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Ion Cyclotron Waves and Mirror Modes in Saturn's Magnetosphere

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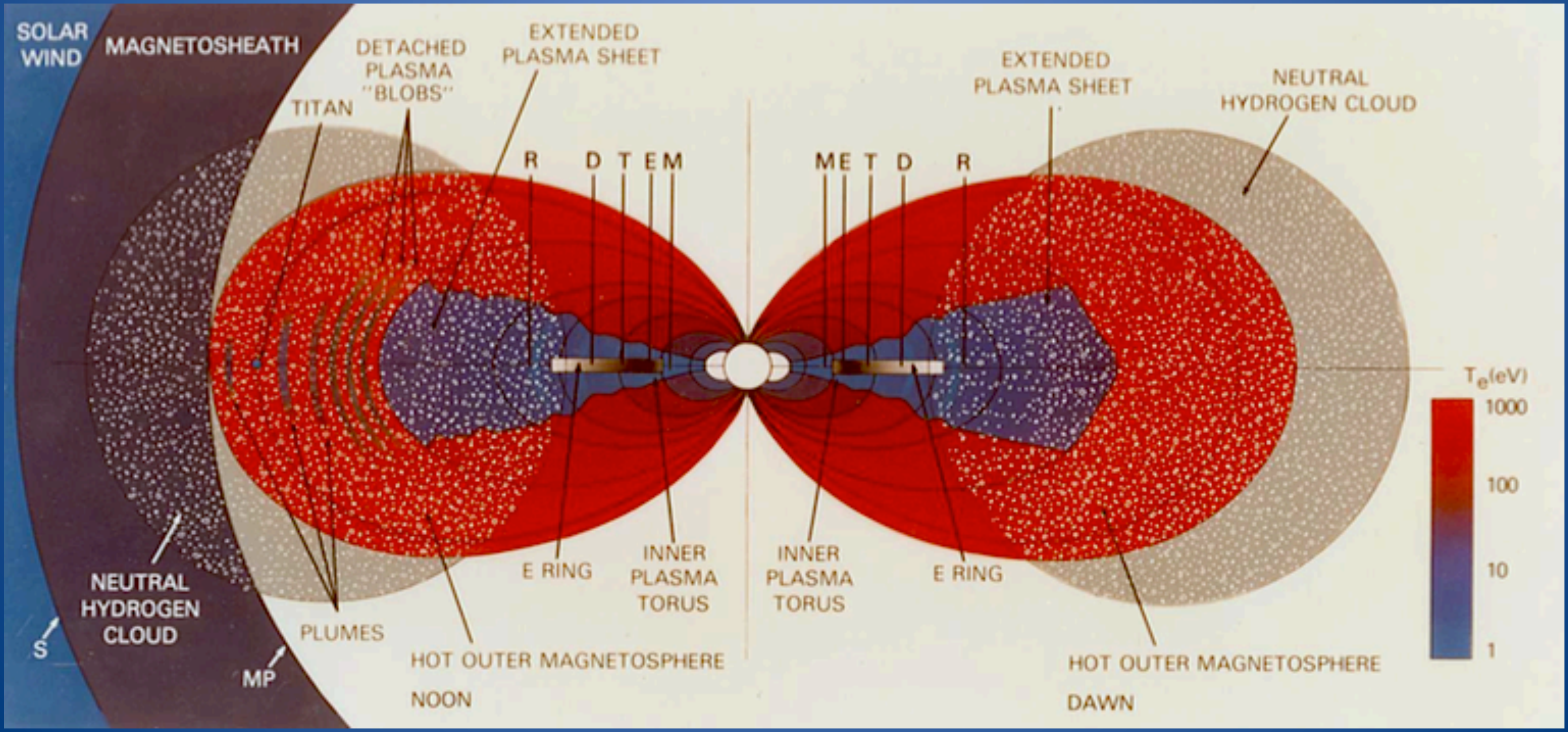
Saturn's Magnetosphere

Saturn exhibits a nearly dipolar field, the magnetic equator being slightly shifted northwards due to quadrupolar term. Different characteristics are encountered at different distances from the planet.



Enceladus

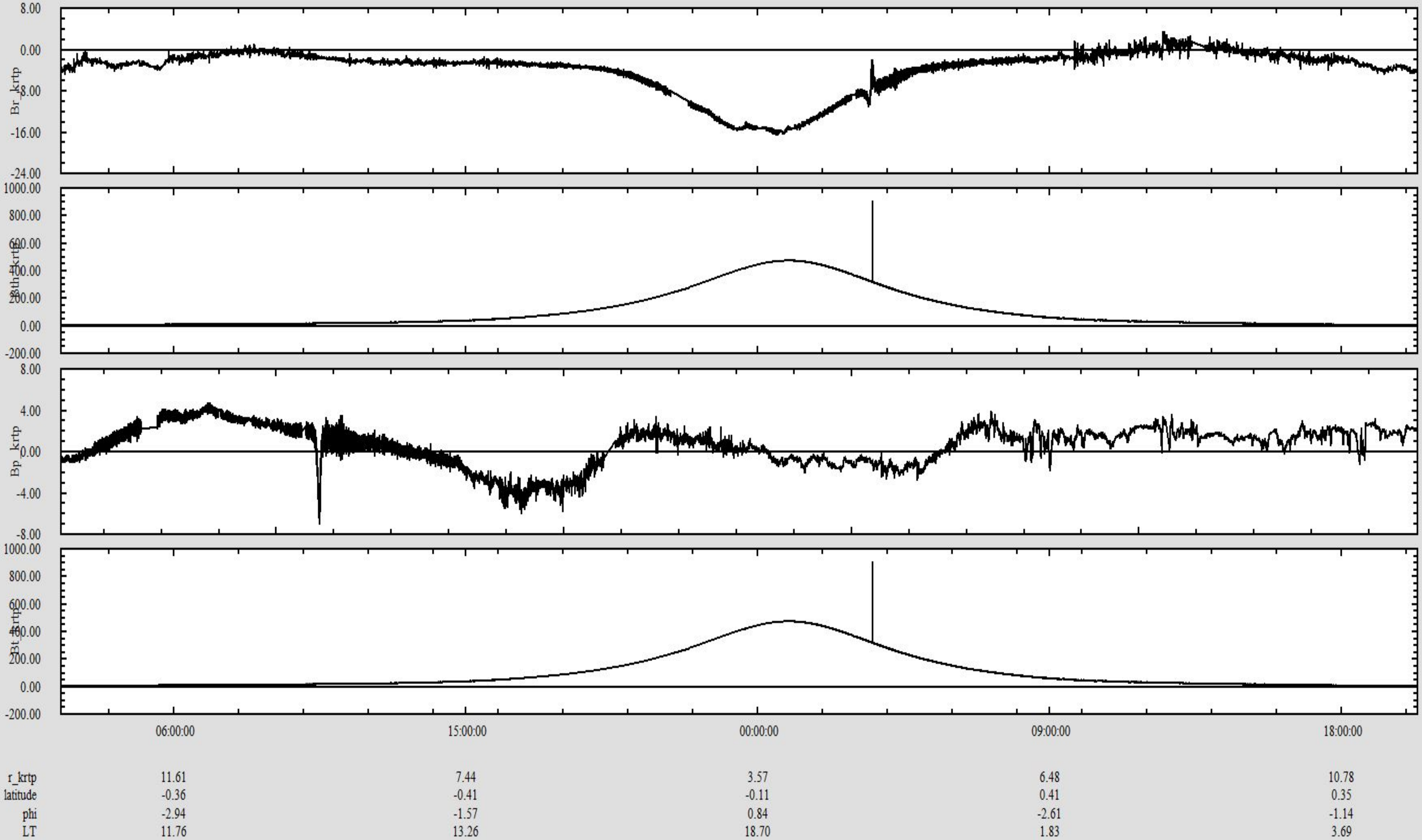
- $R \sim 3.95\ R_S$
- Ice crust, liquid interior ocean
- 2:1 Tidal locking with Dione

Image credit: JPL/NASA

GEOLOGICAL ACTIVITY

- Cryovolcanoes in southern pole region
- Mass loading rate ~ 200 kg/s
- H_2O , traces of molecular nitrogen, methane, and carbon dioxide
- Enceladus' geysers are the main source of Saturn's plasma sheet

Cassini MAG Data



Ion Cyclotron Waves (2)

Ion cyclotron waves are transverse plasma waves typical of regions where the total pressure is dominated by the magnetic pressure and the velocity distribution of ions is non-Maxwellian.

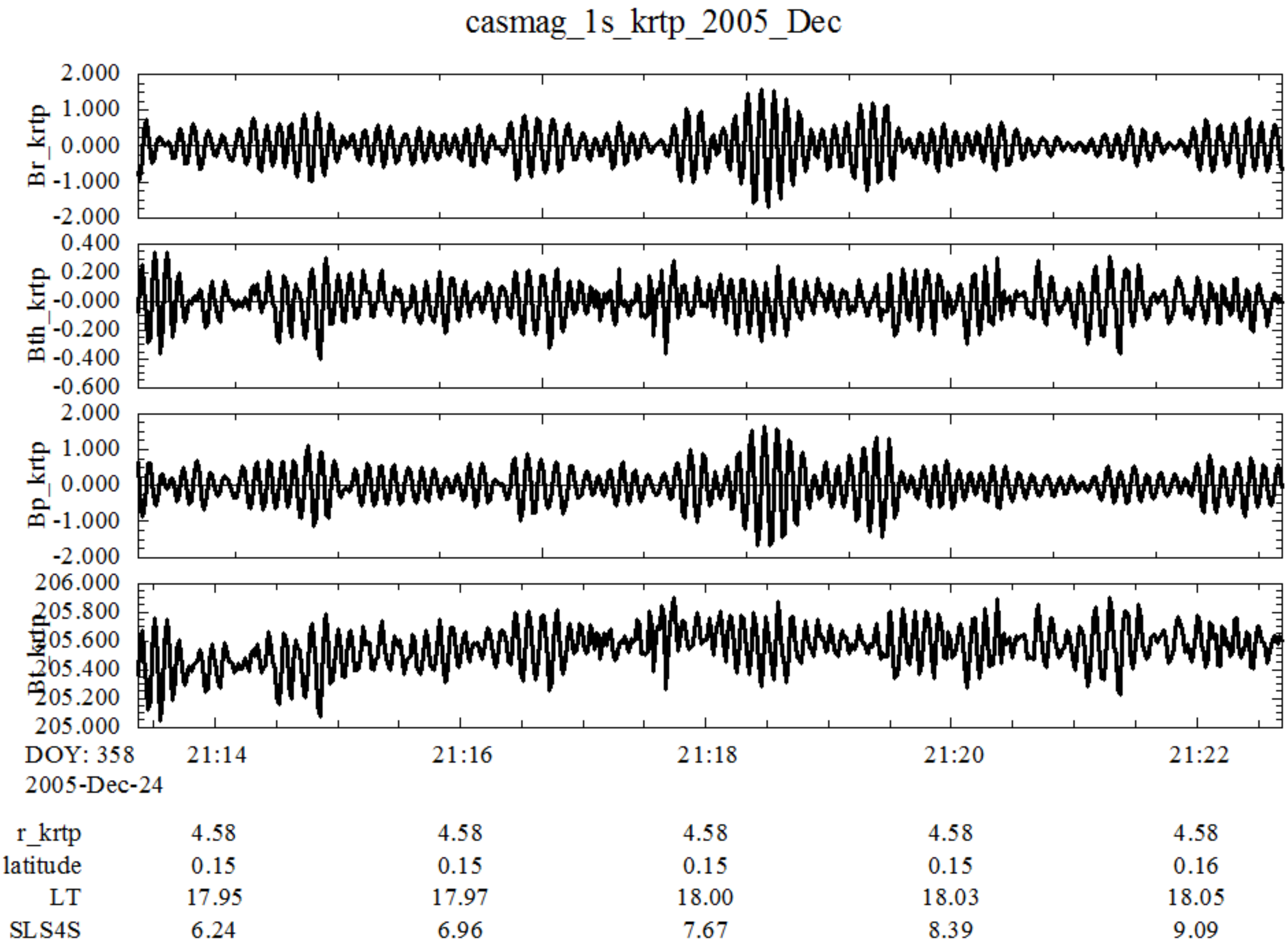
$$\beta = \frac{n k_B T}{B^2 / 2\mu_0}$$

- Quasi circular polarization in perpendicular components
- Propagation mostly along magnetic field lines (**k** x **B** = 0)
- Dominant in regions up to ~ 6 R_S
- B_R , B_ϕ components!

Resonant ions produced mostly by charge exchange due to interaction between neutral species ejected plumes and corotating plasma.

- Local time dependence
- R dependence
- Amplitudes up to 2.3 nT
- Frequencies close to gyrofrequencies of water group ions

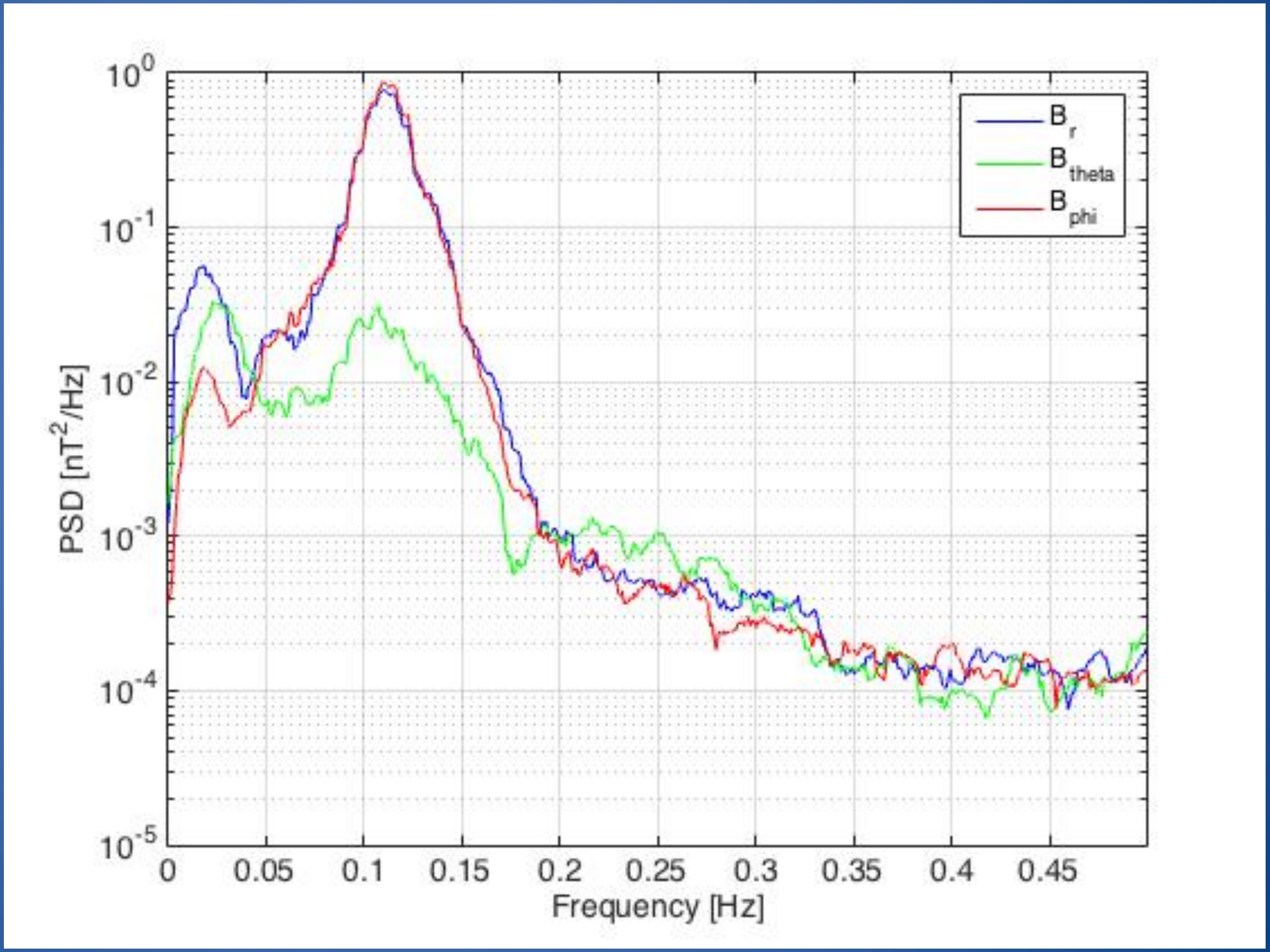
Ion Cyclotron Waves



Ion Cyclotron Waves (3)

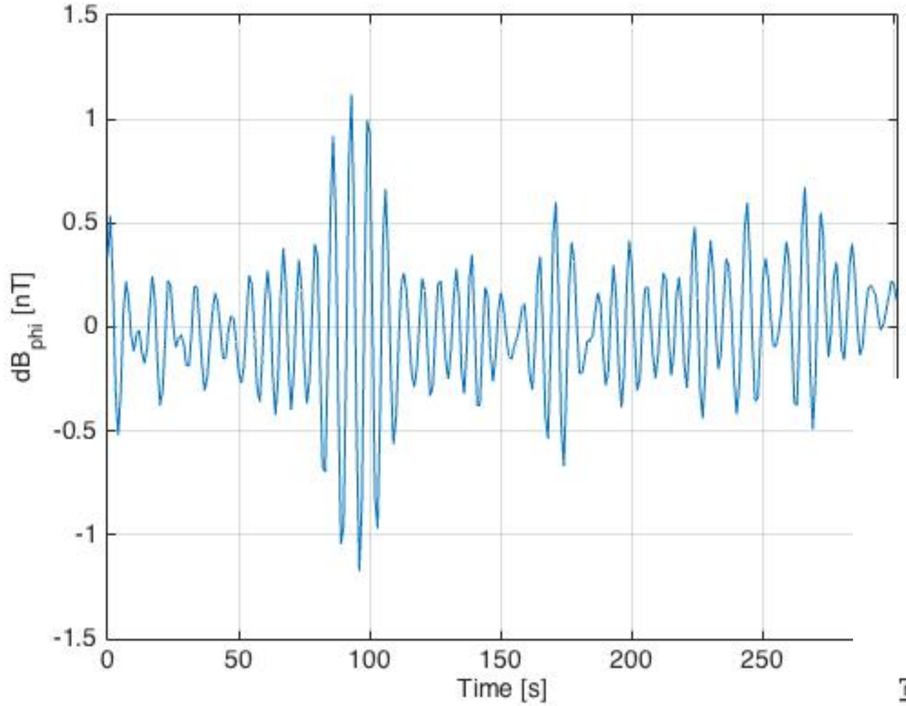
Power spectral density generated using Splash and plotted on MATLAB.

- Δt ~ 8.3 minute
- 4.58 R_S
- 12/24/2005
- running avg ~ 8

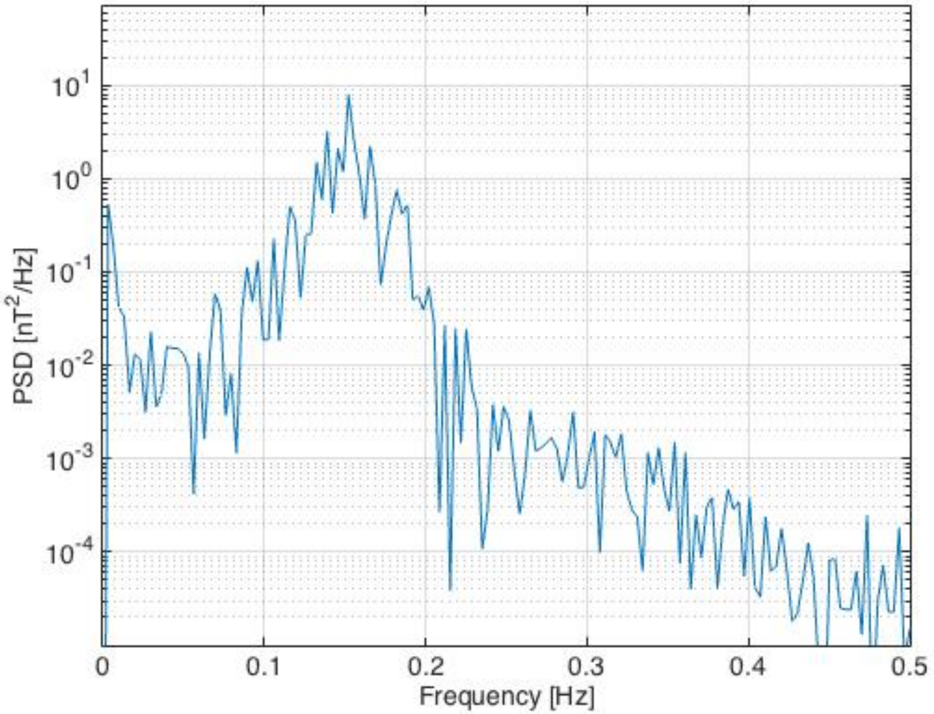


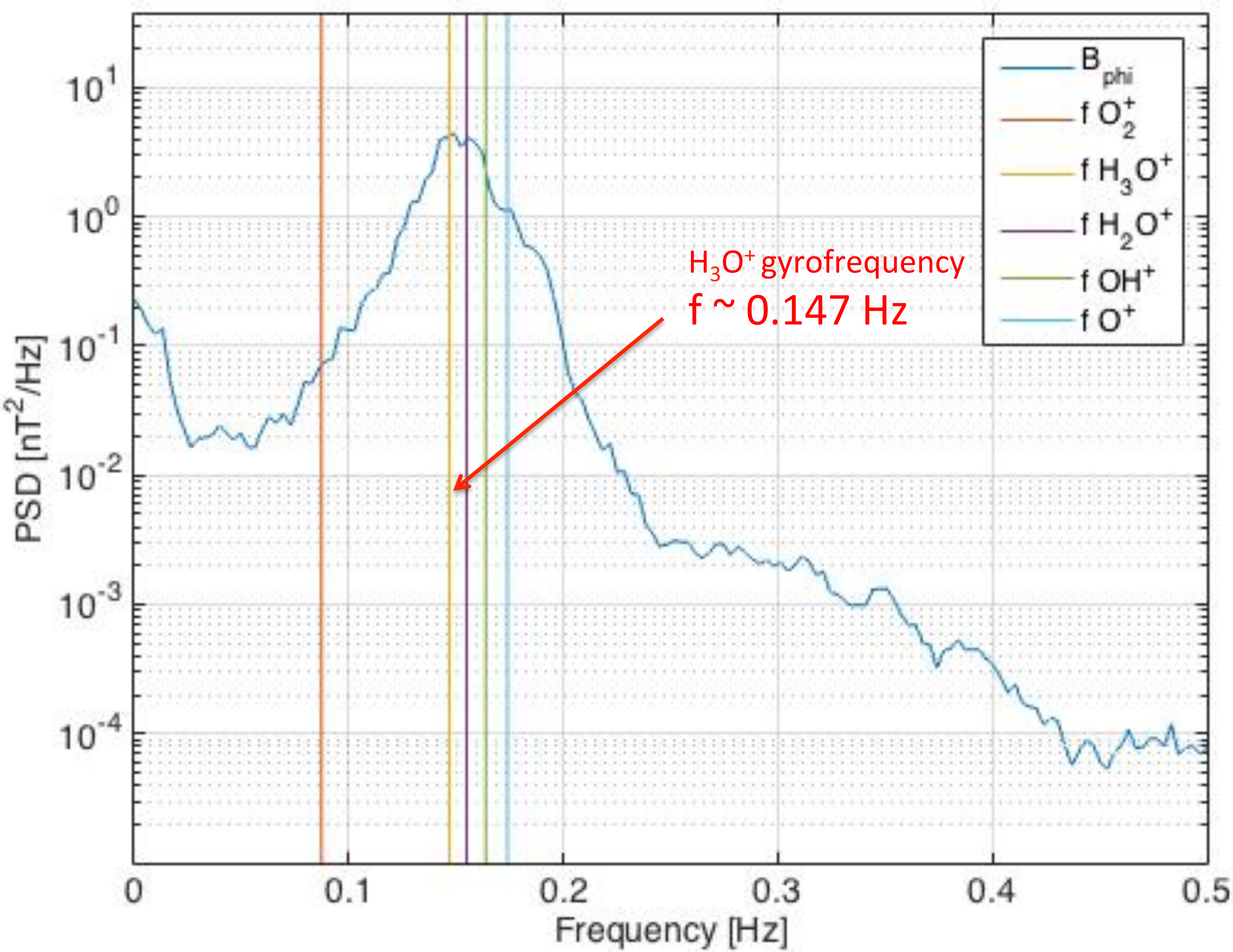
SPLASH/MATLAB generated PSD plot in the three components

Ion Cyclotron Waves (4)



For instance, let us look at a **5 min** signal in one of the perpendicular magnetic field components, B_ϕ





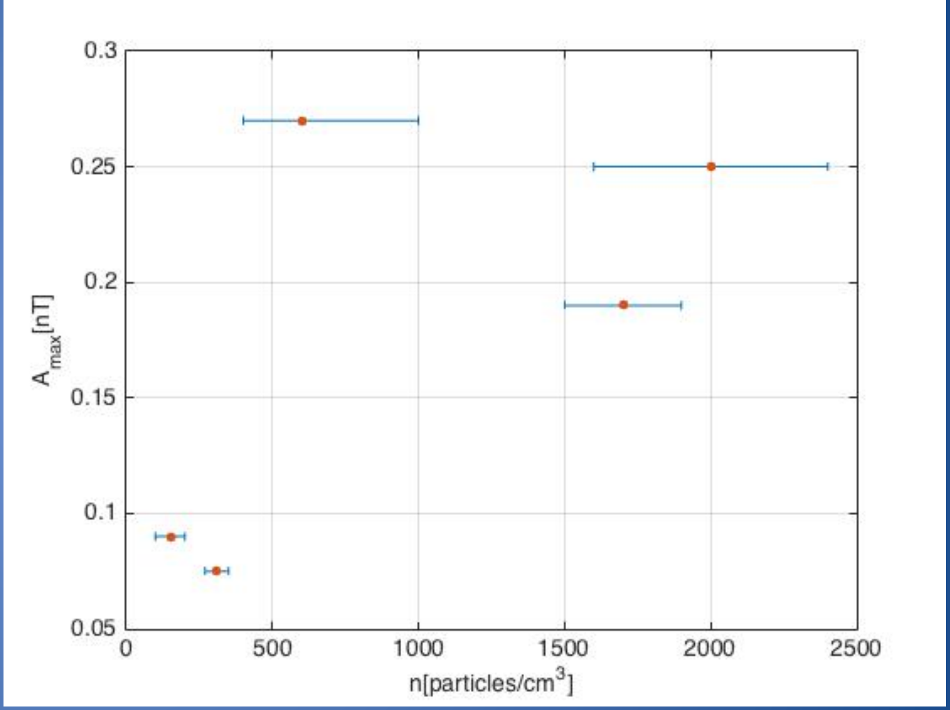
PSD [nT^2/Hz]
10^1
10^0
10^-1
10^-2
10^-3
10^-4
0
0.1
0.2
0.3
0.4
0.5
Frequency [Hz]
B_phi
f O_2^+
f H_3O^+
f H_2O^+
f OH^+
f O^+
H_3O^+ gyrofrequency
f ~ 0.147 Hz

What determines ICWs amplitude?

Pick-up ion densities drive the fluctuation amplitude.

COMPLEX PICTURE!!!

- Densities of neutral species
- Plasma sheet ion densities
- Pick-up velocity (keplerian, corotational)



MATLAB plot for Amplitude vs.total neutral density

- Local Time
- Radial distance
- Distance from magnetic equator

Mirror Modes

Mirror modes are plasma instabilities typical of regions with strong temperature anisotropies. Differently from ICWs, they USUALLY prosper in high β environments, such as planetary magnetosheaths.

- Highly irregular occurrence
- ~ Non-propagating along field lines
- Parallel field component B_θ
- Frequencies lower then ICWs frequencies
- Local Time dependence
- Dominate total B fluctuations at R > $6R_S$

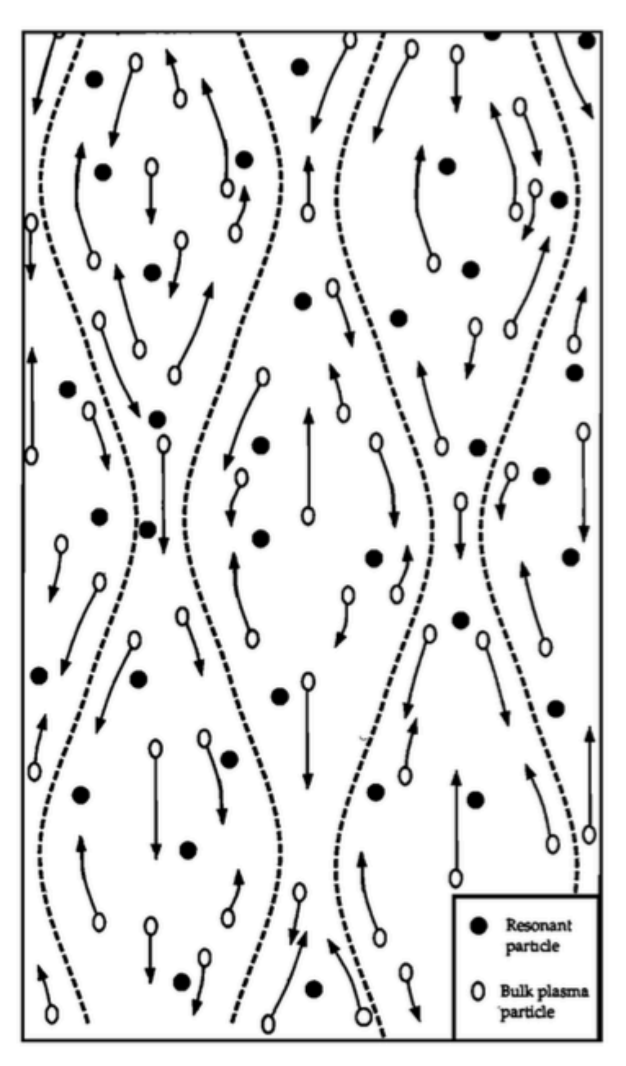


Image taken from Kivelson, Southwood, *Mirror Instability:1. Physical Mechanism of Linear Instability,* 1993

MMs: Instability Condition

Instability initially treated as MHD fluid instability. For a complete treatment based on kinetic theory see *Hasegawa* 1969.

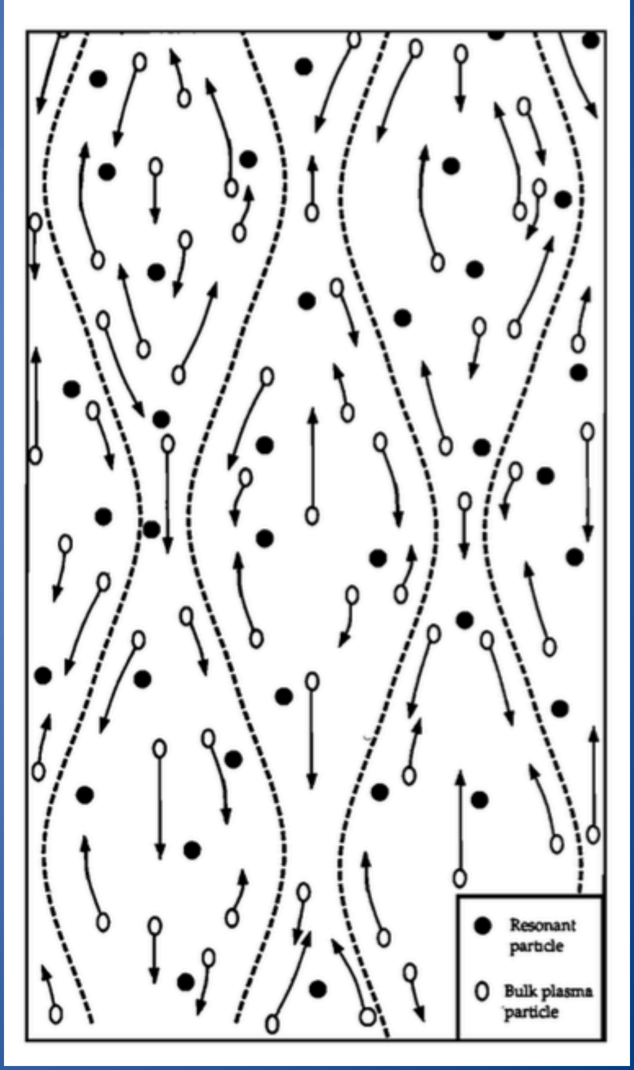
$$1 + \beta_\perp \left(1 - \frac{T_\perp}{T_\parallel}\right) < 0$$

Instability condition

$$-\frac{\gamma}{k_\parallel} = \frac{B^2}{\mu_o} \frac{1 + \beta_\perp \left(1 - \frac{T_\perp}{T_\parallel}\right)}{2\pi (T_\perp^2 / T_\parallel) F_{res}}$$

Growth rate (*Kivelson and Southwood,*1993*)*

Inverse proportionality with distribution function of resonant particles!

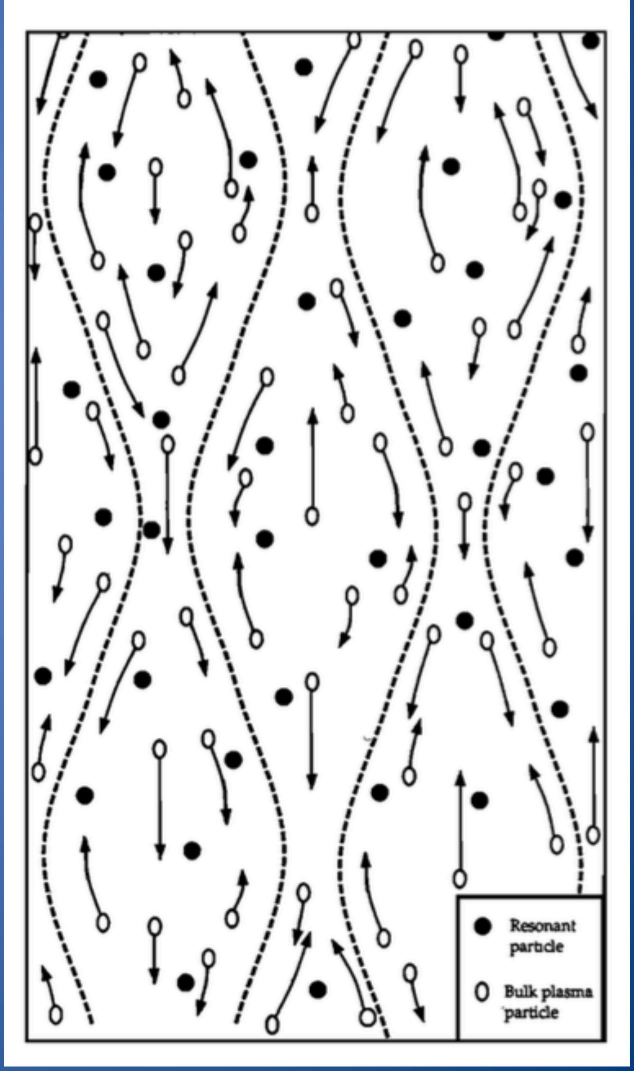


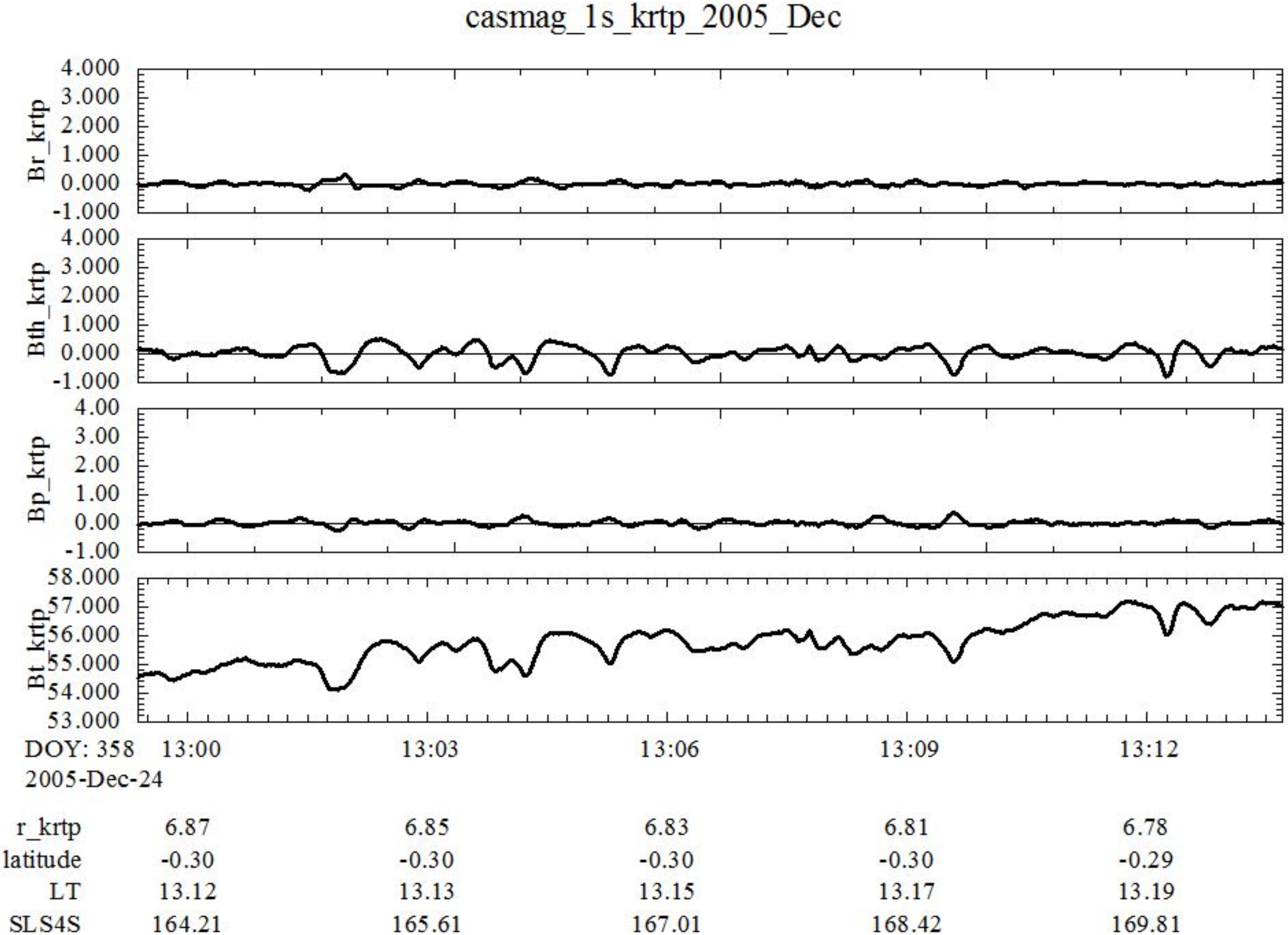
MMs: role of resonant particles

As suggested by *Southwood and Kivelson (1993)*, particles can be separated into two classes when analyzing the physical mechanism leading to MMs.

BULK PLASMA PARTICLES (high parallel velocity): these particles move along field lines and encounter a *spatial field variation*. They exchange kinetic energy between the parallel and perpendicular components.

RESONANT PARTICLES (low parallel velocity) do not move a significant distance along the field in the instability growth time 1/γ. *Their kinetic energy is not conserved*.



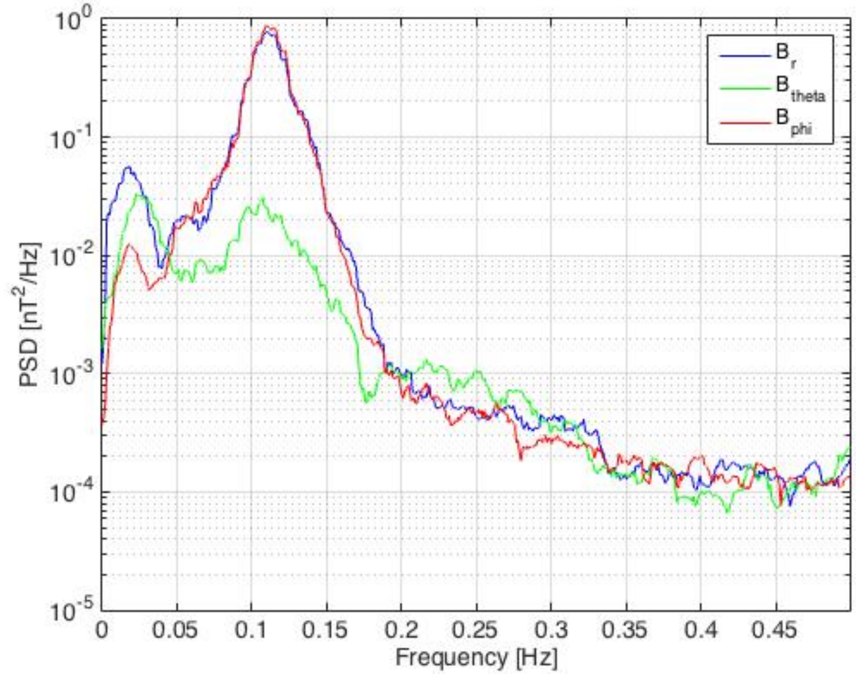


casmag_1s_krtp_2005_Dec
Br_krtp
4.000
3.000
2.000
1.000
0.000
-1.000
Bth_krtp
4.000
3.000
2.000
1.000
0.000
-1.000
Bp_krtp
4.00
3.00
2.00
1.00
0.00
-1.00
Bt_krtp
58.000
57.000
56.000
55.000
54.000
53.000
DOY: 358 13:00 13:03 13:06 13:09 13:12
2005-Dec-24
r_krtp 6.87 6.85 6.83 6.81 6.78
latitude -0.30 -0.30 -0.30 -0.30 -0.29
LT 13.12 13.13 13.15 13.17 13.19
SLS4S 164.21 165.61 167.01 168.42 169.81

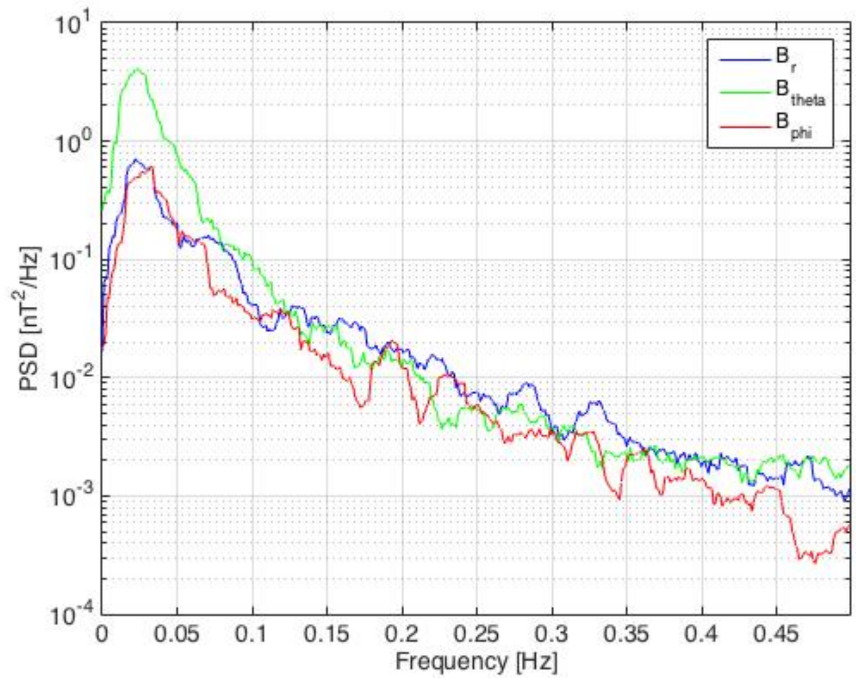
ICWs

vs.

MMs



PSD [nT^2/Hz]
Frequency [Hz]
B_r
B_theta
B_phi

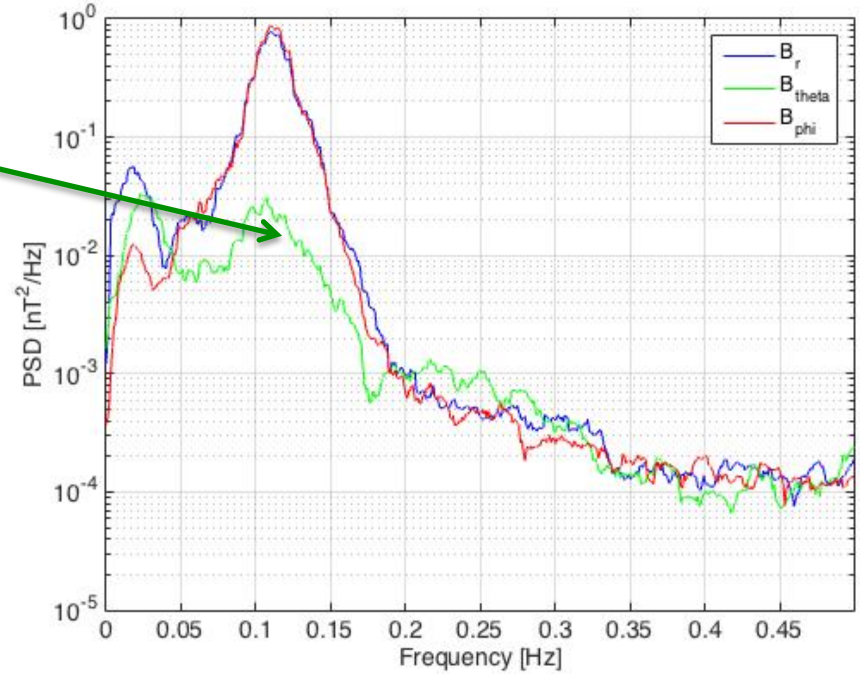


PSD [nT^2/Hz]
Frequency [Hz]
B_r
B_theta
B_phi

B_θ

4.58 R_S ; 24/12/05

ICWs

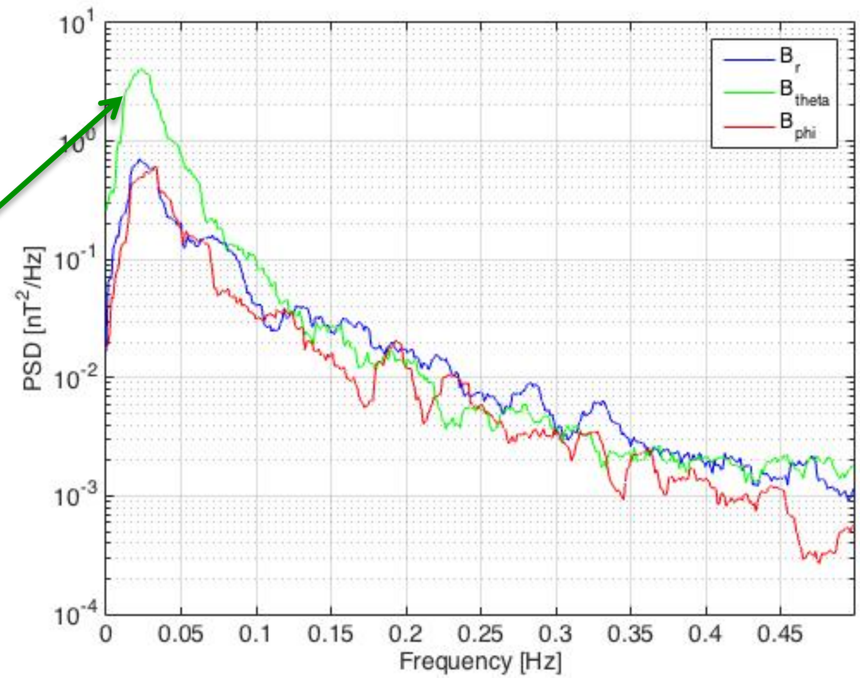


vs.

MMs

6.83 R_S ; 24/12/05

B_θ



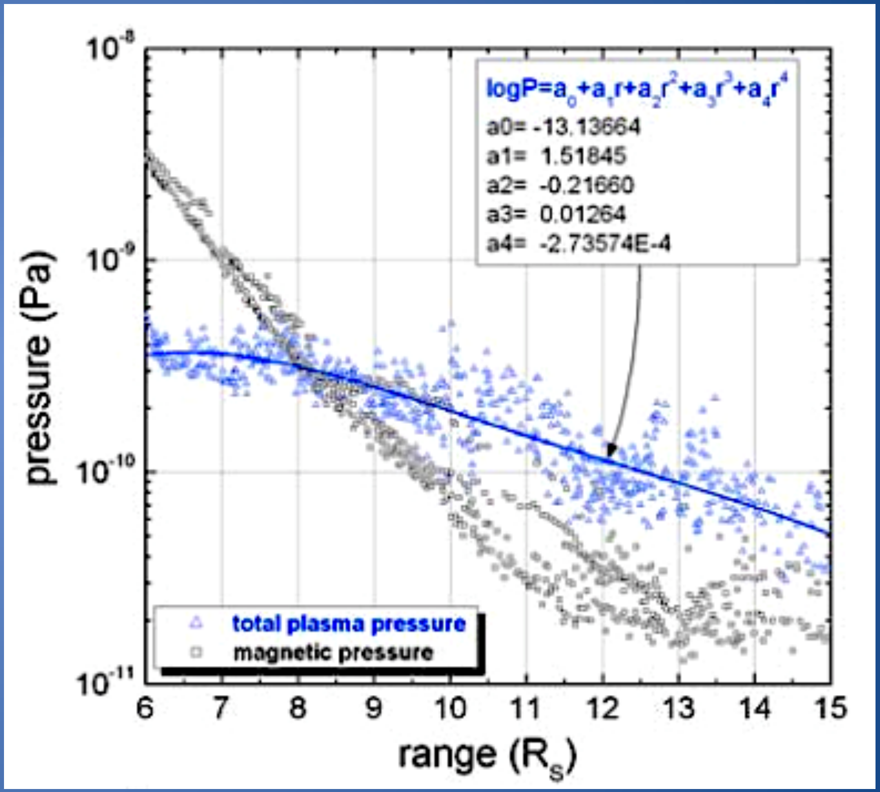
MMs: Instability Condition (2)

The instability condition depends on the strength of magnetic field and on the plasma temperature anisotropy:

$$1+\beta_{\perp}\left(1-\frac{T_{\perp}}{T_{\parallel}}\right)<0$$

If the perpendicular plasma β-parameter is known, it can be used to calibrate a lower limit for the temperature anisotropy coefficient:

$$c_a=\frac{T_{\perp}}{T_{\parallel}}$$



Sergis et al., *Particle pressure, inertial force, and ring current density profiles in the magnetosphere of Saturn, based on Cassini measurements*, 2010

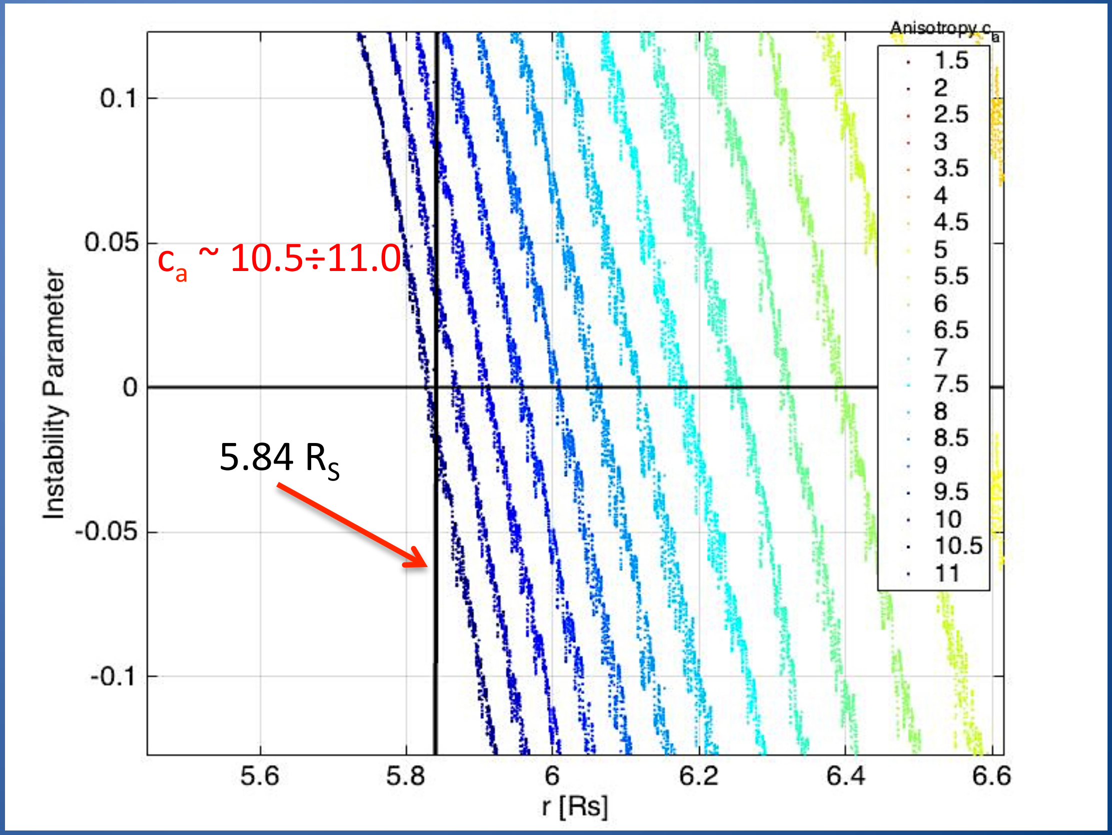
MMs: Instability Condition (3)

We observed mirror mode instabilities up to 5.84 R_S for a daytime low inclination orbit in the Feb2005 dataset.

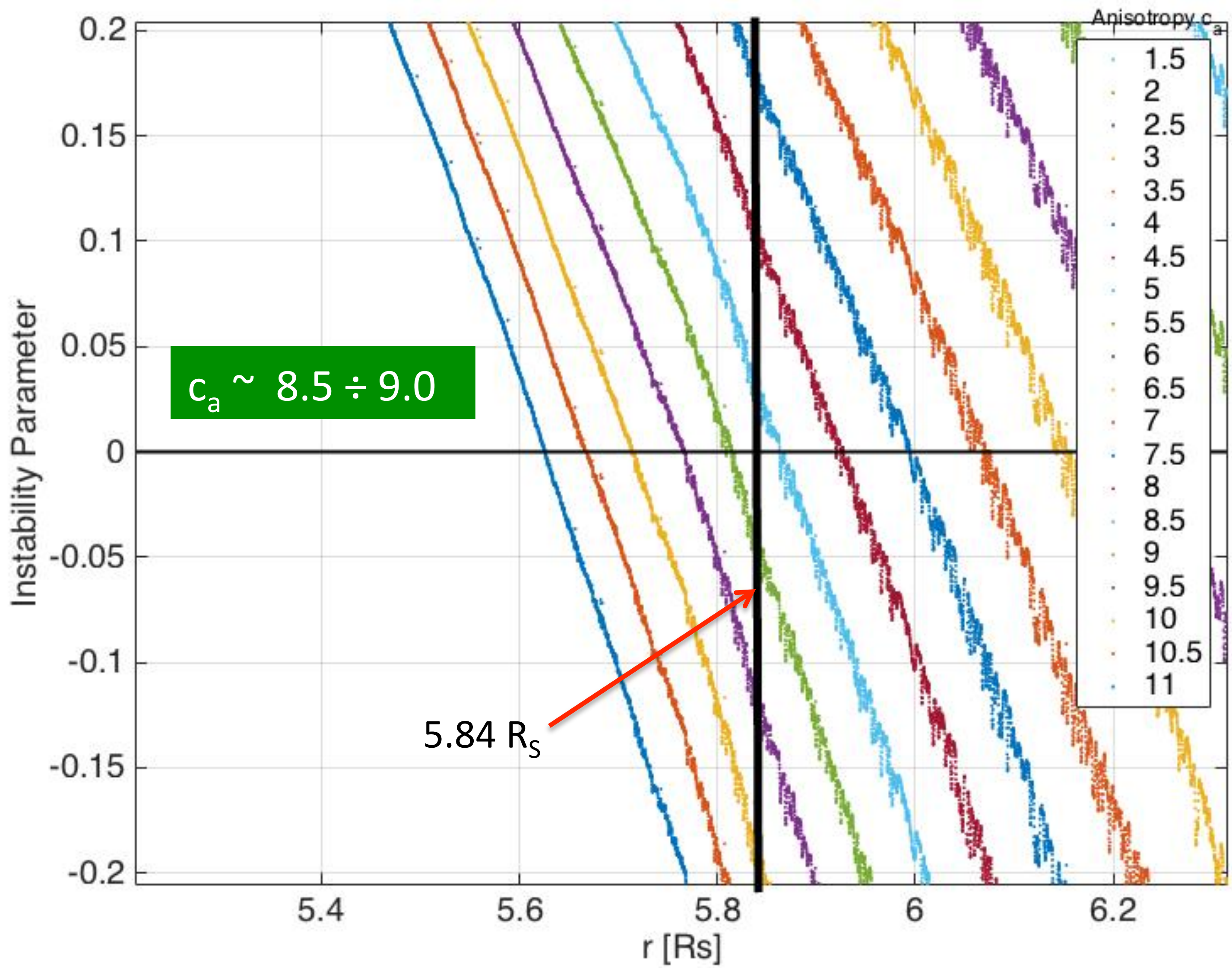
A value for the anisotropy coefficient c_a ~ 10.5 ÷ 11.0 is obtained using the fit for total particle pressure by Sergis et al. 2010. Such value is not consistent with that obtained by Wilson et al. 2008 for water group ions (c_a ~ 3 ÷ 8) in the region near 5.5 R_S).

BUT

$$p = \frac{2p_{\perp} + p_{\parallel}}{3}$$



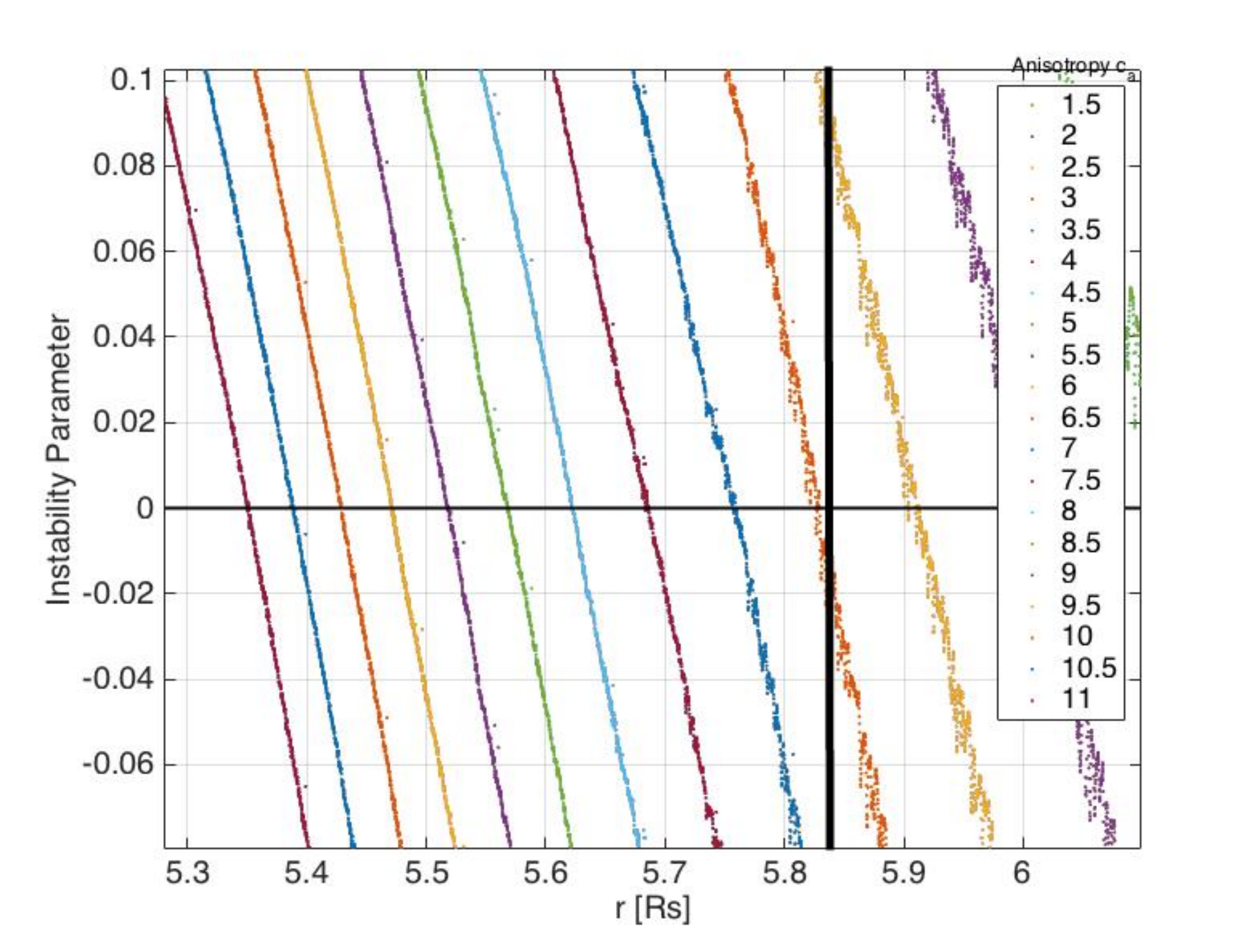
MMs: Instability Condition (4)



MMs: Instability Condition (5)

We can think of inserting a correction parameter **b** , taking into account various effects which lead to uncertainty on the value of $\beta_\perp$ (such as unavailable electron moments at R ~ 10 R_S, large scatter of fit). For **b** = 1.5:

$c_a \sim 6.0 \div 6.5$



in agreement with CAPS measurements.

Summary of Results

- PSD constructed starting MAG data: presence of ICWs at frequencies close to water group ions gyrofrequencies
- ICWs are the main contribution to magnetic field fluctuations up to $6R_S$.
- ICWs max amplitudes ~ 2.3 nT near the magnetic equator.
- Short lived ion cyclotron episodes in dayside orbits.
- No simple polinomial or logarithmic relation between ICWs amplitudes and neutral species densities.
- Mirror mode instability dominates at $r > 6R_S$, we suggest this is due to lower density of ion cyclotron resonant particles.
- Evident mirror mode structure distribution is quite irregular with respect to ICWs: large silent regions with almost no field fluctuations.
- Temperature anisotropy lower limit derived by fitting Cassini Magnetometer and Cassini Plasma Spectrometer data of $\mathbf{c_a \sim 8.5 \div 9.0}$.

Perspectives & Miscellaneous

- **Solar Probe +** will orbit close to the Sun, among scientific goals investigation of coronal heating problem: wave heating or magnetic reconnection?
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- **Juno** mission to Jupiter: study of magnetic phenomena in polar regions

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