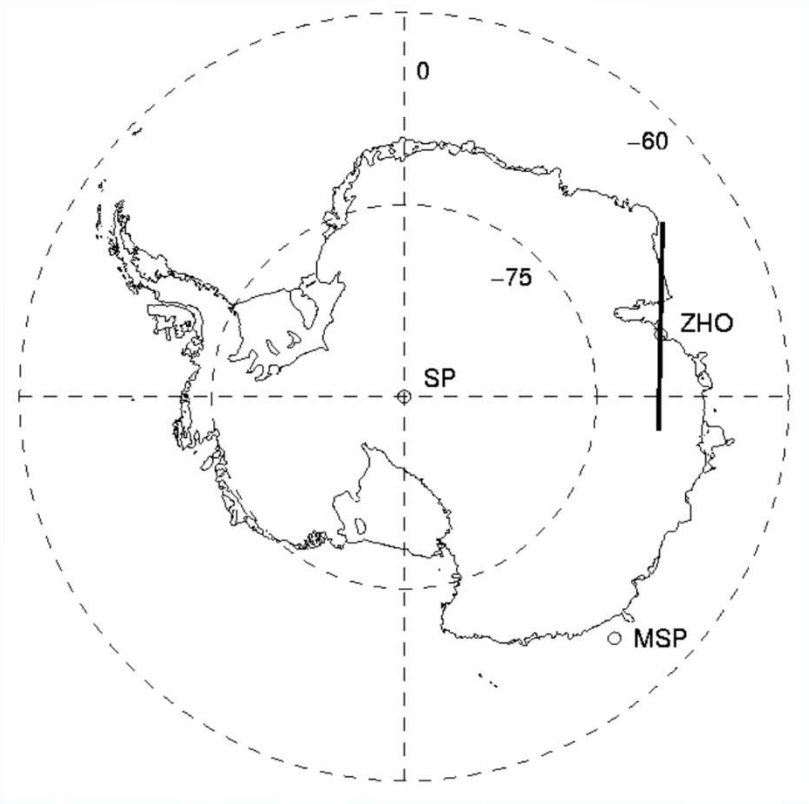
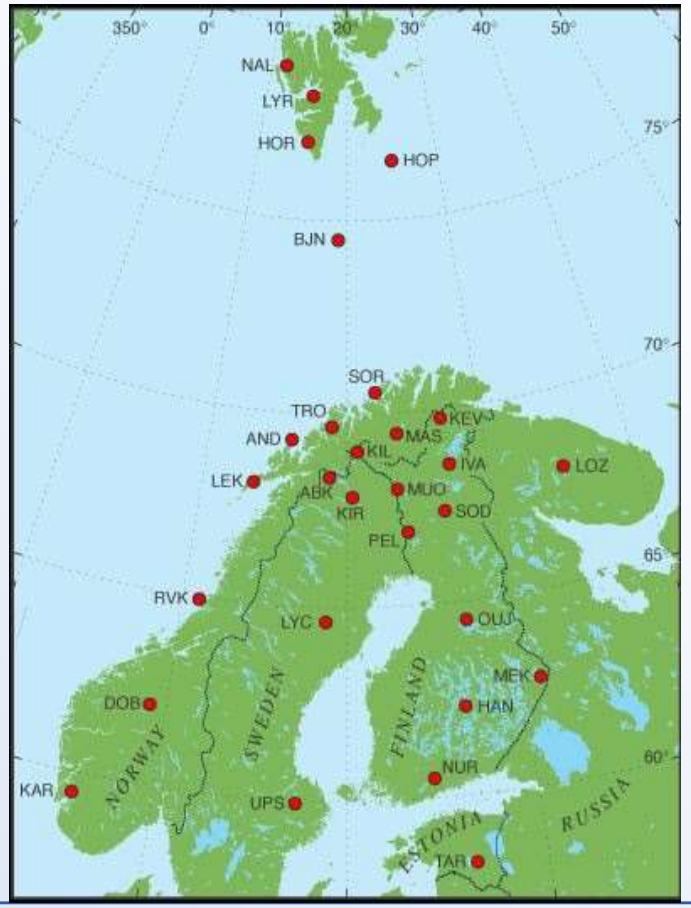
https://space.fmi.fi/image/www/index.php?

Conjugate magnetic measurements





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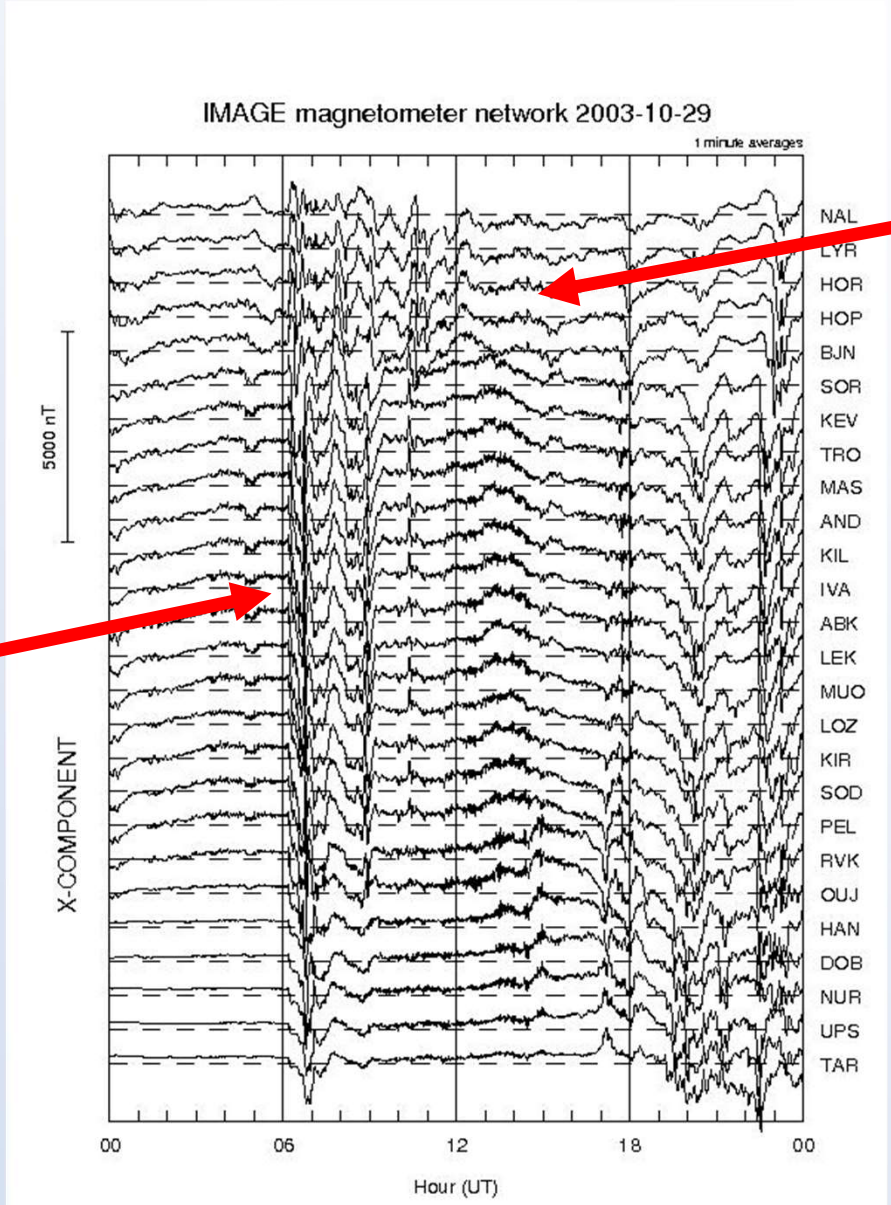
Geomagnetic activity at high latitudes during magnetic storms

Pc5 pulsations

Storm-time substorms



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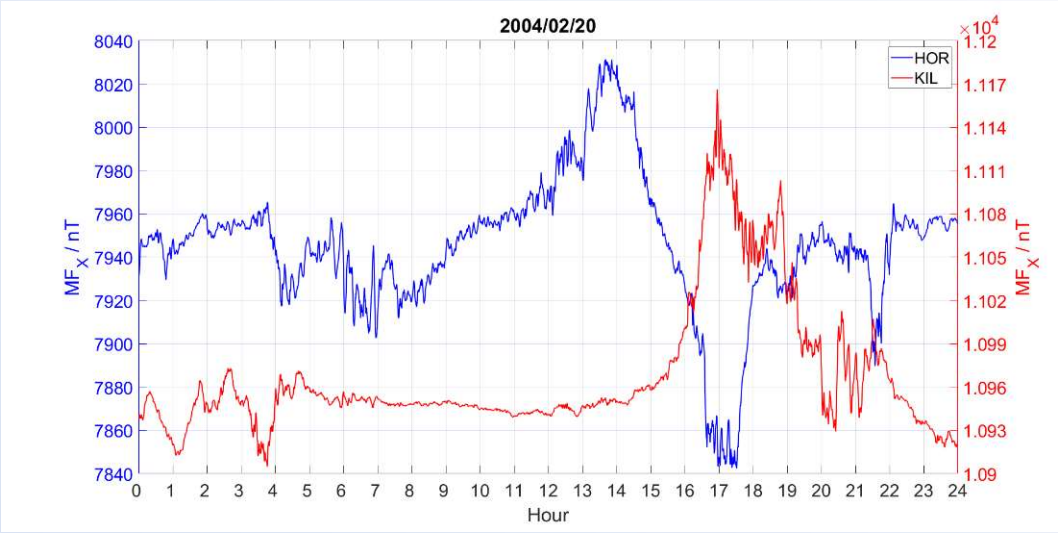
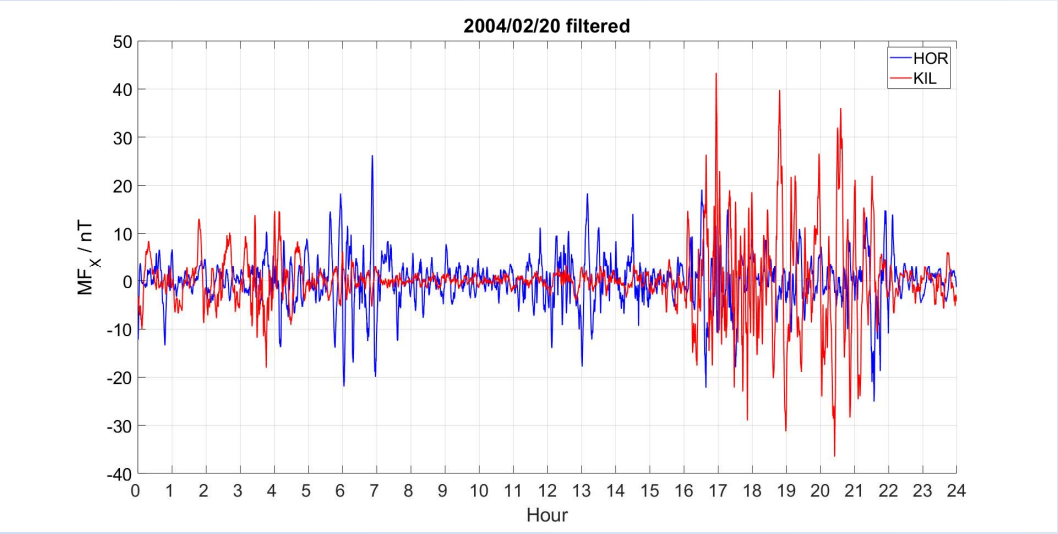
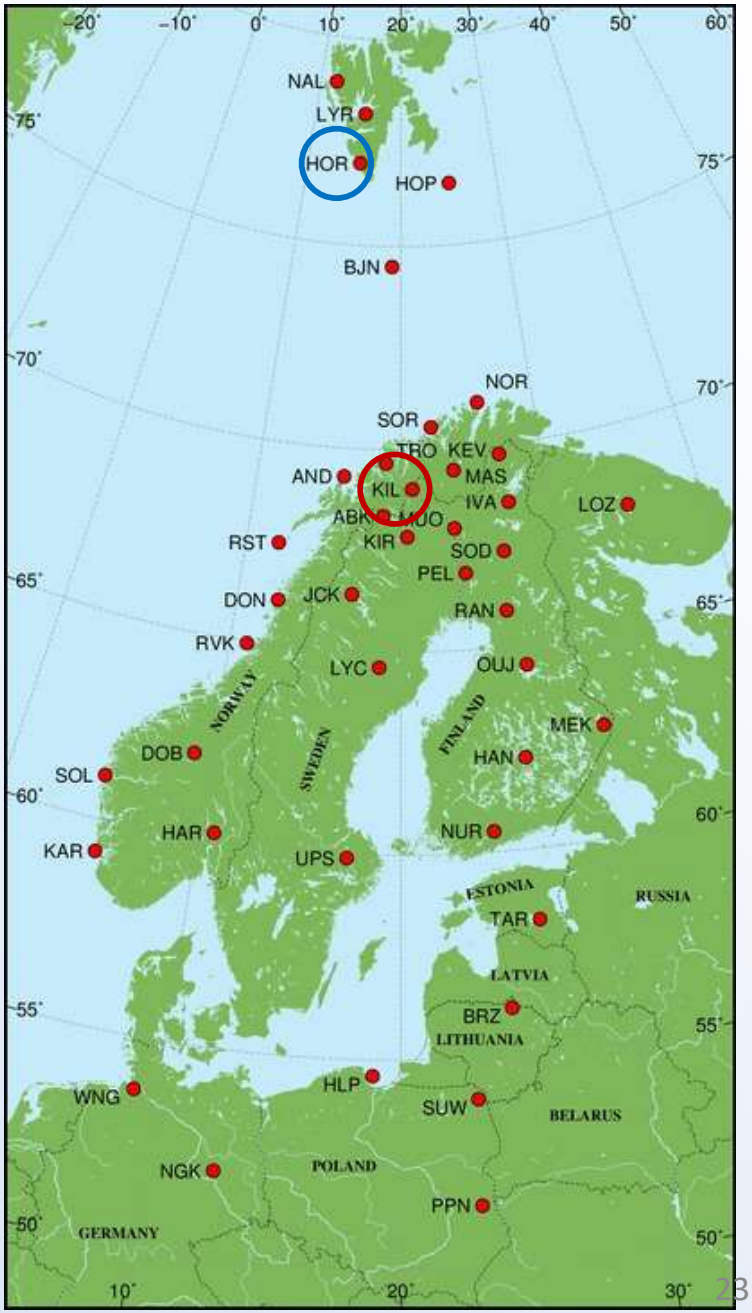
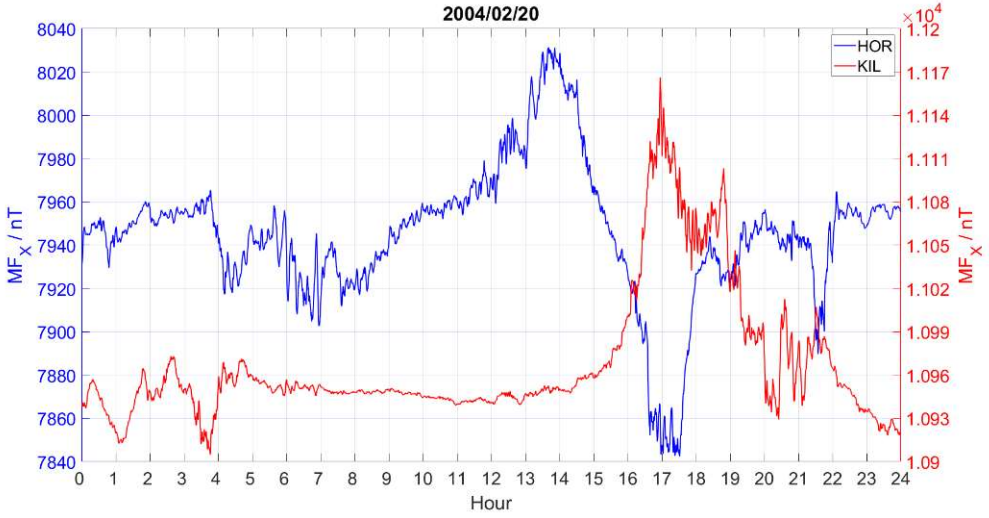
Filtering magnetic data

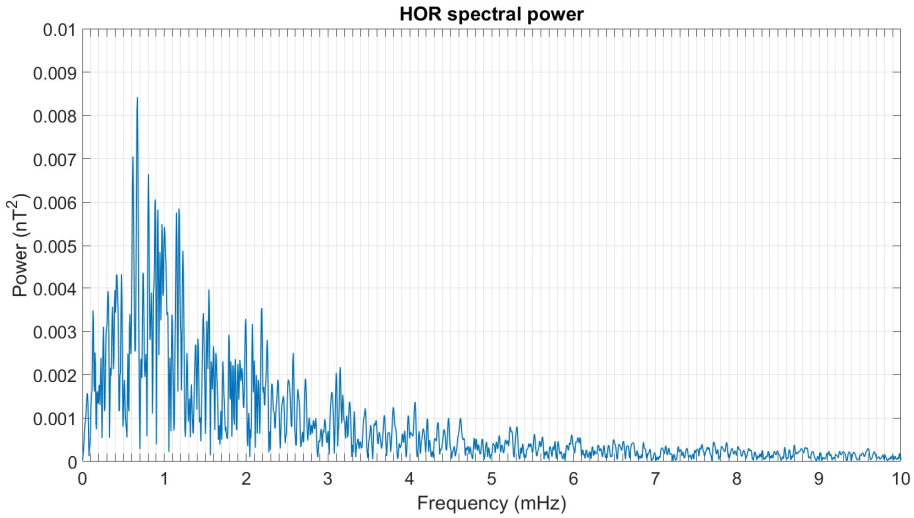


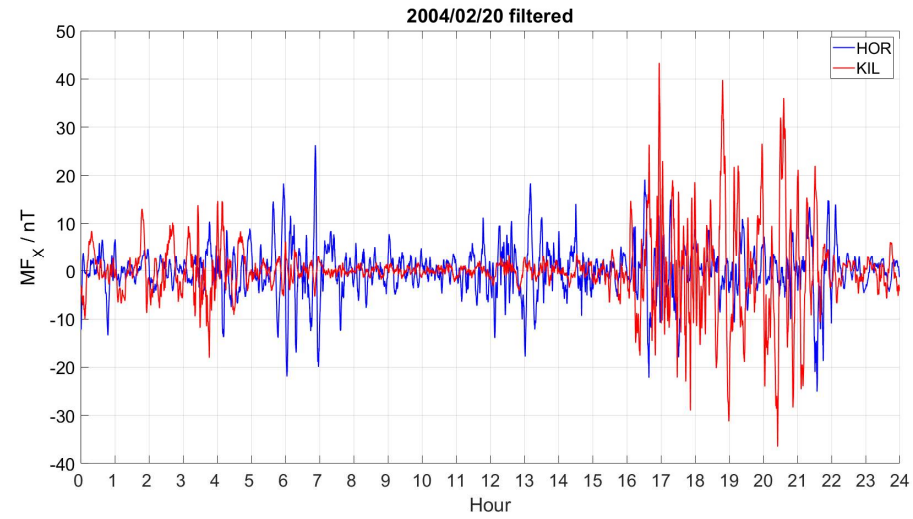


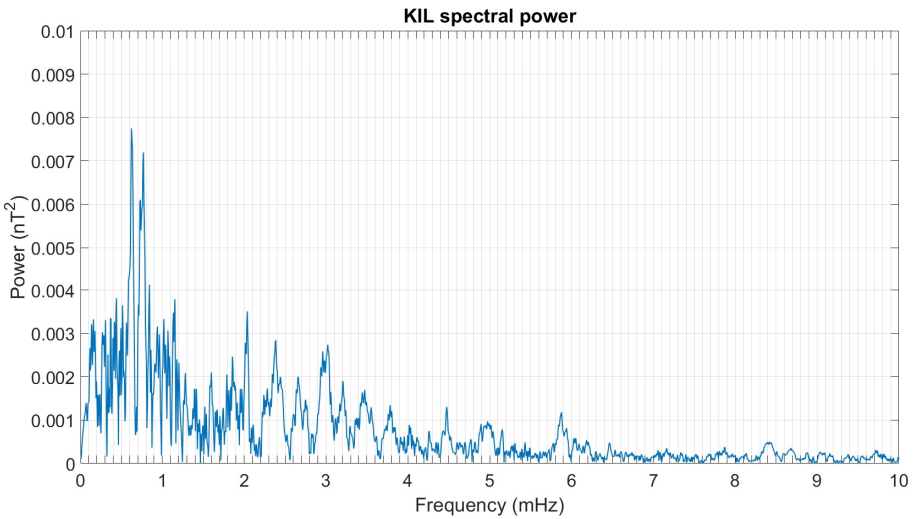


Filtering magnetic data for FFT*



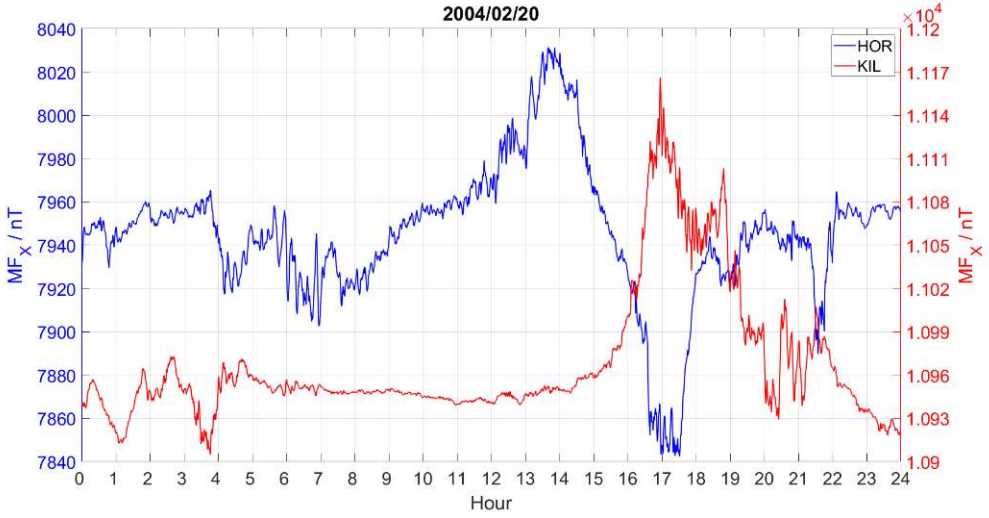


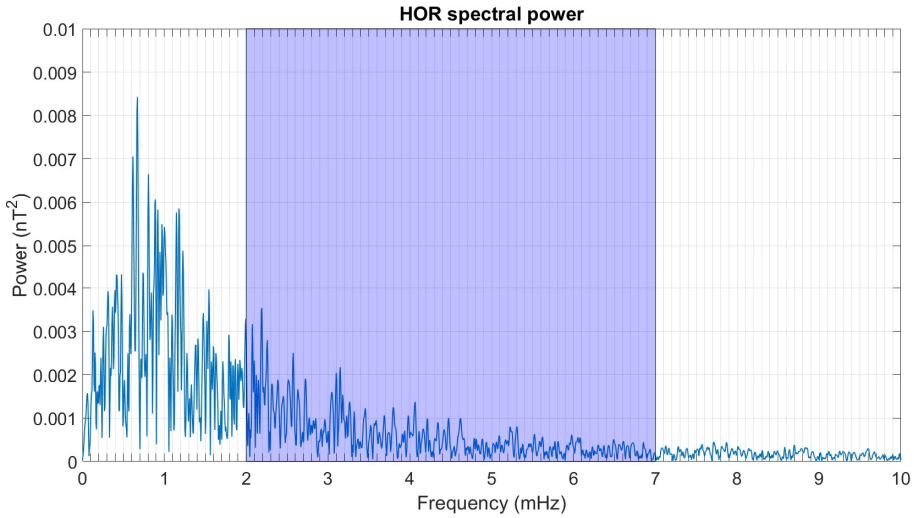


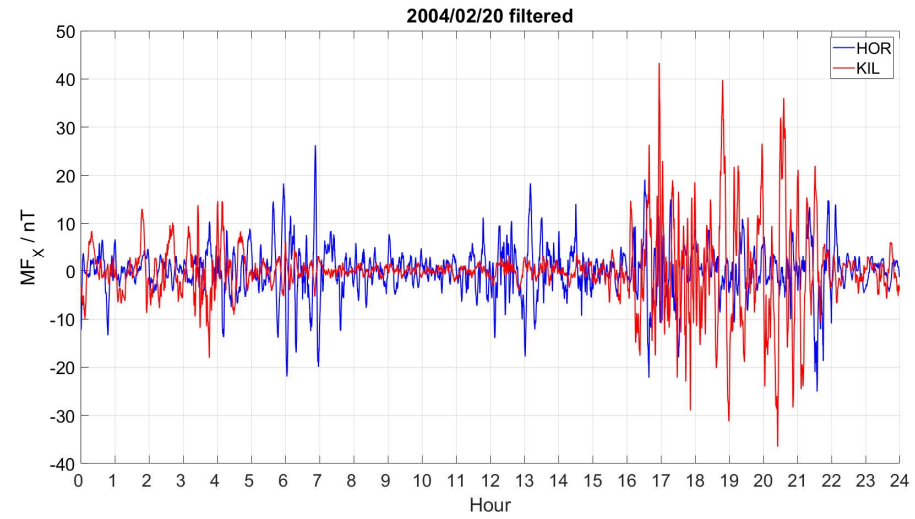


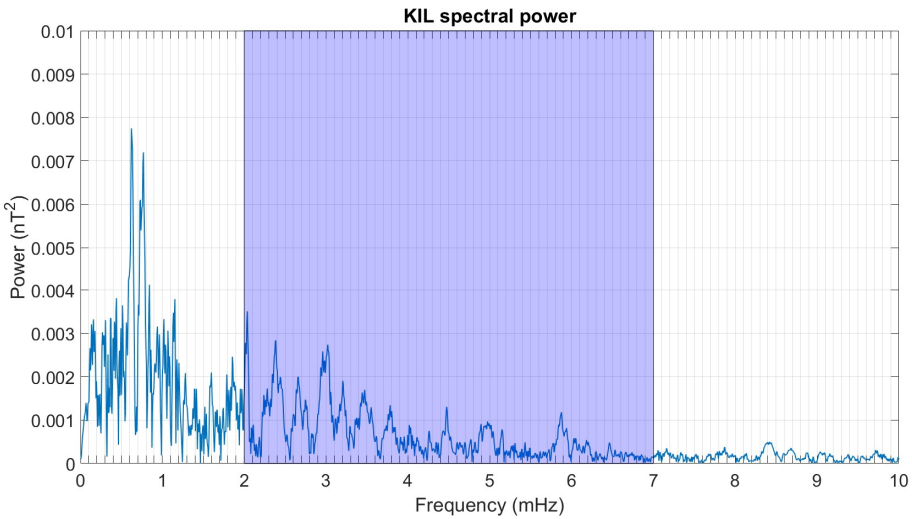
* Fast Fourier Transform

Filtering magnetic data for FFT

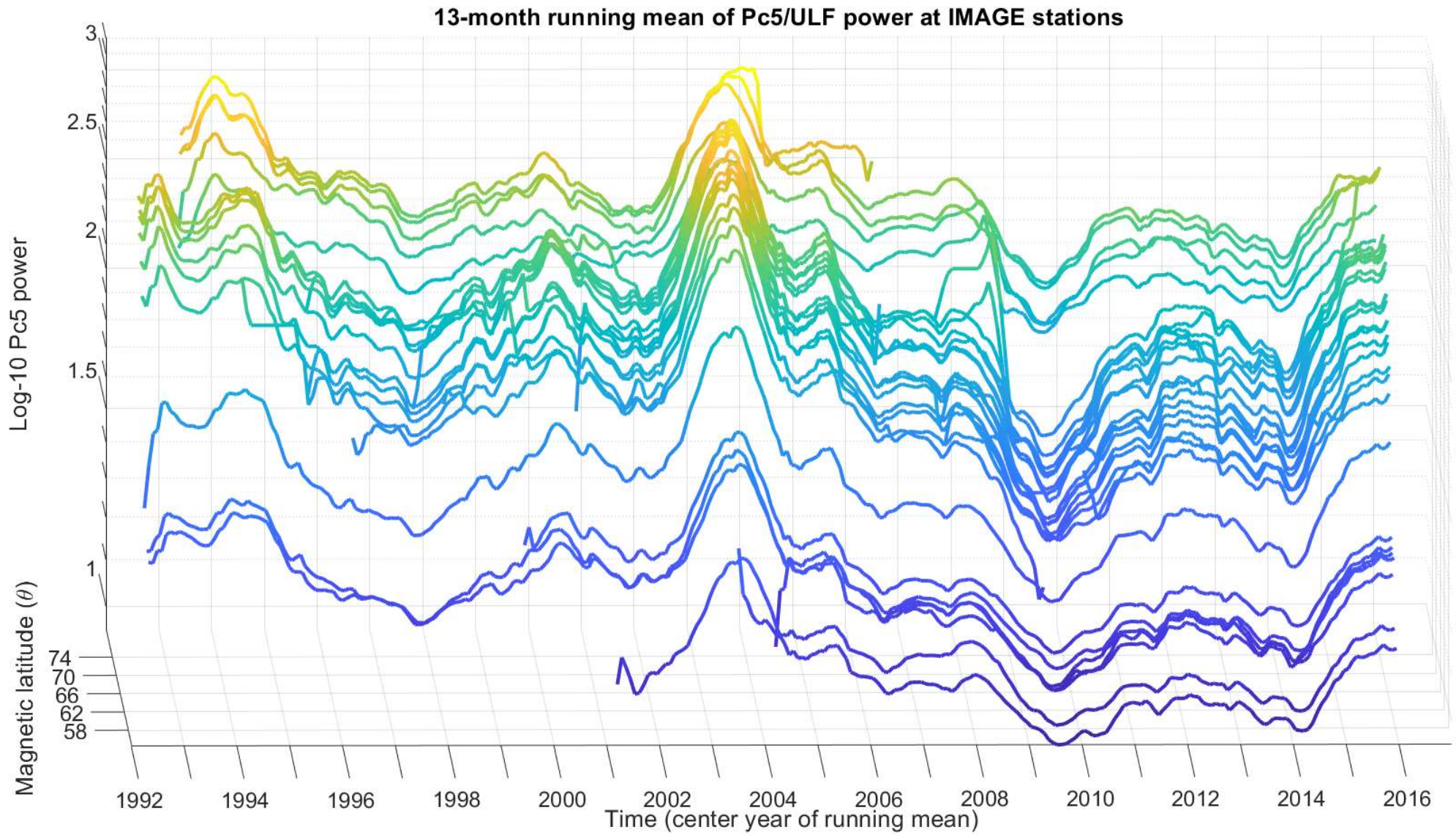


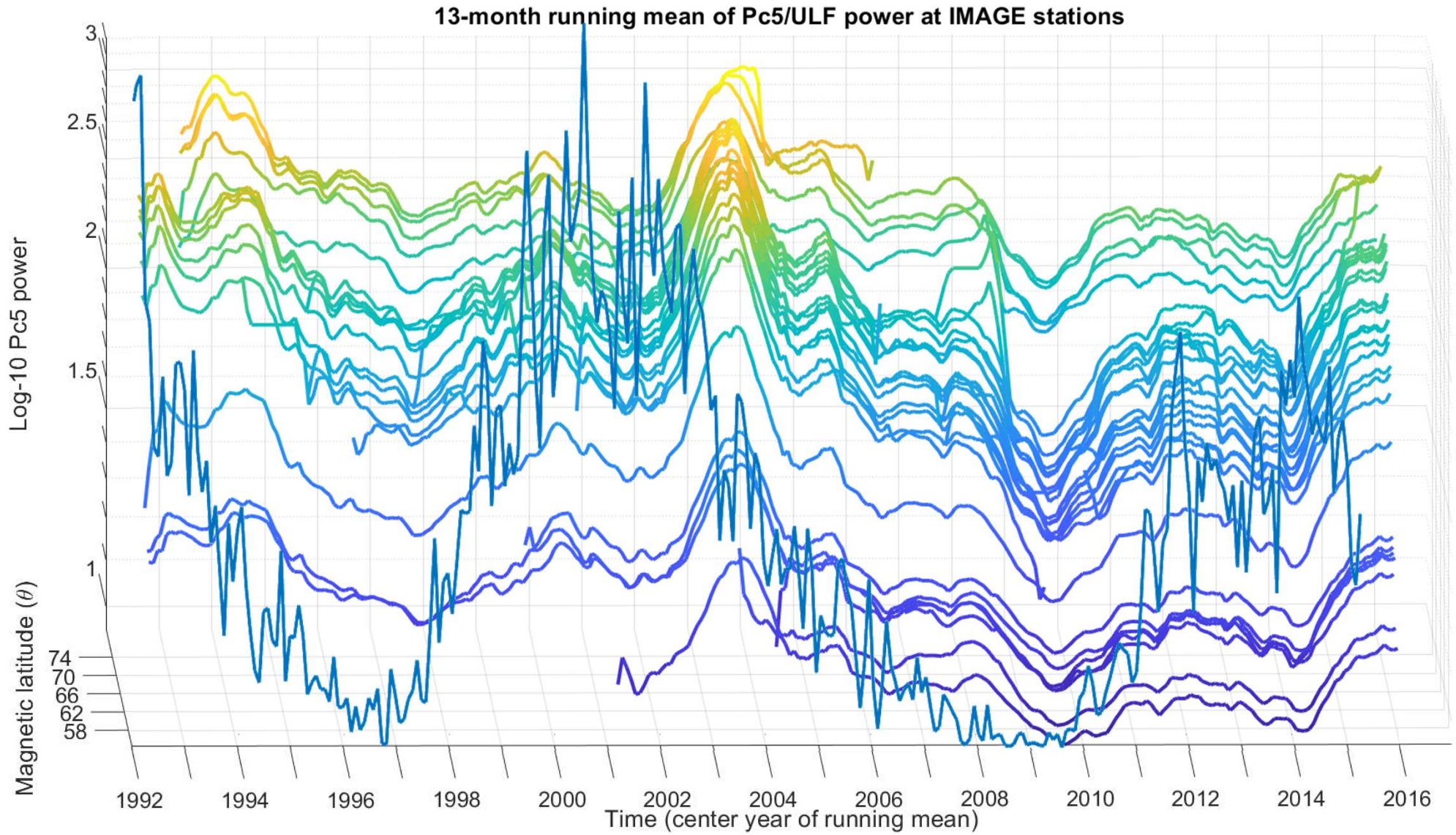






Pc5 waves


13-month running mean of Pc5/ULF power at IMAGE stations
Log-10 Pc5 power
3
2.5
2
1.5
1
Magnetic latitude (θ)
74
70
66
62
58
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
2016
Time (center year of running mean)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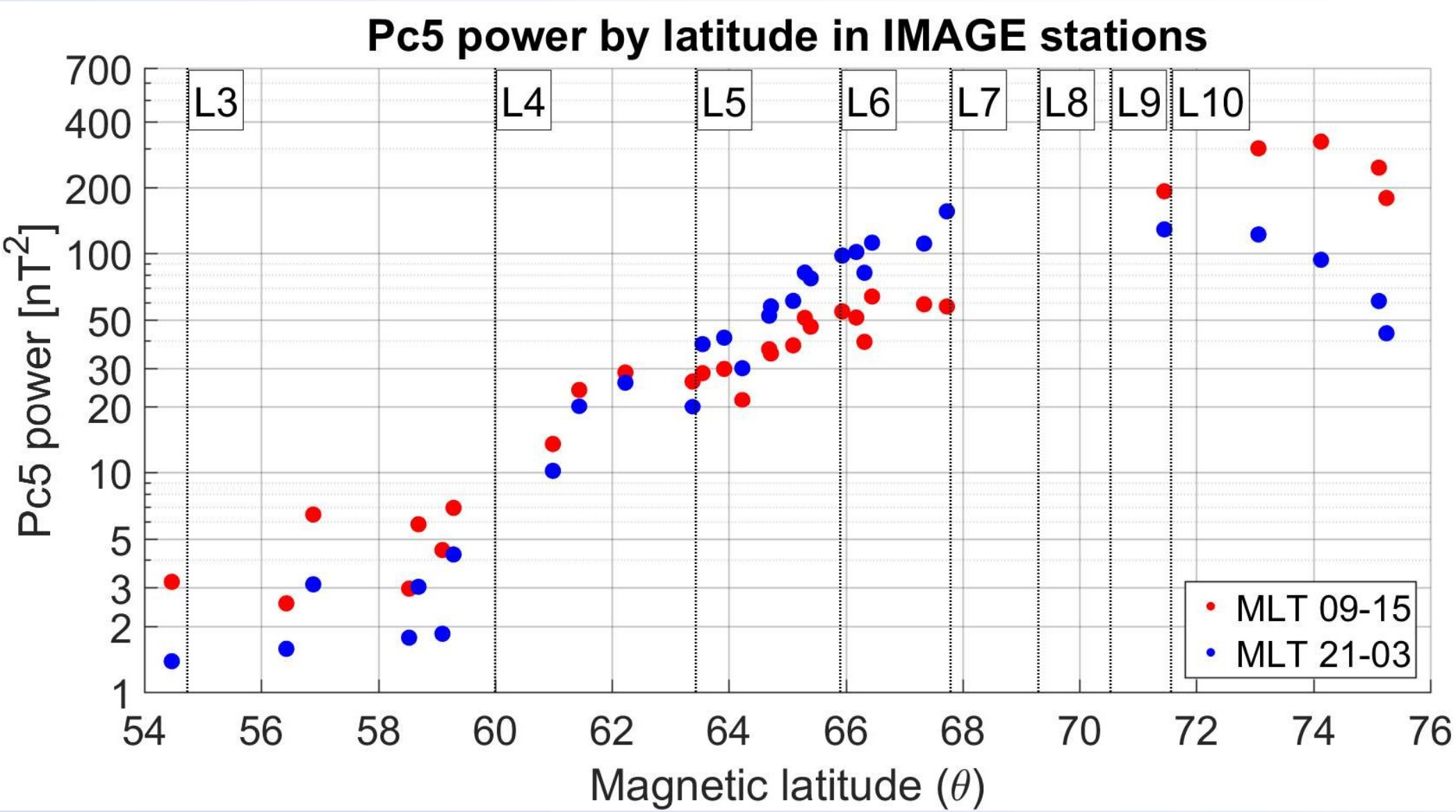
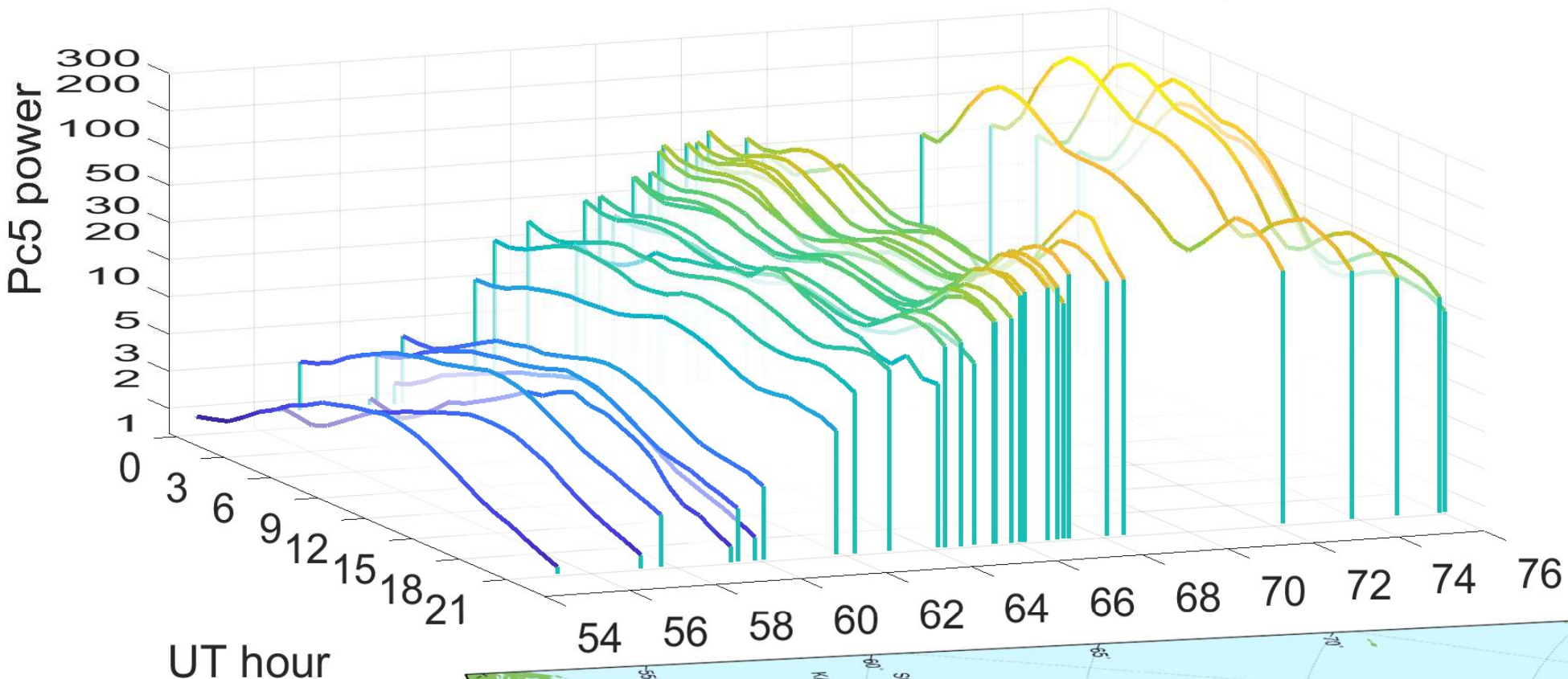
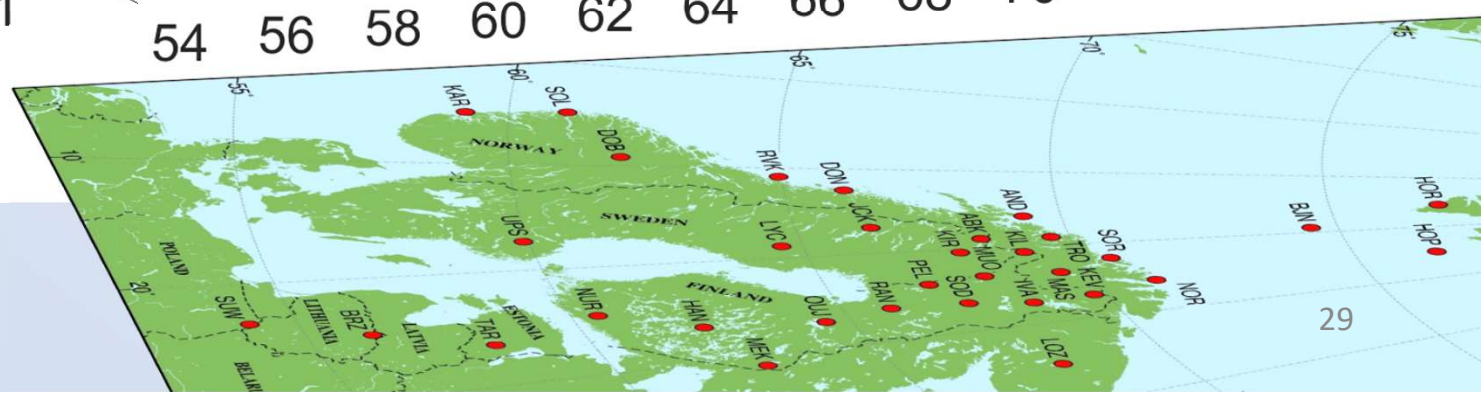


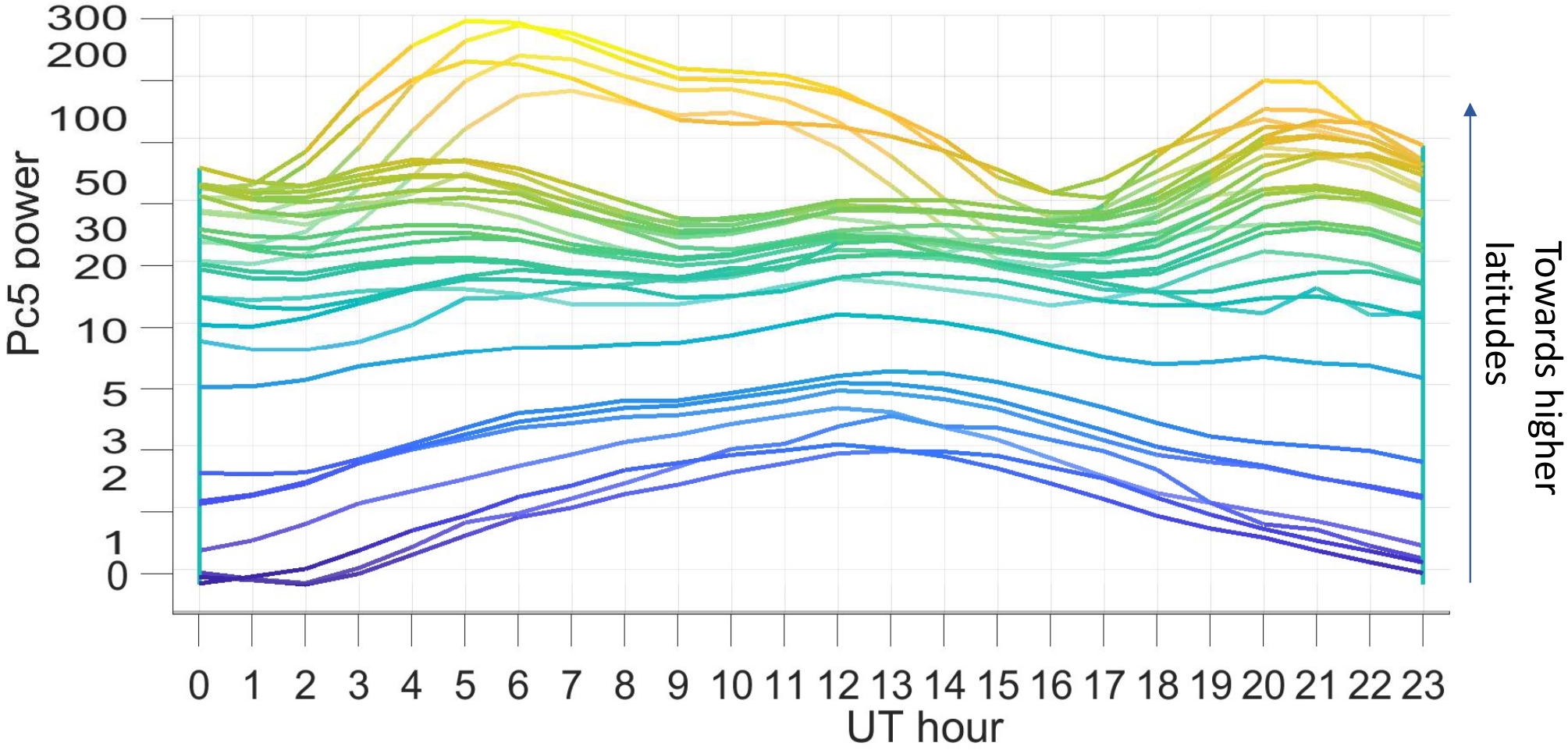
$*\ L = 1/\cos^2\theta$

Pc5 power in IMAGE stations in various UT hours, mean $\log_{10}$ of 1998-2008

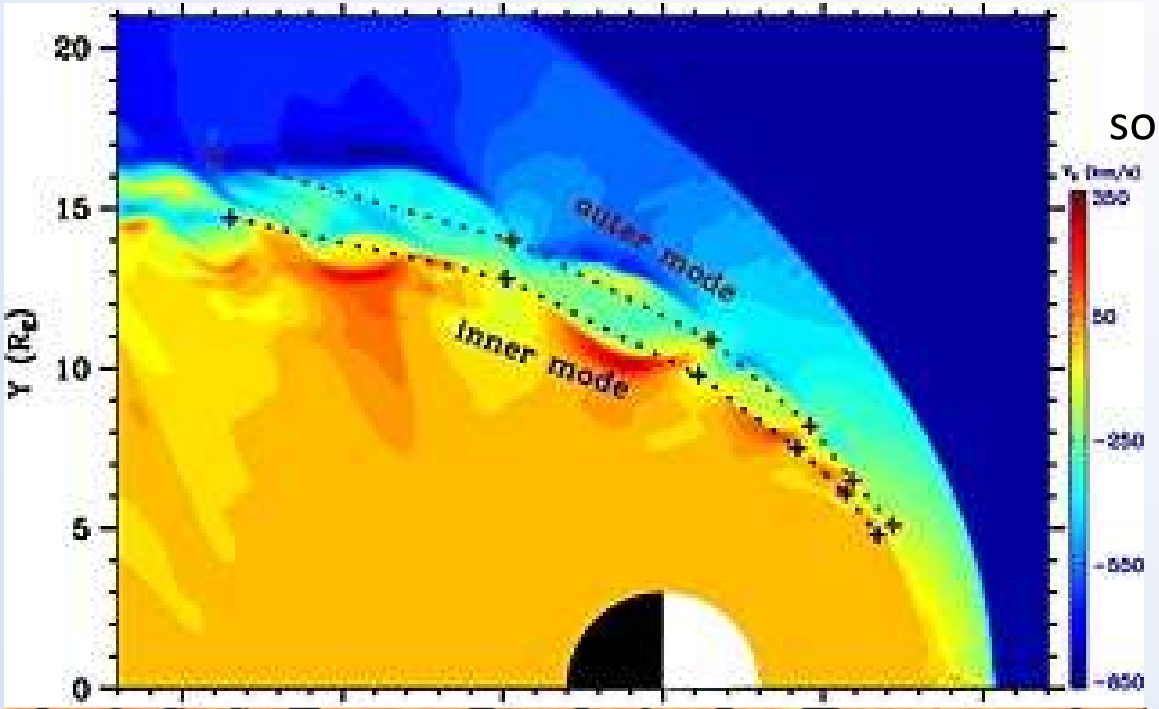




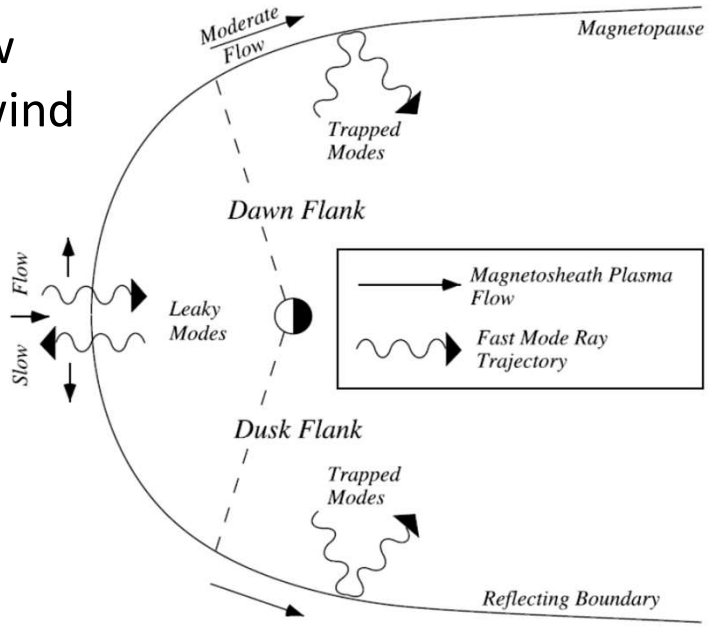
Sampling by the hour

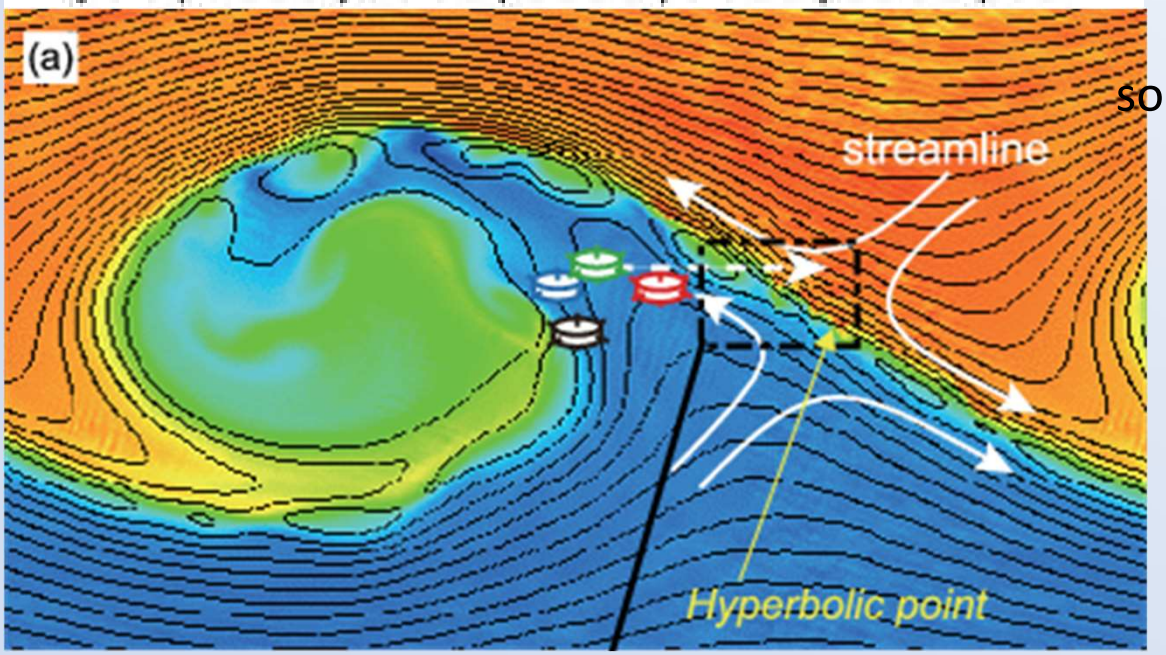


Magnetospheric waveguide

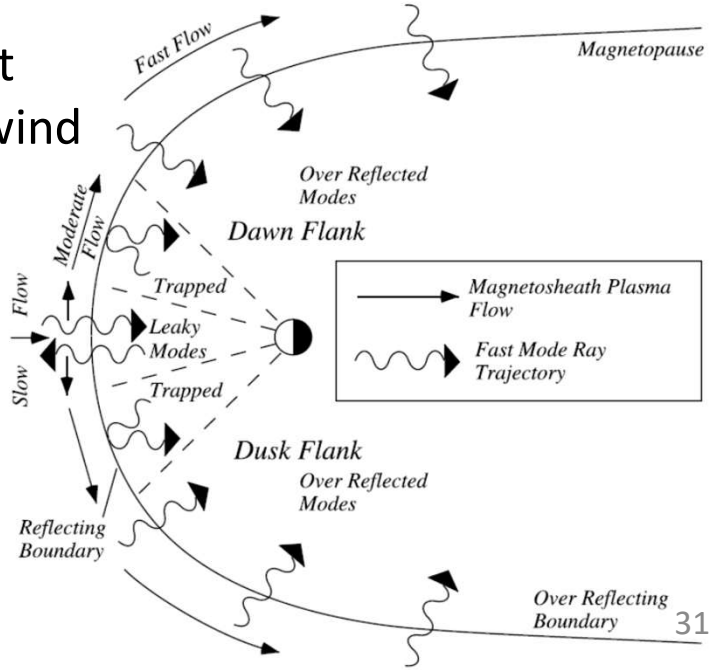


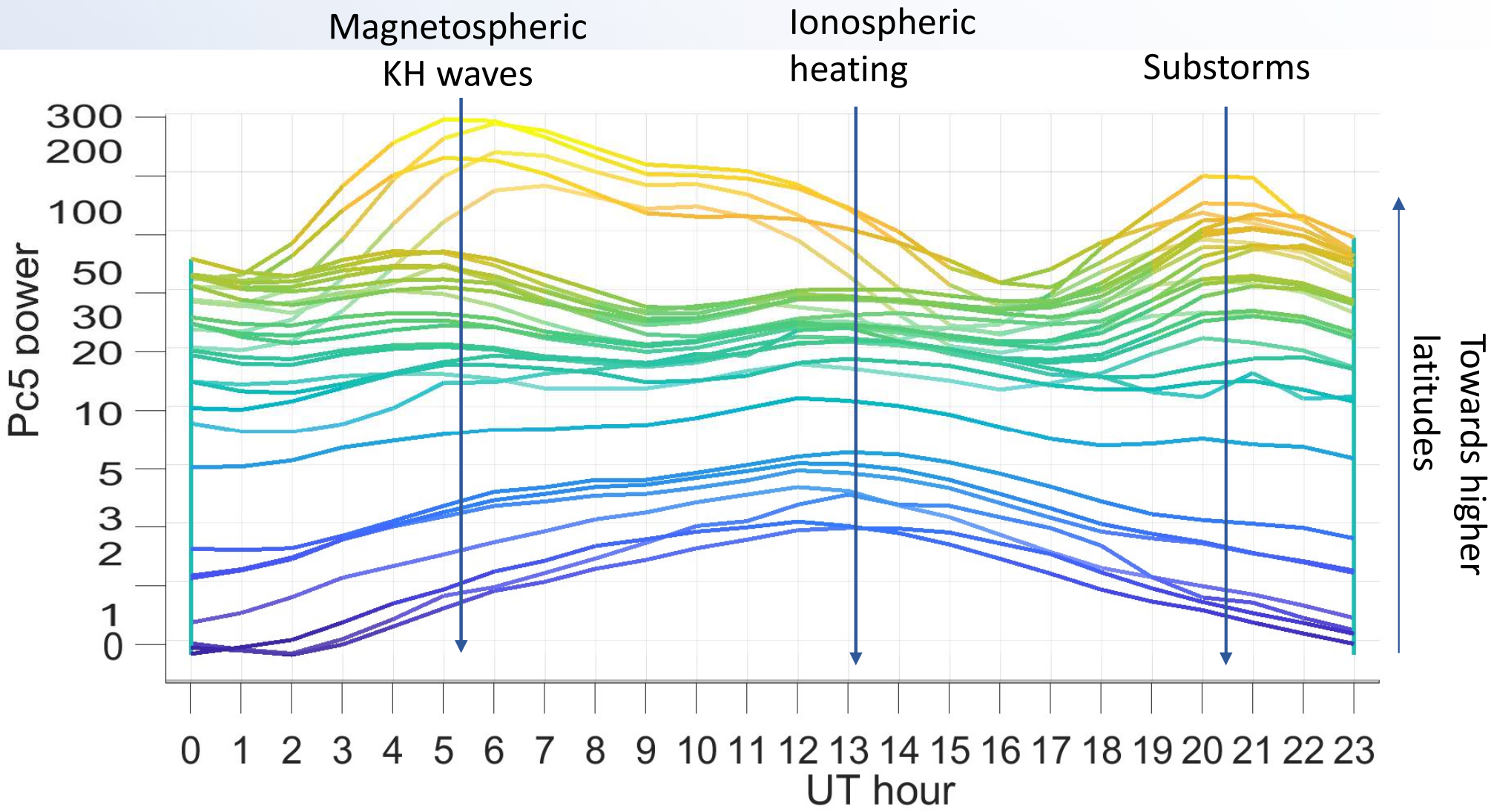
Slow solar wind

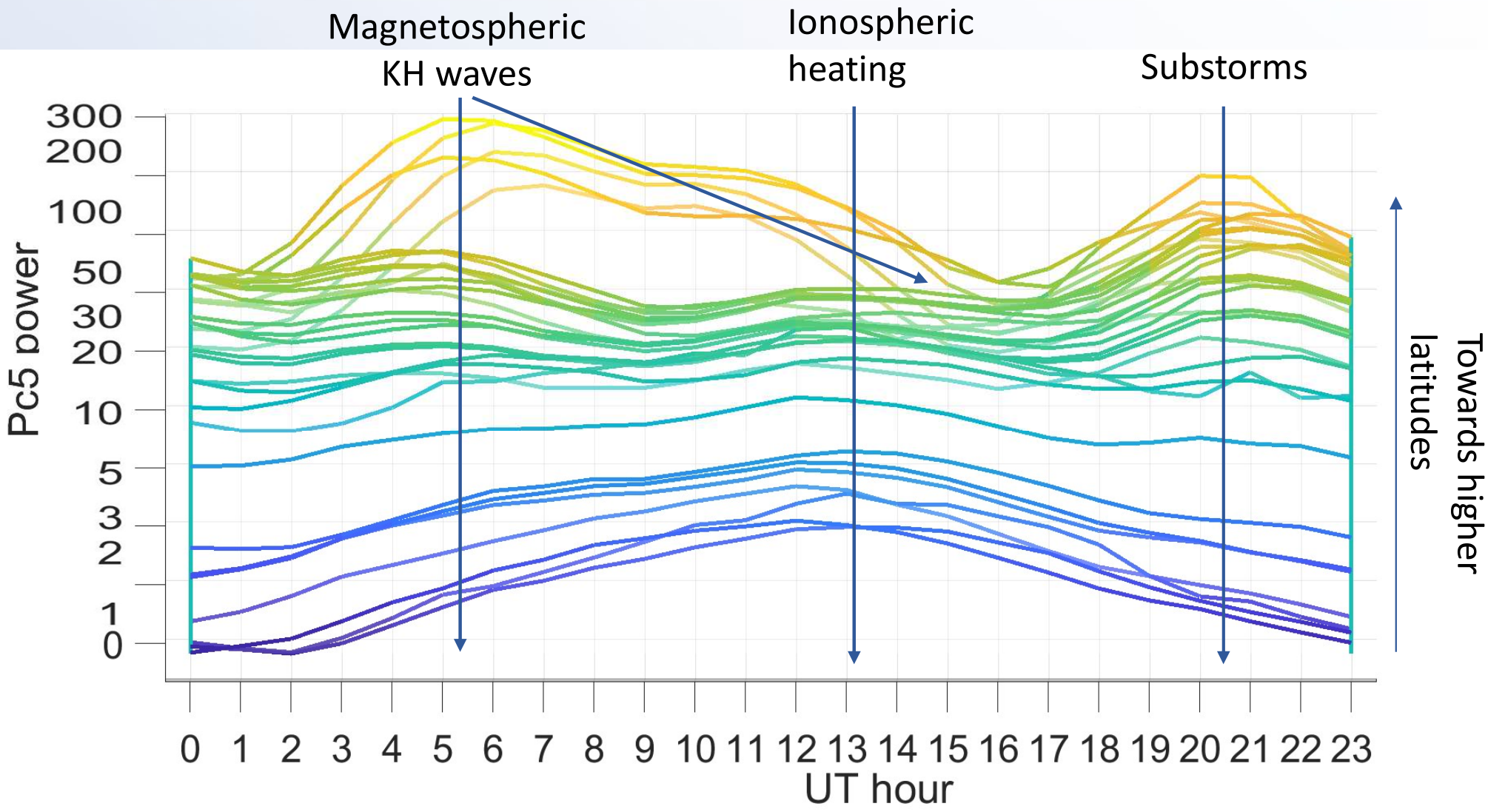




Fast solar wind




Magnetospheric
KH waves
Ionospheric
heating
Substorms
Pc5 power
300
200
100
50
30
20
10
5
3
2
1
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
UT hour
Towards higher
latitudes


Magnetospheric
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0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
UT hour
Towards higher
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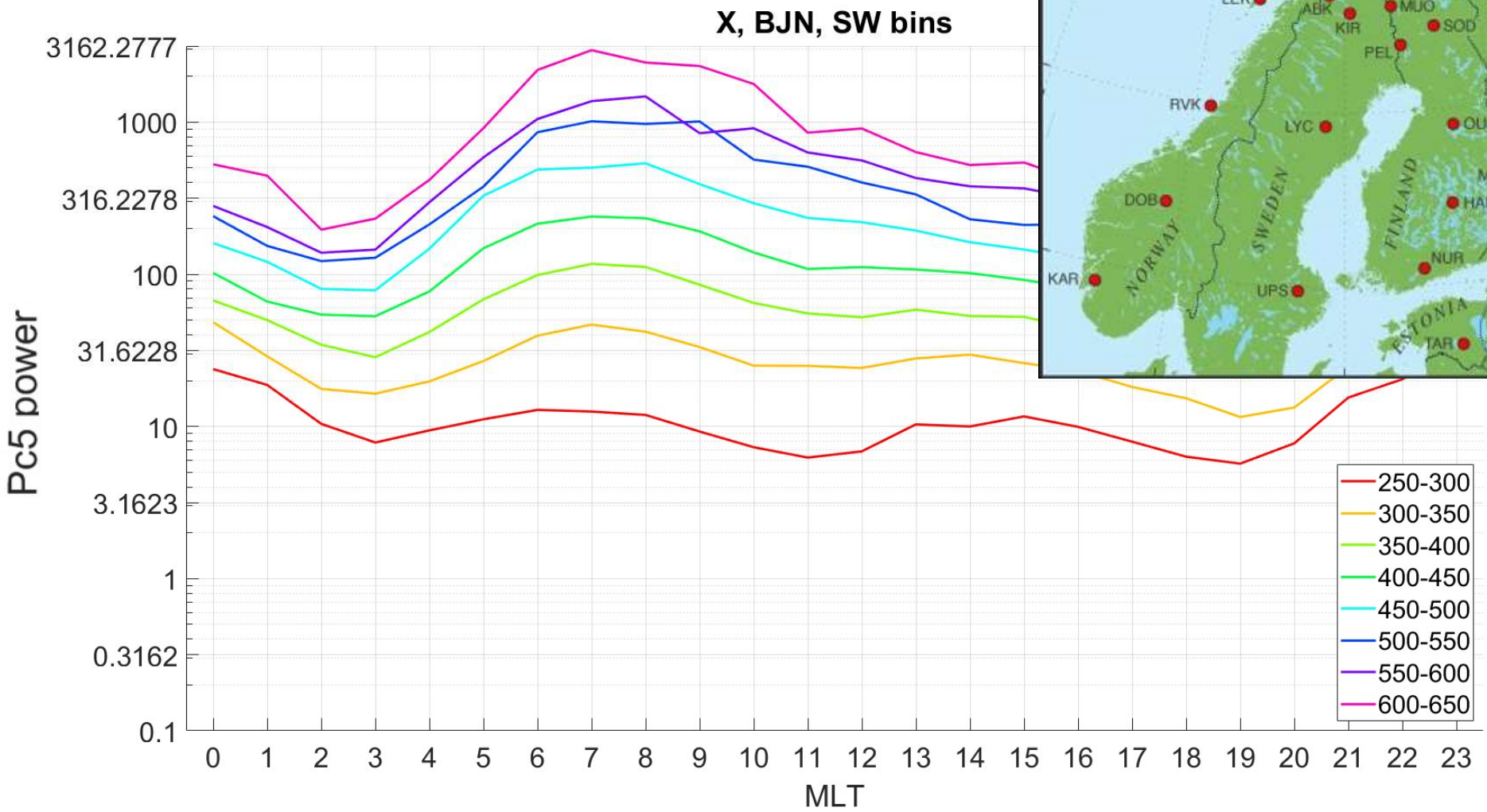
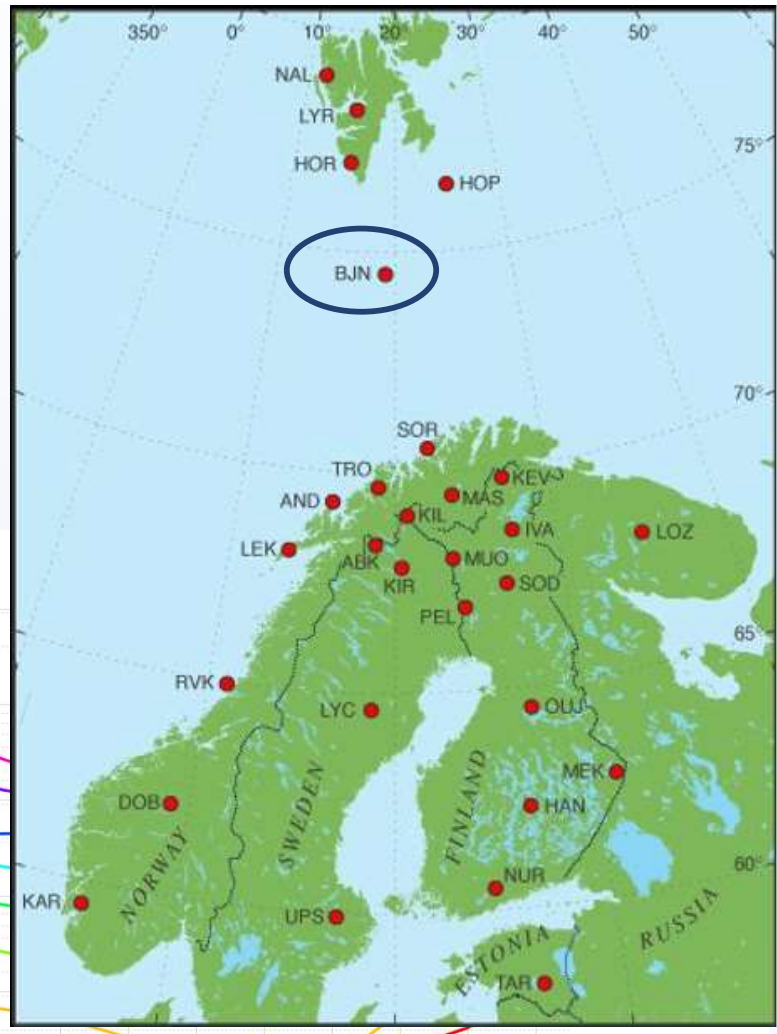
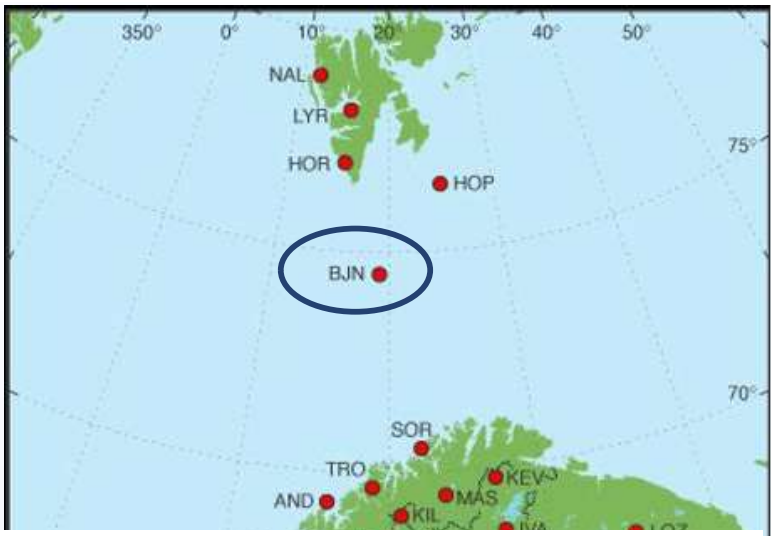
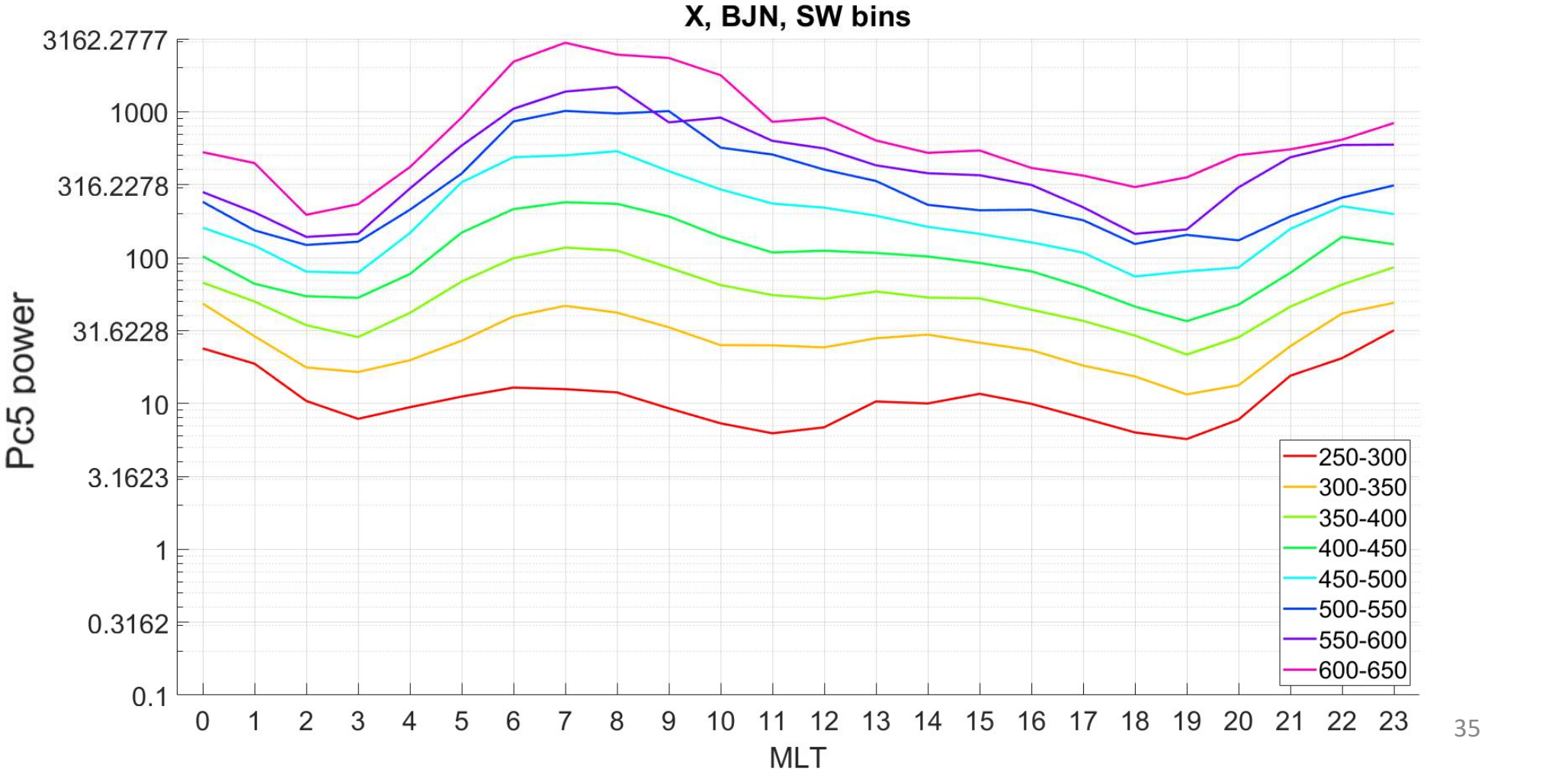
Effect of solar wind speed





Effect of solar wind speed