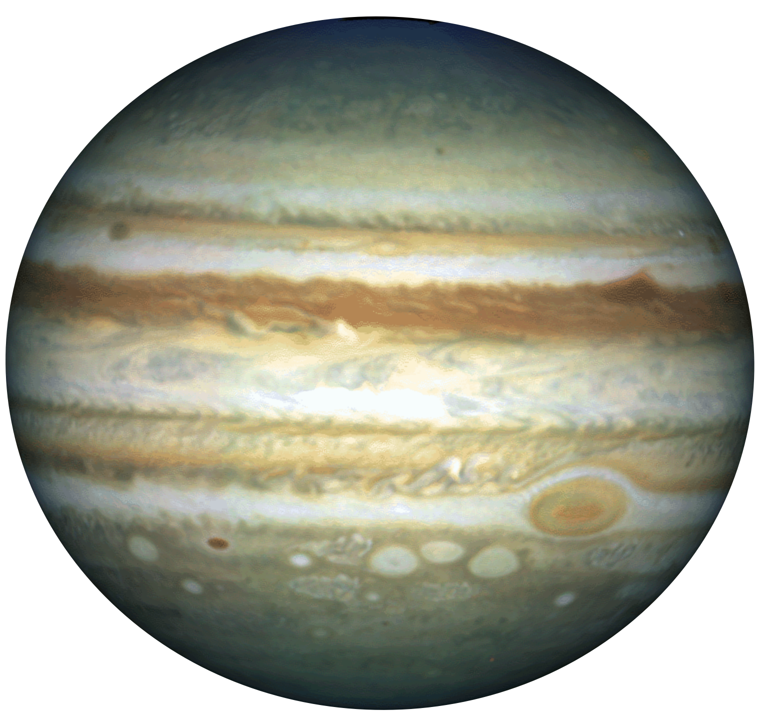
New insight on Jupiter's inner structure from seismic measurements

Patrick Gaulme, François-Xavier Schmider, Jean Gay, Tristan Guillot[1,2], Cédric Jacob

A&A **504**, A130 (2011)



[1] Observatoire de la Côte d'Azur, CNRS, Nice

[2] UCSC, Santa Cruz, USA (Fulbright visiting prof)

Probing deep...

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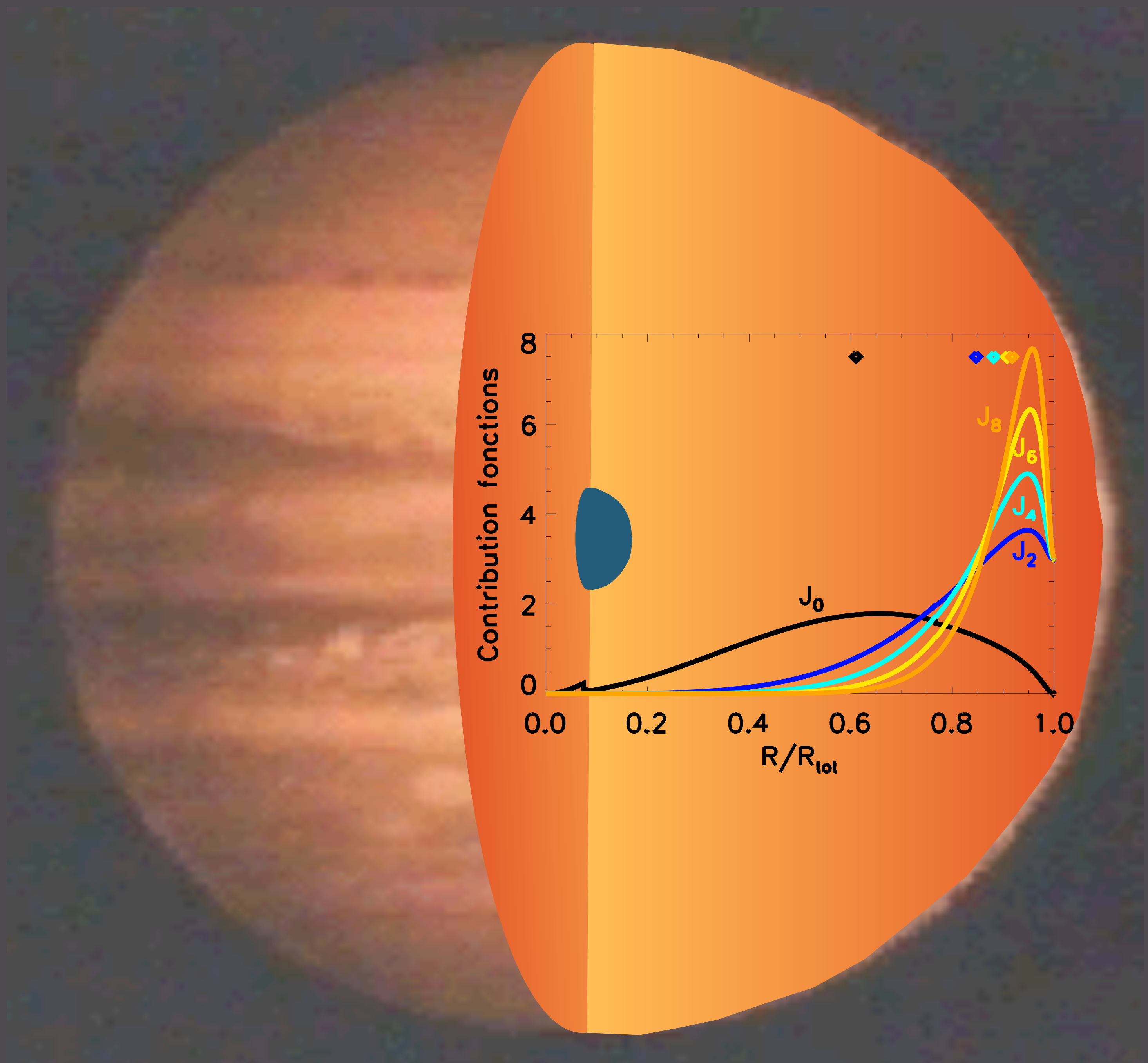
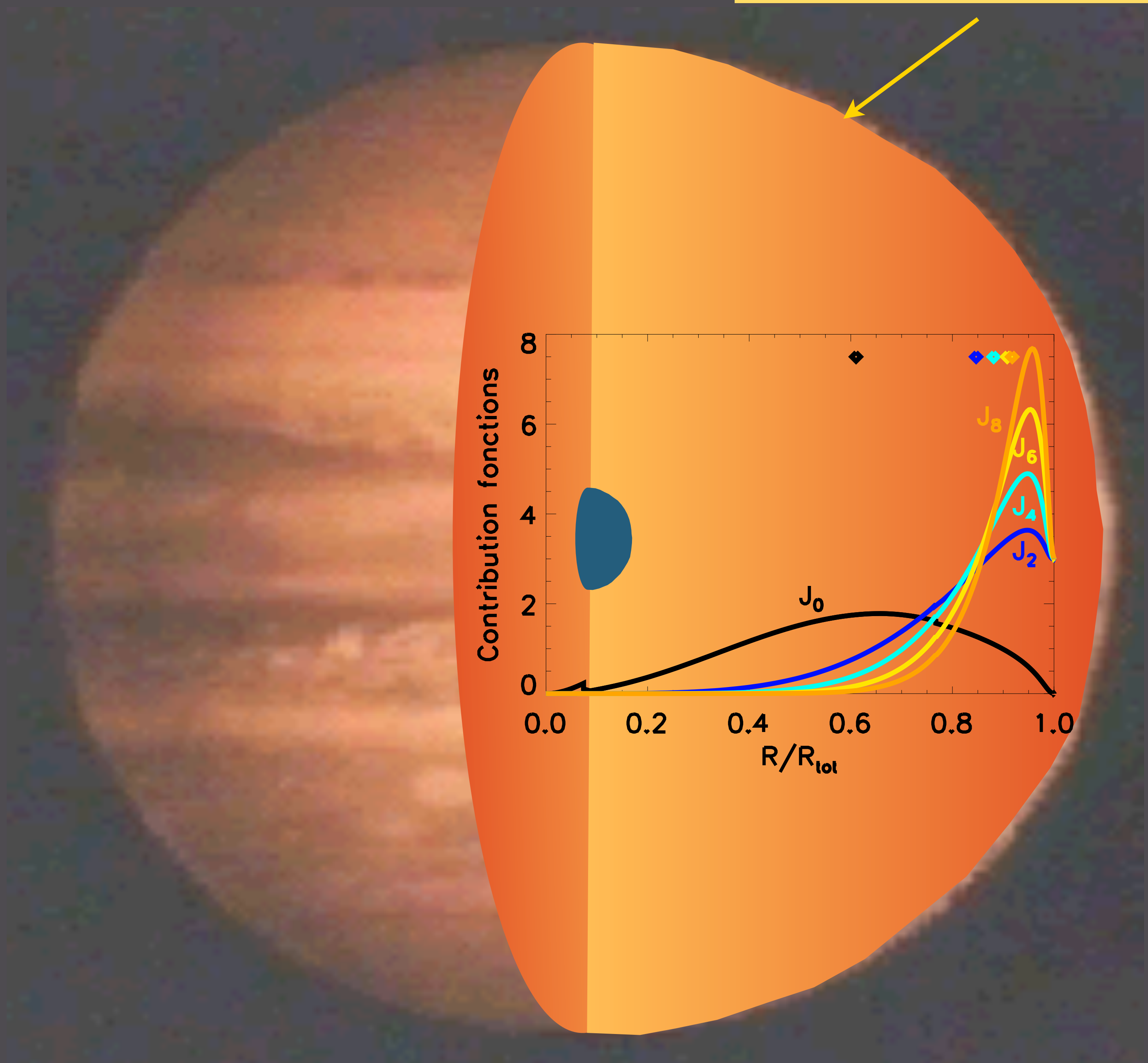


Probing deep...

Atmospheric probes (spectroscopy, in situ): skin-deep measurement of the composition



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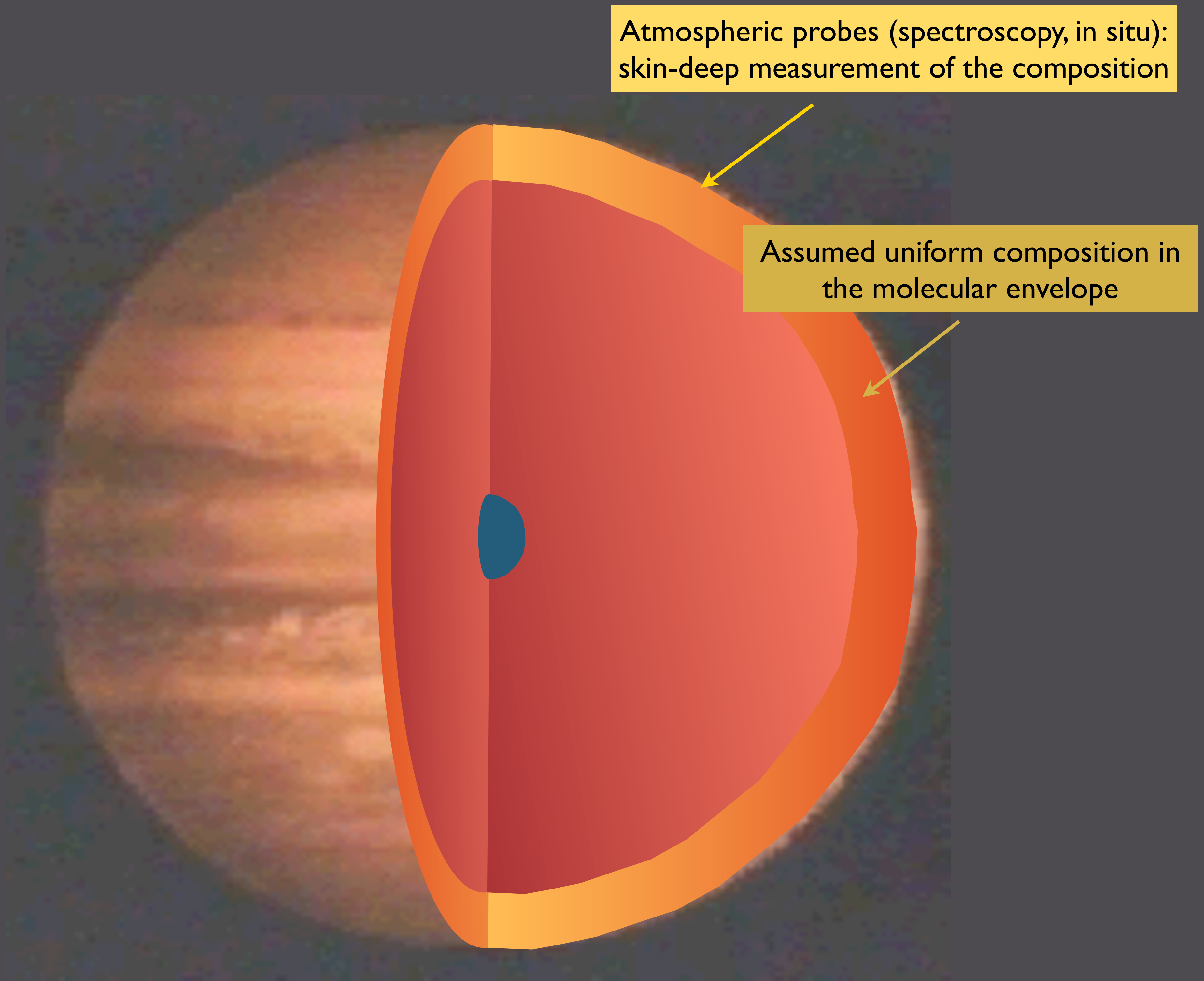

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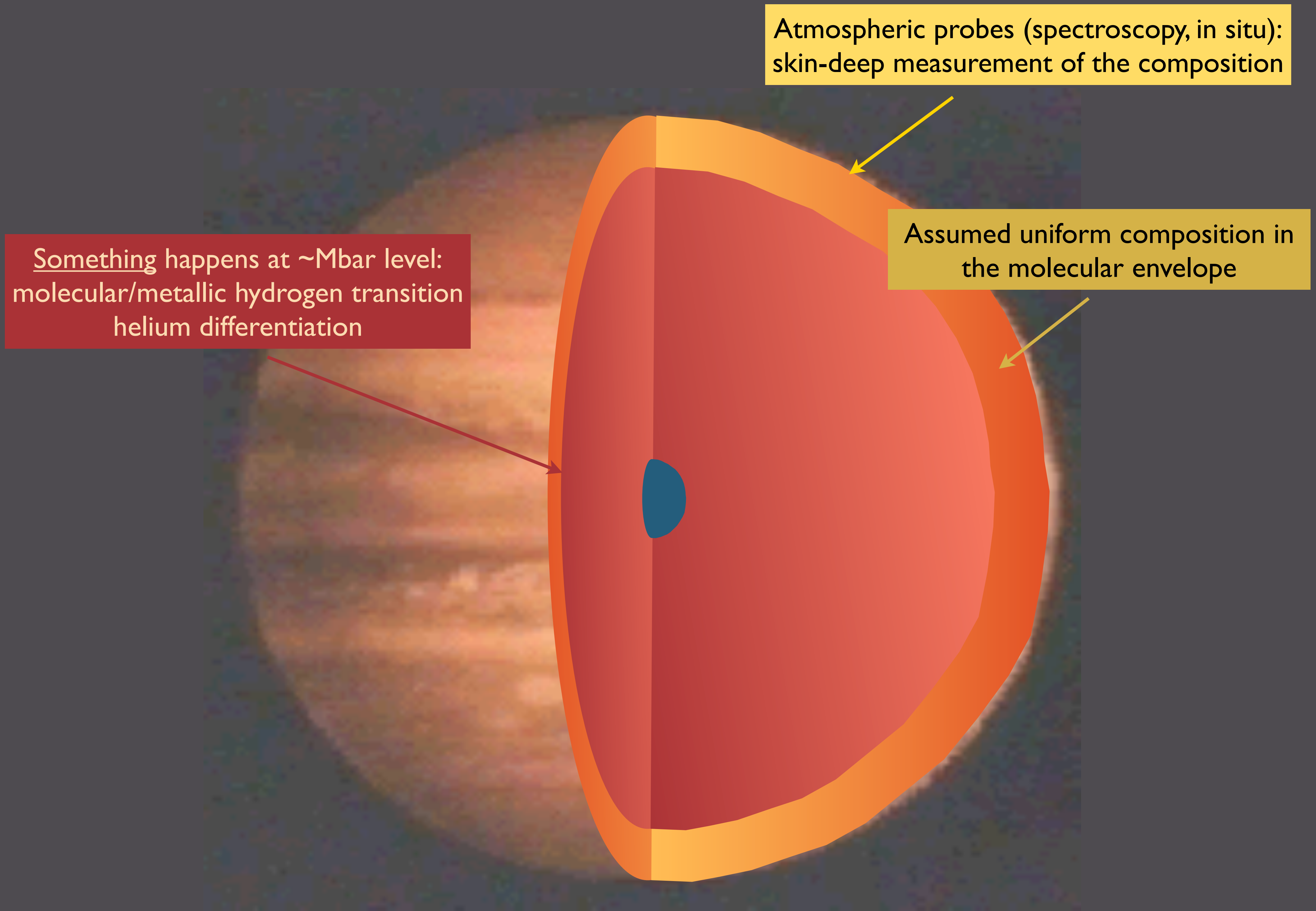

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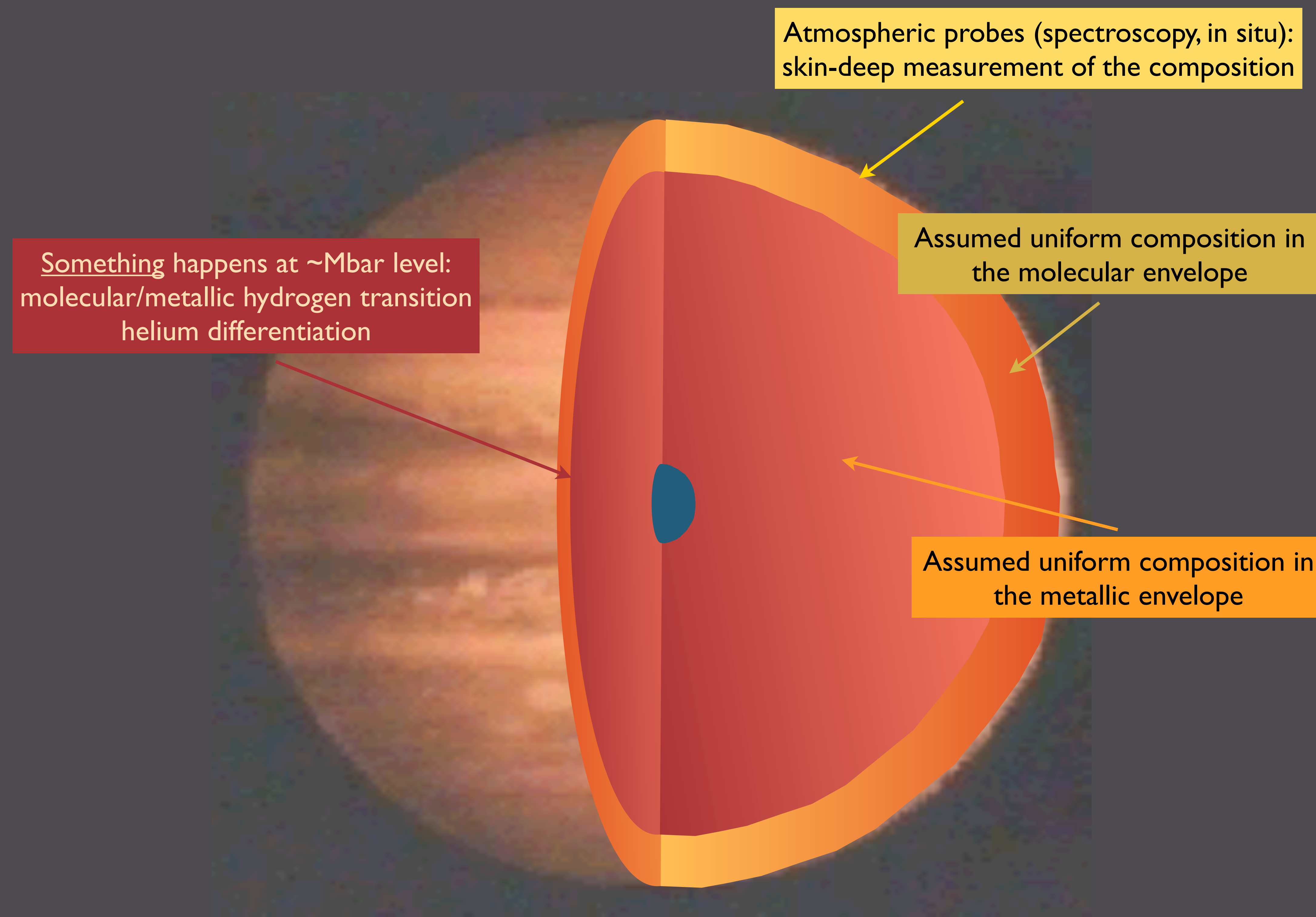

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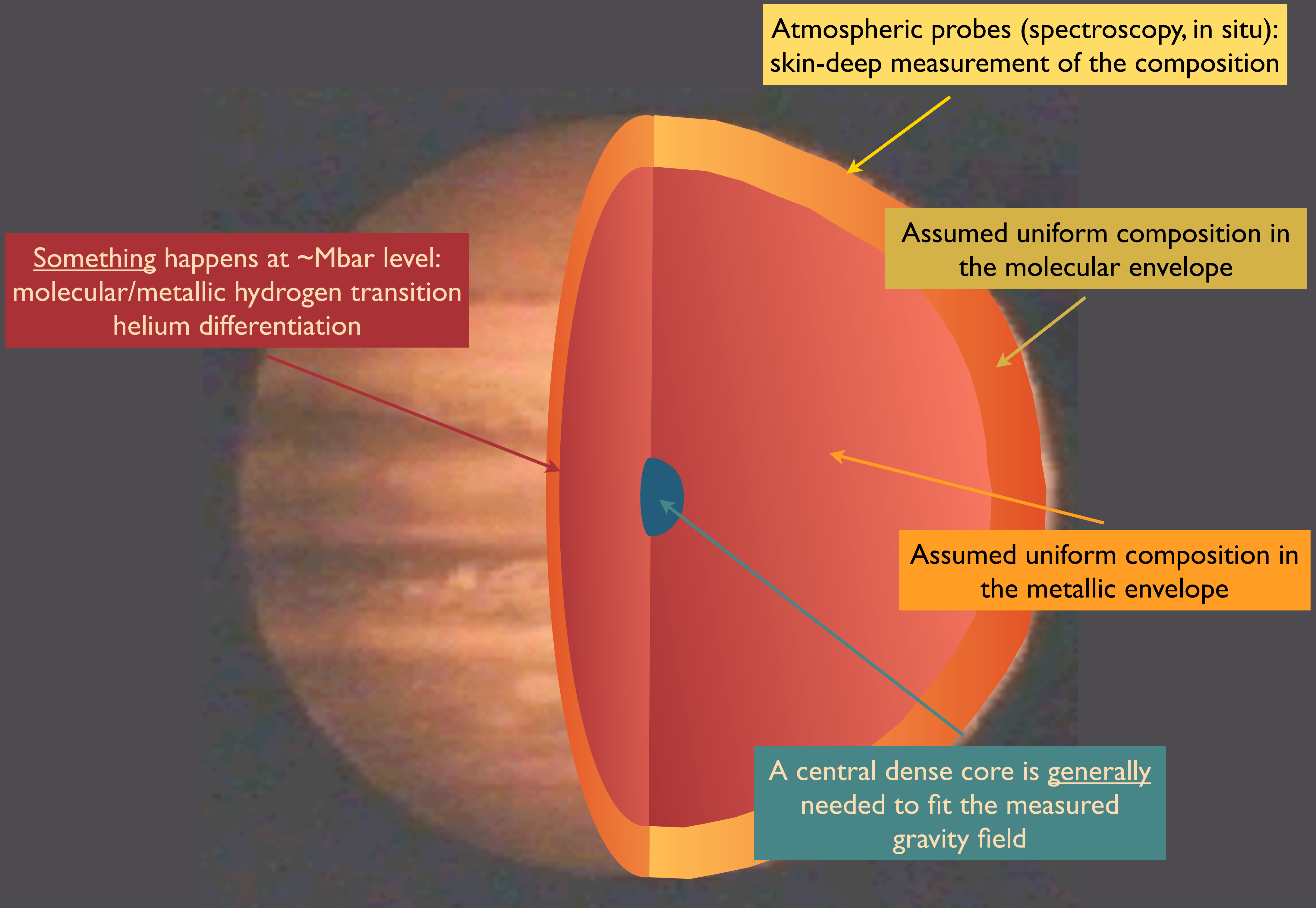
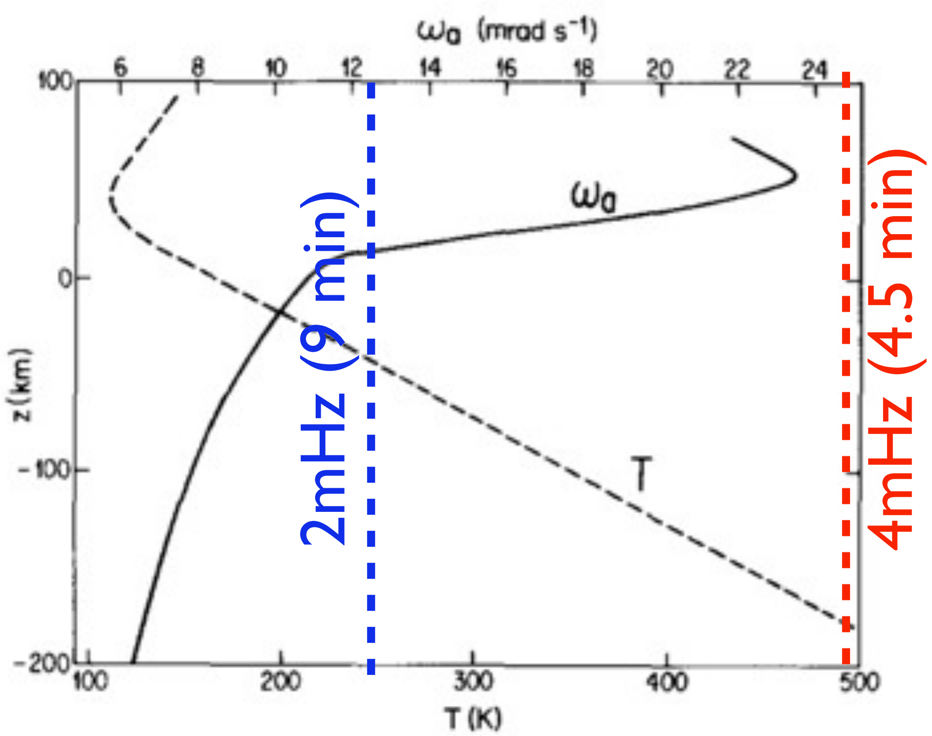
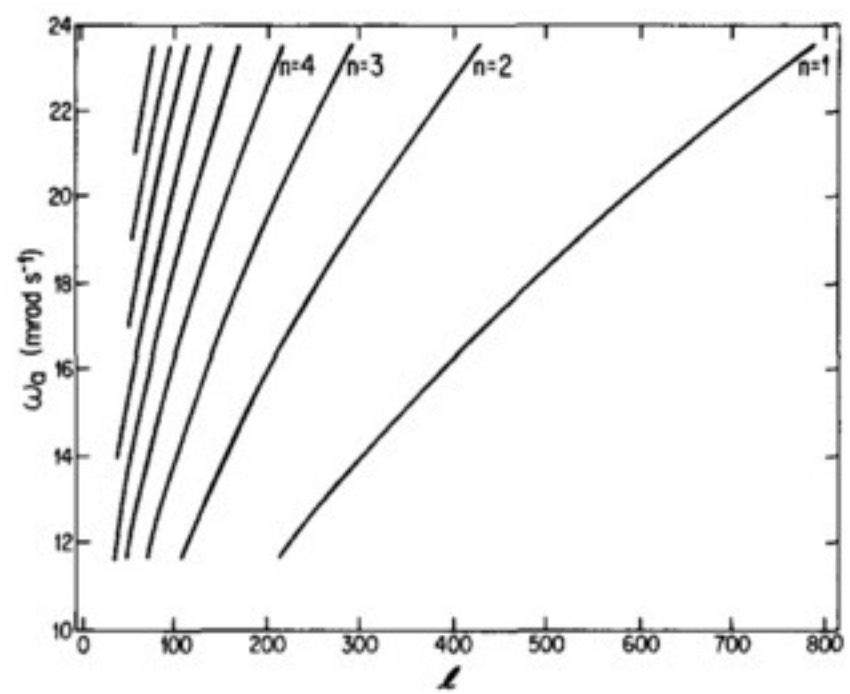


Theoretical bases

Vorontsov et al. (1976) and subsequent work: identification of free oscillation modes

Bercovici & Schubert (1987): Trapped high degree accoustic waves (form + excitation)





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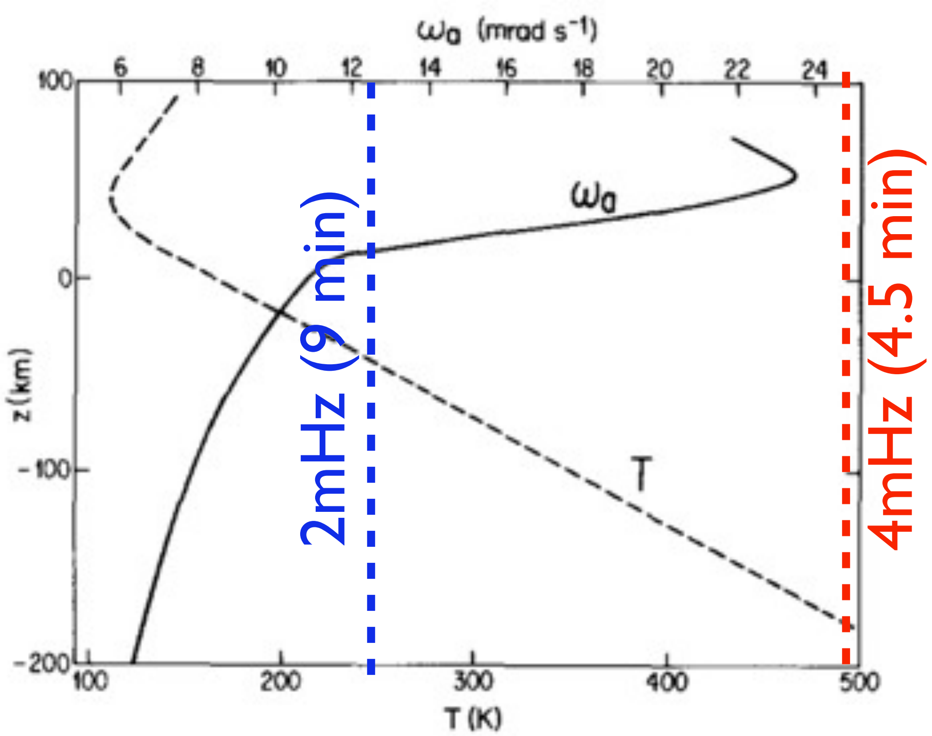

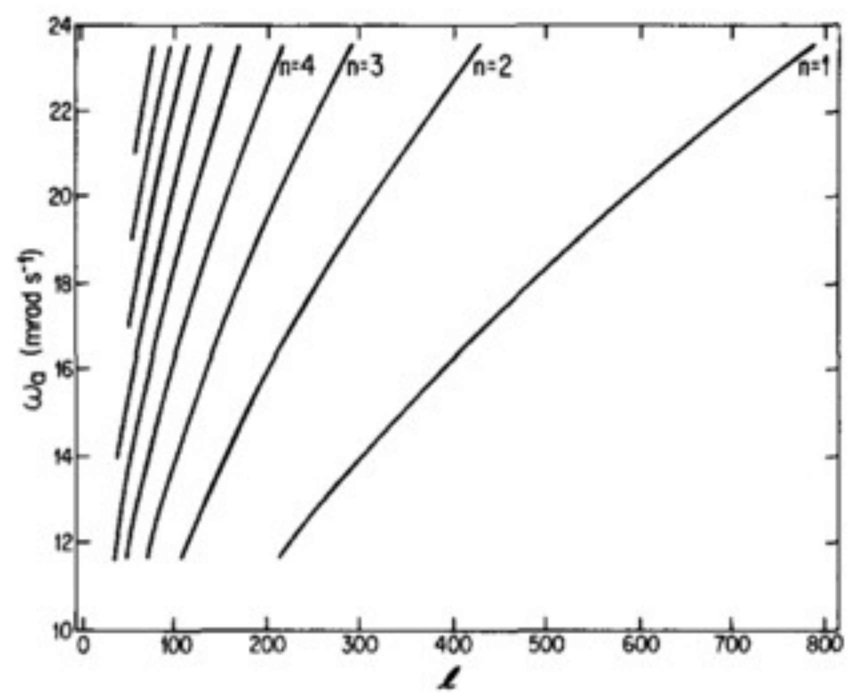

For eddy (or convective) velocities between 10 and 80 m sec^{-1} and length scales on the order of a scale height (~20 km at the 1-bar level), the periods of turbulent motions match well with the standing wave periods (4.5–9 min).

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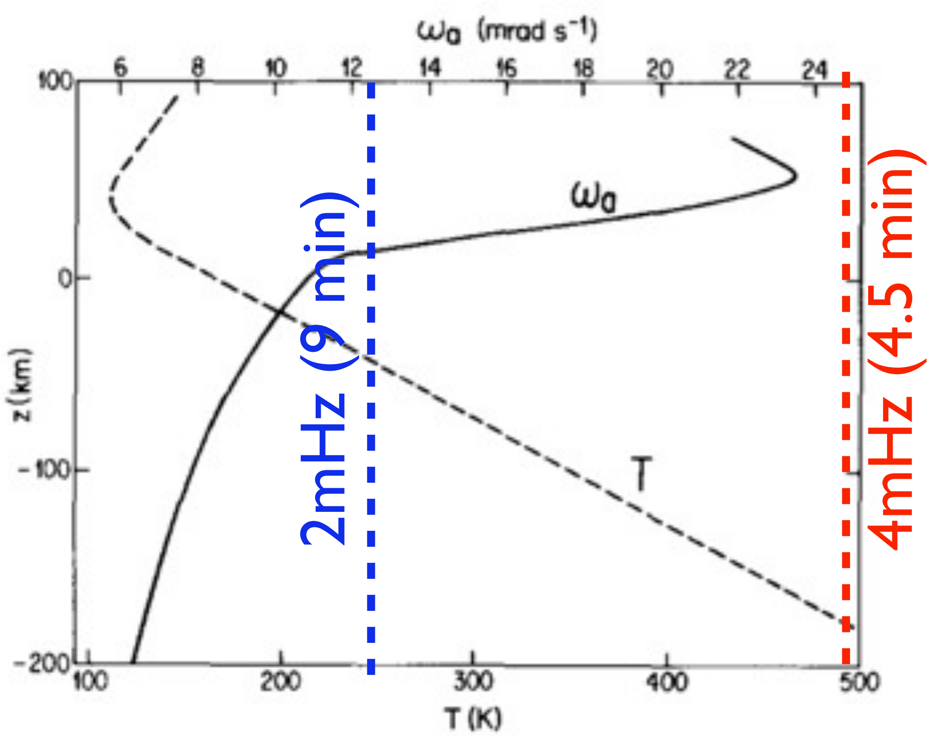

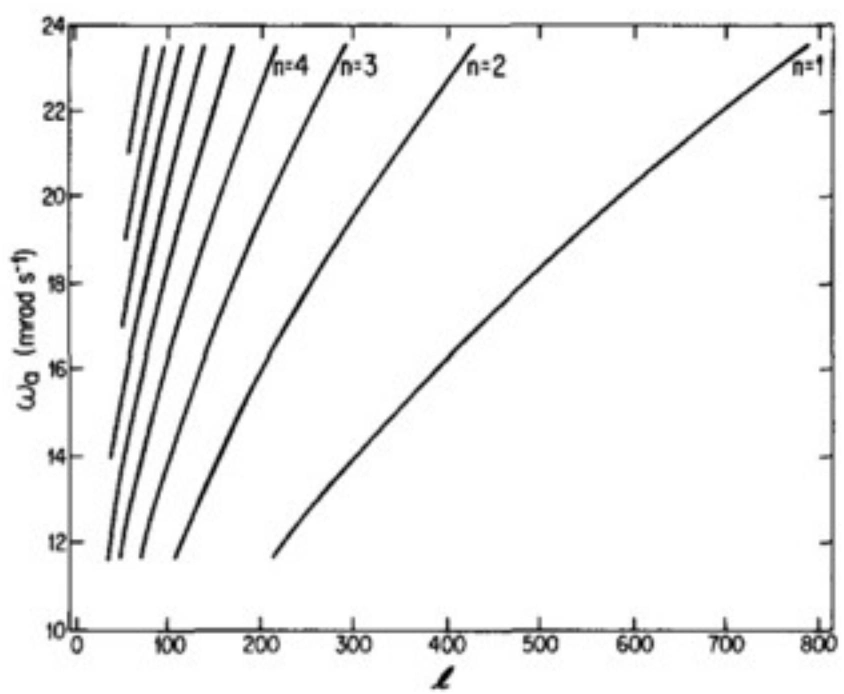

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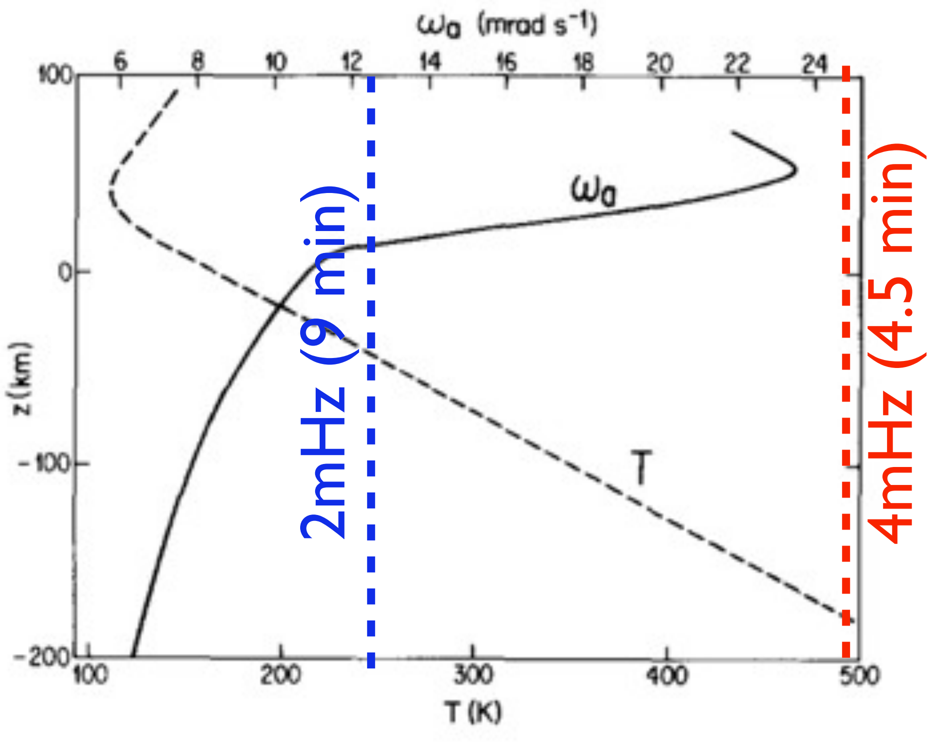

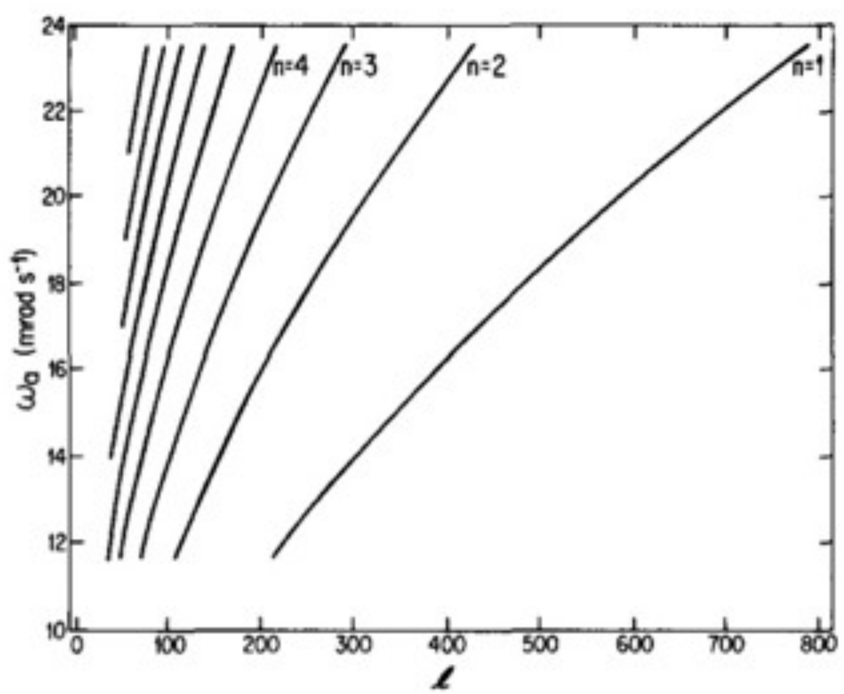

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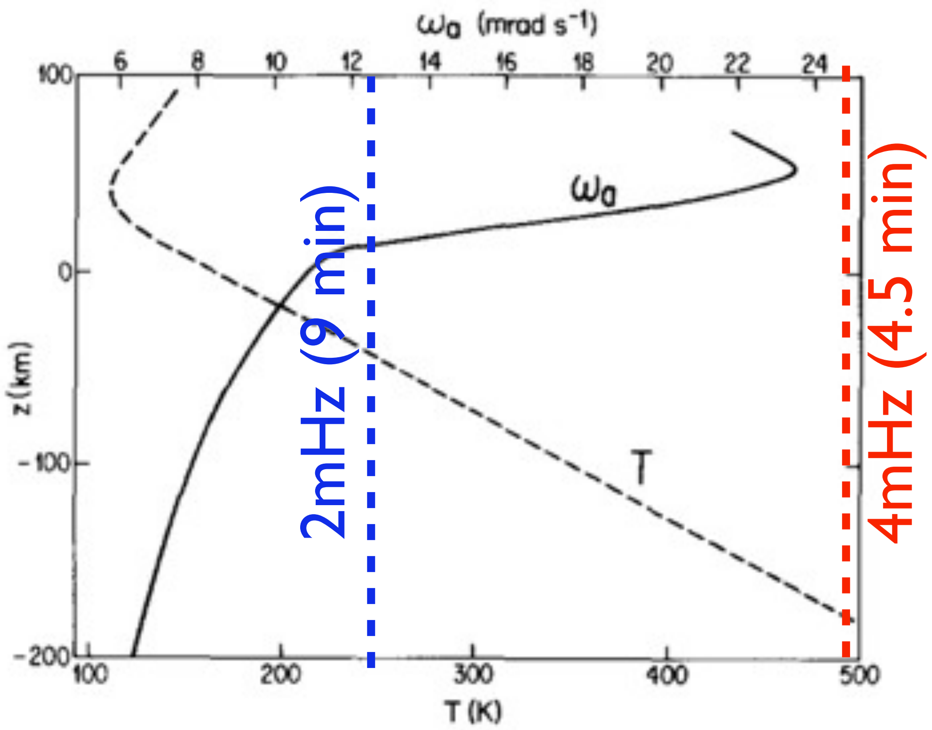

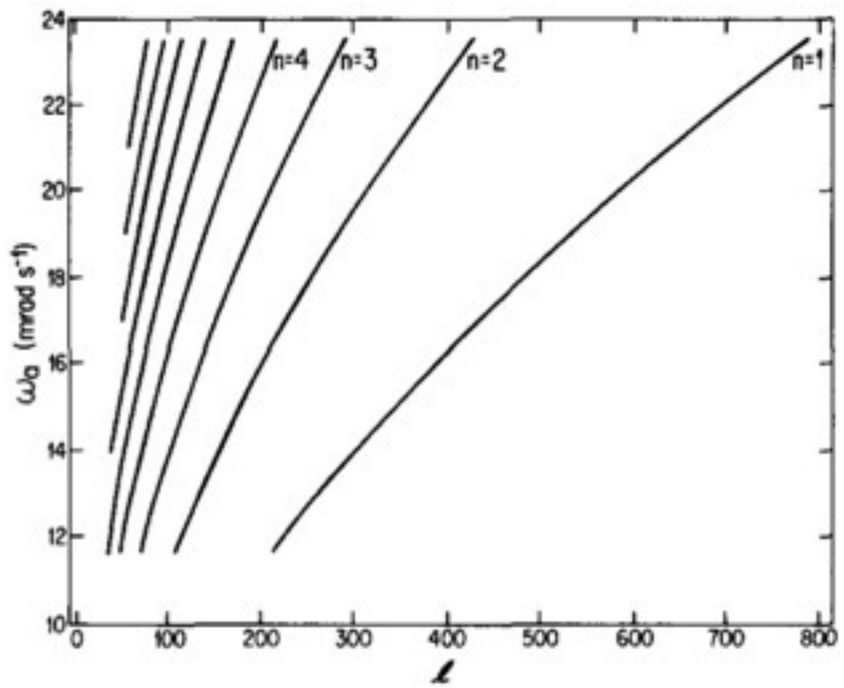

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=> u_0~0.5m/s

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  - $\tau_{lifetime} \sim \tau_{mode}$ $(Fw/\epsilon F_{tot})$ ~10mn (25000/(13600x1%)) ~ 1.3 days

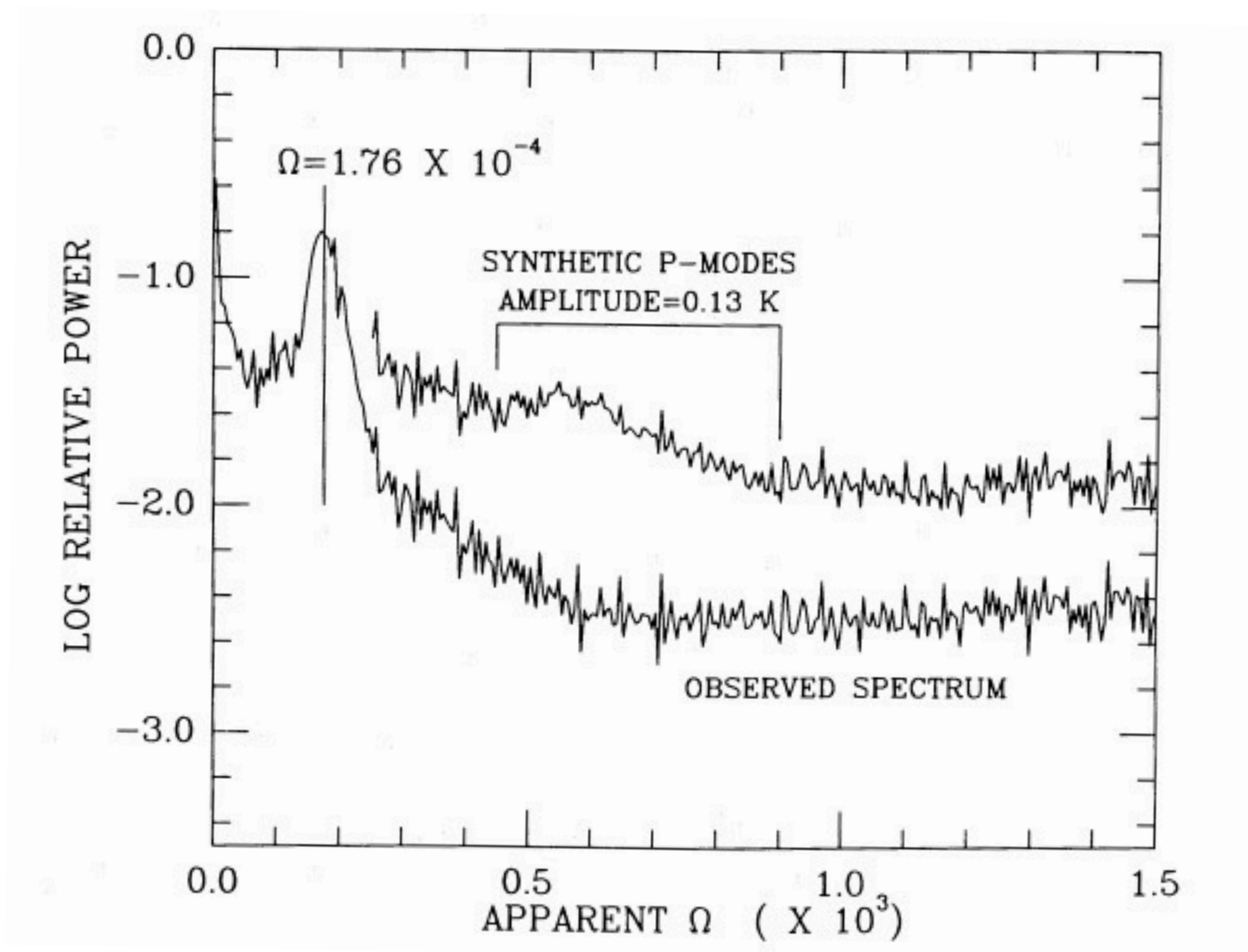
Theoretical bases

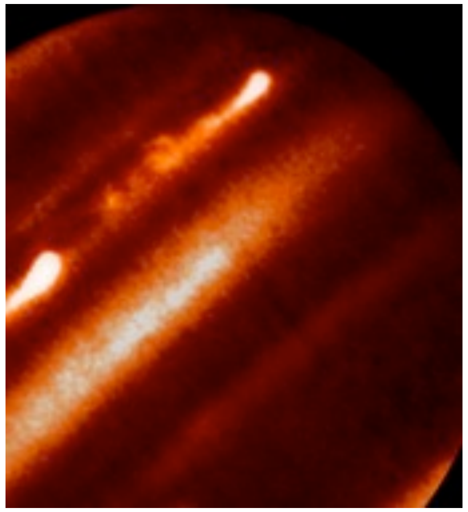
Vorontsov et al. (1974) and subsequent work: identification of free oscillation modes

Bercovici & Schubert (1987): Trapped high degree accoustic waves (form + excitation)

Standing acoustic waves, with periods between about 4.5 and 9 min, may be trapped in a wave duct beneath Jupiter's tropopause. Detection of these oscillations by observations of Doppler shifting of infrared and ultraviolet absorption lines would offer a new and important method for probing the giant planet's deep atmosphere and interior. Information would be revealed on Jupiter's thermal and density structure and the depth to which its zonal winds penetrate. Standing oscillations in the molecular hydrogen envelope are modeled and their theoretical eigenfrequencies are presented as they might appear in actual data analysis. Several forcing functions for wave generation are considered. These include coupling with turbulent and convective motions, thermal overstability due to radiative transfer, effects of wave propagation in a saturated atmosphere, and consequences of *ortho*- to *para*hydrogen conversion. Although the forcing mechanisms couple well with the acoustic waves, allowing for possible maintenance of the oscillations, the contribution they make to velocity amplitudes is very small, between 1.0 and 0.1 m sec^{-1}. This implies that the Doppler shifting caused by the waves may be unresolvable except, perhaps, by methods of superposing time records of oscillations to enhance acoustic signals and diminish random noise.

IR Observation



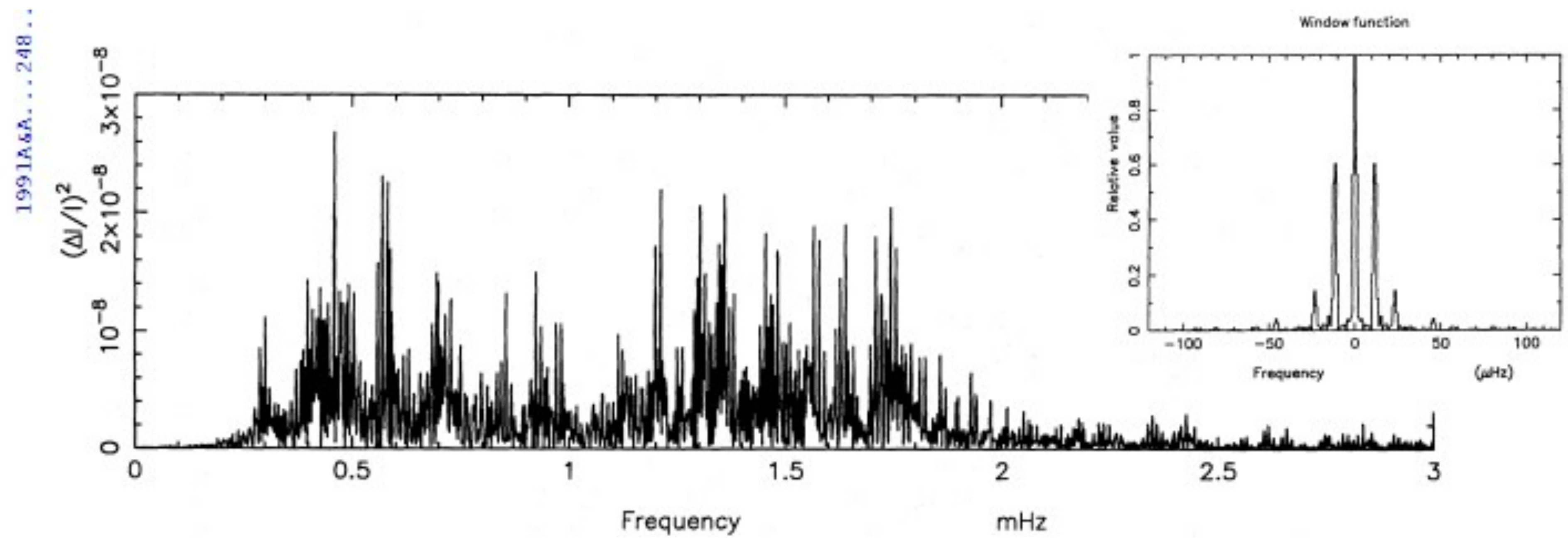


IRTF

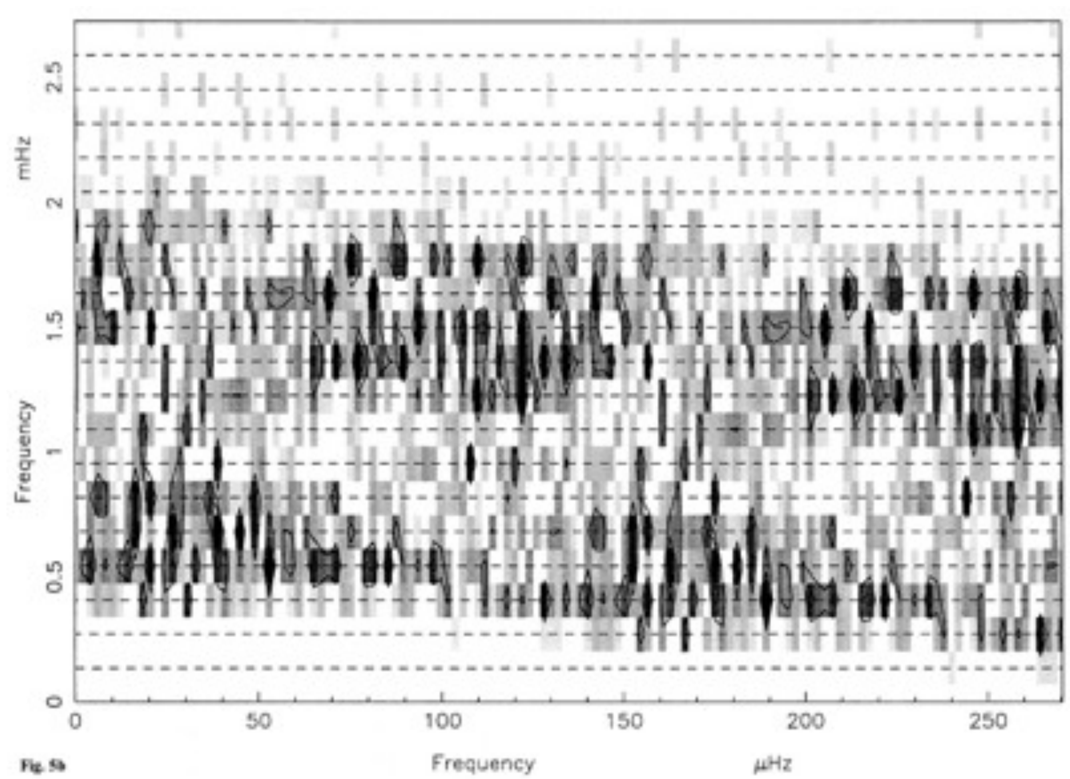
Deming et al. (1989)

No oscillation at the 0.07K level, equivalent to ~1m/s velocity

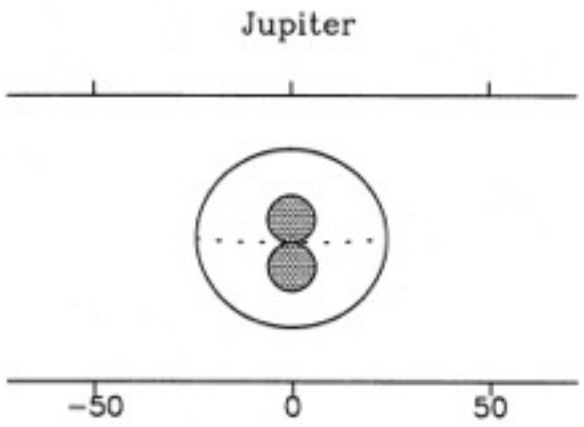
Doppler shift observations

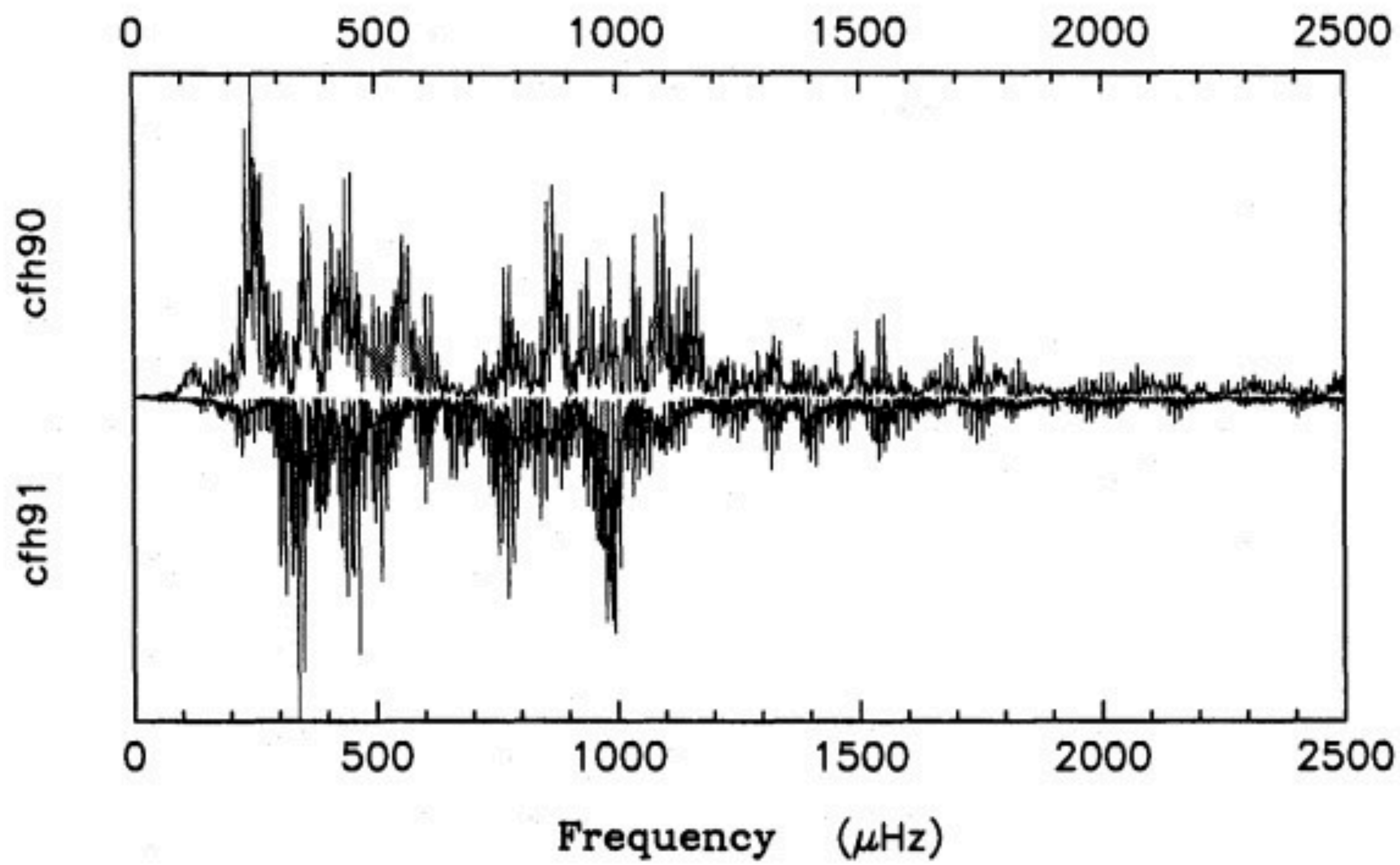


Schmider et al. (1991)

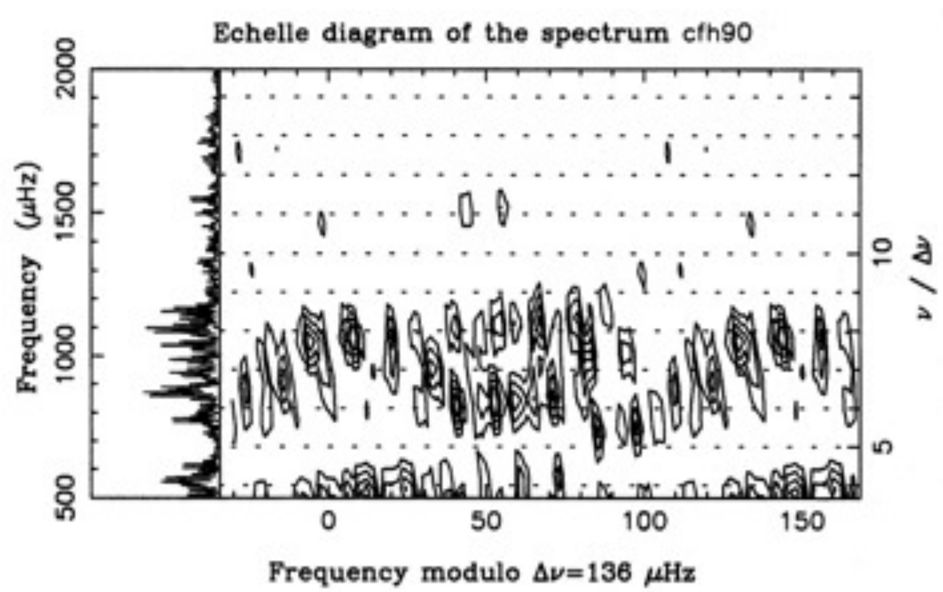


Fourier Transform Spectrometer Observations





Mosser et al. (1993)



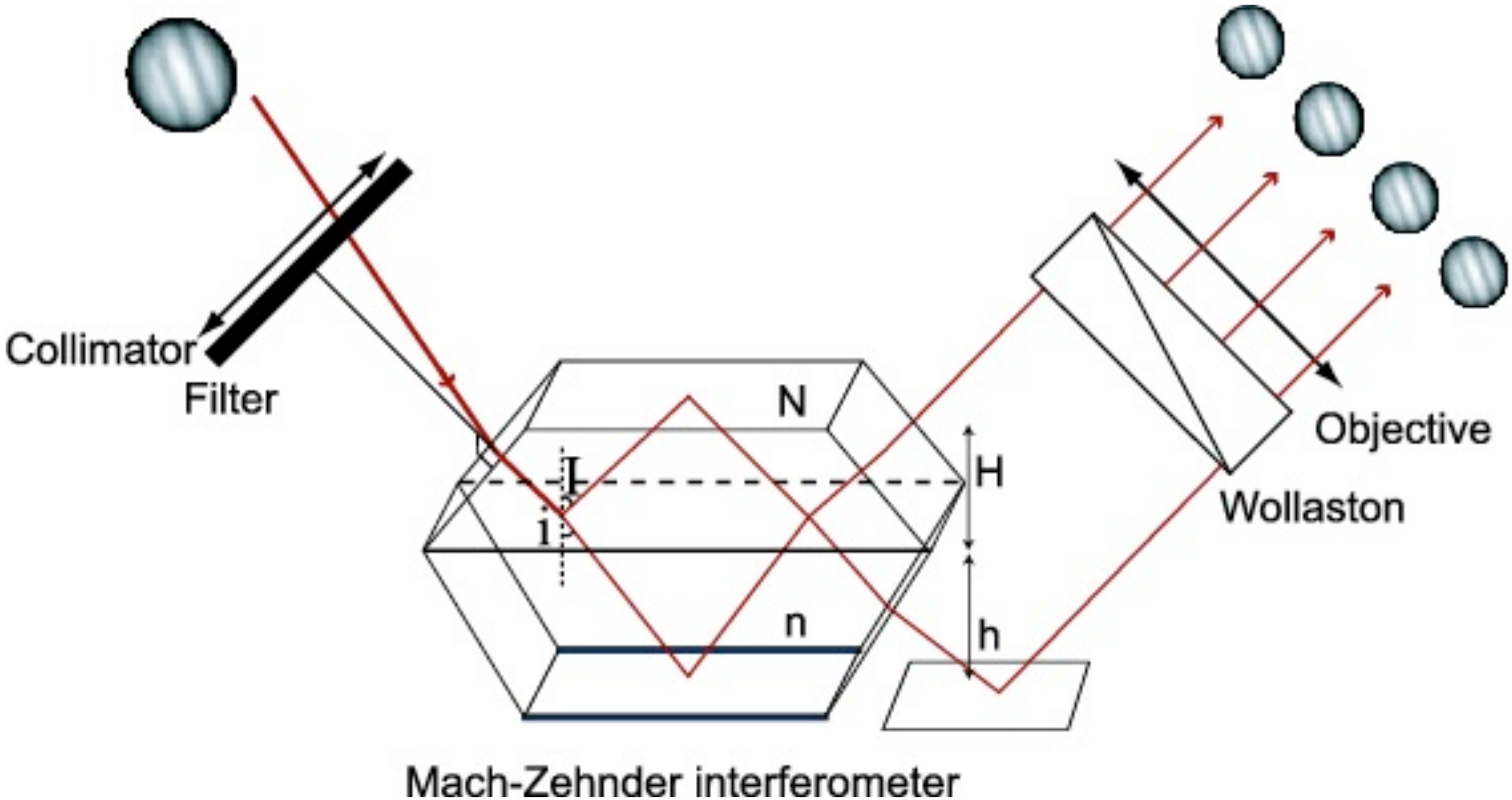
Other works

- Marley & Porco (1992): Resonance of f-modes, possible gaps in Saturn's rings
- Provost et al. (1993): Asymptotic calculation with jovian core
- Lee (1993): Non-perturbative approach including rotation
- Mosser et al. (1994): Link with the observables
- Gudkova et al. (1995): Influence of the troposphere & core, inverse problem
- Lederer & Marley (1995): Power spectrum contaminated by albedo features at f<700mHz, but not above

SYMPA

Seismographic Imaging Interferometer for Monitoring of Planetary Atmospheres

Magnesium triplet: 517nm



Schmider et al. A&A (2007)
Gaulme et al. A&A (2008)

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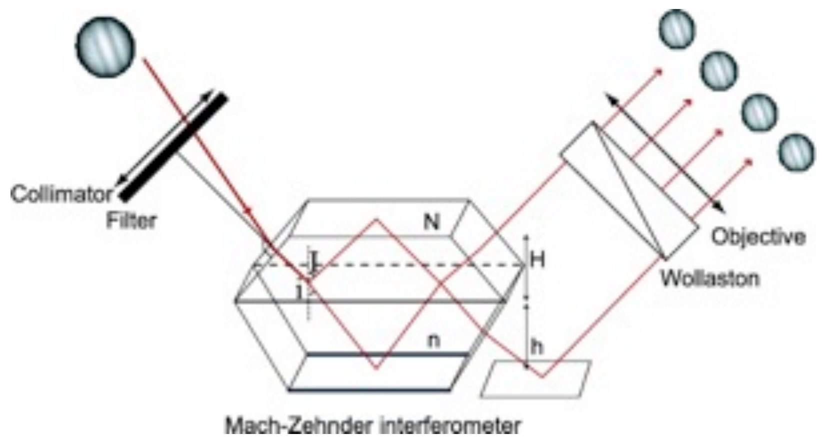


fringe contrast

$$I_1(x,y) = \frac{I_0(x,y)}{4}\left[1 - \gamma\cos\phi(x,y)\right]$$
$$I_2(x,y) = \frac{I_0(x,y)}{4}\left[1 - \gamma\sin\phi(x,y)\right]$$
$$I_3(x,y) = \frac{I_0(x,y)}{4}\left[1 + \gamma\cos\phi(x,y)\right]$$
$$I_4(x,y) = \frac{I_0(x,y)}{4}\left[1 + \gamma\sin\phi(x,y)\right]$$

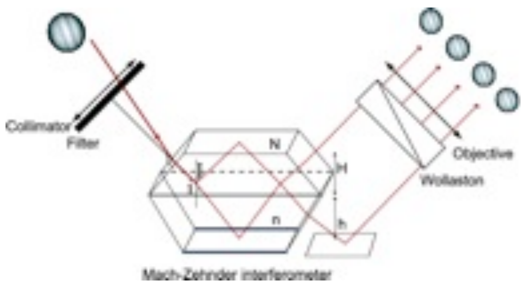
wave phase map: $\phi(x,y) = 2\pi\sigma_0\Delta(x,y)\left(1 + \frac{v_D}{c}\right)$

$$U = \frac{I_1 - I_3}{I_1 + I_3} \propto \gamma\cos\phi$$
$$V = \frac{I_2 - I_4}{I_2 + I_4} \propto \gamma\sin\phi$$

$$Z = U + iV \propto \gamma\, e^{i\phi}.$$

$$Z_{J,flat} = Z_{jup} \times Z_0^* \times Z_{J,rot}^* Z_{E,rot}^* \times Z_{E/J}^* \times Z_{J/S}^* \propto \exp\left(i4\pi\sigma_0\Delta\frac{v_{osc}}{c}\right)$$

Gaulme et al. A&A (2008)



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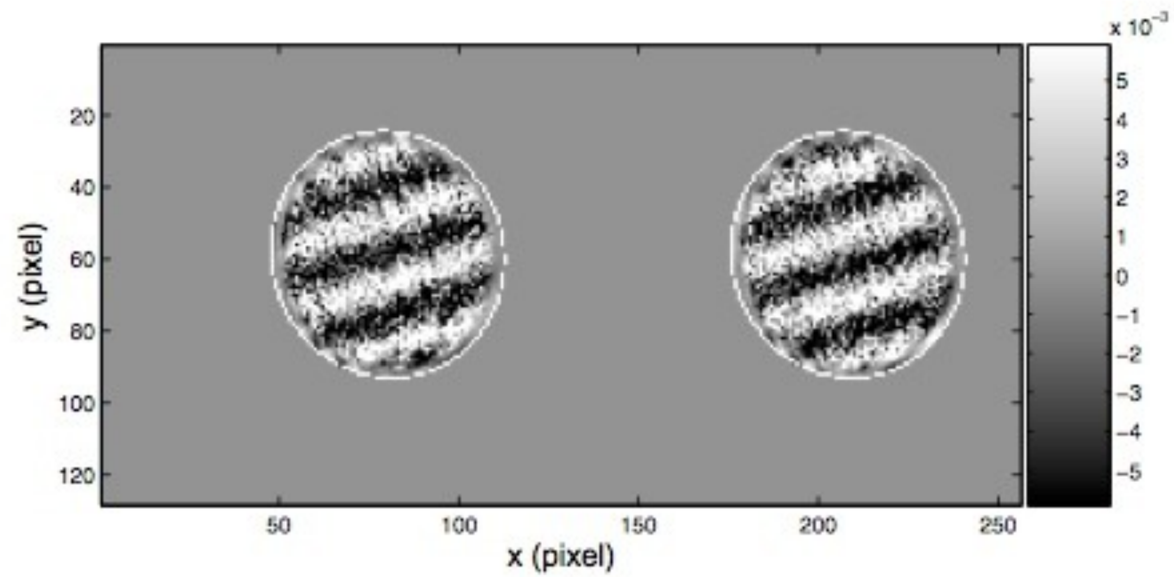
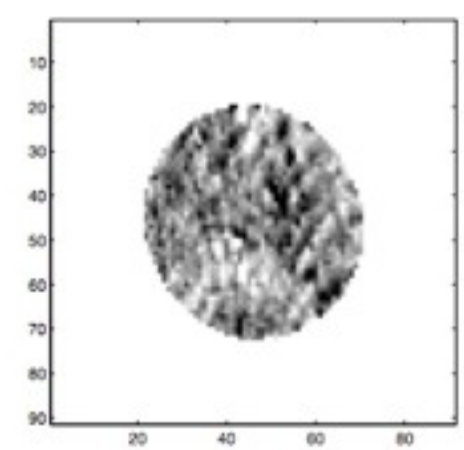
$$
\begin{aligned}
Z_{\mathrm{J,flat}} &= Z_{\mathrm{jup}} \times Z_0^* \times Z_{\mathrm{J,rot}}^* Z_{\mathrm{E,rot}}^* \times Z_{\mathrm{E/J}}^* \times Z_{\mathrm{J/S}}^* \\
&\propto \exp\left(\mathrm{i}4\pi\sigma_0\Delta\frac{v_{\mathrm{osc}}}{c}\right)
\end{aligned}
$$

Jupiter’s rotation:

$$Z_{\mathrm{j,rot}} = Z_{\mathrm{jup}} \times Z_0^*.$$



Final velocity map (averaged over 5 mins):



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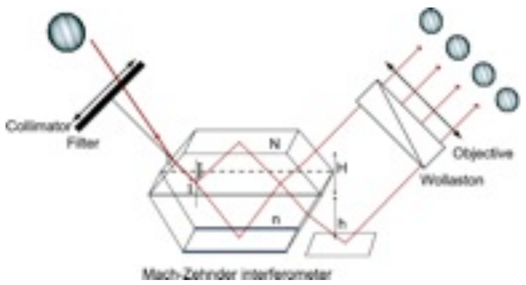
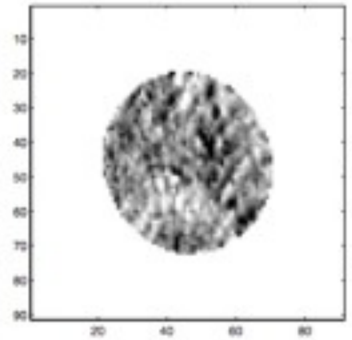
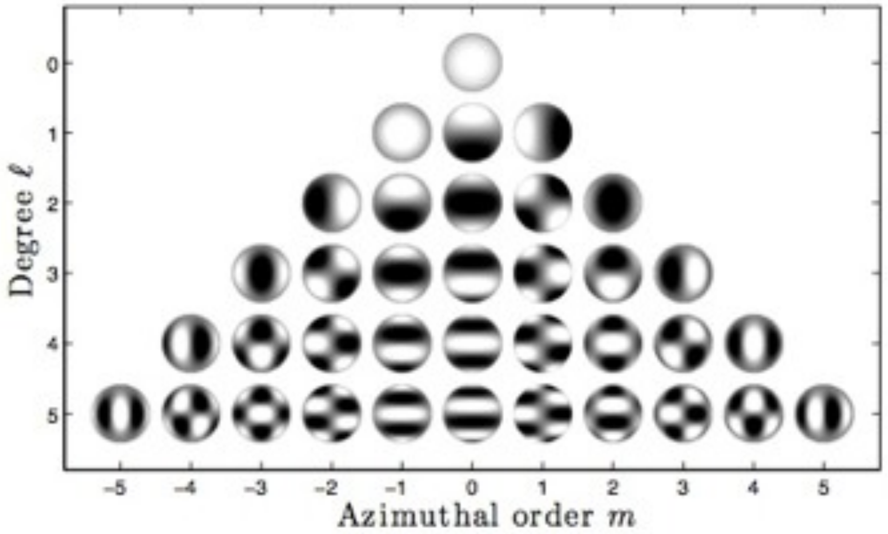


SYMPA: data analysis

velocity map

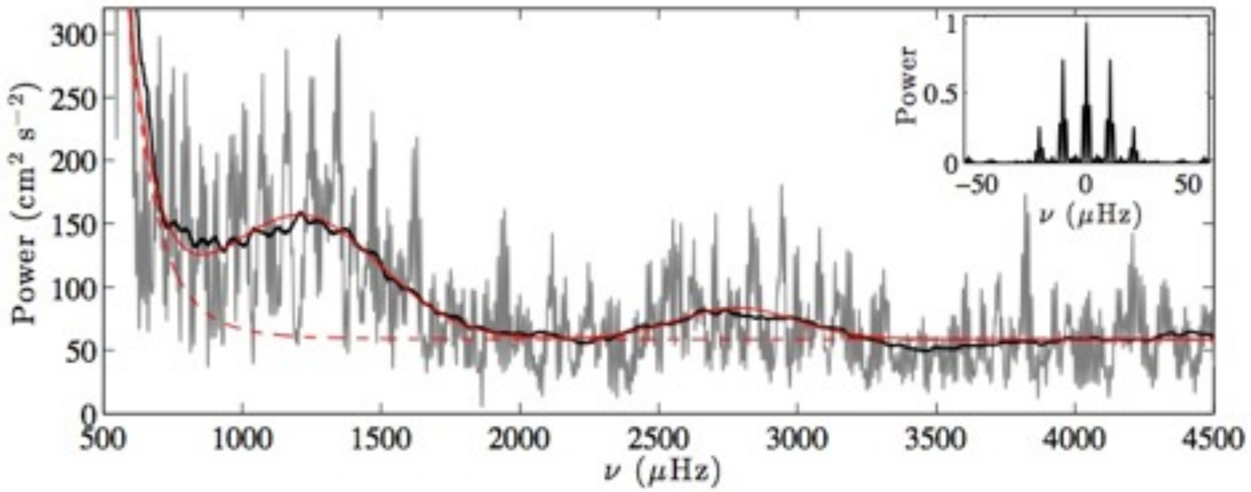


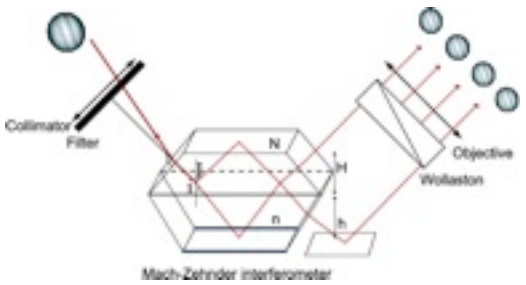
Ylm basis:



Sum of the time series l,m=1,0 & 1,+/-1

Power spectrum:





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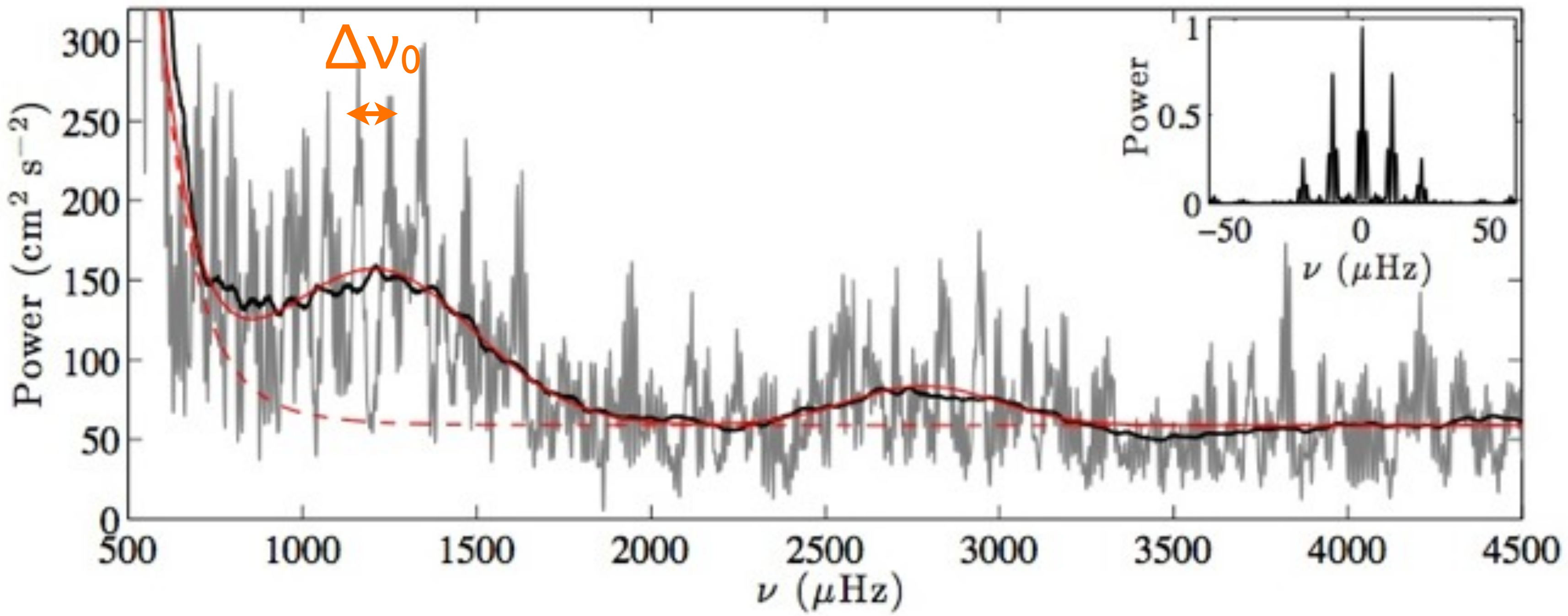
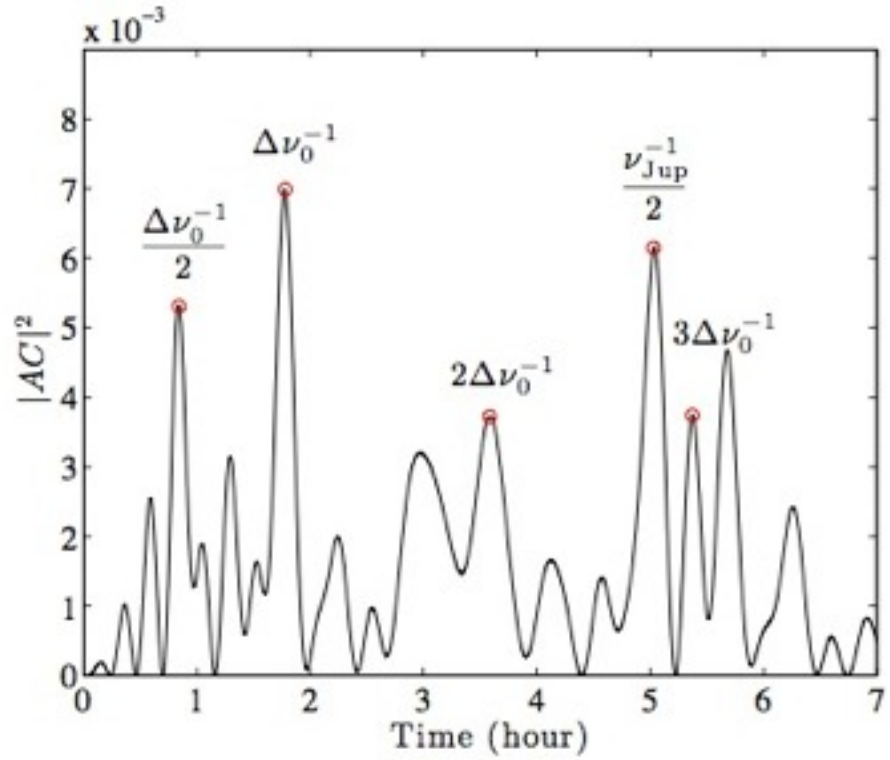
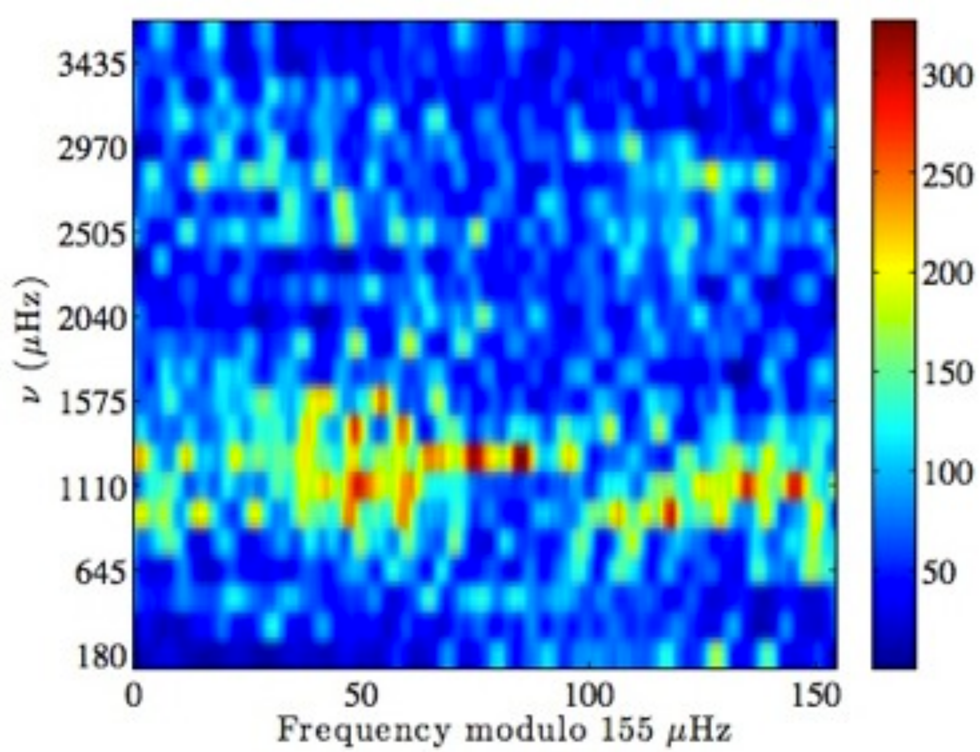


Power spectrum of the power spectrum:



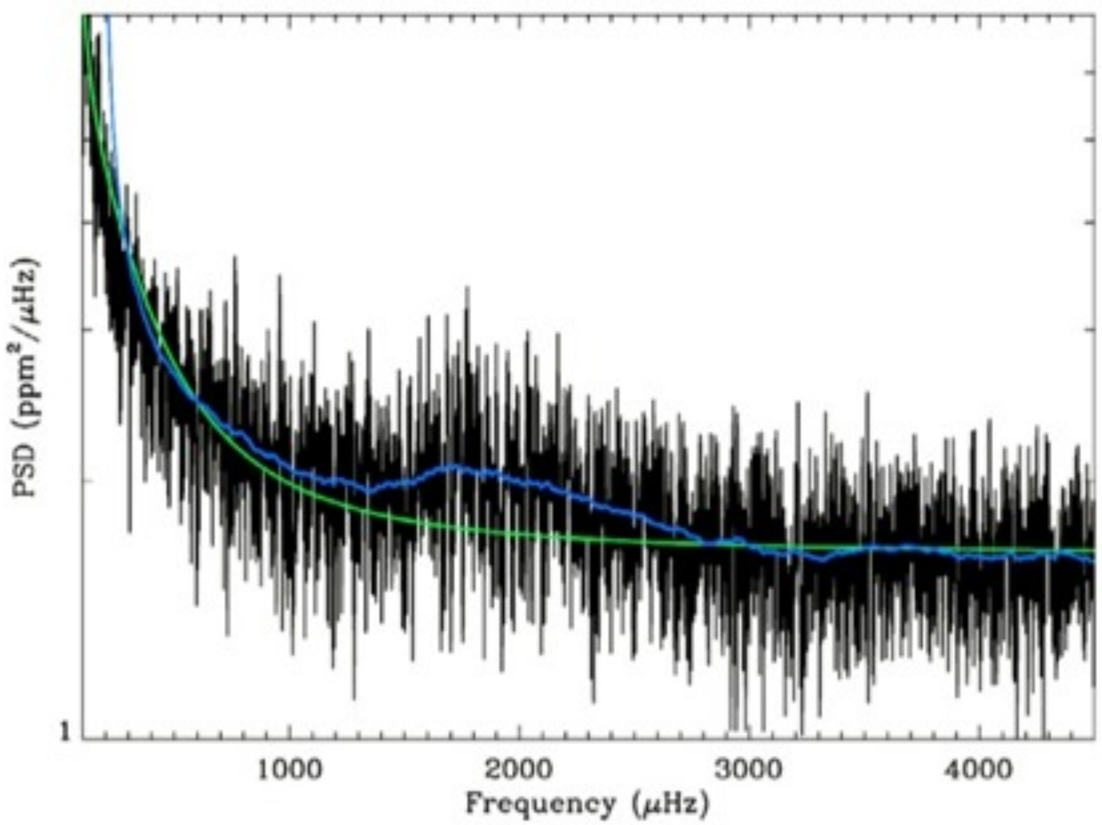
Gaulme et al. A&A (2011)

Echelle diagram



Analysis of a CoRoT lightcurve

Power spectrum of HD 181906:



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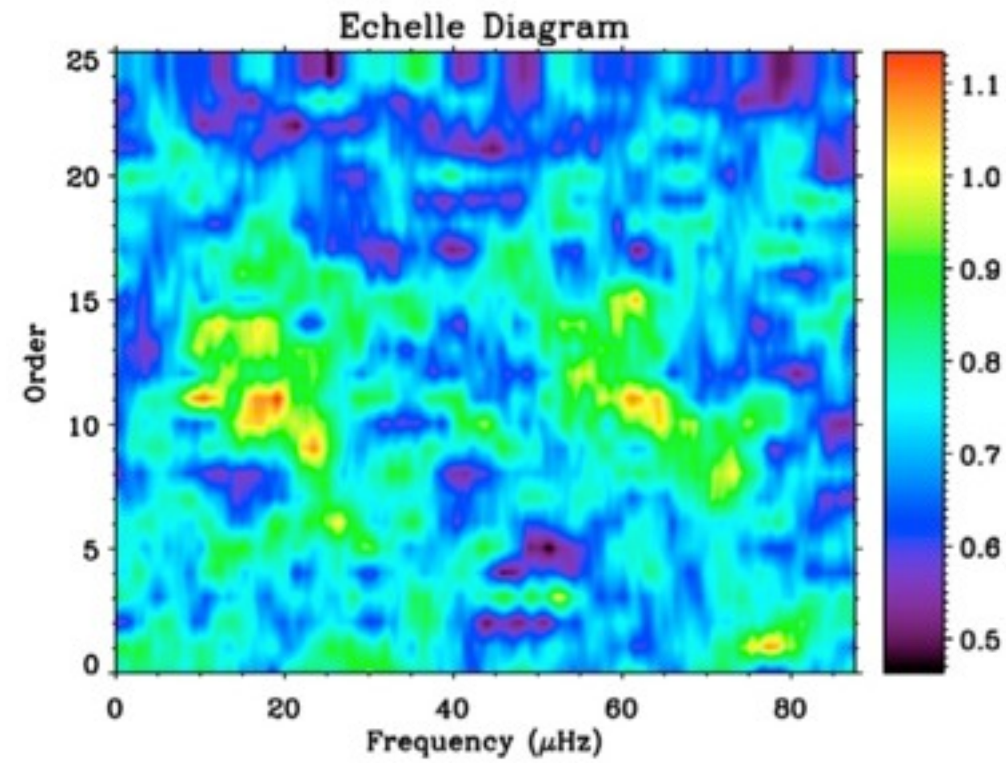
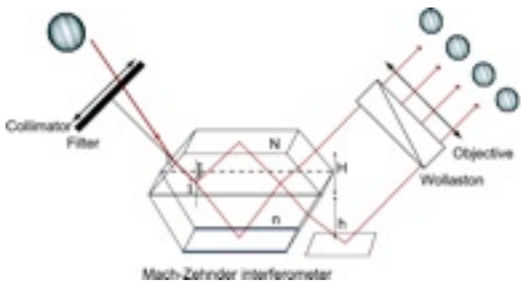


$\Delta\nu = 87.5 \pm 2.6\ \mu\text{Hz}$

Comparison with other stars

Stars	HD 181906 this paper	HD 49933 Appourchaux et al. (2008)	HD 181420 Barban et al. (2009)	HD 175726 Mosser et al. (2009b)	Procyon Arentoft et al. (2008)
Spectral type	F8	F5	F2	F9/G0	F5
$T_{\rm eff}$	6300 ± 150 K	6780 ± 130 K	6580 ± 105 K	6000 ± 100 K	6514 ± 27 K
[Fe/H]	−0.11 ± 0.14 dex	−0.37 dex	0.00 ± 0.06 dex	−0.22 ± 0.1 dex	−0.05 dex
$v \sin i$	10 ± 1 km s^{-1}	9.5 – 10.9 km s^{-1}	18 ± 1 km s^{-1}	13.5 ± 0.5 km s^{-1}	3.16 ± 0.5 km s^{-1}
$\Delta\nu$	87.5 ± 2.6 µHz	85.9 ± 0.15 µHz	~75 µHz	~97µHz	~55 µHz
$\nu_{\rm max}$	1900 µHz	1760 µHz	1500 µHz	2000 µHz	900 µHz
$A_{\rm max}$	3.26 ± 0.42 ppm	4.02 ± 0.57 ppm	3.82 ± 0.40 ppm	~1.7 ppm	~8.5 ppm

Garcia et al. (2009)



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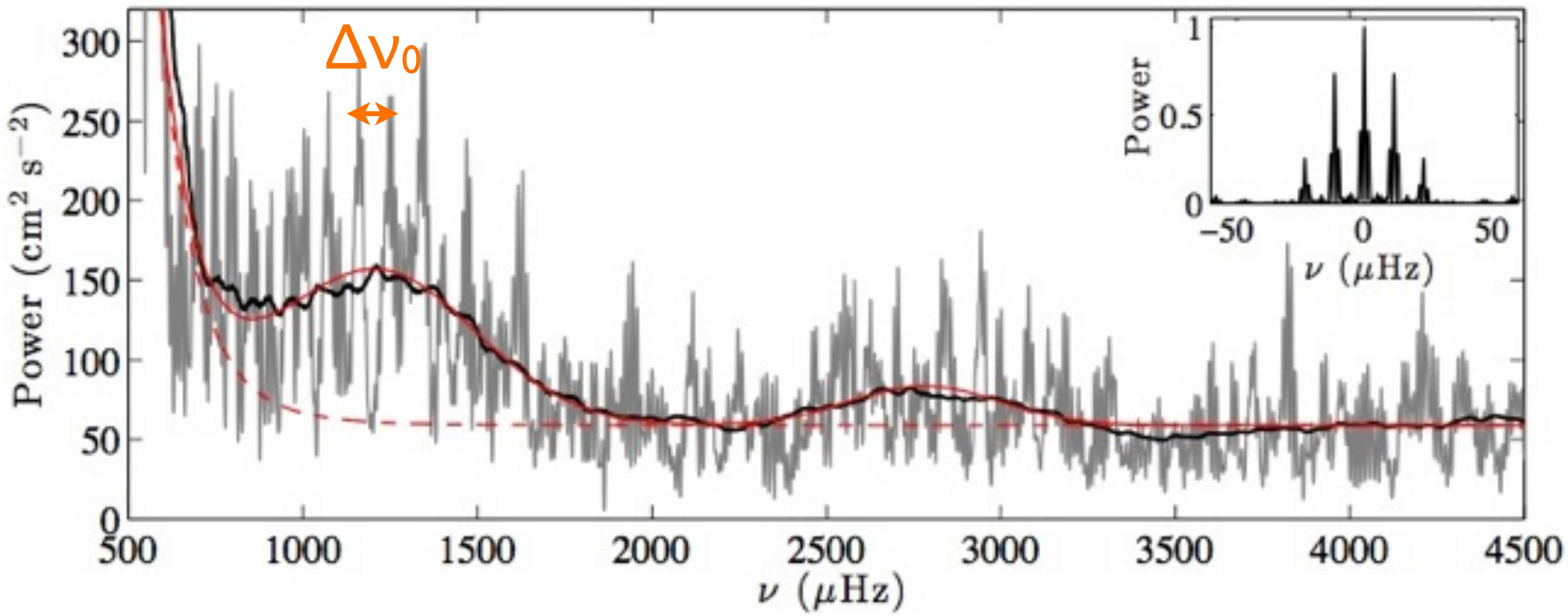
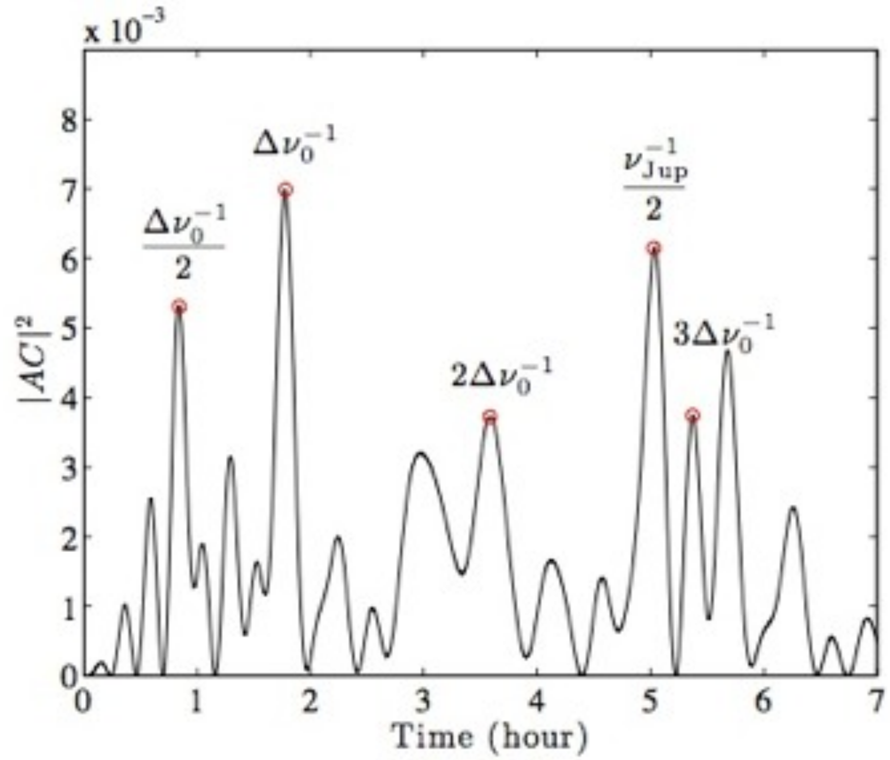


Power spectrum of the power spectrum:



Gaulme et al. A&A (2011)

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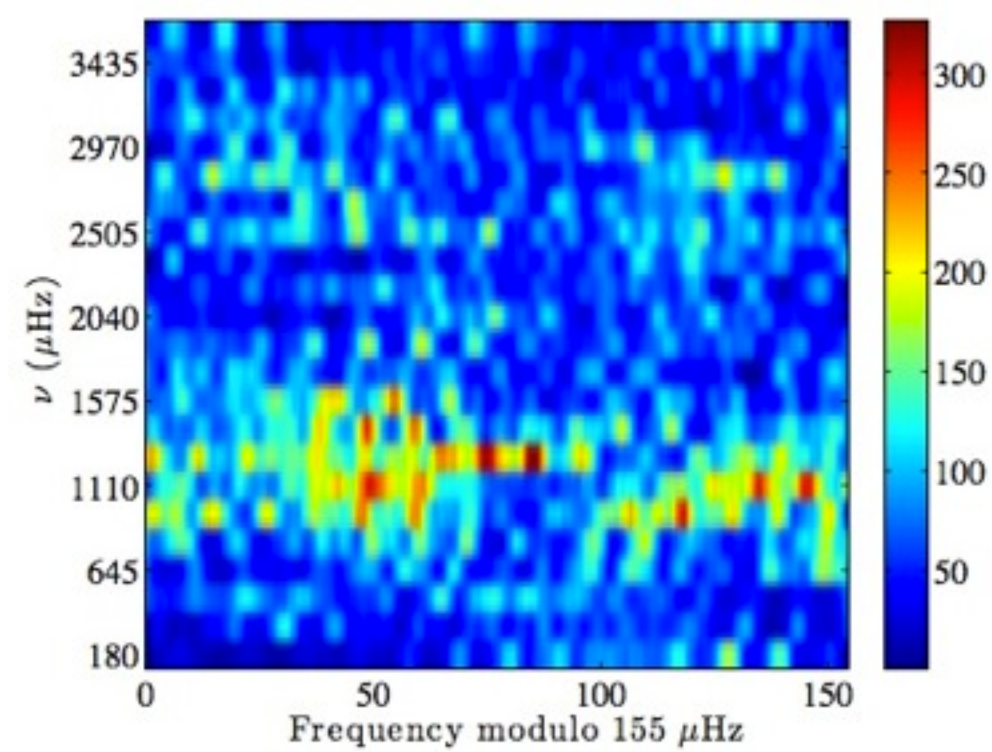

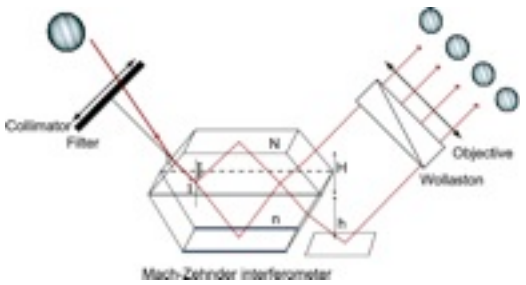

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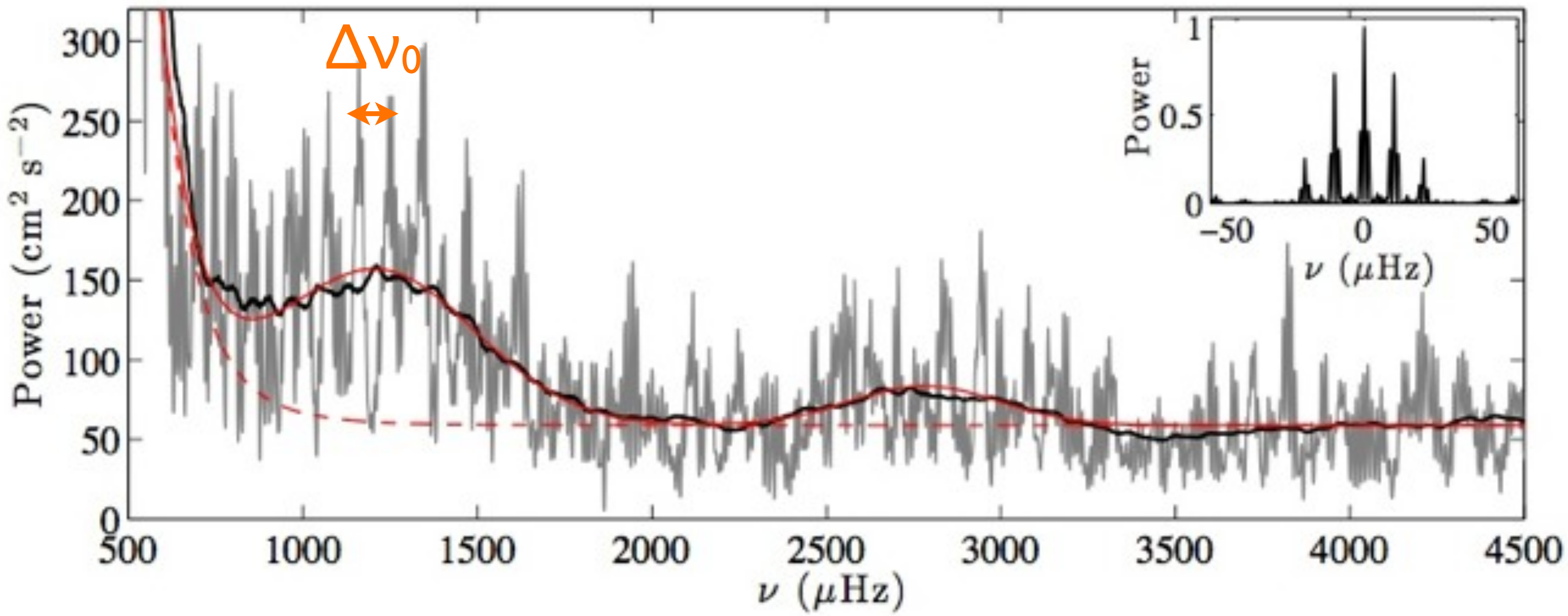


Frequencies & amplitudes
of the peaks:

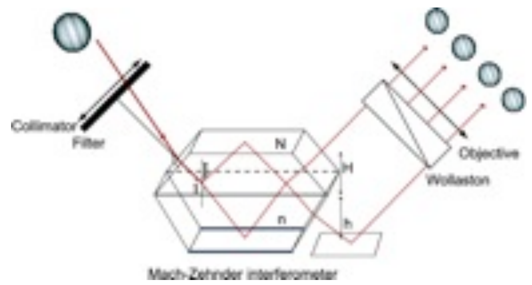
ν μHz	Velocity cm s^{-1}	Error cm s^{-1}	ν μHz	Velocity cm s^{-1}	Error cm s^{-1}
792	44.0	-6.2/+3.9	1478	46.4	-6.5/+4.1
854	46.7	-6.6/+4.2	1533	37.3	-5.3/+3.3
915	34.1	-4.8/+3.0	1615	40.9	-5.8/+3.7
970	48.7	-6.9/+4.4	1753	33.0	-4.6/+2.9
1011	51.4	-7.2/+4.6	1939	32.0	-4.4/+2.8
1066	45.7	-6.4/+4.1	2110	30.1	-4.2/+2.7
1094	42.4	-6.0/+3.8	2535	30.3	-4.3/+2.7
1162	54.1	-7.6/+4.8	2714	30.6	-4.3/+2.7
1245	53.8	-7.6/+4.8	2837	36.2	-5.1/+3.2
1341	51.5	-7.3/+4.6	2947	41.1	-5.8/+3.7
1410	40.7	-5.7/+3.6	3071	30.7	-4.3/+2.7

Gaulme et al. A&A (2011)

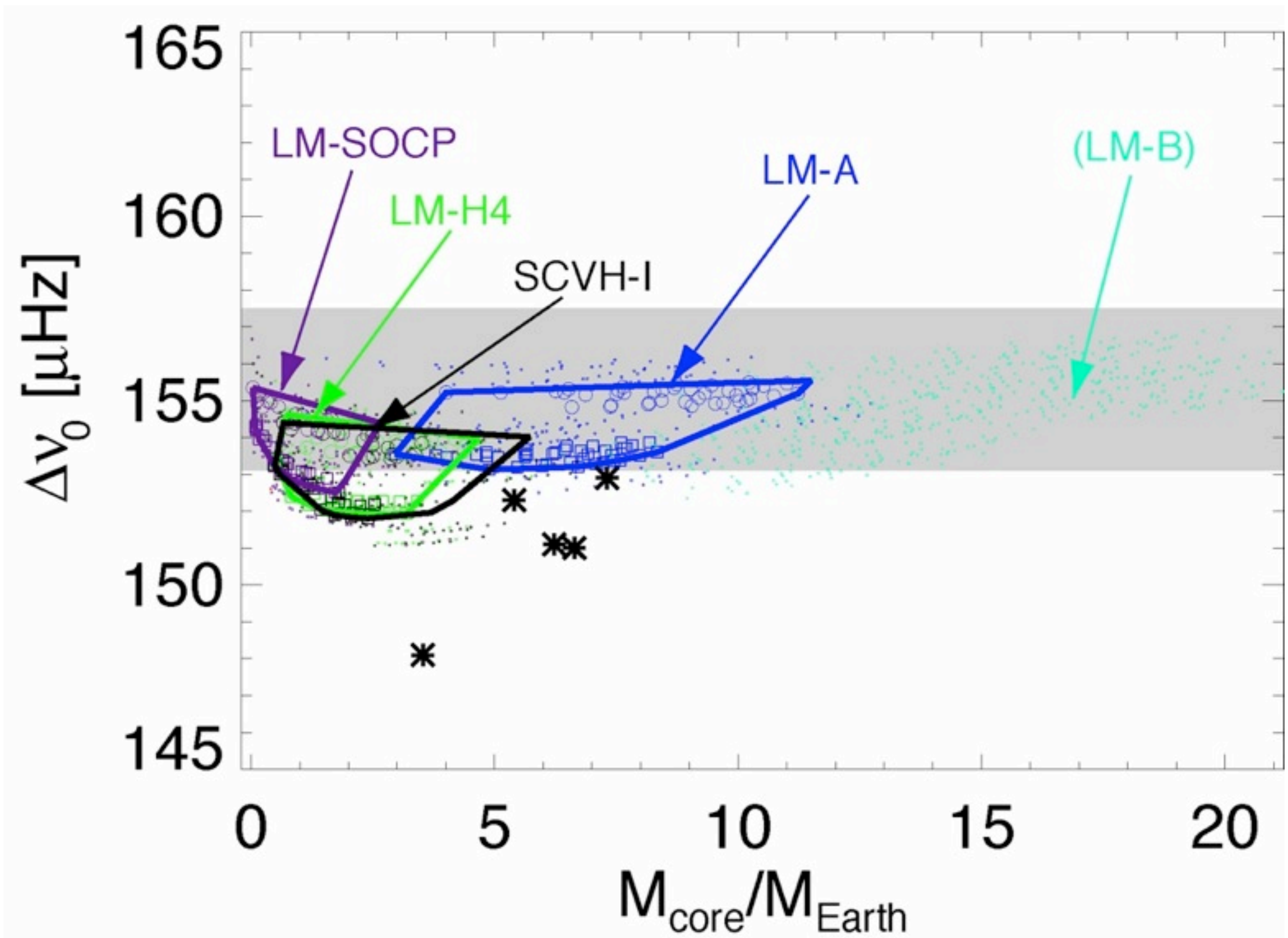
Oscillation frequencies

$$\nu_{\max} = 1213 \pm 50 \ \mu\text{Hz}$$

$$\Delta\nu_0 = 155.3 \pm 2.2 \ \mu\text{Hz}.$$



SYMPA & interior models



Gaulme et al. A&A (2011)

T. Guillot 28 oct 2011

What is next?

- Juno's arrival at Jupiter in 2016
  - Accurate gravity field measurements (up to J10 and beyond)
  - Accurate mapping of the magnetic field
  - Constraints on the deep water abundance (radiometry)

- JUICE: an ESA mission to the Jupiter-system
  - Proposal for an on-board sismometer called DSI-ECHOES (PI: F-X Schmider)

- Future ground-based observations
  - Jupiter is becoming a good target again for Northern hemisphere observations