ULF* waves and related phenomena

*ultra-low frequency

Space Climate 2022

Reko Hynönen
Sodankylä Geophysical Observatory
Reko.Hynonen@oulu.fi

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
    - Descriptive categories by period and regularity
    - 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

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/decelera plasma

- Geomagnetic Pc an ulsations

period and regularity

Notation	Period R , 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)

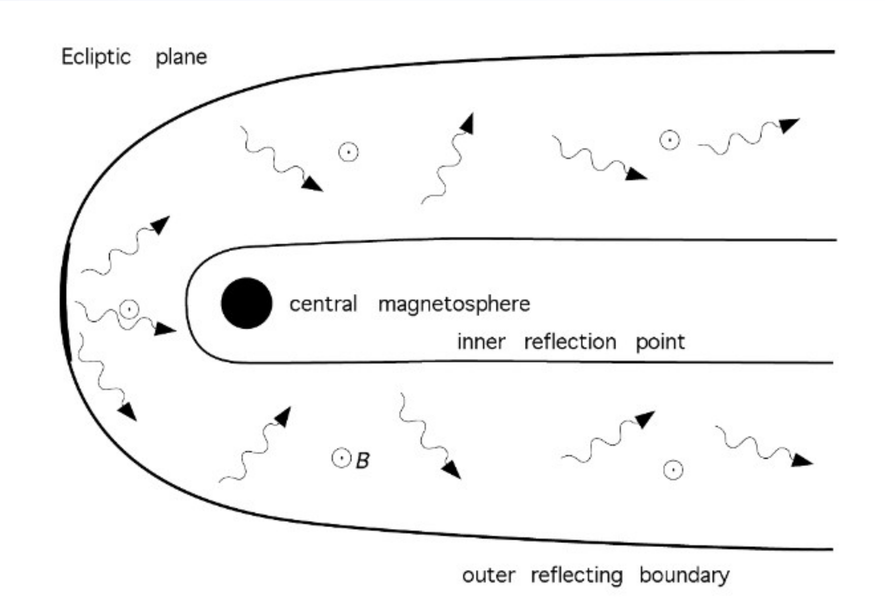
https://doi.org/10.1029/JZ069i001p00180

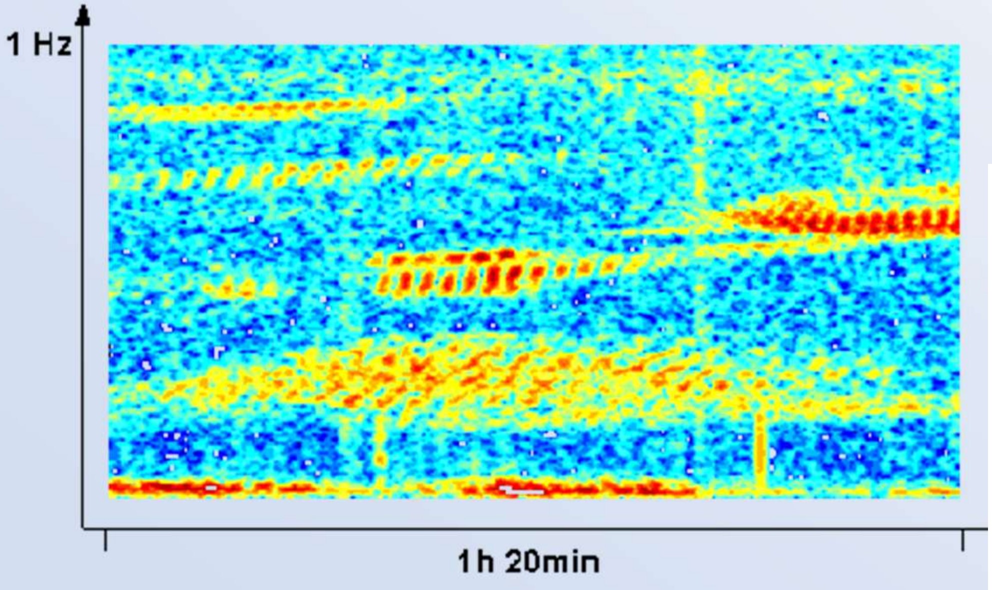
Hydromagnetic waves

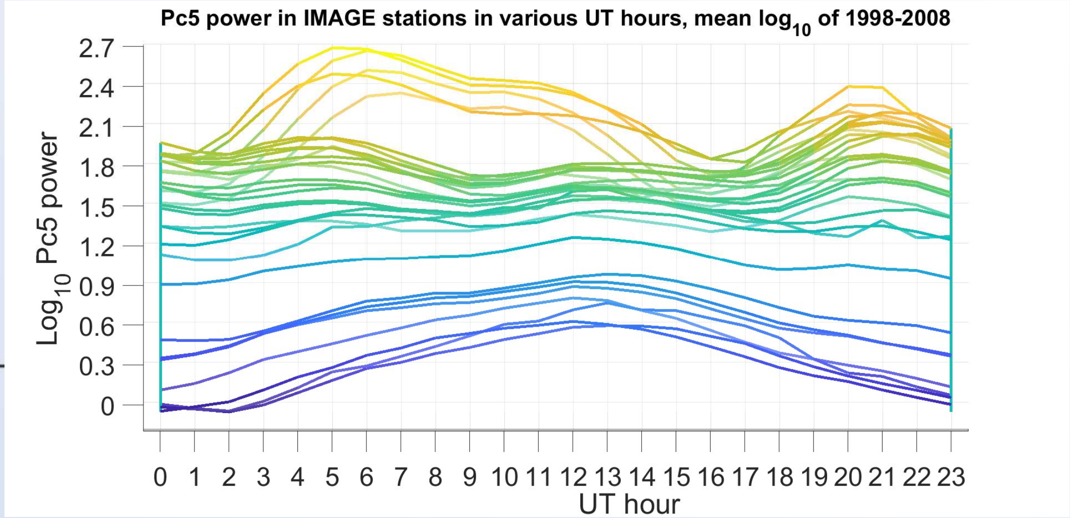
~ Waves in a magnetic field within electrically conducting fluid (plasma)

Content

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





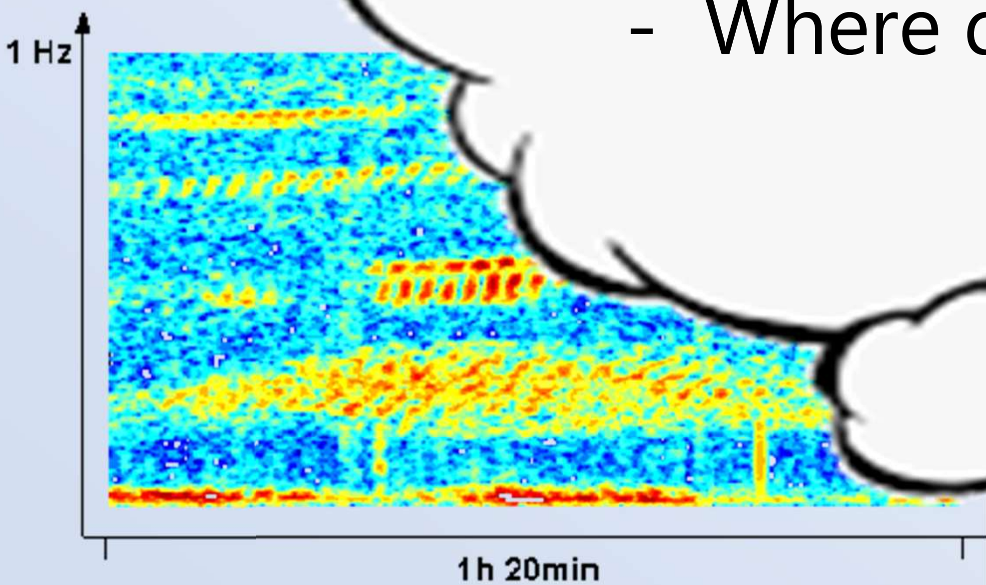


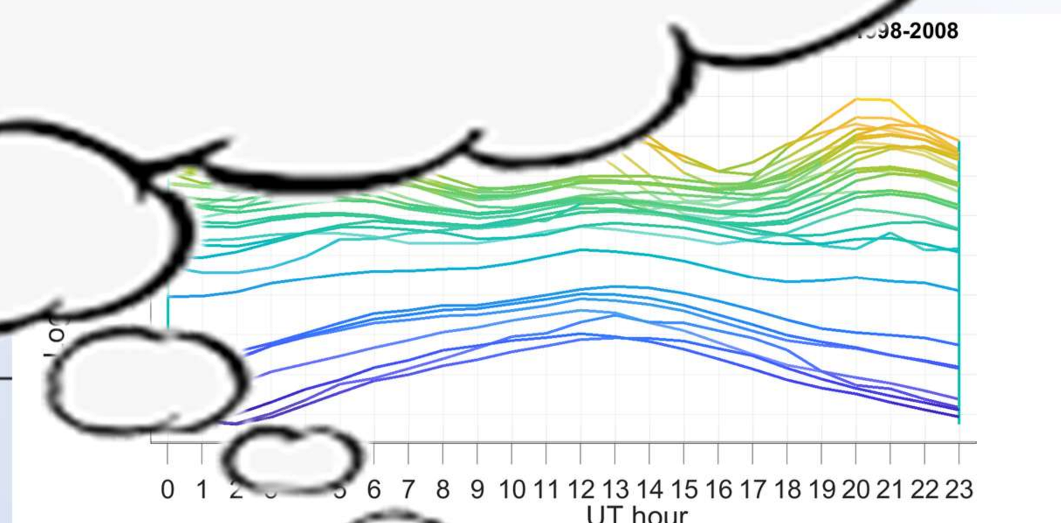
Content

- Some waves in pl
- Magnetosp
  ionosp
  phen
- Statis

Learning goals:

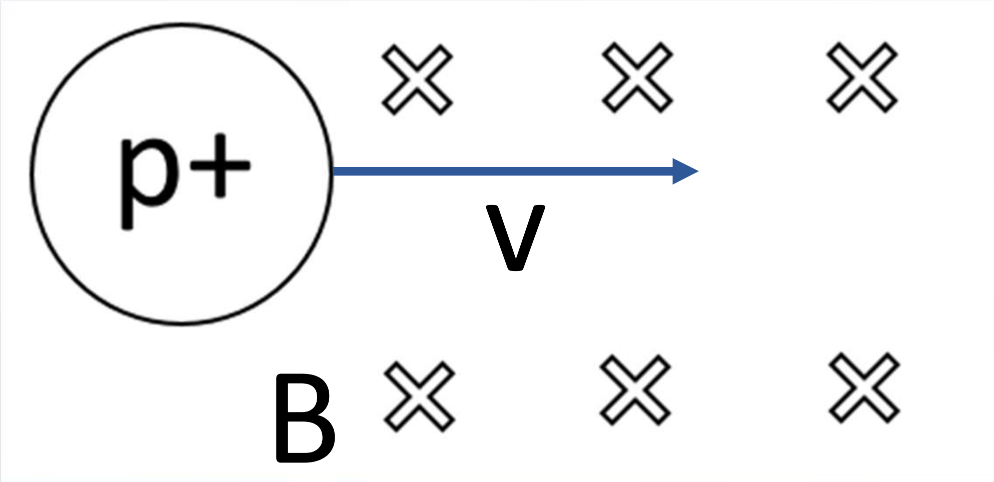
- What is ULF wave?
- Some examples of ULF waves
- Where do they occur?





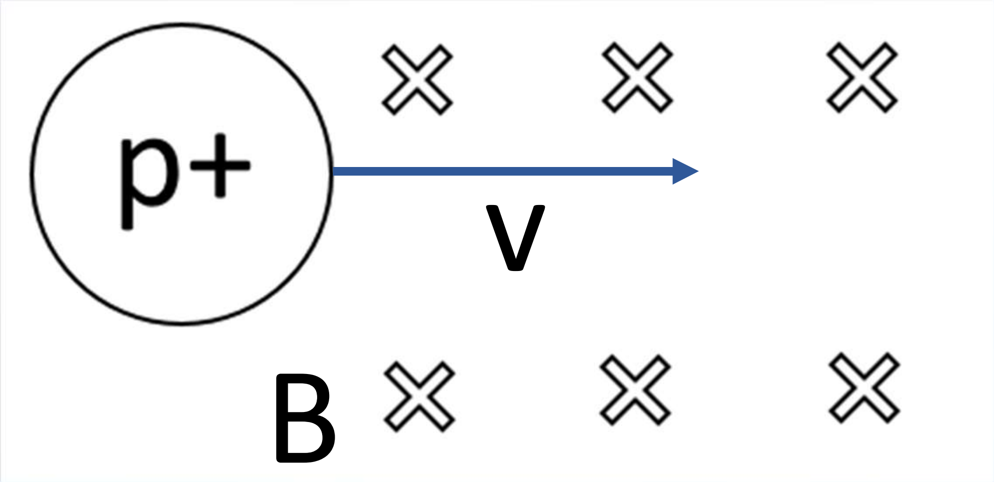
Cyclotron frequency

- Charged particle in an magnetic field



Cyclotron frequency

- Charged particle in an magnetic field



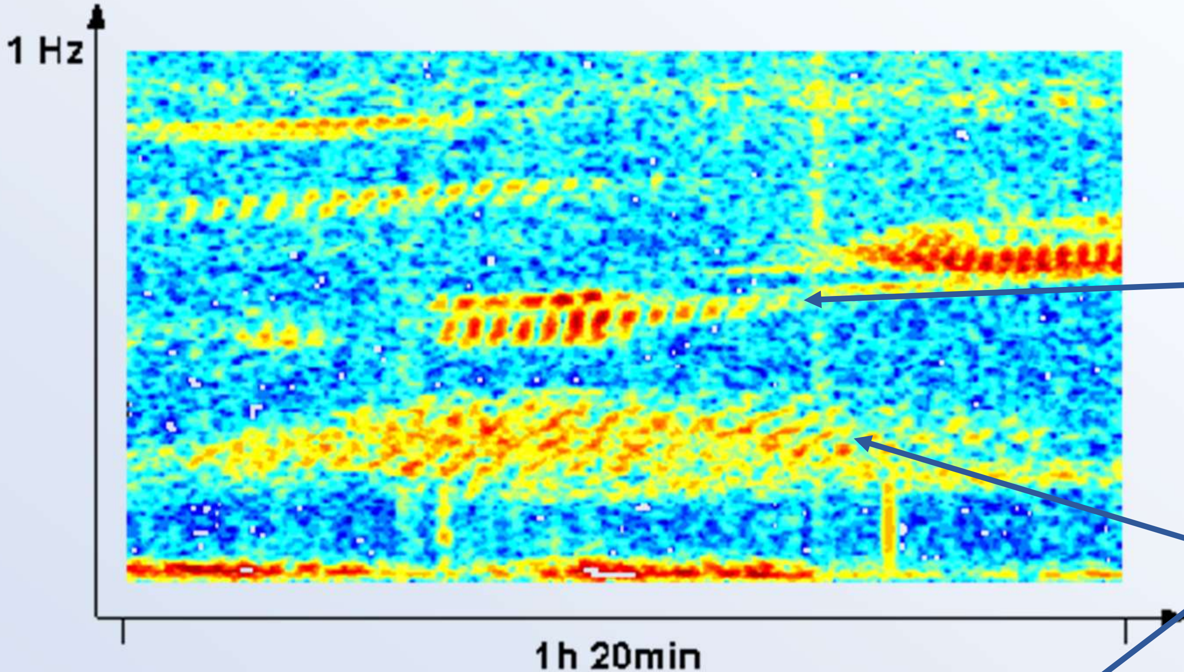
→ Undergoes cyclic motion at cyclotron frequency

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

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

*Electromagnetic ion cyclotron

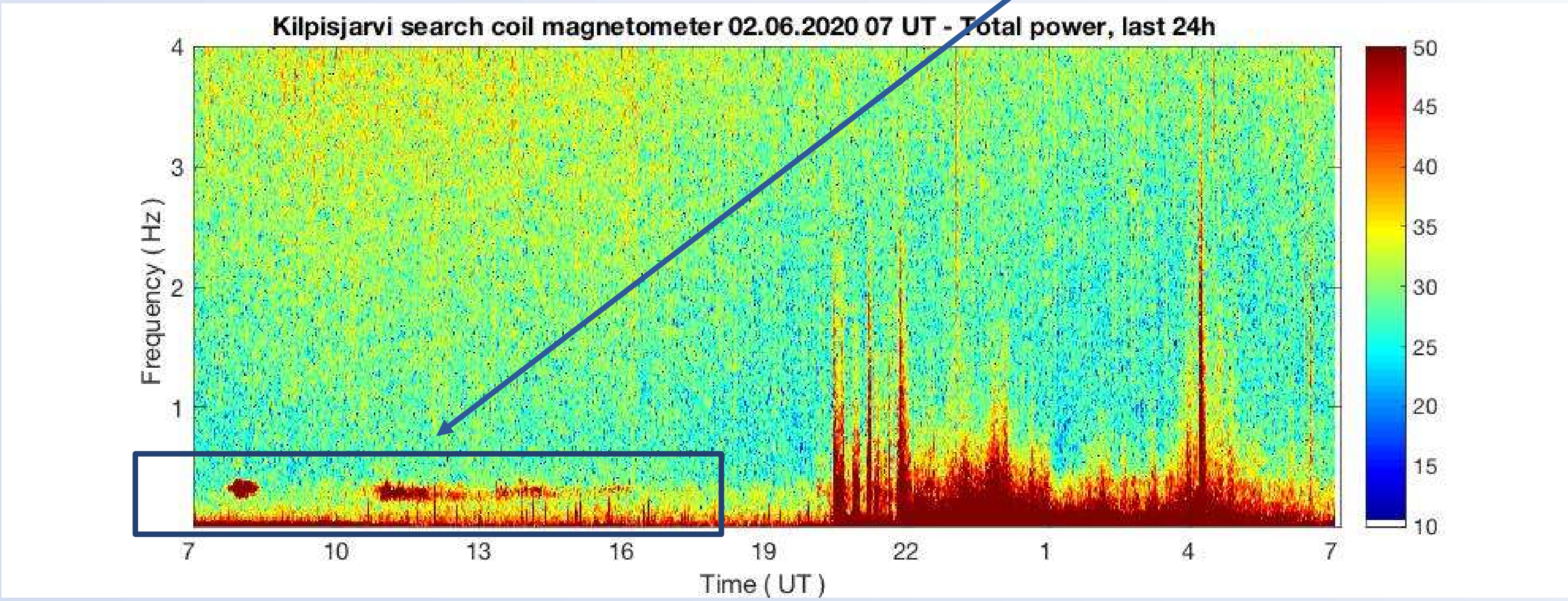
Ion cyclotron waves



Pulsations:

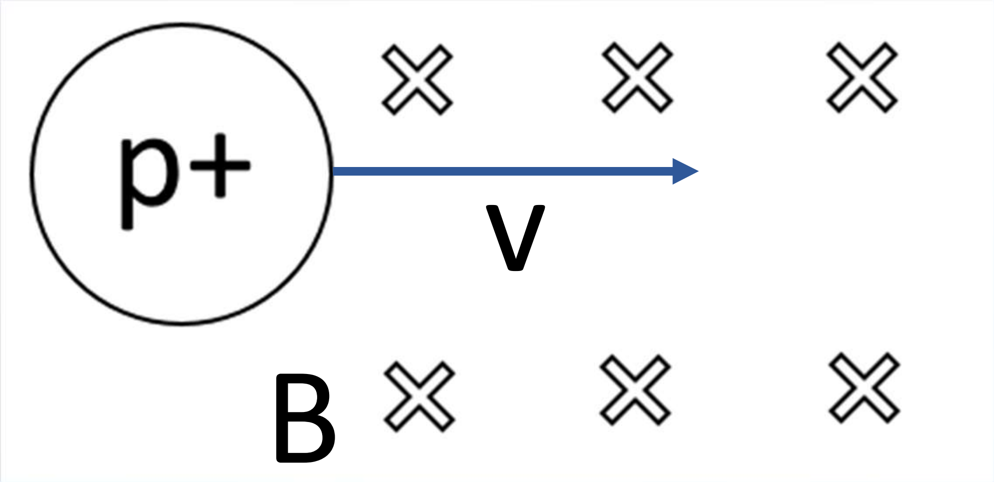
Pc1, 200-1000 mHz
”pearl pulsations”

Pc2, 100-200 mHz
”EMIC wave trains”



Cyclotron frequency

- Charged particle in an magnetic field



→ Undergoes cyclic motion at cyclotron frequency

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

- **ν ~ cyclotron frequency of proton ~ an ability to influence and accelerate/decelerate plasma**

KILLER ELECTRONS

…IN SPACE!

ULF waves as precursors of "killer electrons"

ULF wave frequencies ~ ion cyclotron frequencies

→ One can “tap” into another

→ Electrons of MeV energies in the radiation belts

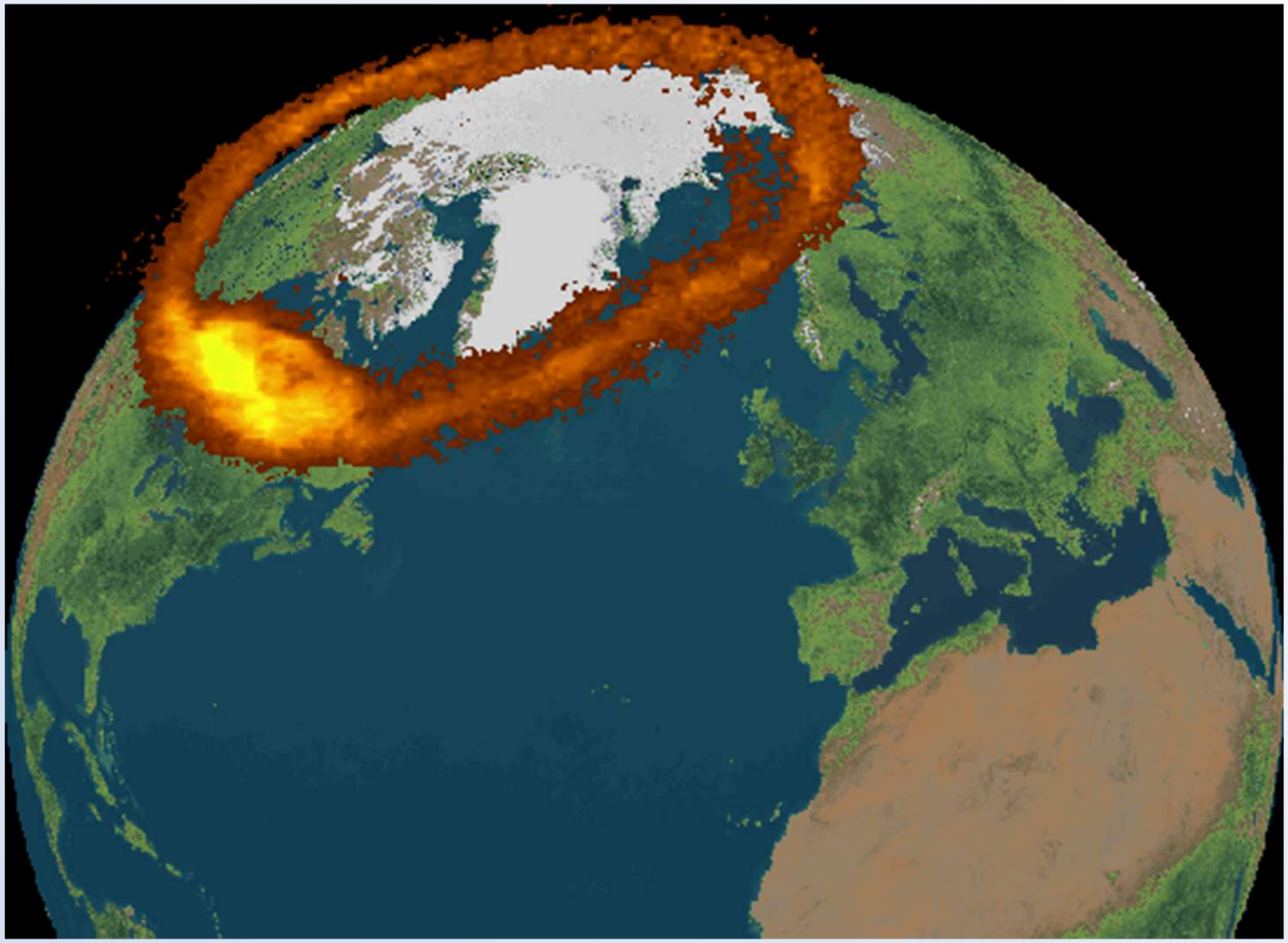


Image credit: NASA

Oscillating magnetic field: Alfvén waves

”Alfvén waves ~ Ion oscillation waves”

Oscillating magnetic field: Alfvén waves

”Alfvén waves ~ Ion oscillation waves”

Oscillating magnetic field: Alfvén waves

"Alfvén waves ~ Ion oscillation waves"

- Theorized by Hannes Alfvén in 1942
- Oscillation of ions and magnetic field,
  B → **B** + d**B**
- Low frequency (less than ion cyclotron frequency)
  - e.g. in solar wind ~ 2-10 mHz
- Can propagate long distance without dampening.

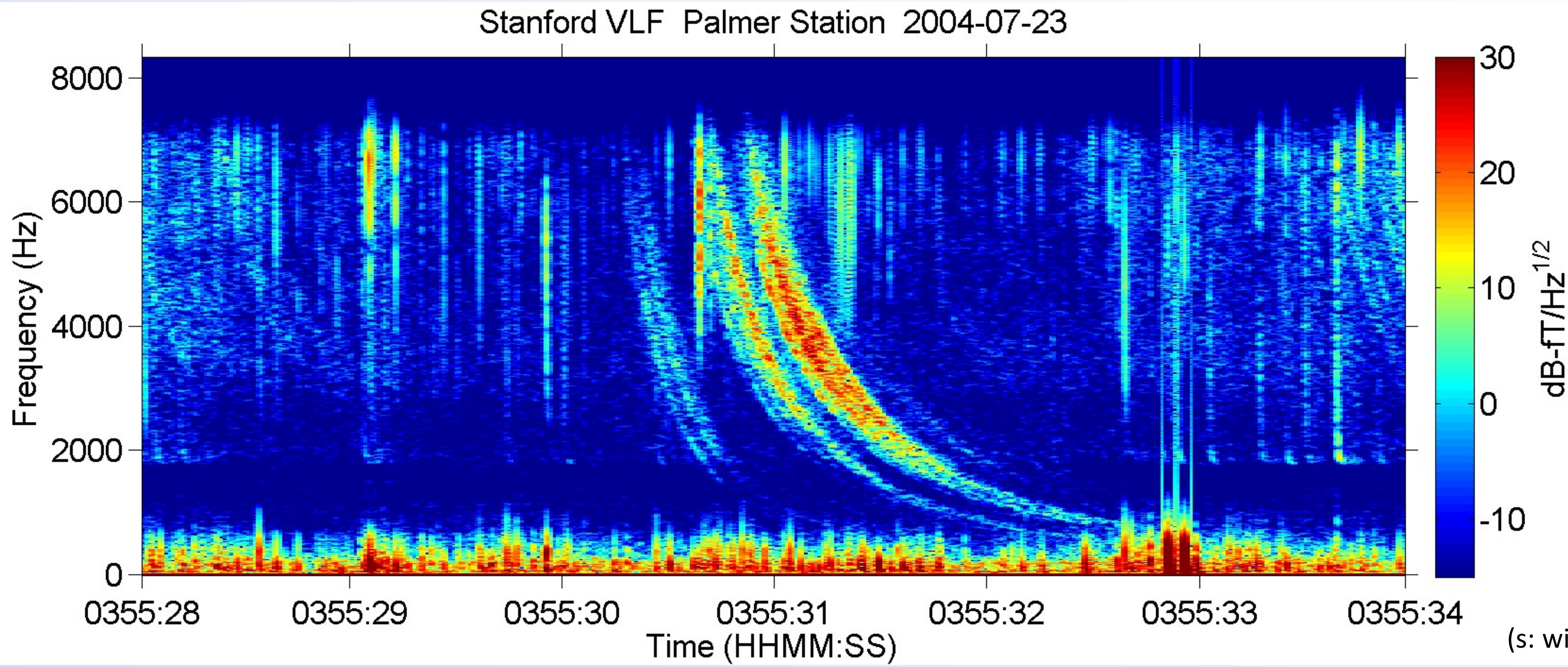
- Alfvén velocity depends on *magnetic field* and *plasma density*.

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

Sonic and magnetosonic waves

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

It's actually a VLF wave



(s: wikipedia)

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

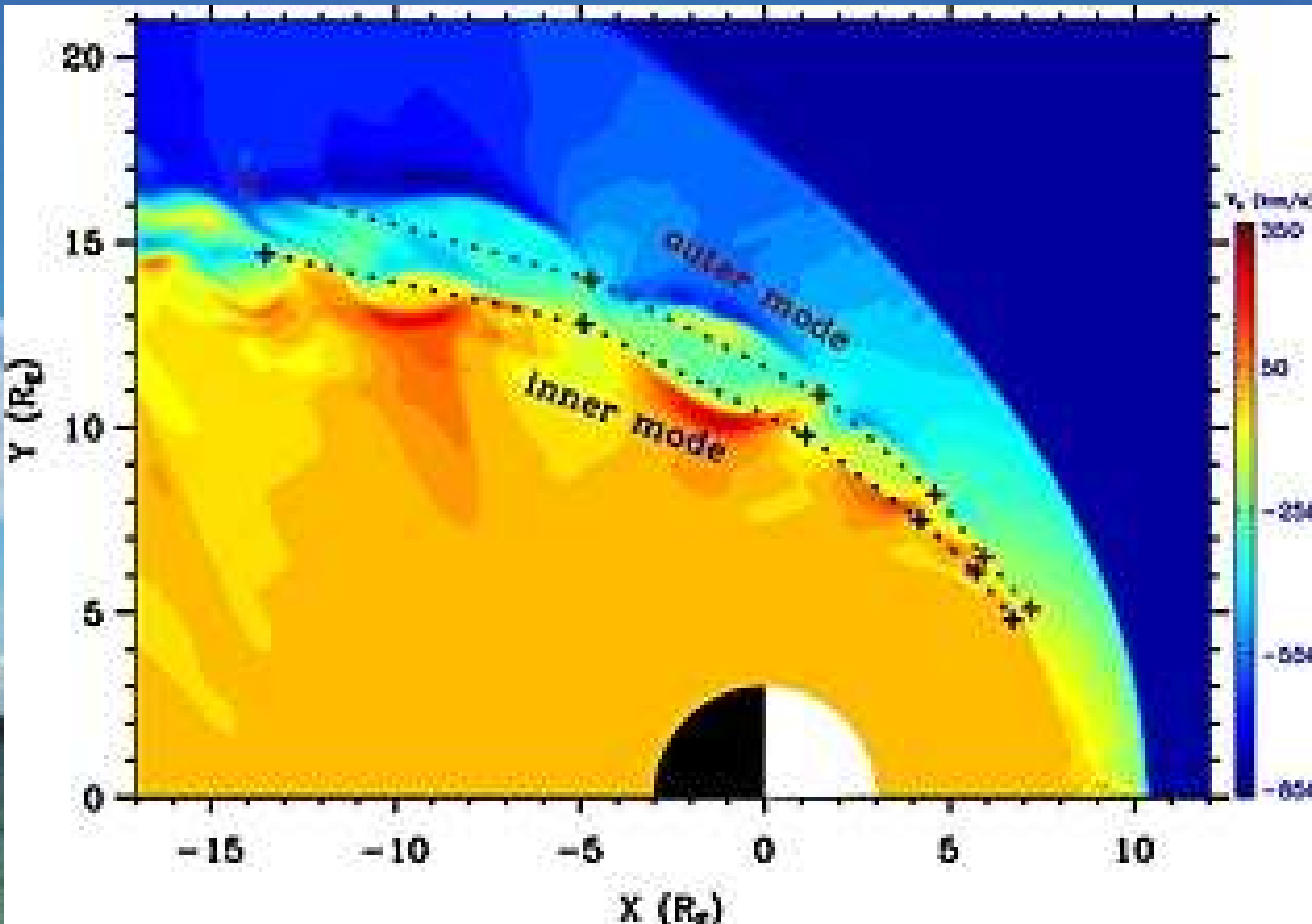
Kelvin-Helmholtz waves

Kelvin-Helmholtz waves

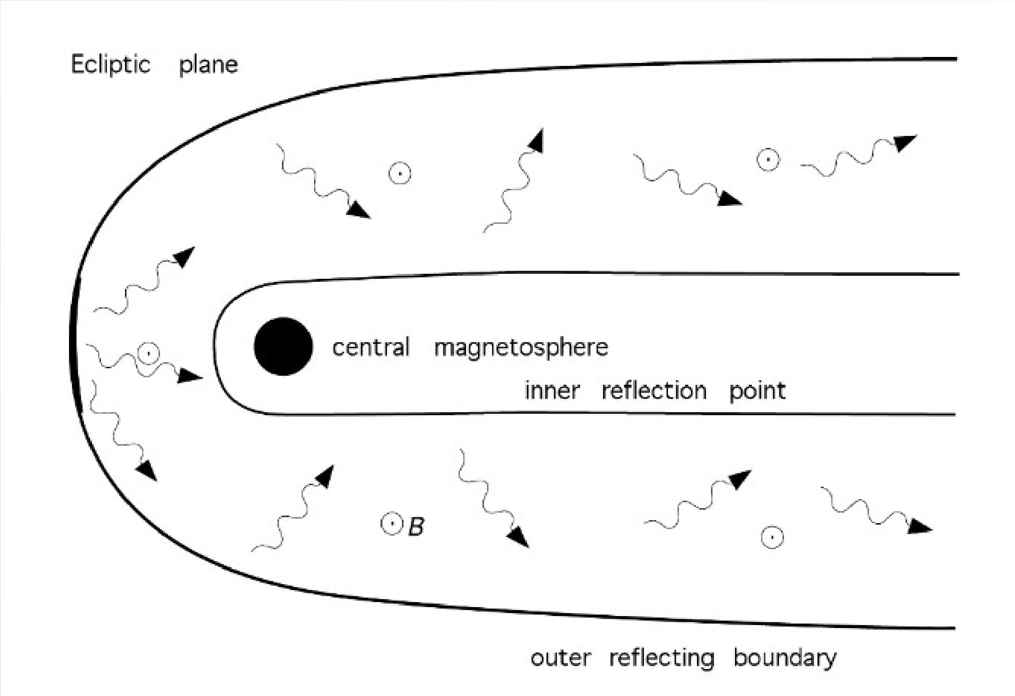
- Instability caused by velocity shear between two fluids
- Greater the speed difference between the fluids, the faster and greater the instability

- Also called KH waves

Kelvin-Helmholtz waves



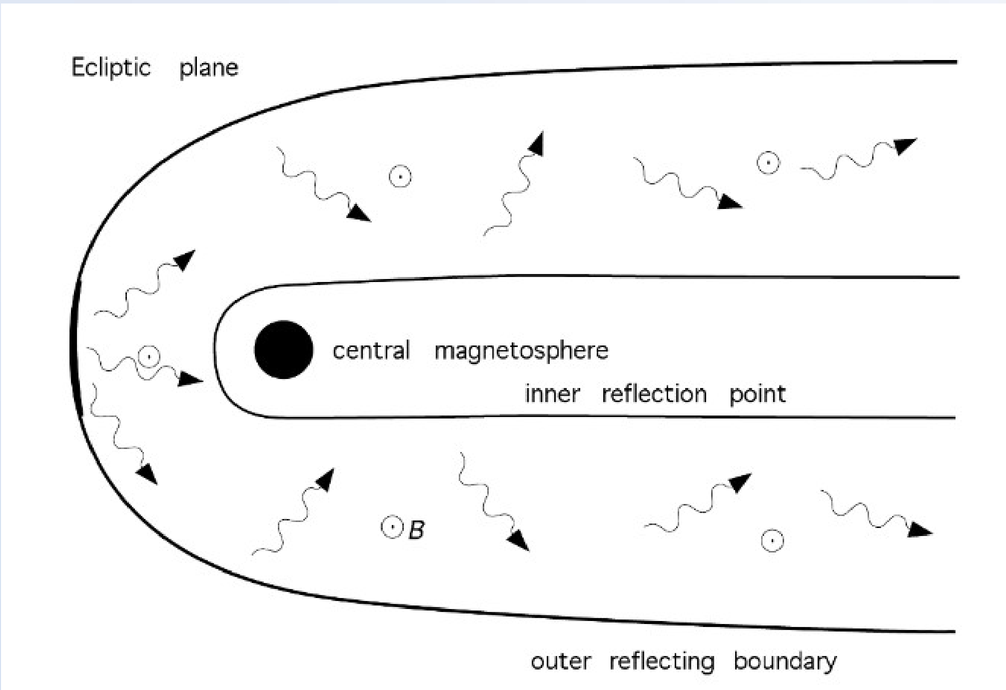
Magnetospheric waveguide



Fast-mode waves bouncing between magnetospheric outer and inner boundaries

Magnetospheric waveguide

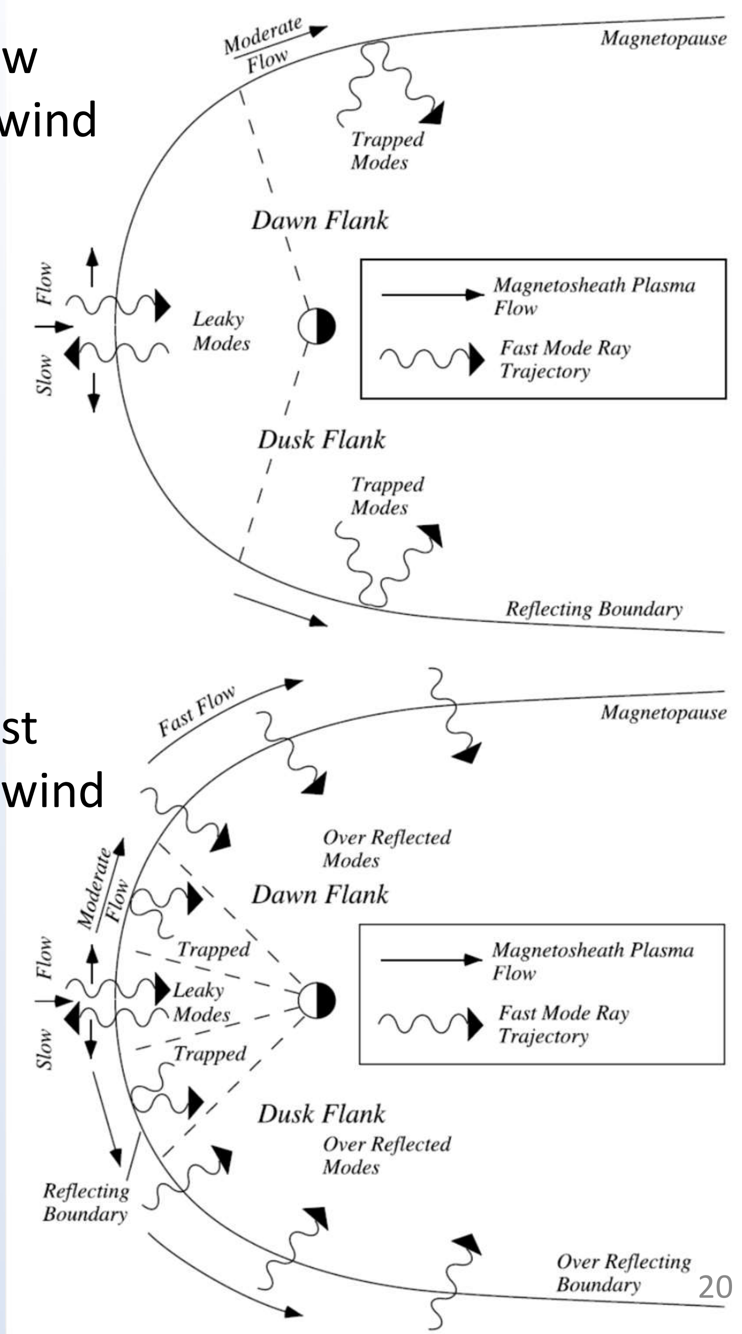
Magnetospheric waveguide



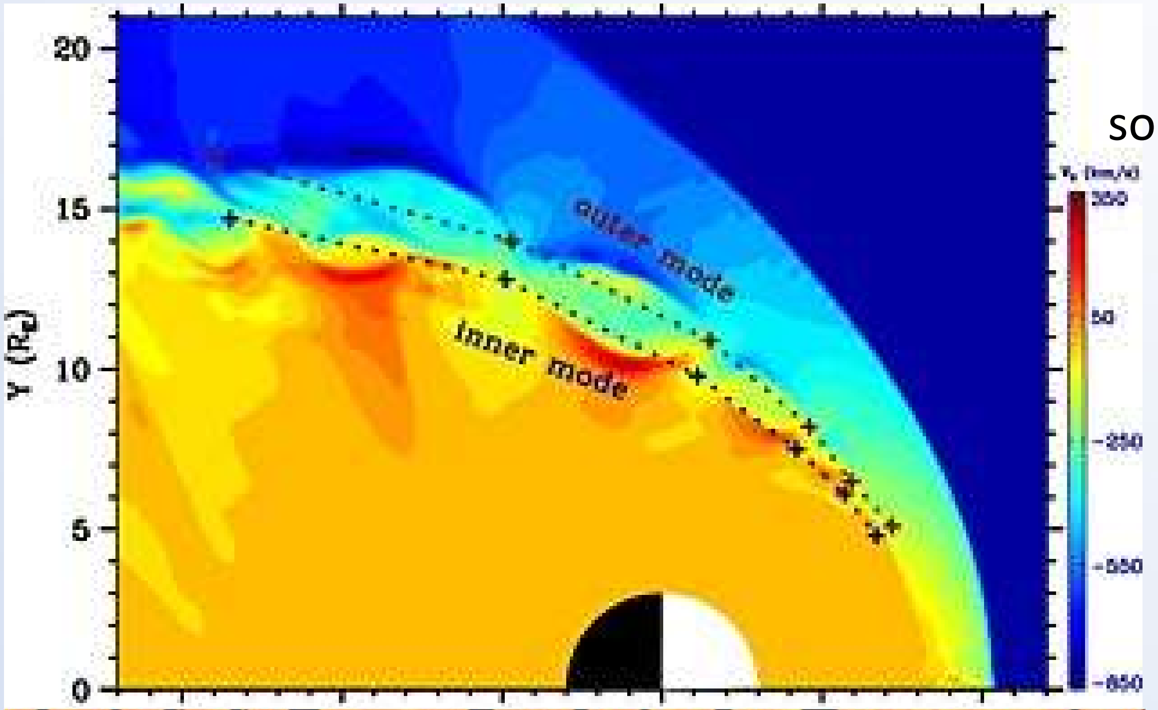
Fast-mode waves bouncing between magnetospheric outer and inner boundaries

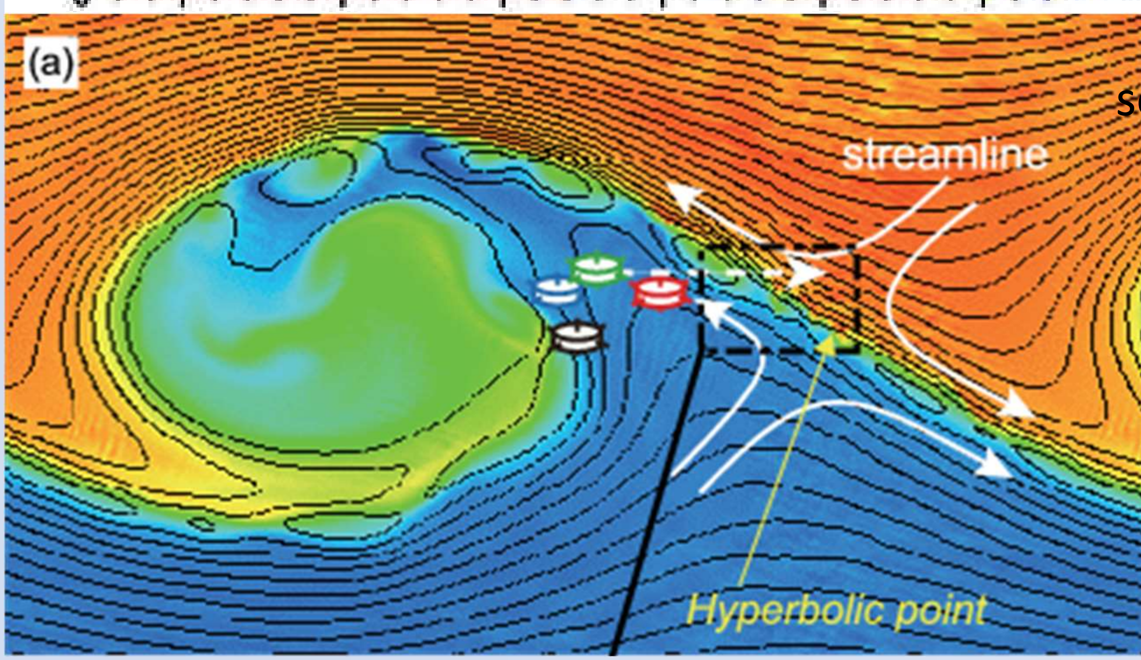
Slow solar wind

Fast solar wind



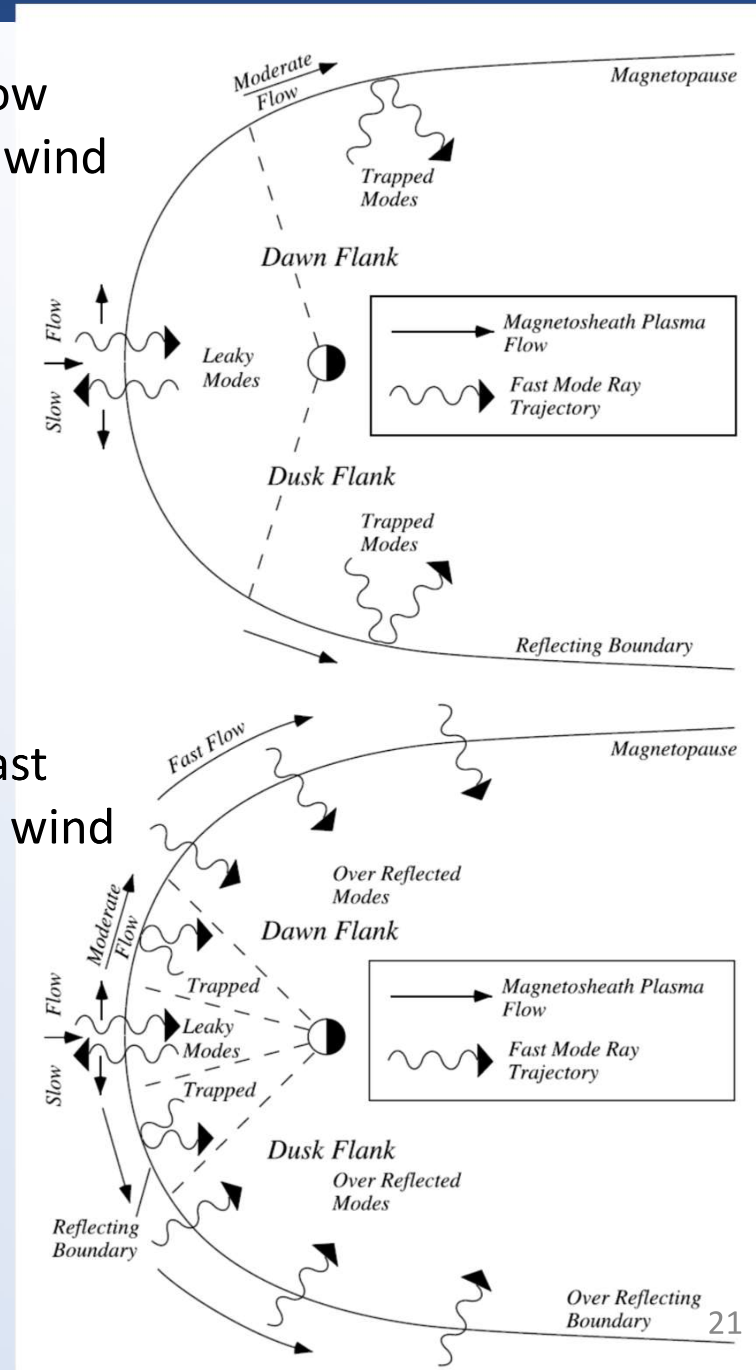
Magnetospheric waveguide





Slow
solar wind

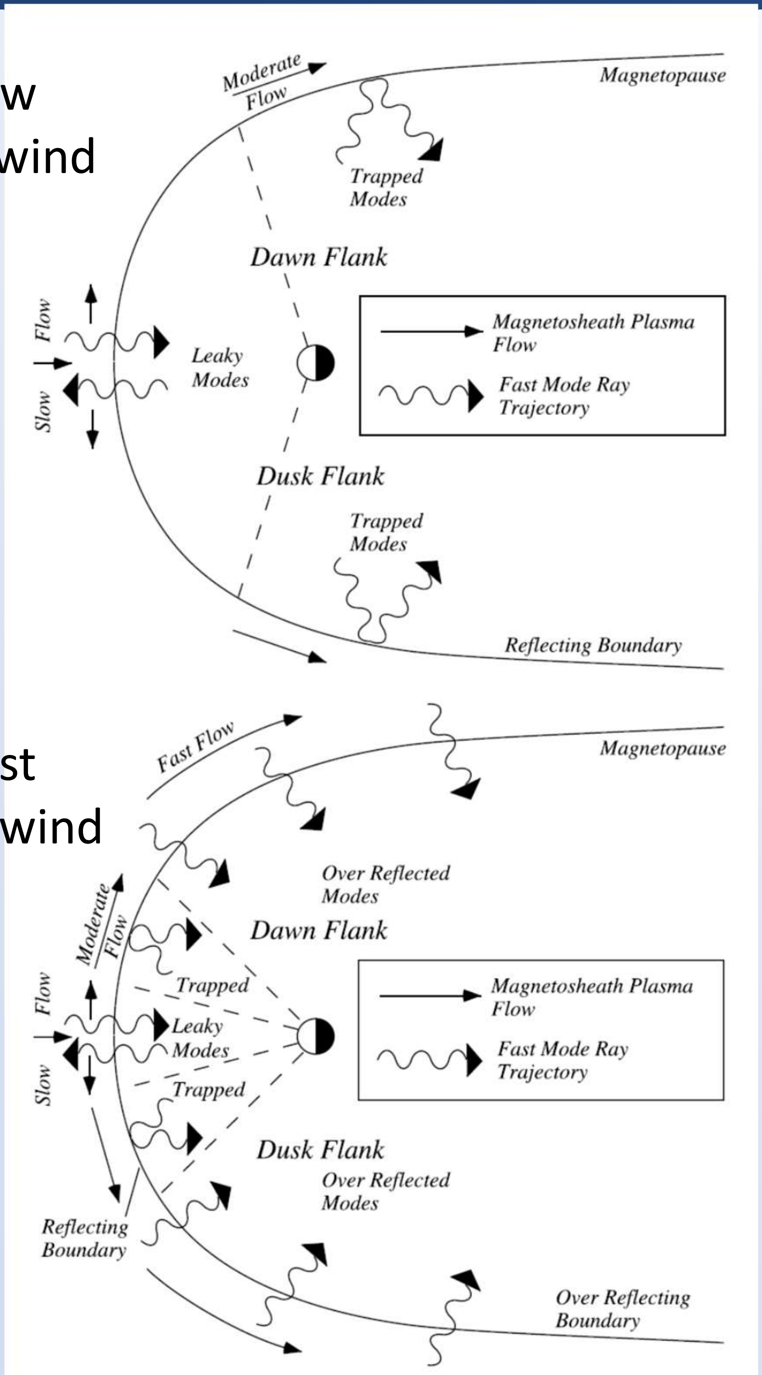
Fast
solar wind

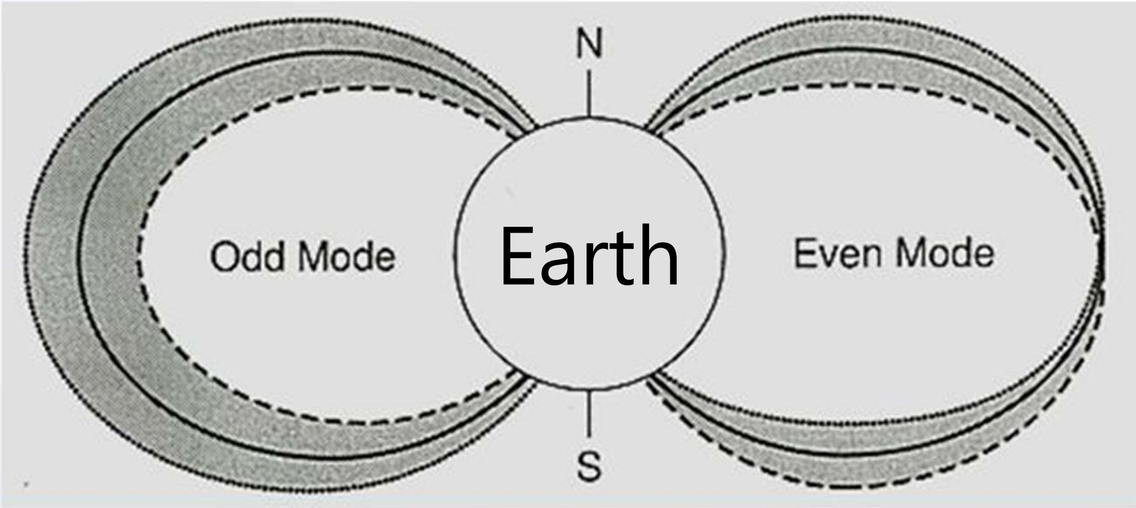


Field line resonance

Slow
solar wind

Fast
solar wind



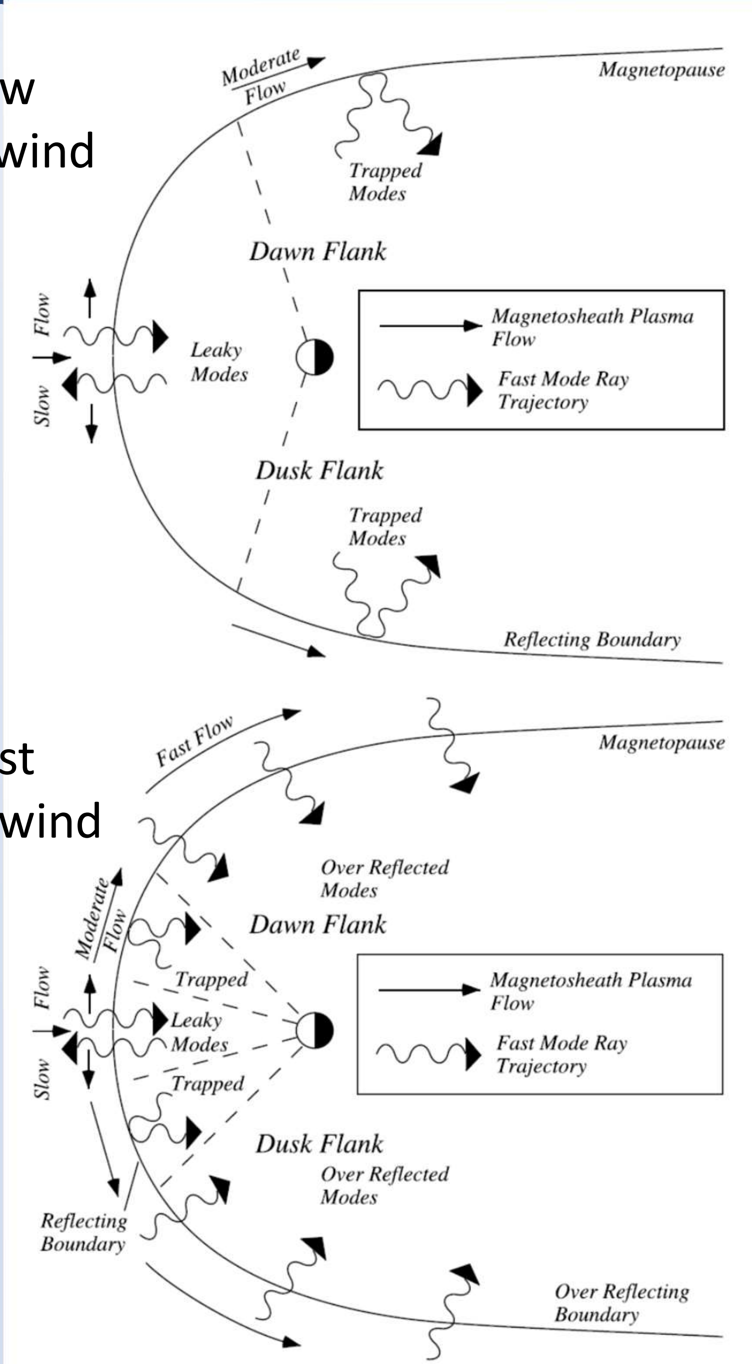


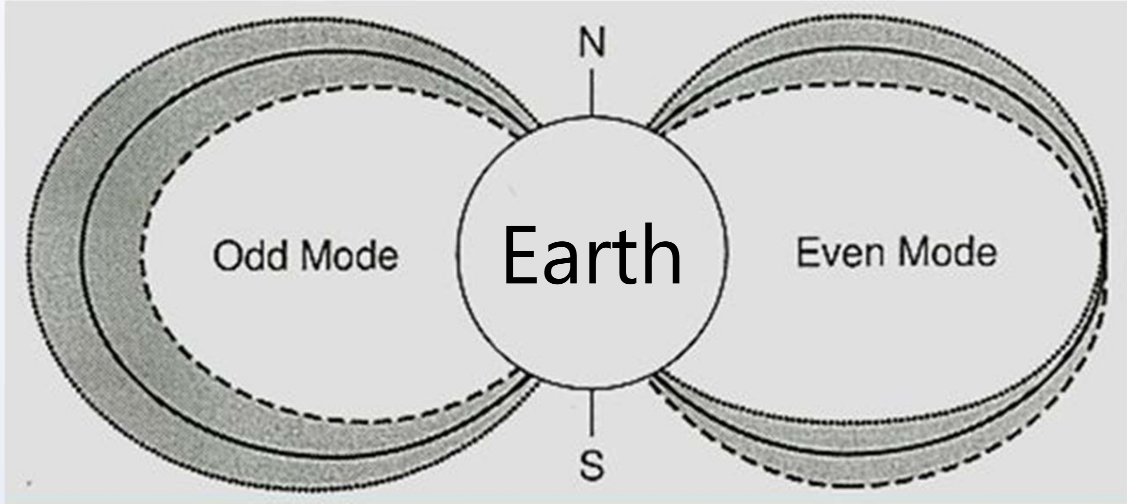
Shear Alfvén waves

Field line resonance

Slow
solar wind

Fast
solar wind





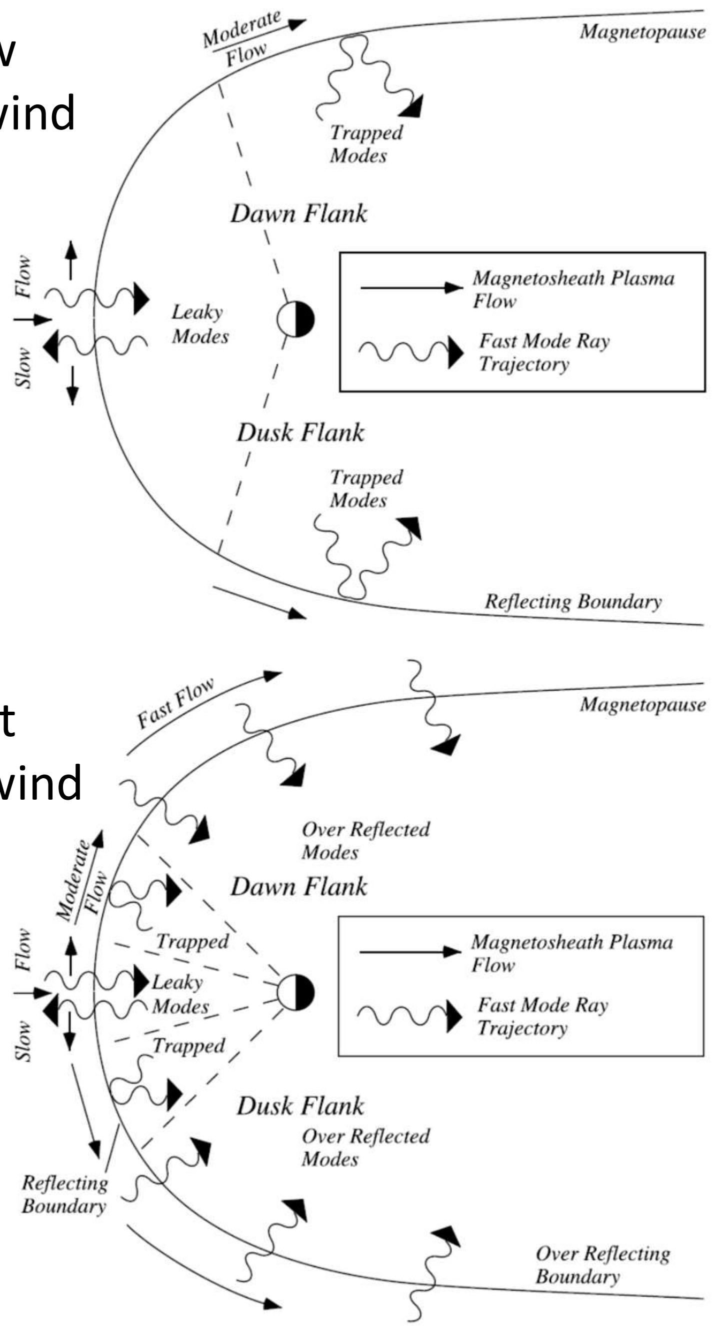
Shear Alfvén waves

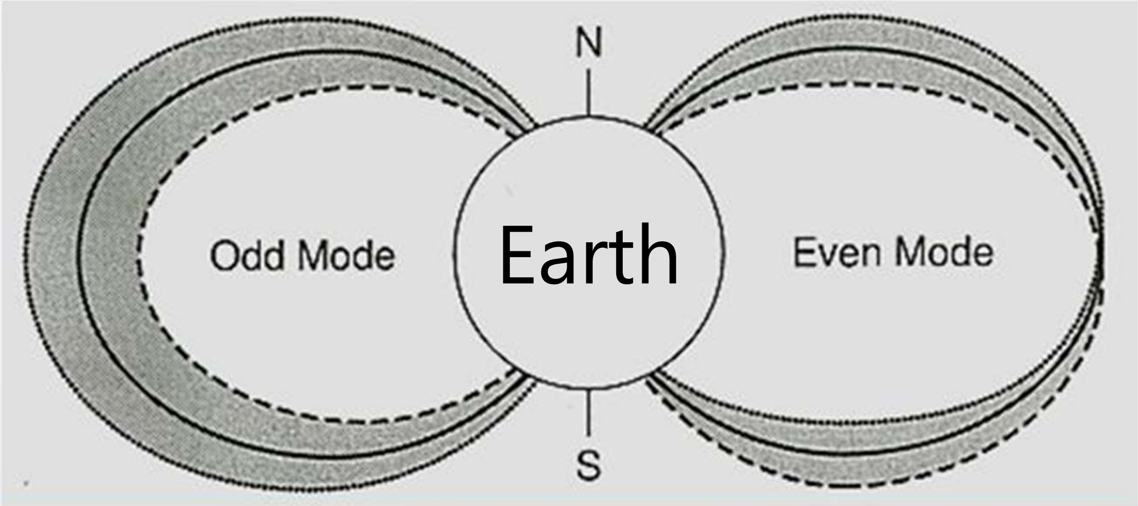
→ Fast mode magnetosonic wave dampens fast, losing energy to particles and other waves

Field line resonance

Slow
solar wind

Fast
solar wind





Shear Alfvén waves

→ Fast mode magnetosonic wave dampens fast, losing energy to particles and **other waves**
→ transforms into shear Alfvén wave traversing the magnetic field lines

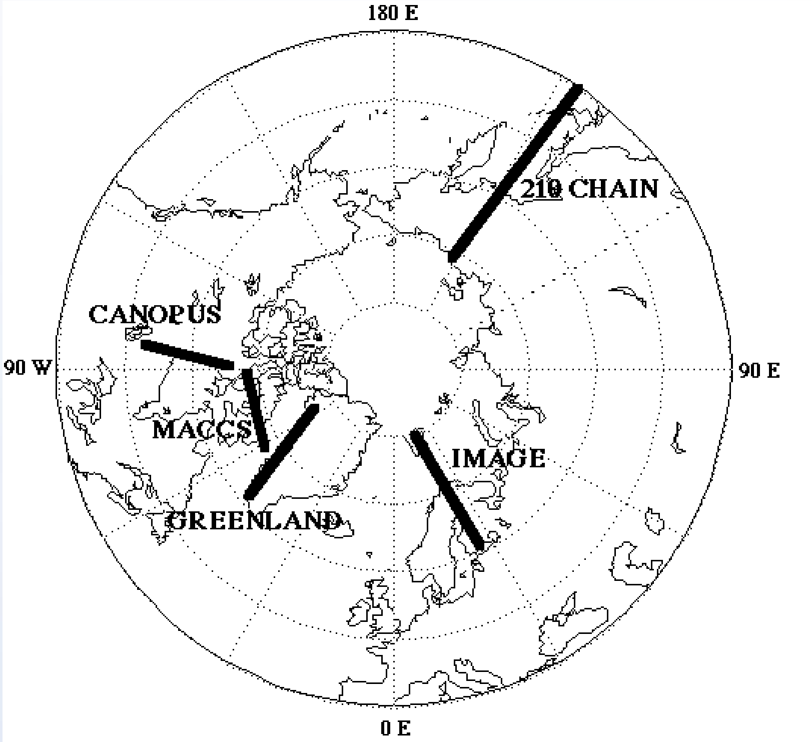
(Lots of *criticism* though: The frequency should vary by field line and latitude. But it's only detected sometimes, and not at consistent frequencies. Not always detected at conjugate stations.)

Kinds of waves

- Electromagnetic Ion Cyclotron (EMIC) waves, ~ 200 mHz – 1 Hz
- Alfvén waves – ion oscillation waves
  ~ 2-10 mHz in the solar wind
  ~ 2-10 mHz as field line resonances
  (~ 100 mHz – 1 Hz in ionospheric Alfvén resonator)
- Sound waves and magnetosonic waves (like whistlers)
- Plasma instabilities:
  - Kelvin-Helmholtz waves

Magnetometer chains

- IMAGE network
- CARISMA (earlier CANOPUS)
- 210 CHAIN
- Greenland chain
- MAGDAS
- Scandinavian SME (only historical data).

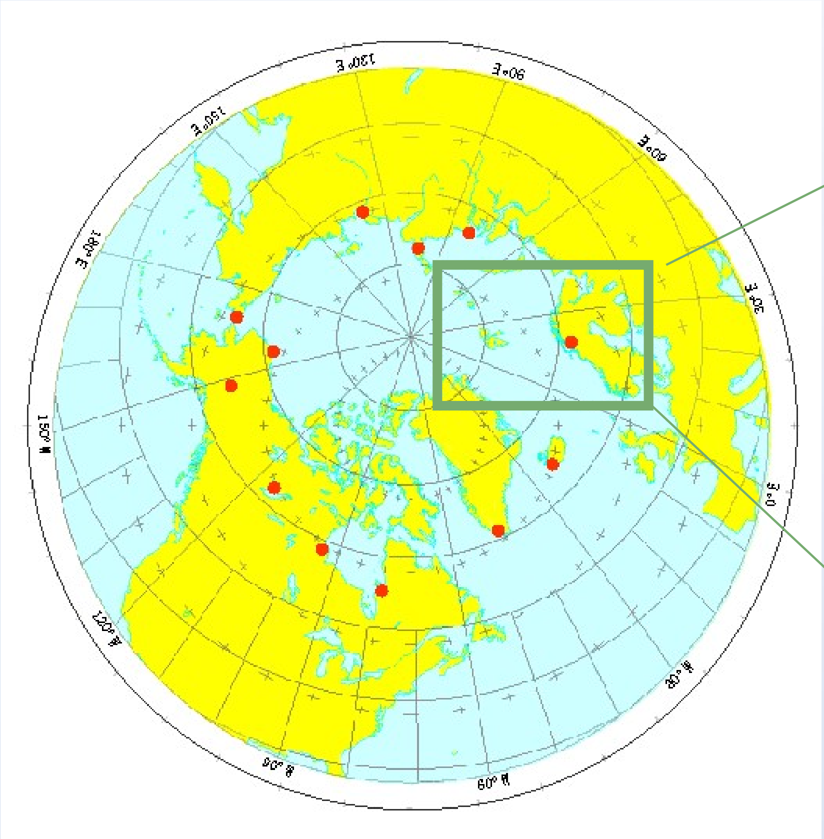


Aalto University
School of Electrical Engineering

UNIVERSITY OF OULU

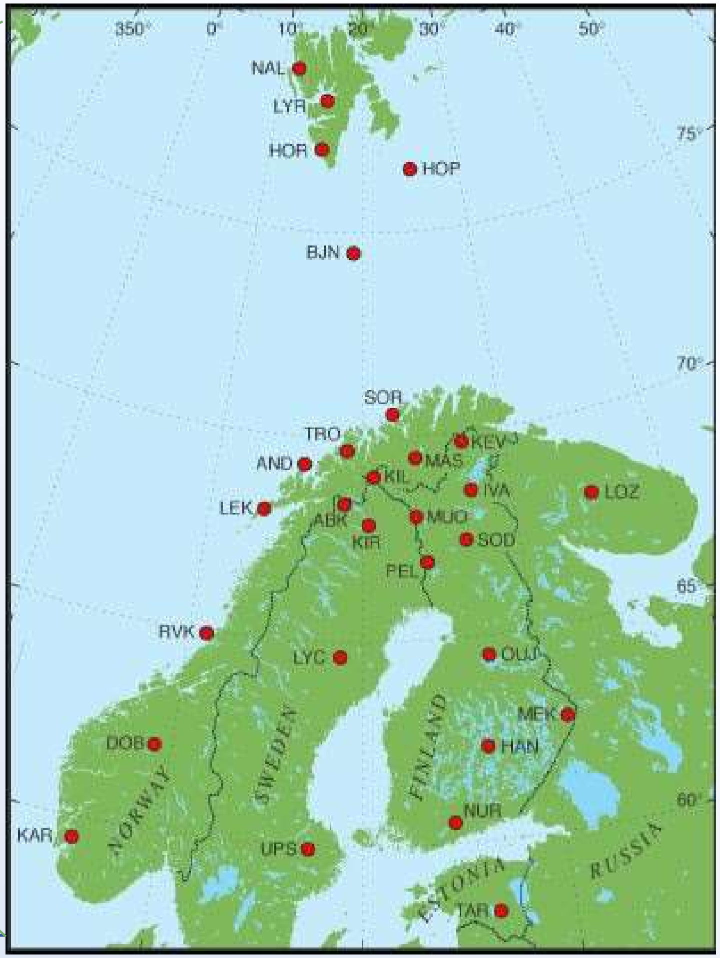
Magnetometer networks

12 Kyoto AL observatories



Fluxgate magnetometers

29 IMAGE observatories



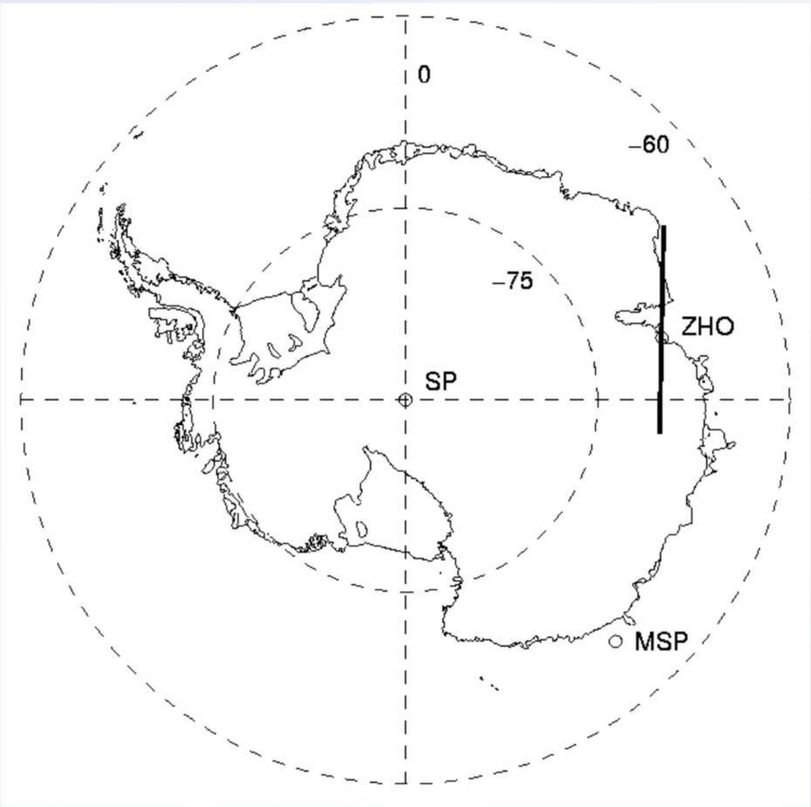
Courtesy of Häkkinen

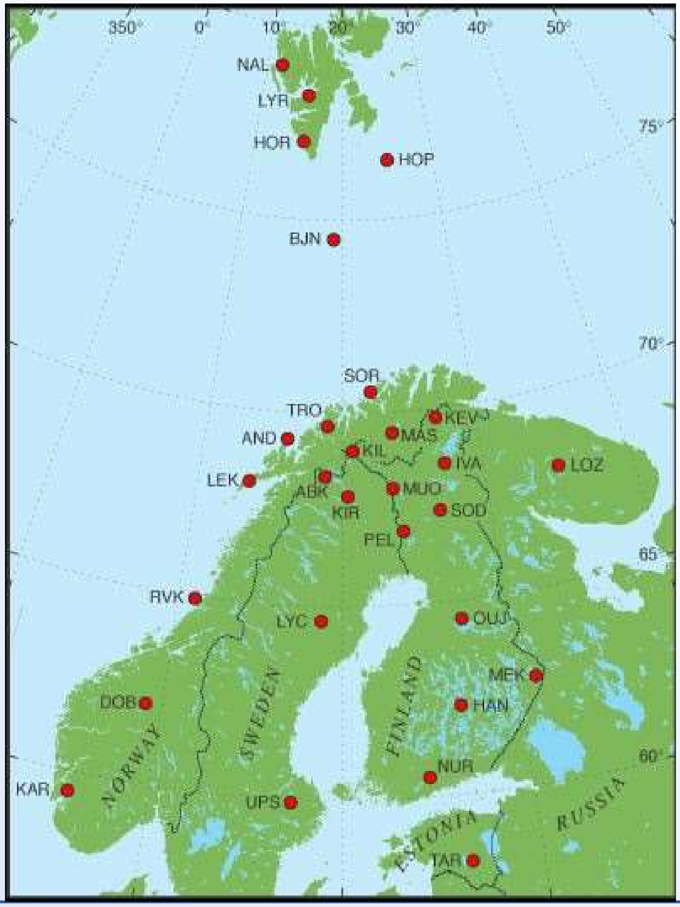
Aalto University
School of Electrical Engineering

UNIVERSITY OF OULU

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

Conjugate magnetic measurements

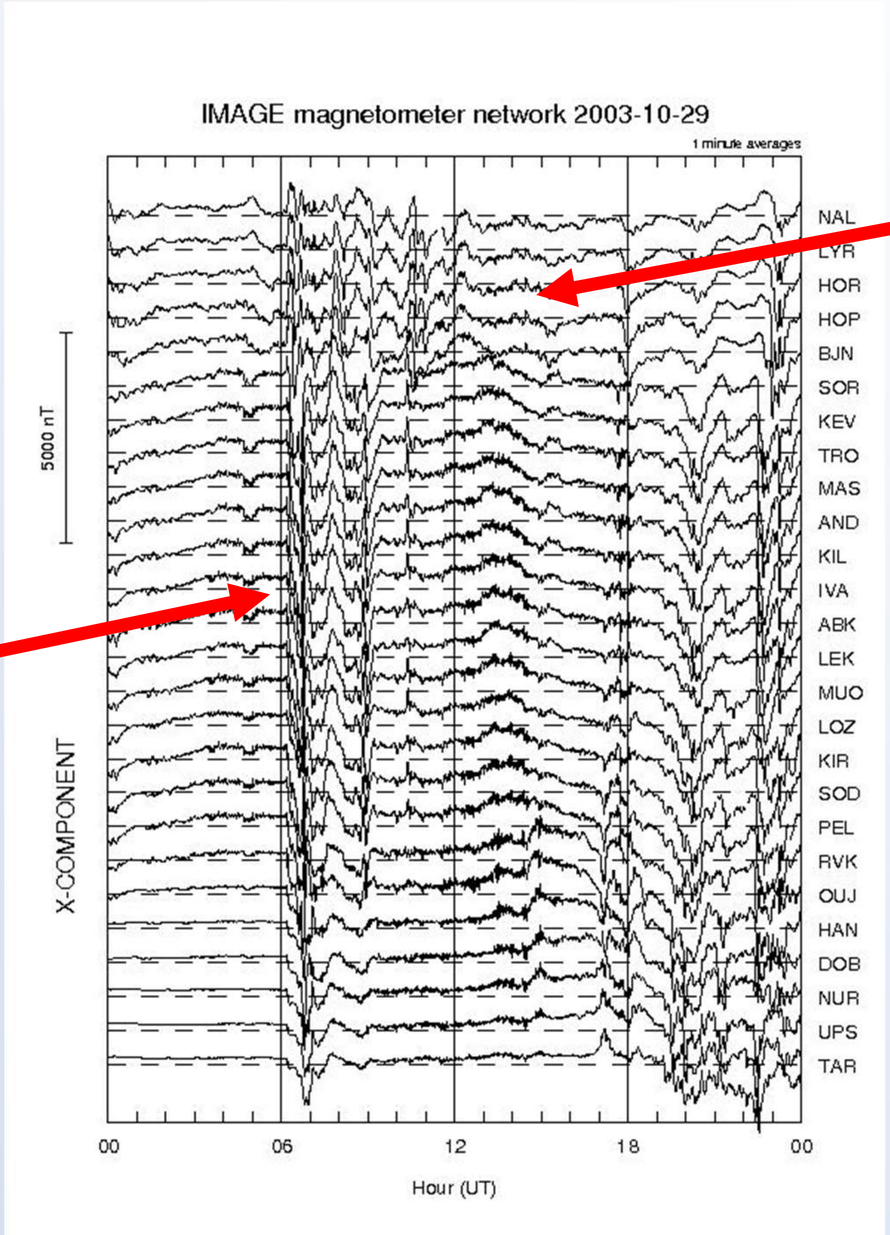




Aalto University
School of Electrical
Engineering

UNIVERSITY OF OULU

Geomagnetic activity at high latitudes during magnetic storms



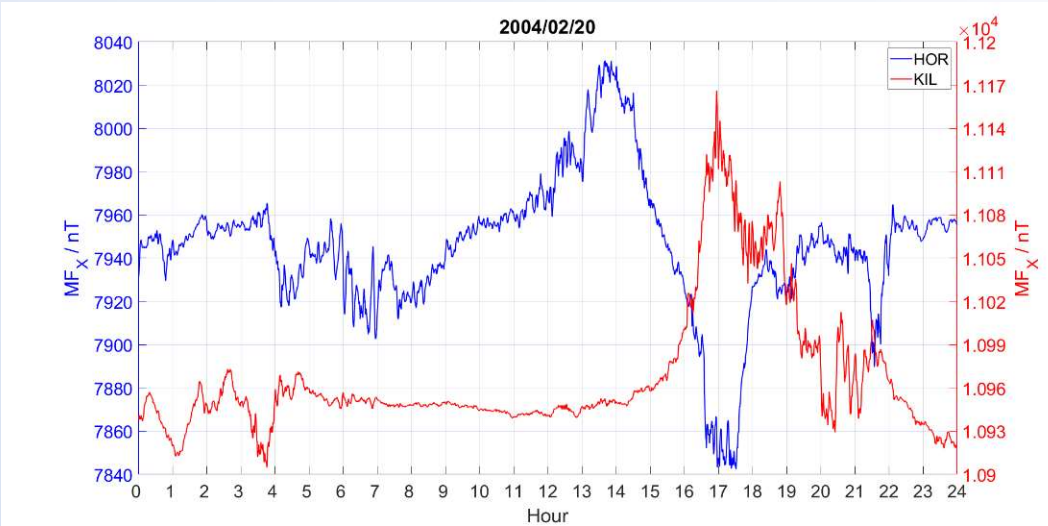
Pc5 pulsations

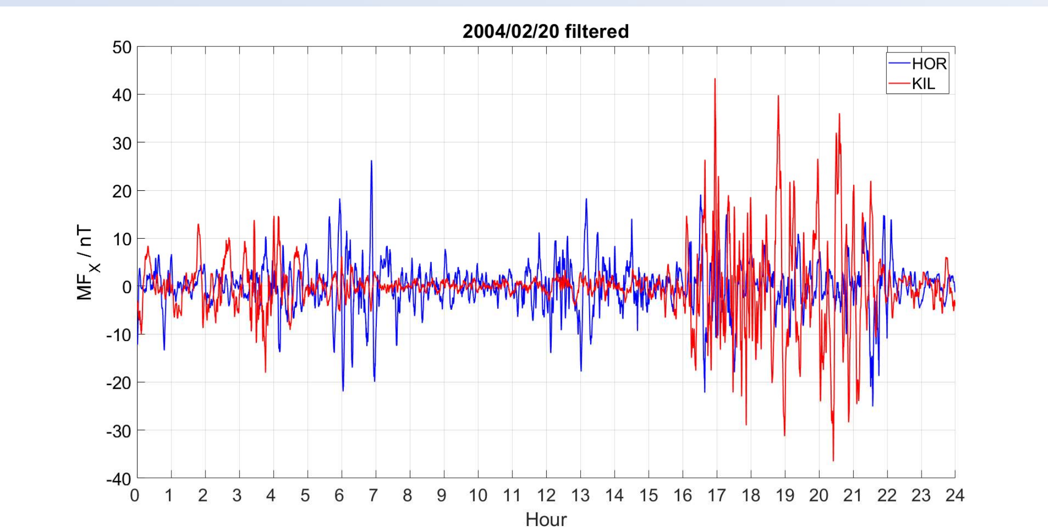
~ 2-7 mHz
(T = 2-8 min)

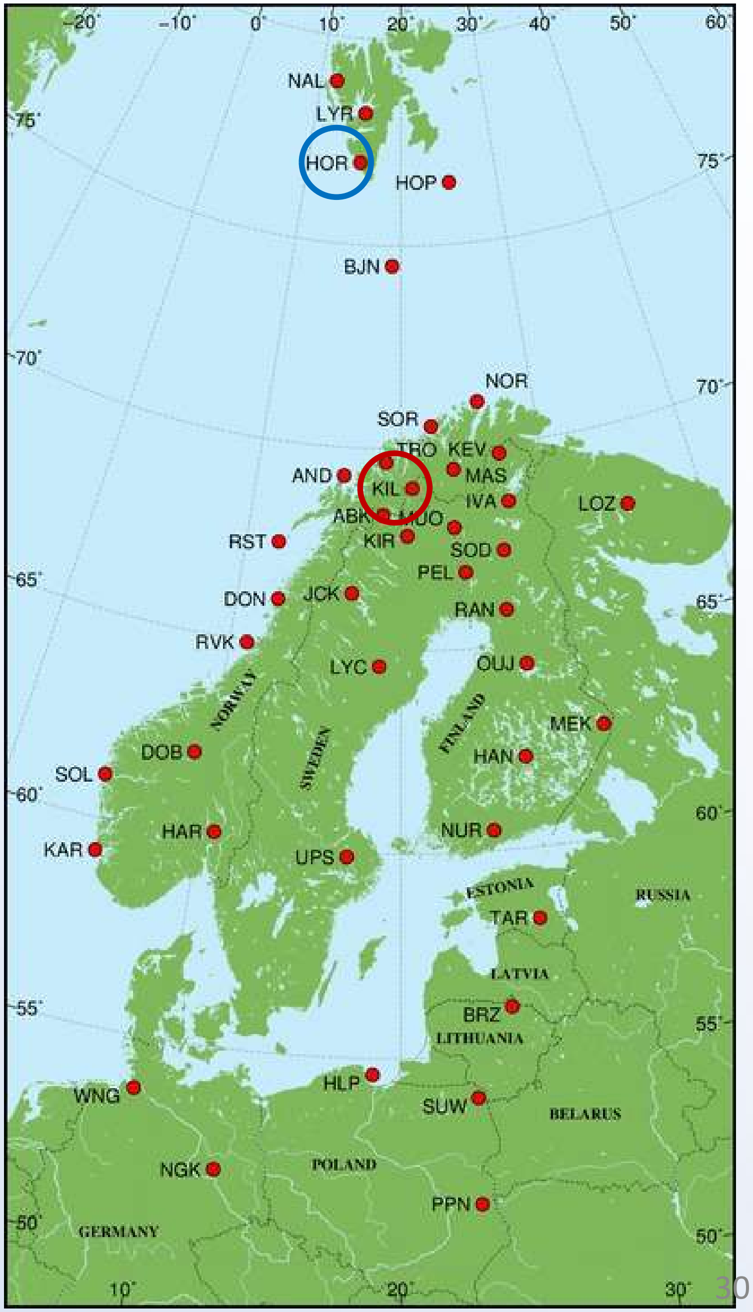
Storm-time substorms

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

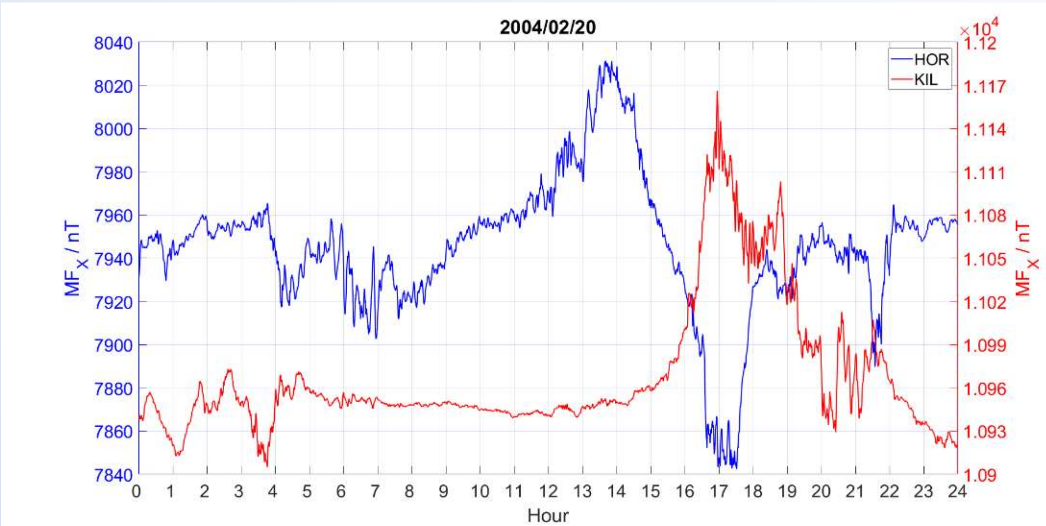
Filtering magnetic data

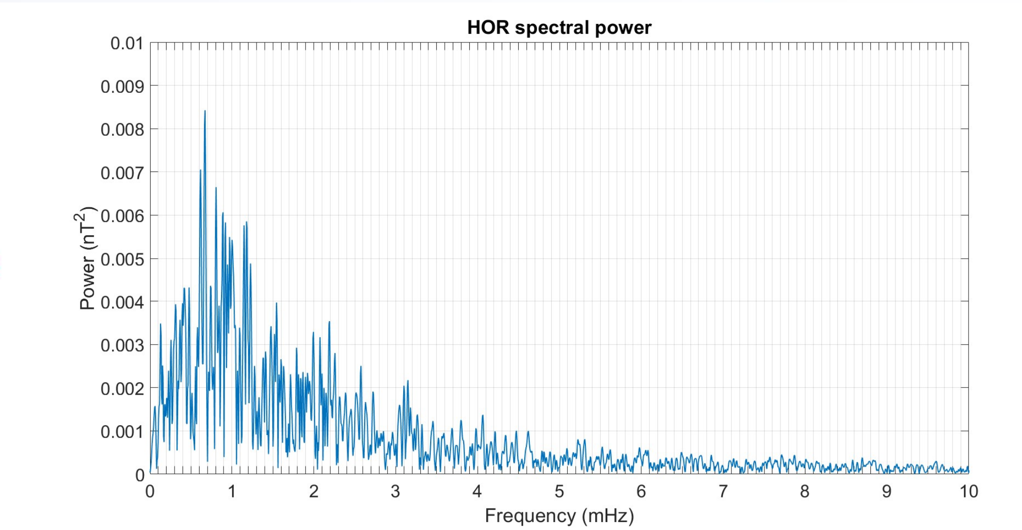


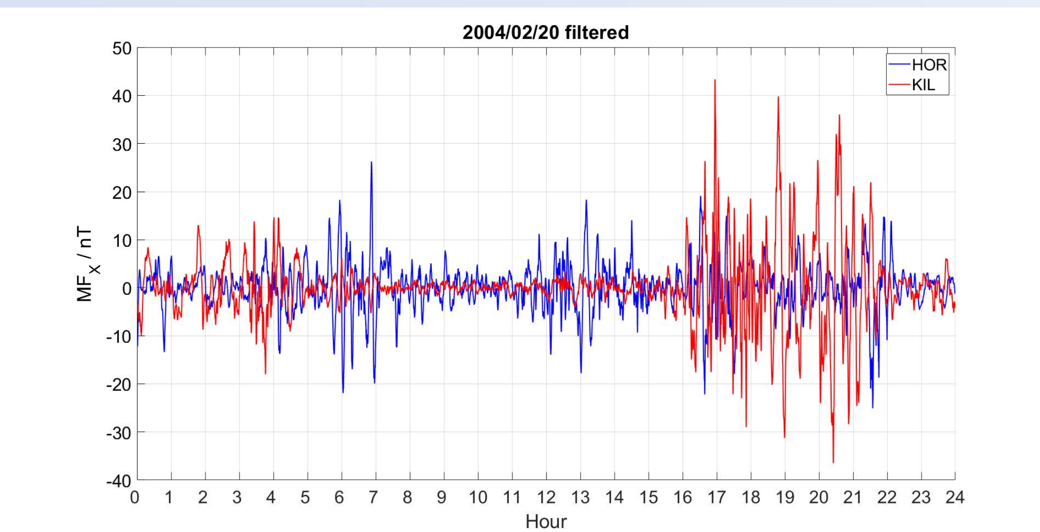


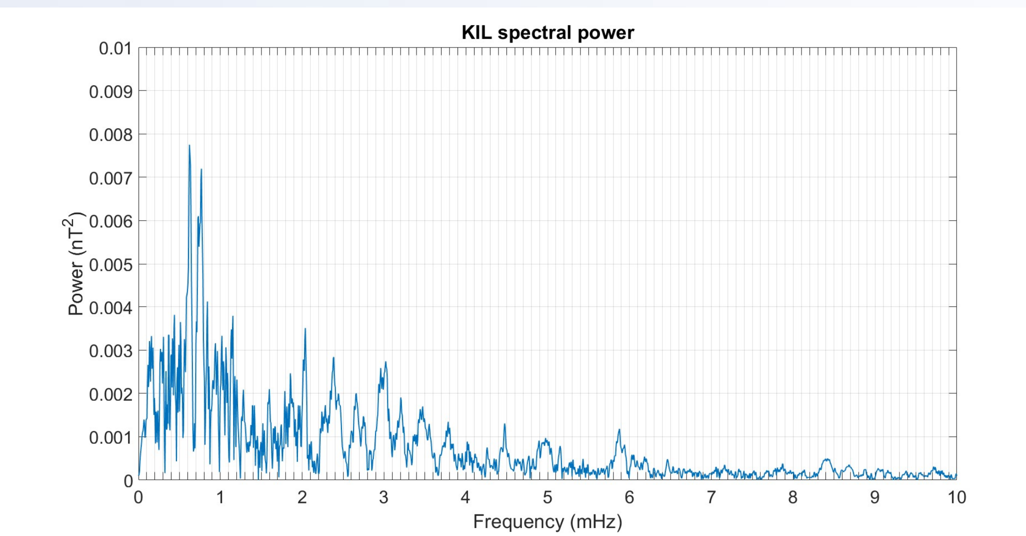


Filtering magnetic data for FFT*



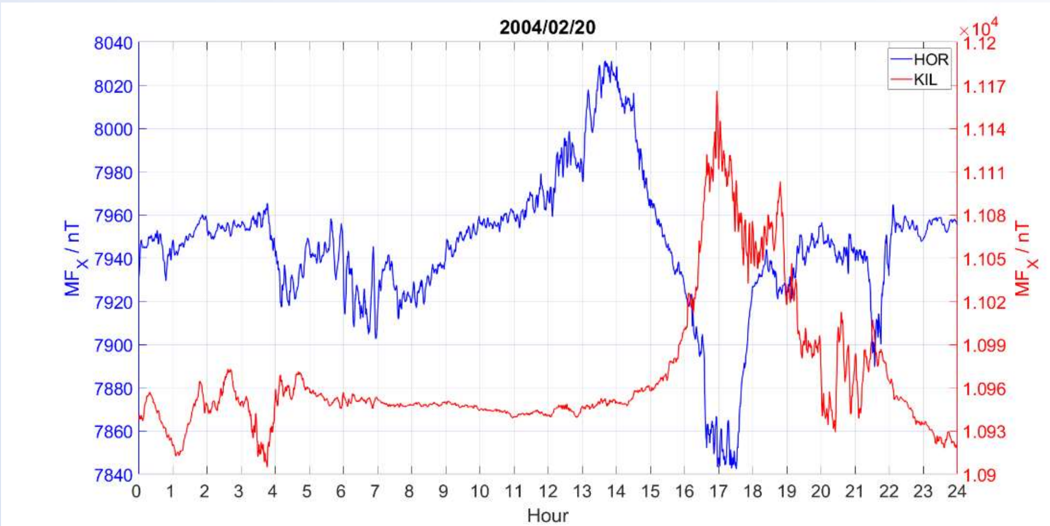


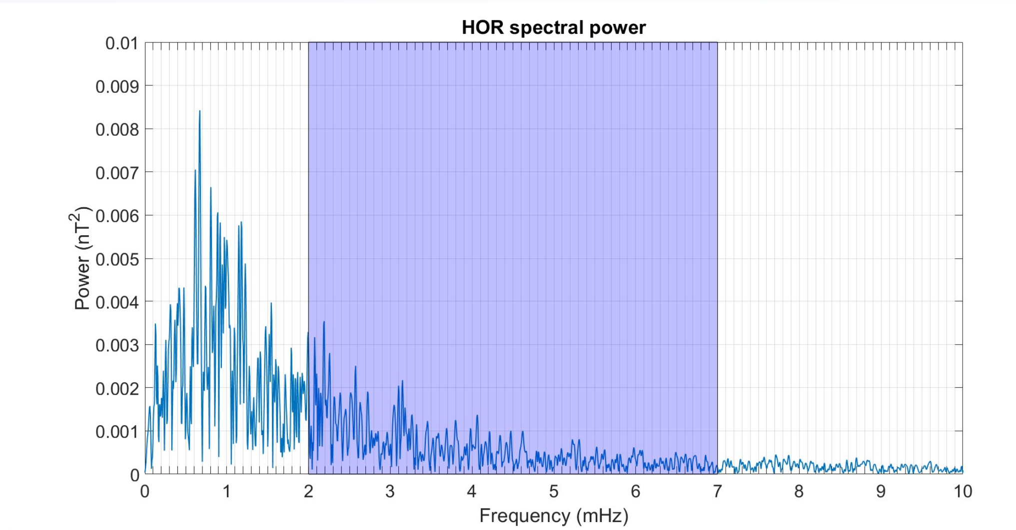


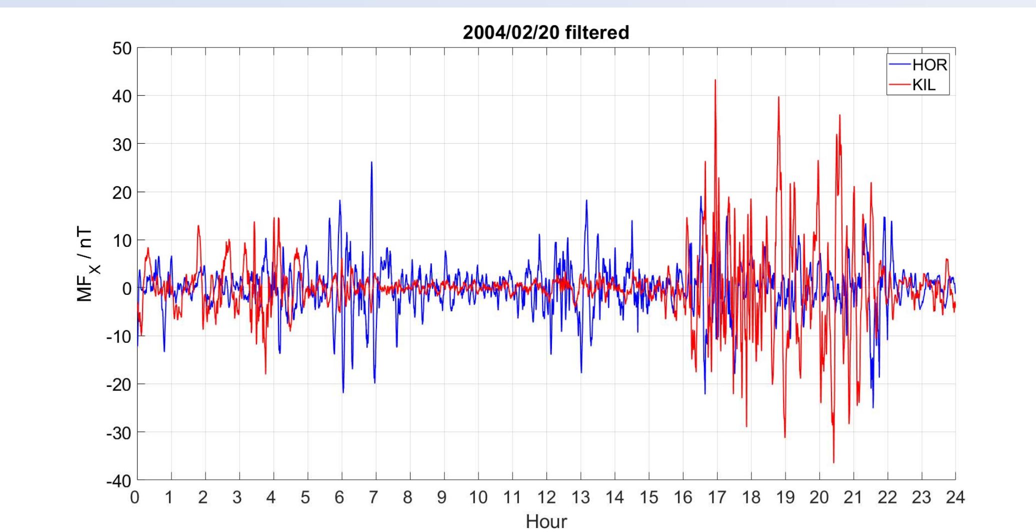


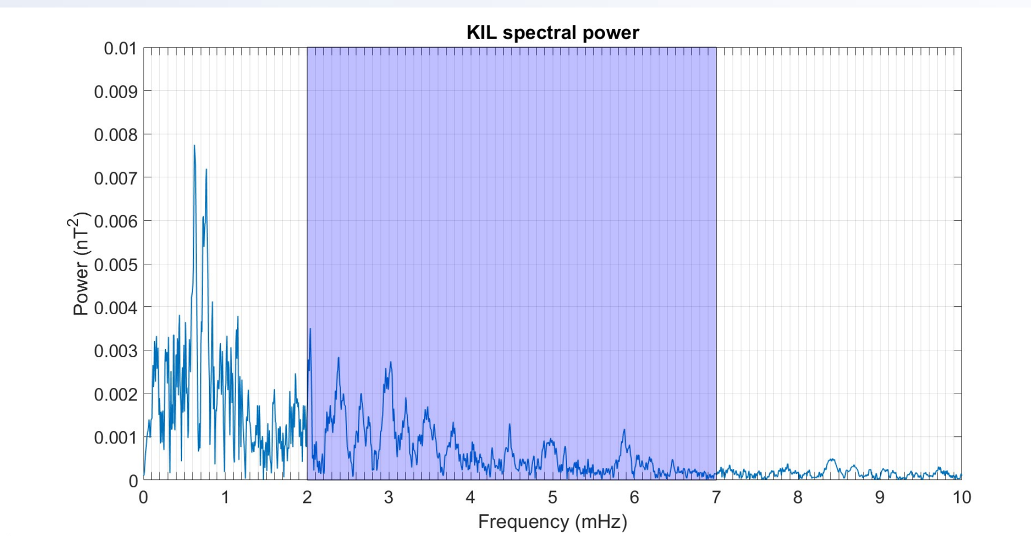
* Fast Fourier Transform

Filtering magnetic data for FFT

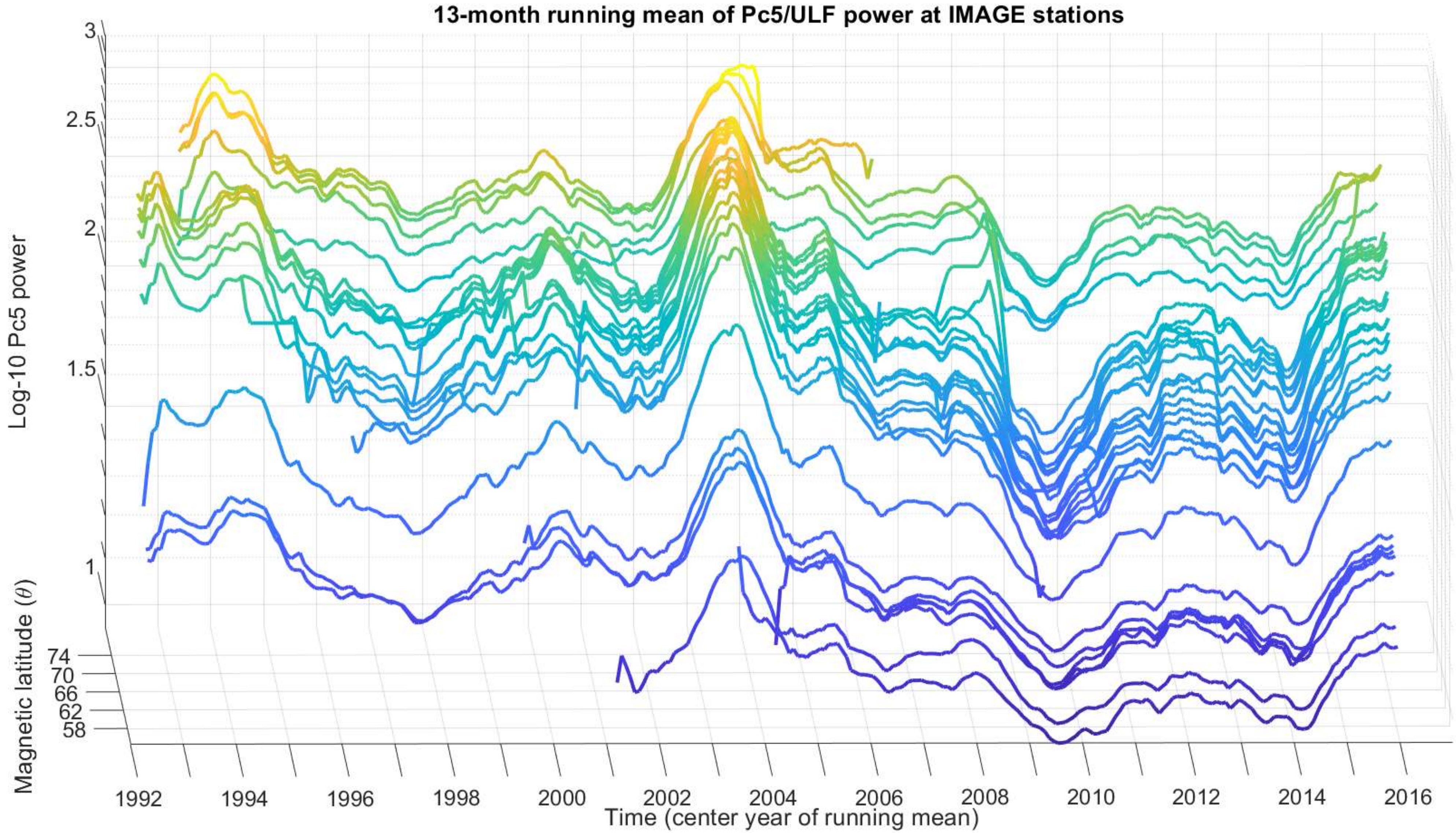


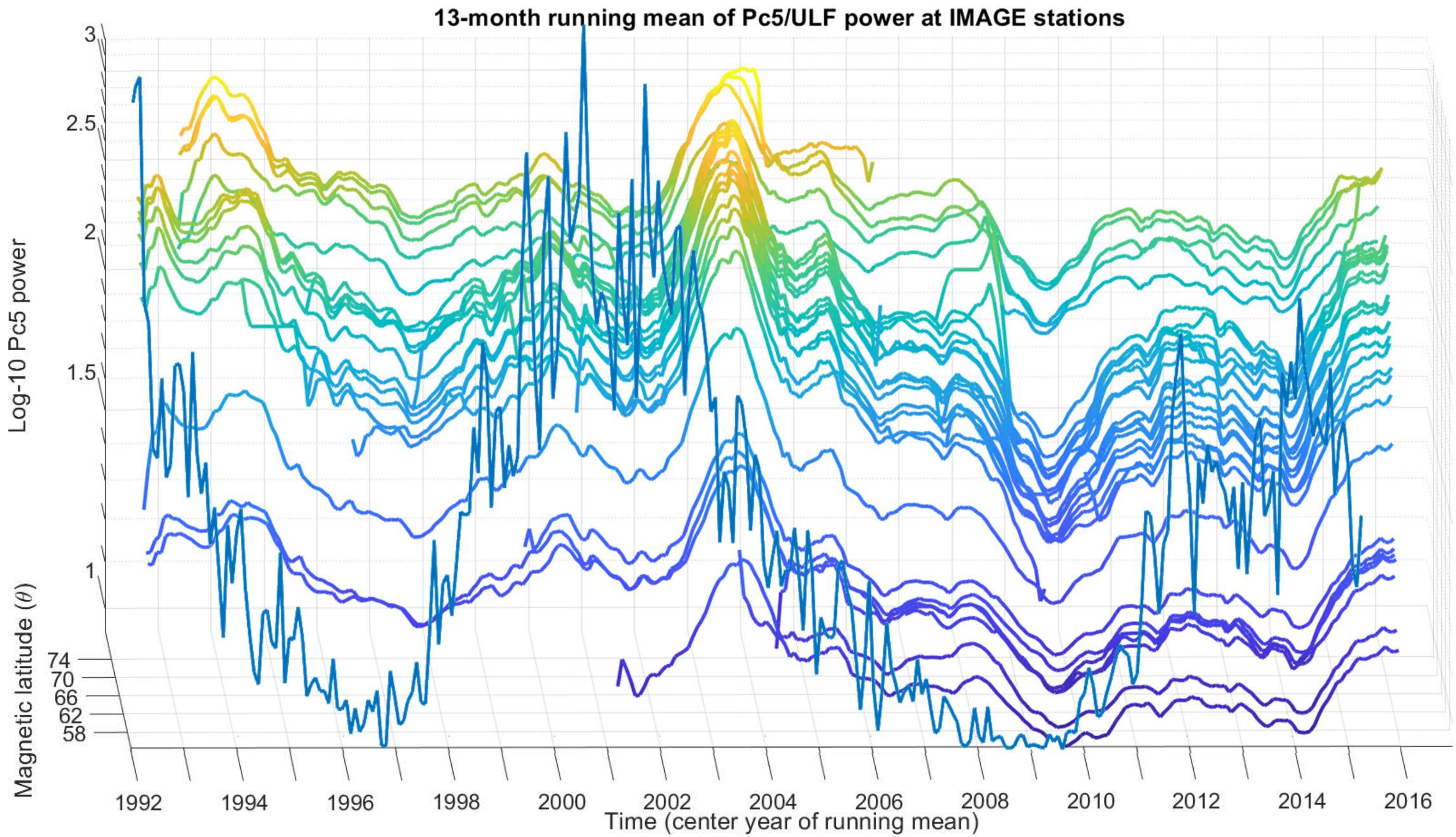


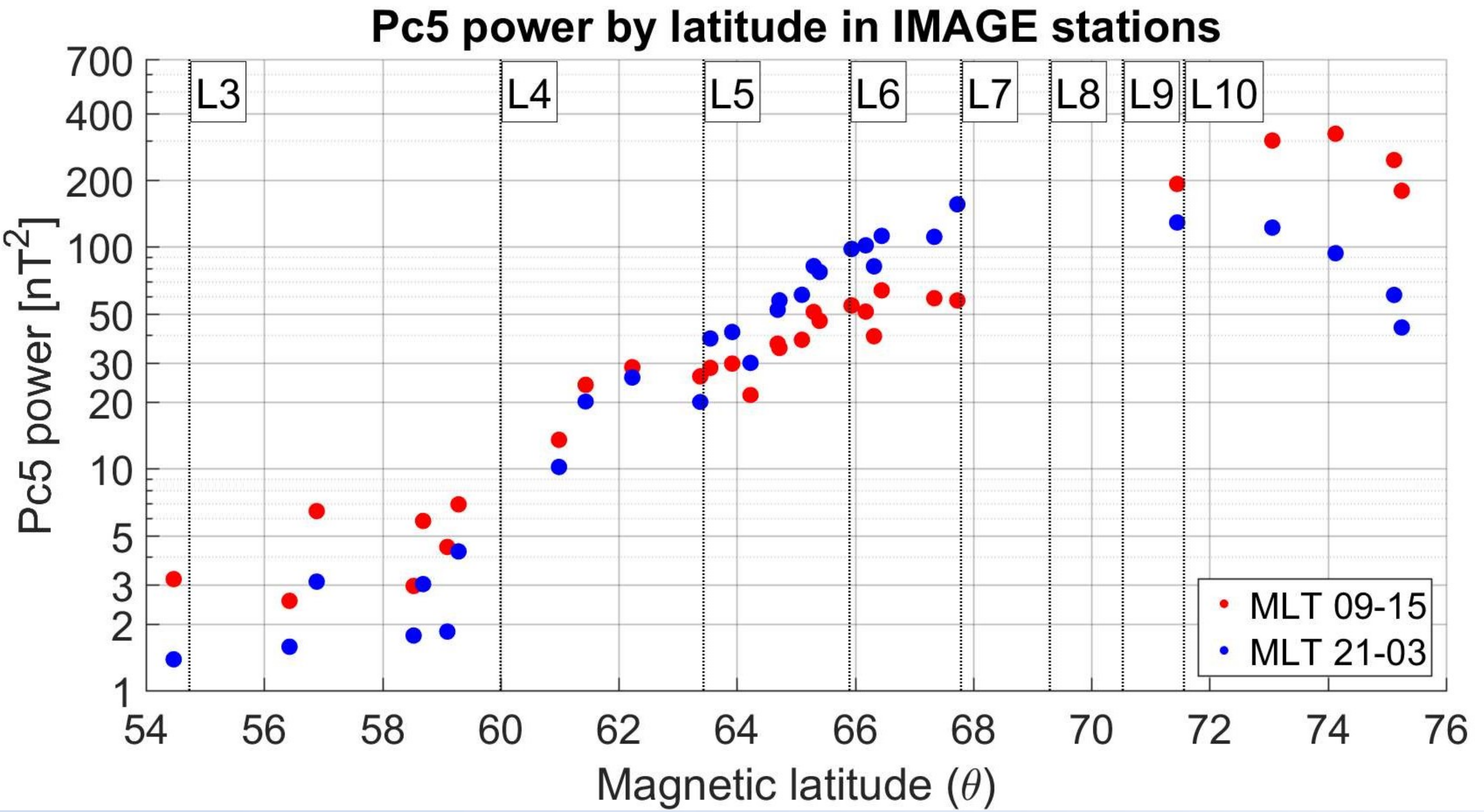




Pc5 waves

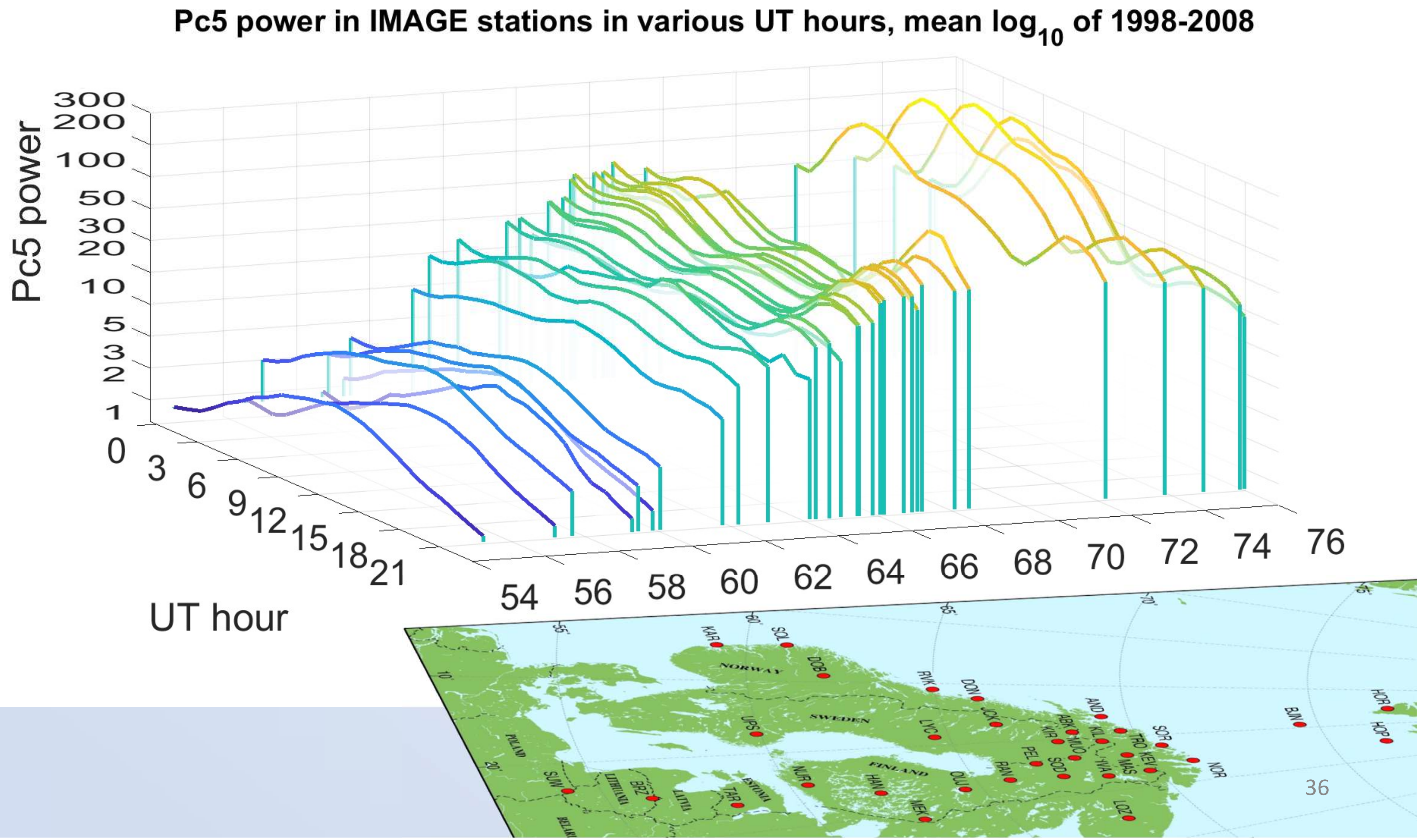

13-month running mean of Pc5/ULF power at IMAGE stations
Log-10 Pc5 power
3
2.5
2
1.5
1
Magnetic latitude (θ)
74
70
66
62
58
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
2016
Time (center year of running mean)


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)



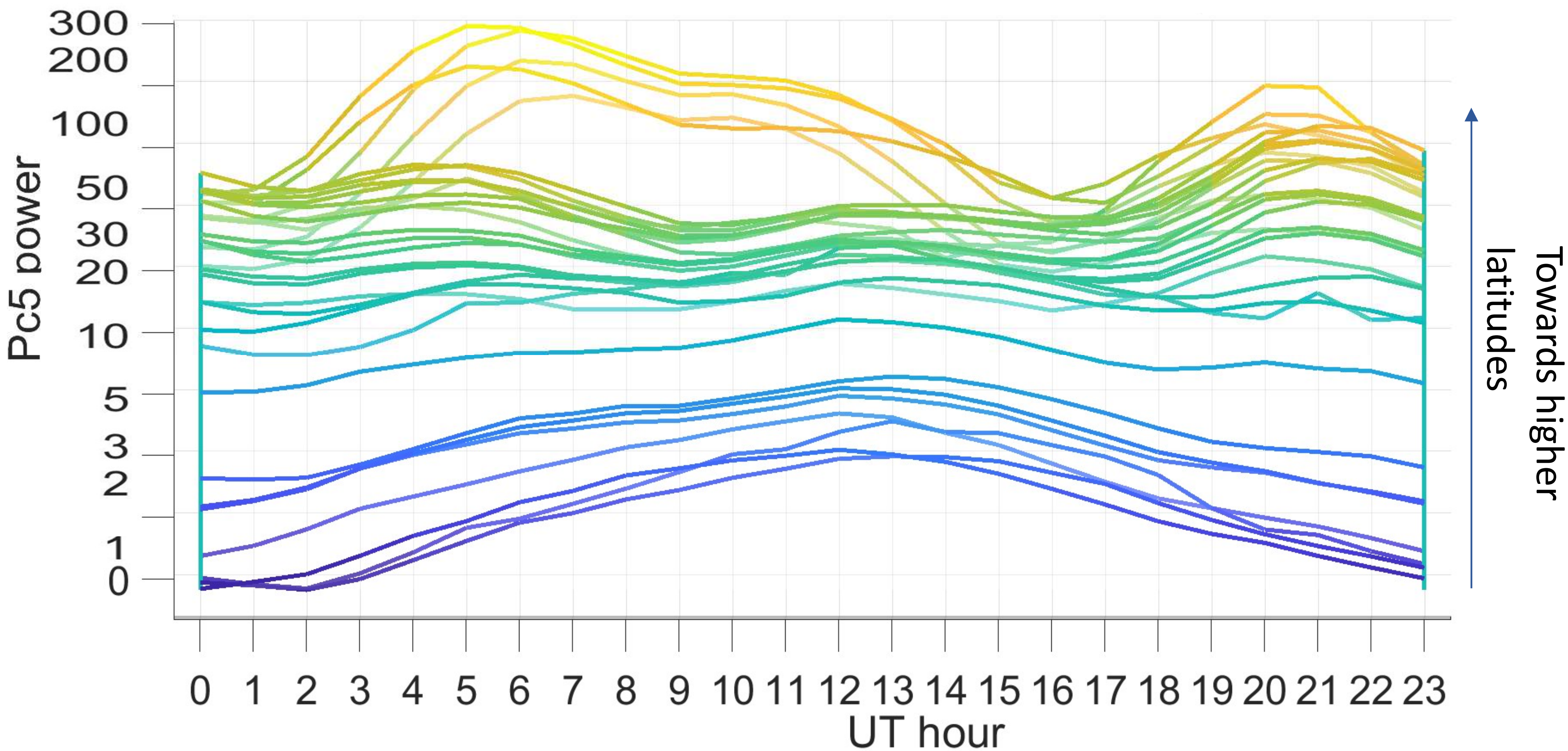
$* \ L = 1/\cos^2 \theta$

Adapted from Hynönen et al. (2020)

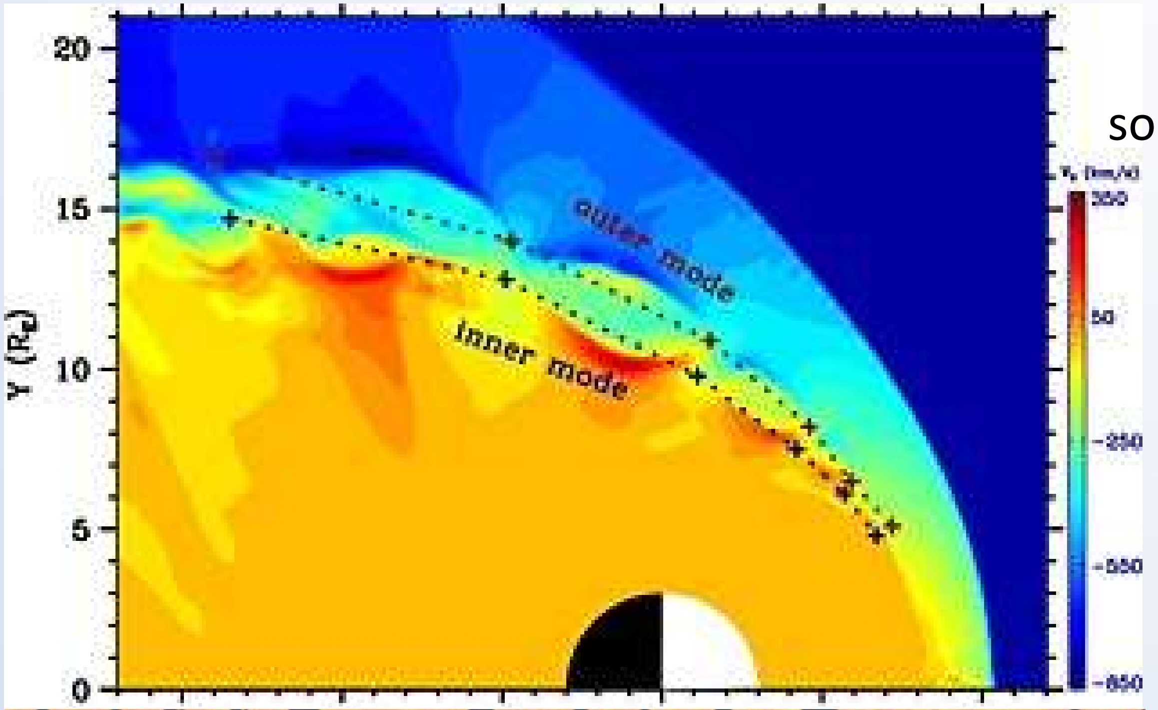


Pc5 power in IMAGE stations in various UT hours, mean $\log_{10}$ of 1998-2008
Pc5 power
300
200
100
50
30
20
10
5
3
2
1
UT hour
0
3
6
9
12
15
18
21
54
56
58
60
62
64
66
68
70
72
74
76
NORWAY
SWEDEN
FINLAND
POLAND
LITHUANIA
LATVIA
ESTONIA
KAR
SOL
DOB
RVK
DON
JCK
AND
ABK
KIR
MUO
KIL
TRO
SOR
KEV
MAS
NOR
PEL
SOD
IVA
RAN
OUL
HAN
MEK
NUR
UPS
LYC
TAR
BRZ
SUW
LOZ
BJN
HOR
HOP

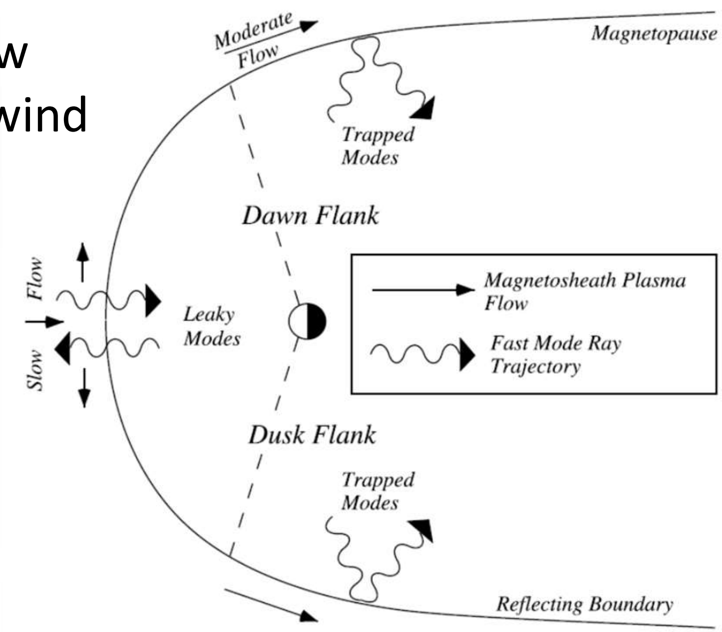
Sampling by the hour

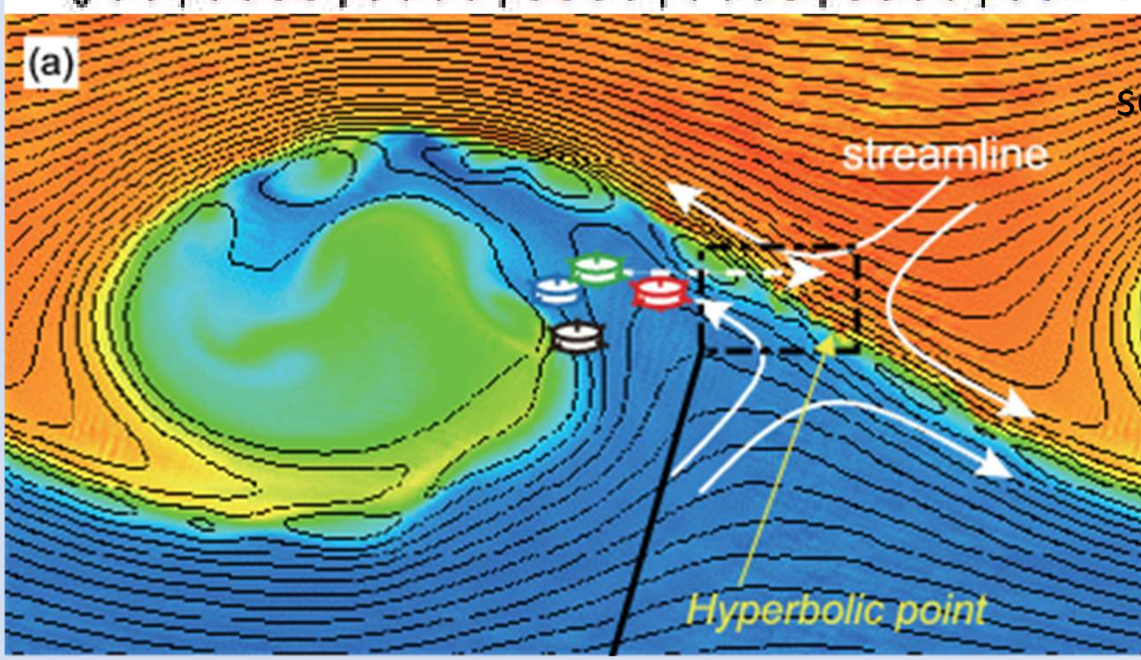


Magnetospheric waveguide

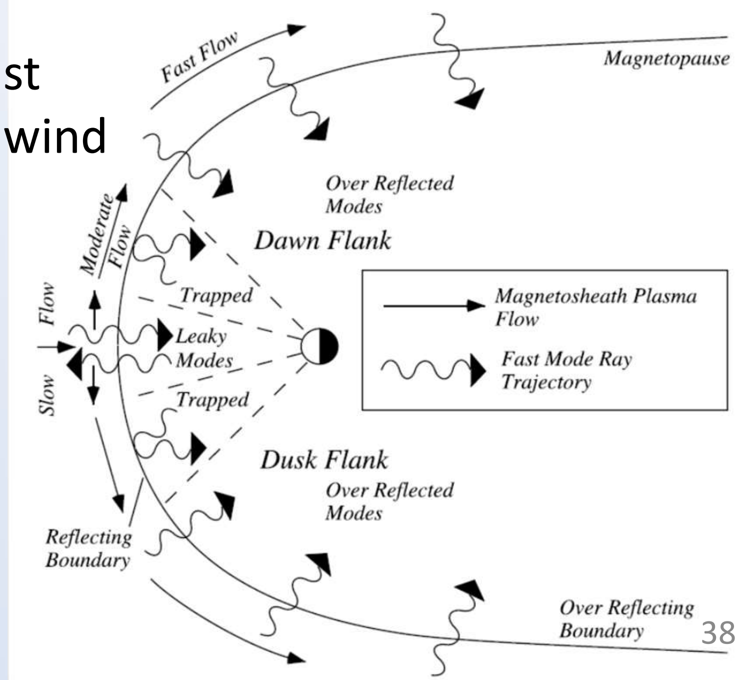


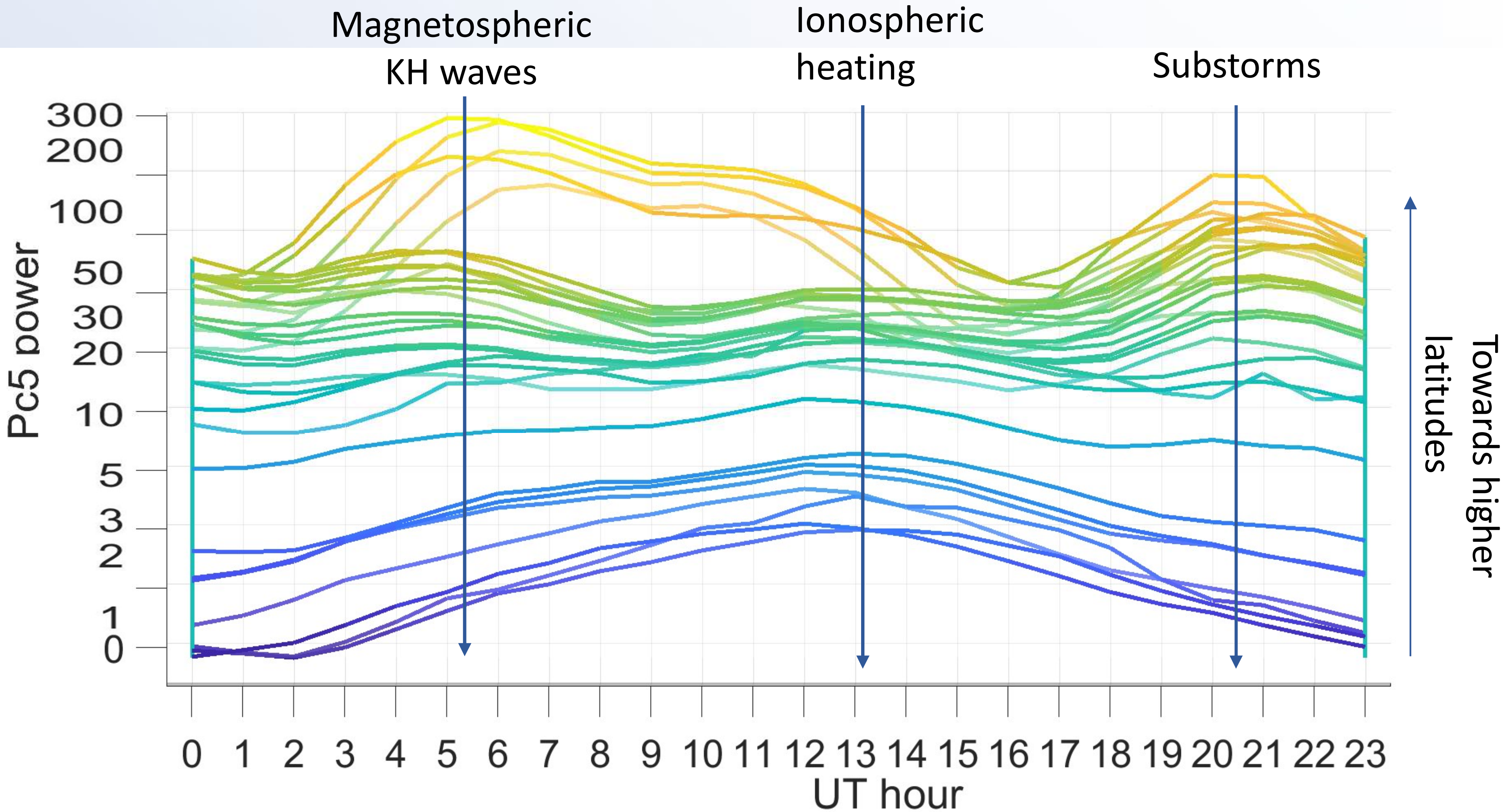
Slow
solar wind



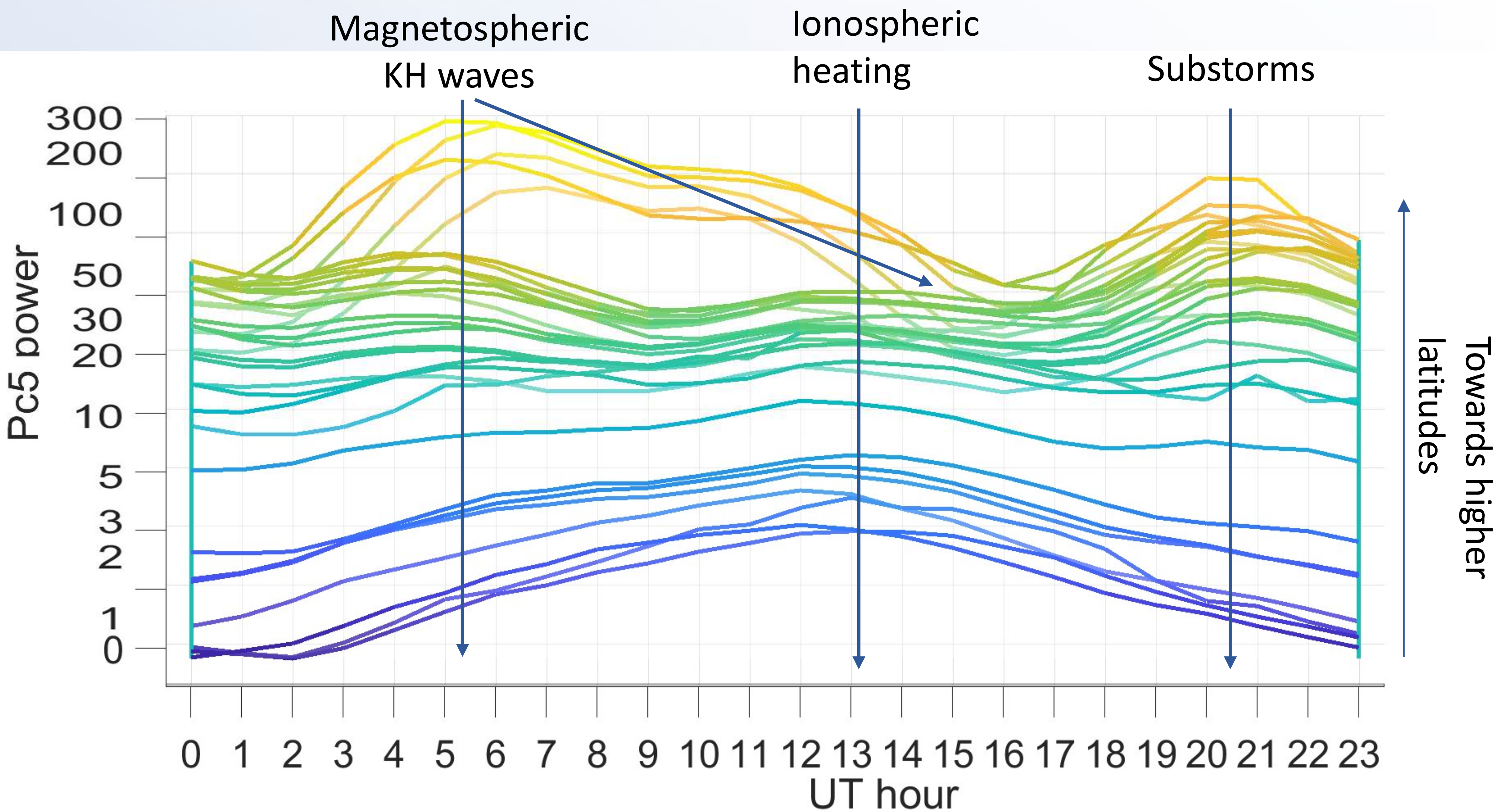


Fast
solar wind



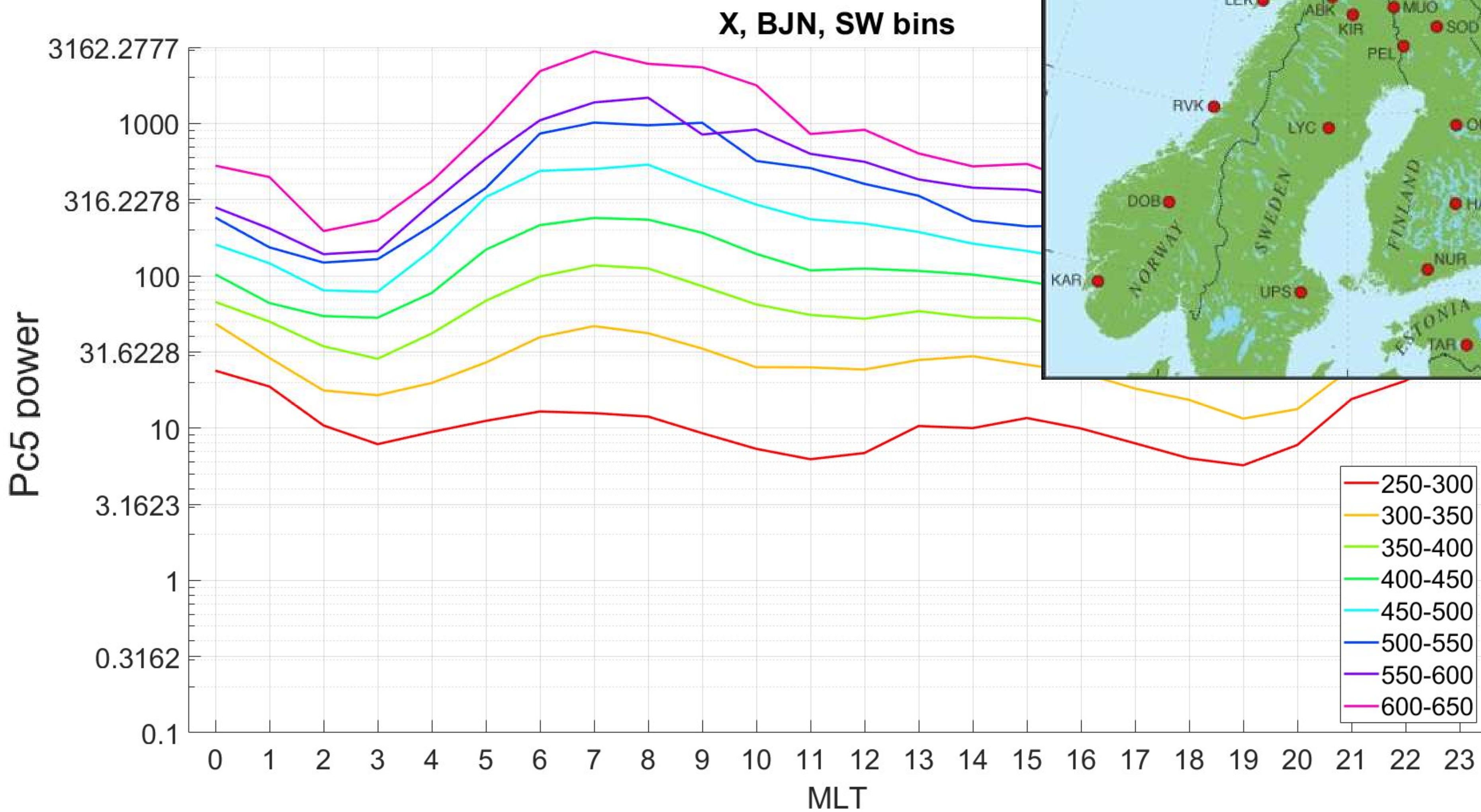


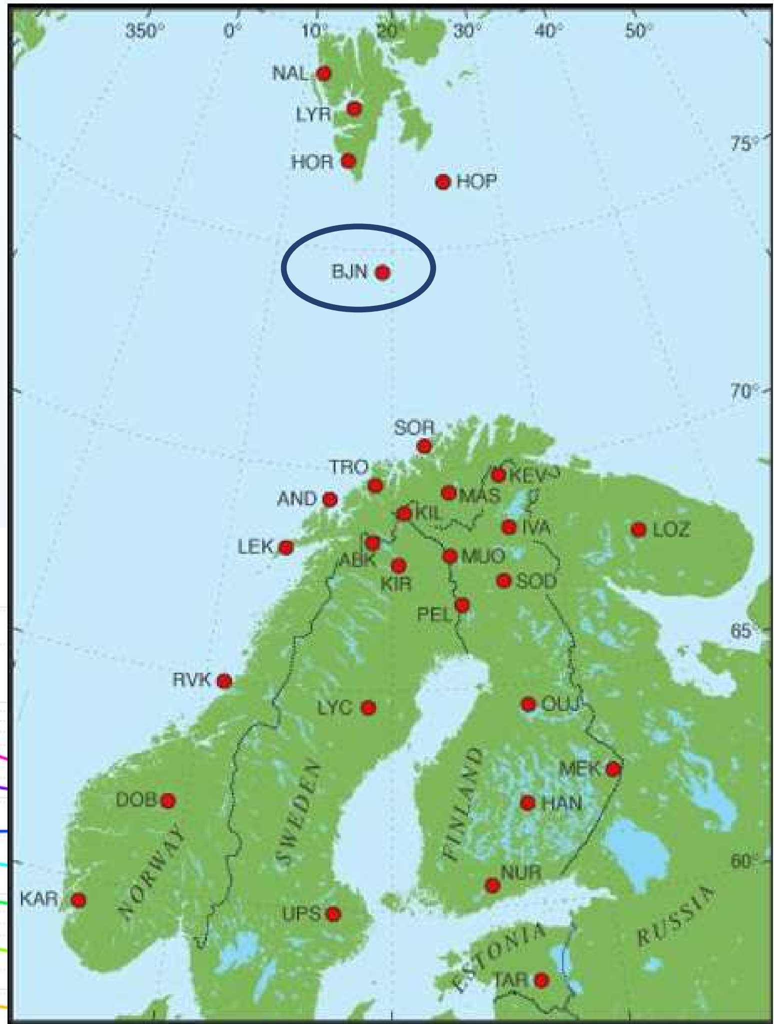
Magnetospheric
KH waves
Ionospheric
heating
Substorms
Pc5 power
300
200
100
50
30
20
10
5
3
2
1
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
UT hour
Towards higher
latitudes



Magnetospheric
KH waves
Ionospheric
heating
Substorms
Towards higher
latitudes
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

Effect of solar wind speed





Effect of solar wind speed