# WAVE EMISSIONS AT ION SCALES

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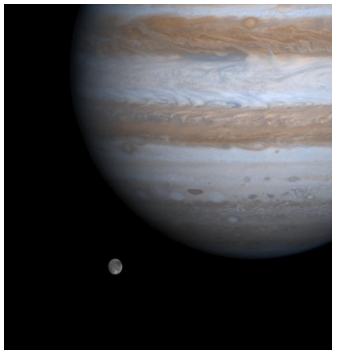
# Jupiter – Ganymede System

Ganymede in true colors seen by Galileo spacecraft (NASA/JPL)



Ganymede and Jupiter seen by Cassini spacecraft (NASA/JPL/University of Arizona)

<u>Jovian environment at Ganymede:</u>

- Mean DC Jovian magnetic field at $15R_J$ ≈120nT
- Co-rotating plasma torus along the orbit of Ganymede. The plasma source is Io.
- The plasma density fluctuates along the orbit (few electrons per $cm^{-3}$): The density is higher when Ganymede is in the Jovian nightside magnetosphere.
- Plasma flow about 100km/s relative to Ganymede. It is higher than the Ganymede orbital speed (≈10km/s) and lower than the local Alfvén and magnetosonic speeds

→ **There is no shock formation and no tail of the Ganymede's magnetosphere.**

<u>Orbit of Ganymede:</u>
Eccentricity: ≈ 0.0013
Orbital Period: ≈ 7.15 days
Inclination to Jupiter's equator: ≈0.20 deg
Distance from Jupiter: ≈$15R_J$ ($10^6$ km)

Jupiter Radius: $R_J$≈ 71 400 km
Ganymede Radius: $R_G$ ≈ 2 630 km

# Interaction of magnetospheres of Jupiter and Ganymede

Ganymede mini magnetosphere is in direct interaction with the Jovian magnetosphere

**Closed and open magnetic field lines:**

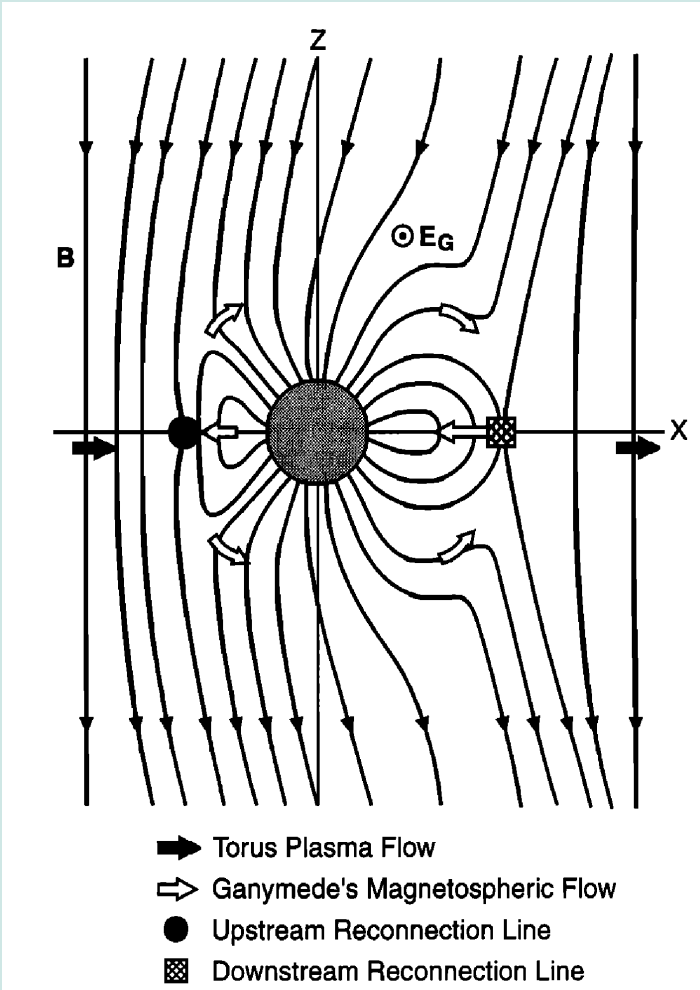
-Some field lines are closed (connect to Ganymede at both ends) up to 30 deg of latitude.

- Otherwise, field lines connect at one end to Jupiter and at the other end to Ganymede.

**Magnetic field lines direction:**

- The Ganymede and Jupiter respective magnetic dipole orientations are almost antiparallel.

- It leads to a configuration in favor of antiparallel reconnection both upstream and downstream of the Ganymede's magnetosphere.



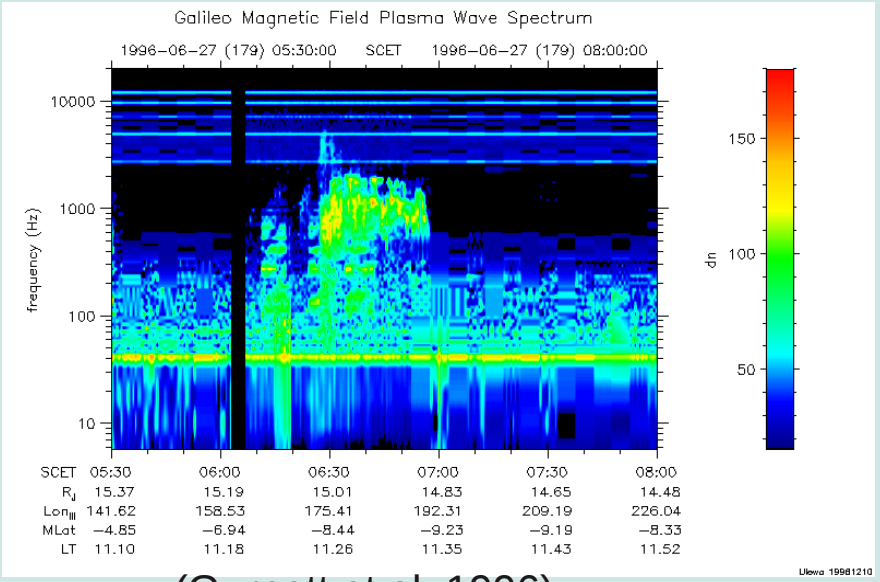

***Volwerk et al.*, 1999:**
Sketch view of Ganymede's magnetosphere

# Plasma wave measurements onboard Galileo

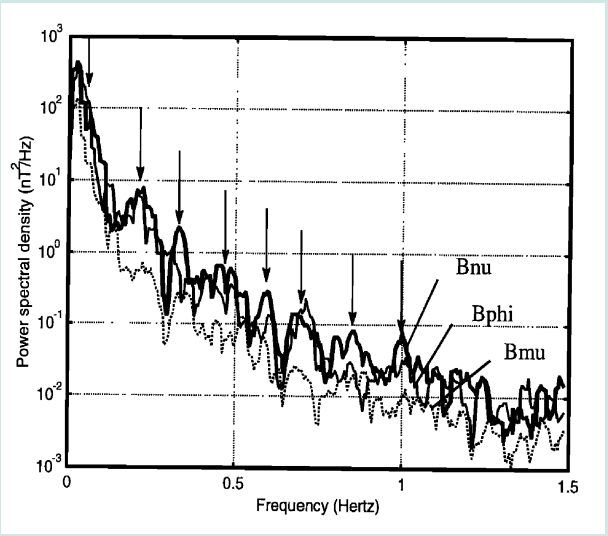
**PWS - Space Plasma Wave Receiver**

Example of magnetic spectra in the frequency range 5Hz-20 kHz.

In the lowest part of spectrum , only the broadband noise at the magnetopause is identified.




(Gurnett et al, 1996)




(Volwerk et al., 1999)

**MAG - Magnetometers** (*Kivelson et al.*, 1992)

**Normal Mode: 1 sample/minute, High resolution: 3Hz**

At Ganymede: 1h of data at 3Hz

The magnetometers have allowed a good determination of the Ganymede magnetic field characteristics.

For the wave studies, Galileo magnetometers are roughly able to cover a frequency range up to 1Hz

**No data at all between 1.5Hz and 5Hz.**
**No good resolution around this frequency interval.**

**Did we miss something?**

# Main knowledge from Galileo related to wave studies close to ion scales at Ganymede:

- Kelvin-Helmholtz waves at the magnetopause (*Kivelson et al.*, 1998)

- Magnetosphere probing with Field Lines Resonator (*Volwerk et al.* 1999)

- Broadband noise at the magnetopause (*Gurnett et al.,* 1998)

- At Io, *Russel et Huddleston* (2000) have reported ion cyclotron waves close to the $S0_2^+$ gyrofrequency

# About the ion scale

The proton gyrofrequency $F_{H+}$ :

at 120 nT ,**$F_{H+}$≈ 1.8Hz**

→This frequency is higher inside the Ganymede magnetosphere.

→This frequency is lower for heavier ions ( q/amu * $F_{H+}$)

**There are no observations at $F_{H+}$ at Ganymede.**
And measurements close to this frequency have a low resolution. (1.5-5Hz)

# About the ion scale

- Wave-ion interactions below $F_{H+}$
- In the spacecraft frame, waves can be observed at higher frequencies (Doppler shift)

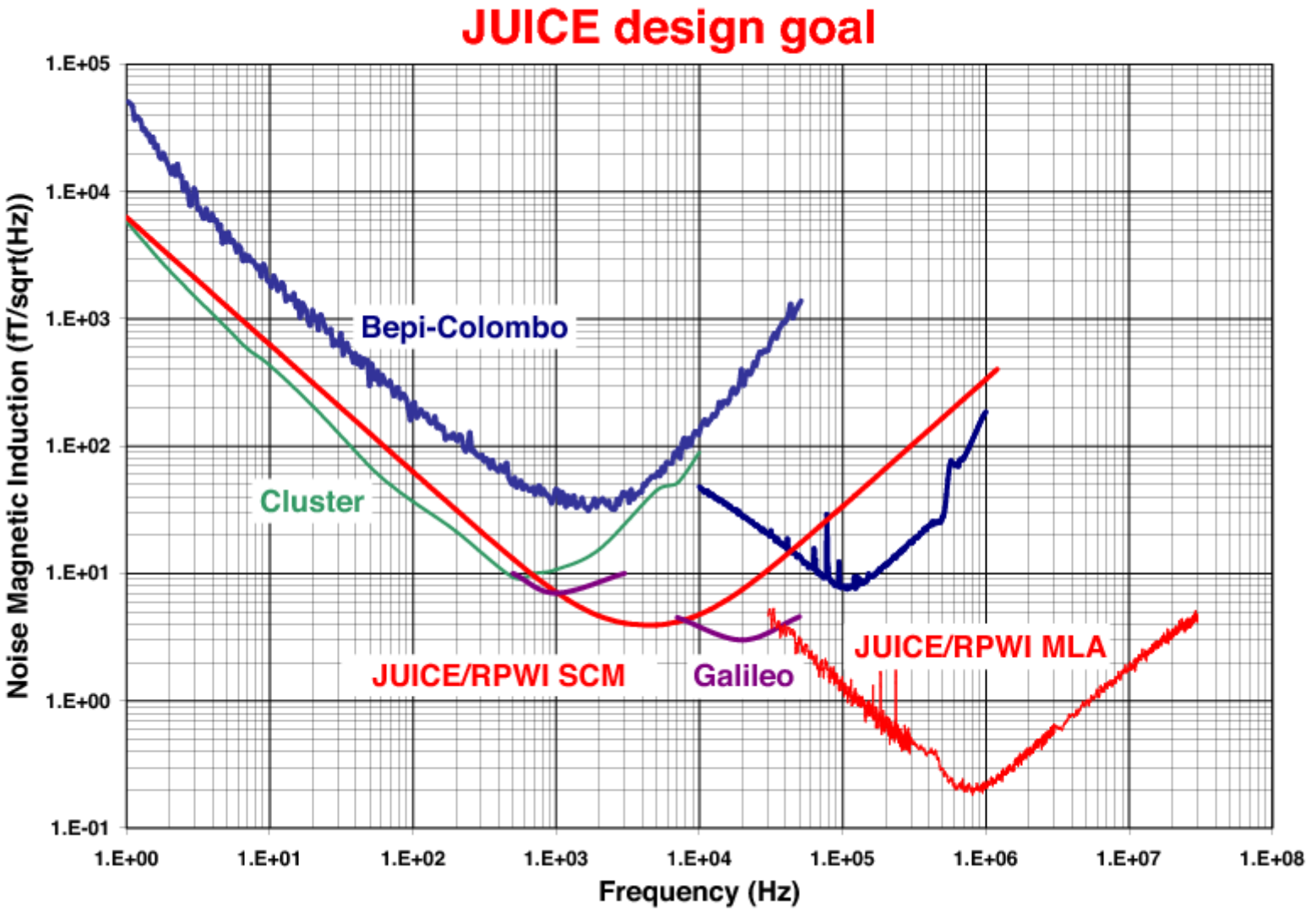
Plasma composition:
Mainly cold H+ inside the Ganymede magnetosphere (max 100-200 particles/cm^3)
(*Frank et al.*, 1997)
In the surrounding Jovian plasma sheet, one can observe heavier, hotter but less dense ions: 02+, S+

**Waves (close to $F_{H+}$ ) interacting with ions have not been observed in Ganymede's neighborhood**

**Note** : Ion cyclotron waves close to $F_{SO+}$ have been detected at Io (*Russel et Huddleston*, 2000)

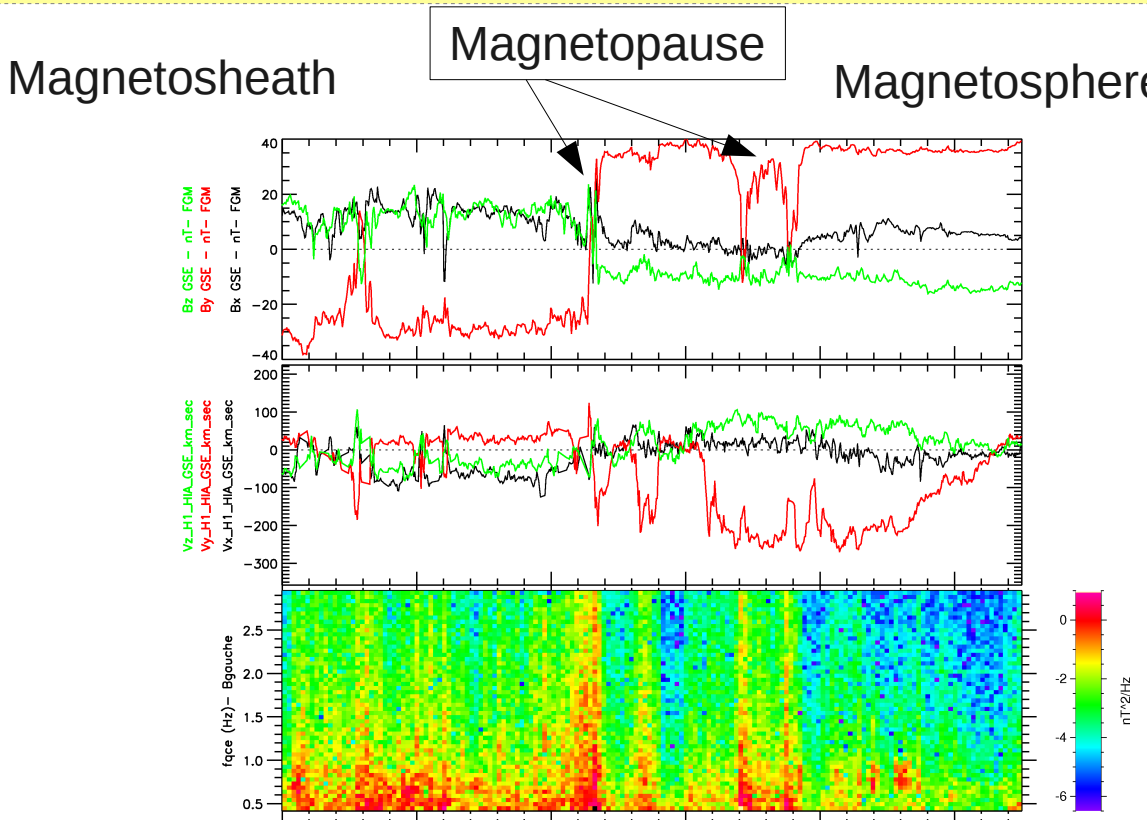
Galileo results in the ULF range to be confirmed:
- Kelvin Helmholtz waves at magnetopause ?
- Field Line Resonances.

# Search coil Transfer Function




→ Close to Cluster sensitivity in the ULF range

# Examples of Cluster observations at Earth

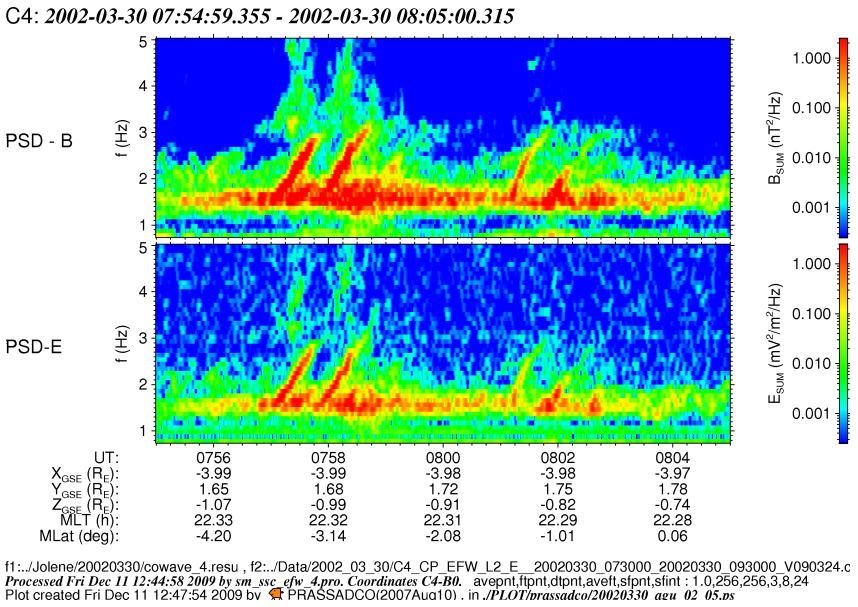



In the Earth magnetosphere both broadband and narrowband emissions are detected at these scales:

-At the magnetopause, broadband emissions are linked with the magnetic field rotation and possible magnetic reconnection

-At the magnetopause, narrowband emissions are linked with local wave-ion intercations

# Examples of Cluster observations at Earth




EMIC+ triggered EMIC

In the Earth magnetosphere, EMIC triggered emissions have been recently observed (*Pickett et al.* [2010], *Omura et al.* [2010], *Grison et al.* [2013]):
In the jovian environment, such waves could in turn energize ions to very high energies.

## And also:

- the polar cusps: the broadband emissions are usually linked with recent plasma injections.
- Ion Cyclotron Waves at $F_{H+}$ and their harmonics in many parts of the magnetosphere
- ...

Main Topics :

- EMIC, eventually triggered (energetic ions), and Harmonics
- Kinetic Alfvén Waves
- Wave Polarization
- Wave-Particle Interactions

Conditions are more stable at Ganymede magnetopause than at Earth magnetopause.

Comparisons between these two environments are useful to evaluate the role played by ULF waves :

- along reconnected field lines,
- linked to plasma injected into the magnetosphere
- in the effects of **B** rotation at magnetopause

# Conclusions

- The mini magnetosphere of Ganymede is in direct interaction with the Jovian magnetosphere.
- **There is a lack of measurements around the proton gyrofrequency in Ganymede's magnetosphere**

- It is worth to  compare the measurements at Ganymede and at Earth relatively to:
    - detection of Ion cyclotron waves and triggered EMIC
    - emissions along the recently reconnected magnetic field lines
    - level of fluctuations at the magnetopause
    - wave polarization