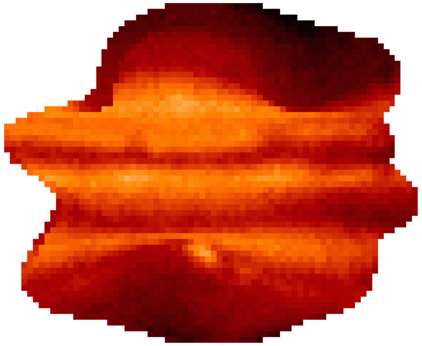
Giant planet seismology



Benoît Mosser
Observatoire de Paris
LESIA

Outline

- Precursory work
- Seismology of giant planets
  - what we know, what we imagine, what we ignore
  - lessons from stars
- From past observations to JOVIAL

Adiabatic oscillations

ICARUS **27**, 109–118 (1976)

The Free Oscillations of Jupiter and Saturn

S. V. VORONTSOV, V. N. ZHARKOV, AND V. M. LUBIMOV

Department of Theoretical Physics, Institute of Physics of the Earth,
Academy of Sciences of the U.S.S.R., Moscow, U.S.S.R.

Received February 21, 1975

The periods and the eigenfunctions have been calculated for the fundamental modes and for the overtones of spheroidal oscillations of Jupiter and Saturn. Along with ordinary oscillations, the core oscillations appear; these eigenfunctions are localized in the planetary core and have an exponential attenuation to the surface. The rotational splittings of the free oscillations have been calculated. Because of rapid planetary rotation, these splittings were found to be of the order of differences between undisturbed frequences. The idea is proposed that the rotational splitting of the spectrum of Saturn may present in the future the unique possibility of determining the bodily rotation period of the planet.

Seismic signal: forcing mechanism, observations

ICARUS 69, 557–565 (1987)

Theoretical expectation
~ 50 cm/s

Jovian Seismology

D. BERCOVICI AND G. SCHUBERT

Department of Earth and Space Sciences, University of California, Los Angeles, California 90024

Received July 31, 1986; revised October 28, 1986

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.

THE ASTROPHYSICAL JOURNAL, 343:456–467, 1989 August 1

IR observations

A SEARCH FOR *p*-MODE OSCILLATIONS OF JUPITER: SERENDIPITOUS OBSERVATIONS OF NONACOUSTIC THERMAL WAVE STRUCTURE

DRAKE DEMING,[1] MICHAEL J. MUMMA, FRED ESPENAK, DONALD E. JENNINGS,[1] AND THEODOR KOSTIUK
Planetary Systems Branch, NASA/Goddard Space Flight Center

GUNTER WIEDEMANN[1,2]
Technical University of Munich; and Max-Planck Institute for Extraterrestrial Physics, Garching

ROBERT LOEWENSTEIN
Department of Astronomy and Astrophysics, University of Chicago

AND

JOSEPH PISCITELLI
Institute for Astronomy, University of Hawaii at Manoa
Received 1988 November 2; accepted 1989 January 4

Negative observation
< 1 m/s

ABSTRACT

We have computed frequencies for *p*-mode oscillations of Jupiter and have used a sensitive observational technique to search for the modes. Because of the long radiative damping time, Jovian *p*-modes will be more adiabatic than in the solar case, and infrared brightness temperature fluctuations represent a sensitive method for their detection. We observed the infrared intensity of the Jovian disk in a broad bandwidth (8–13 μm), using a 20 element linear array. Our measurements were made as a function of longitude, giving maximum sensitivity for sectoral modes, at 20° N and at the equator. No *p*-mode oscillations were seen at the ~0.07 K level in 8–13 μm brightness temperature (equivalent to 1 m s^{-1} in velocity). Applying the Goldreich and Kumar theory for the equilibrium of acoustic energy with turbulence, we conclude that Jovian *p*-modes are not likely to have observable amplitudes. Our observations are consistent with the theoretical expectation that other modes of oscillation, such as occur under the influence of a strong Coriolis force, may provide more useful probes of the Jovian interior. Our data serendipitously reveal the existence of a prominent, nonacoustic, wavelike structure in the 8–13 μm brightness temperature, which occurs both at 20° N and at the equator. This structure was unchanged over two Jovian rotations, implying a very low frequency for the wave. This thermal wave structure is similar in amplitude and spatial scale to the slowly moving thermal features recently discovered in the *Voyager* IRIS data by Magalhães *et al.*, and which these authors attribute to a "deeply-rooted fluid dynamical regime beneath the surface meteorology."

Subject headings: hydrodynamics — planets: atmospheres — planets: Jupiter — wave motions

Jovian seismology

Adiabatic oscillations (François-Xavier Schmider's, Jason Jackiewicz's talk)

Fluid interior: $\Delta\nu_{Jupiter} \sim \Delta\nu_{\odot}$ but $\nu_{max,Jupiter} < \Delta\nu_{max,\odot}$

Rapid rotation, non-negligible oblateness

Forcing mechanism (Ethan Dederick's talk)

Forcing mechanism?

Interior structure (Tristan Guillot's talk)

Size and nature of the core

Bulk composition / heavy elements / mixing process

EOS at high pressure and degenerate conditions

Rotation profile

Observational answers

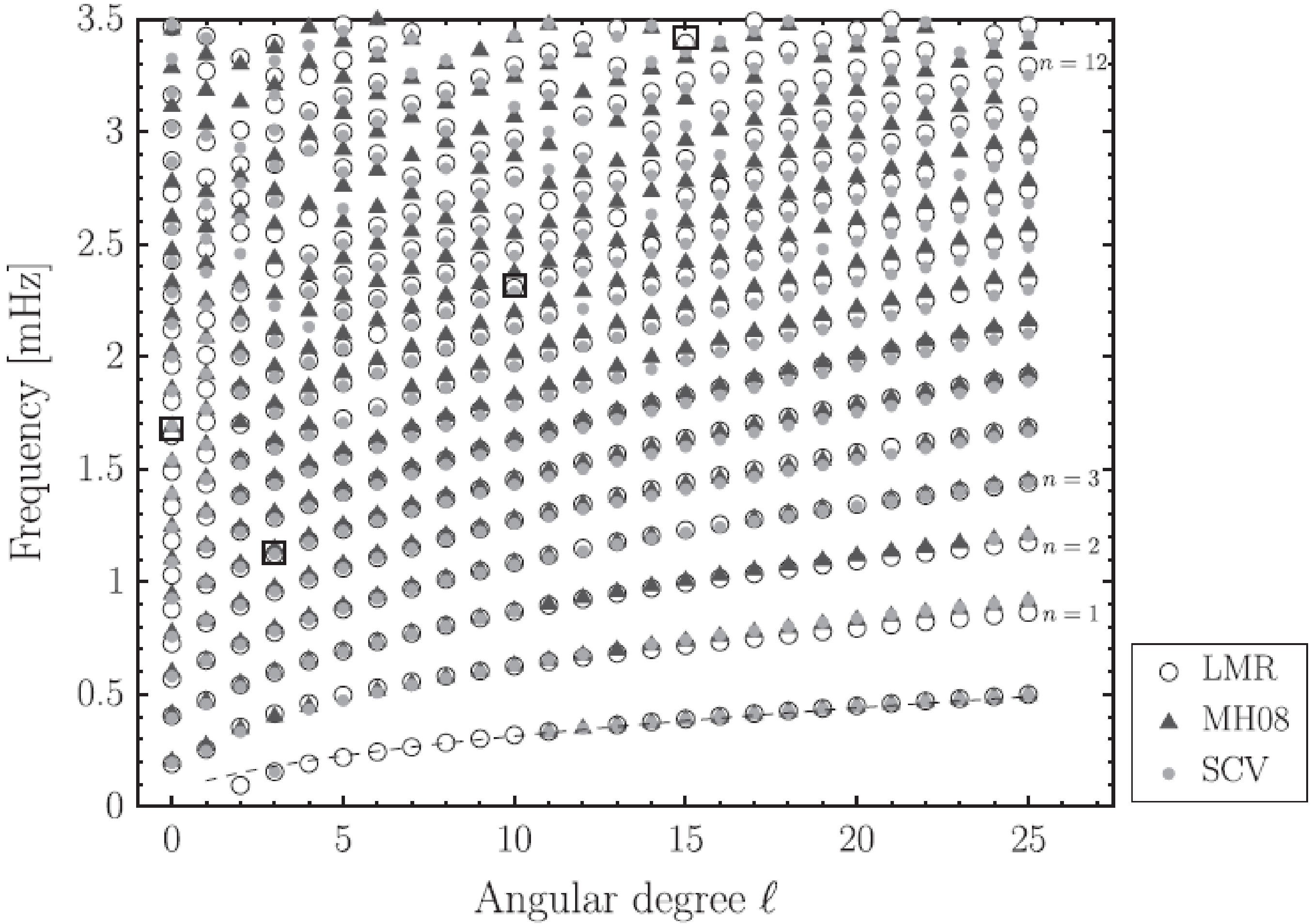
Gravitational moments; Juno?

Seismic observations

[+ Saturn rings seismology (Mark Marley's talk)]

Direct problem

Jackiewicz et al. 2012, Icarus 220, 844



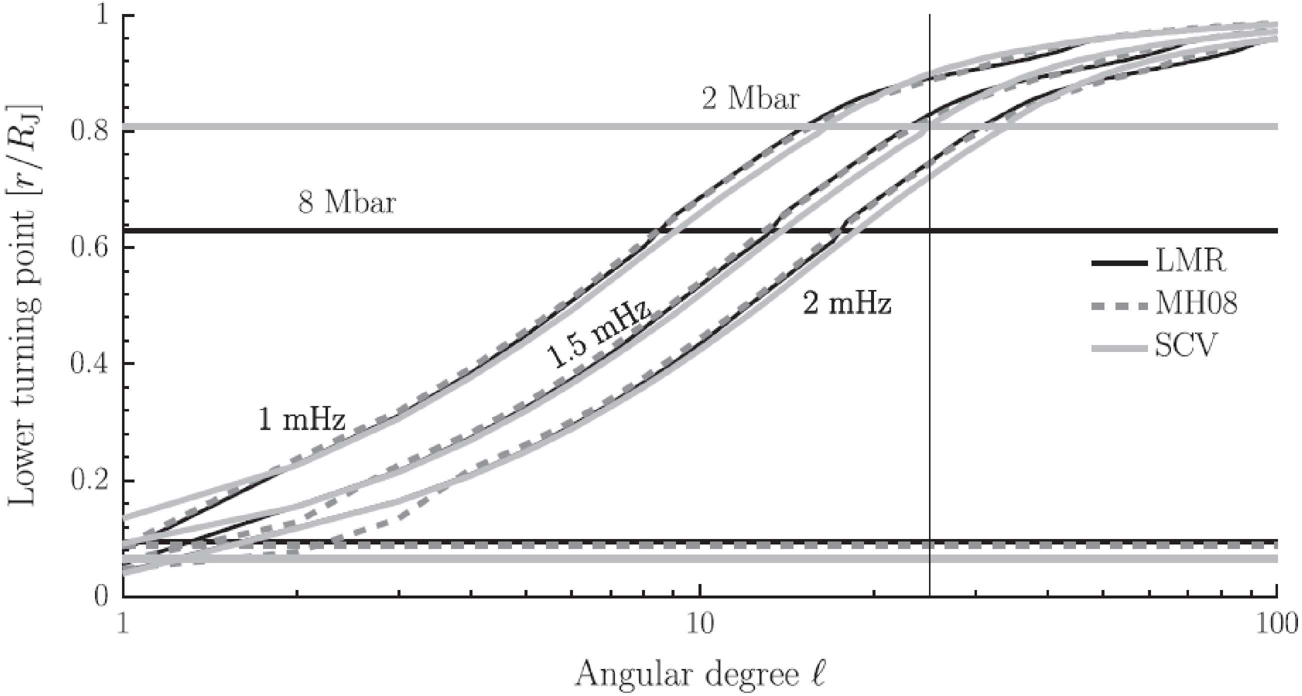
Characterization of interiors models derived from the oscillation spectrum

Direct problem

Observation of high angular degrees → probe of the upper envelope
Lower turning point: $\omega / \ell = c / r$

Jackiewicz et al. 2012, Icarus 220, 844

→ In Jupiter



Observation of ℓ ~15 – 25 to probe the 2 Mbar level

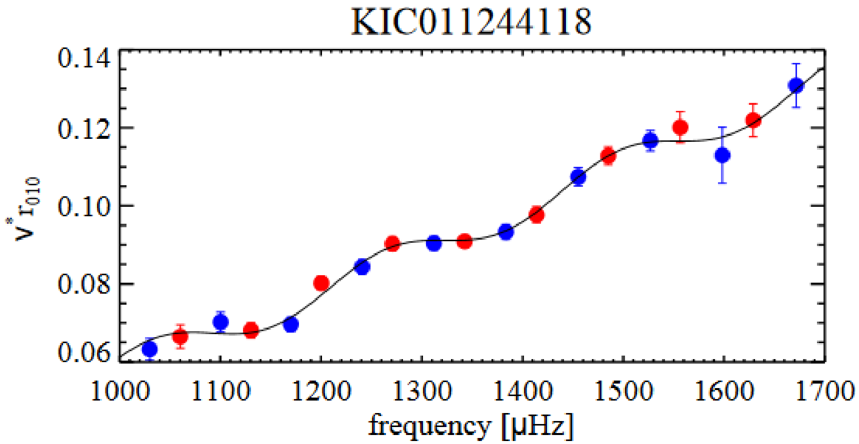
Acoustic glitches in Jupiter?

Glitches = modulation in the oscillation pattern due to sharp gradients of interior structure paramers; period of the glitch → acoustic radius of the discontinuity

In stars, observation of acoustic glitches, of buoyancy glitches

Acoustic glitches of low-degree modes probe

- the base of the convection zone
- the helium second-ionization region



Mazumdar et al. 2012, ApJ 782, 18

→ Jupiter

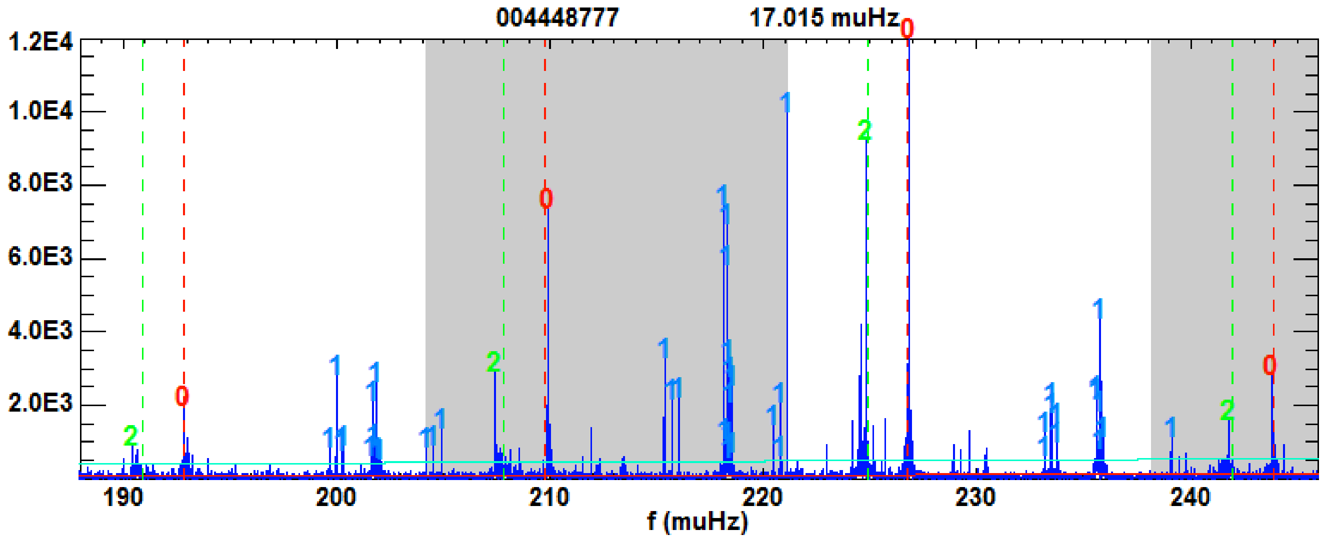
- glitches in low-degree modes probe the region where H becomes metallic
- glitches in medium-degree modes probe the regions just below the surface

Mixed modes in Jupiter?

Mixed modes result from the coupling of pressure waves propagating in the envelope and gravity waves propagating in the core

In stars, gravity modes form in the radiative core of evolved stars

→ Direct view in the core: size, mass, rotation



→ Jupiter

- Gravity modes in the radiative core?
- Possible coupling? (requires $N_{BV,core}$ > angular oscillation frequencies)

Conventional forcing mechanism

Convection!

Classical view

$A \sim L^{1} M^{-1}$

→ $A_{Jup} \sim A_{\odot} / 10^{6}$

Jupiter as a star

$A \sim L^{0.818} M^{-1.32} T_{eff}^{-1}$ (valid from MS to RG, Huber et al. 2011)

→ $A_{Jup} \sim A_{\odot} / 50$

To be investigated

Radiative damping

Quality factor

Unconventional mechanisms?

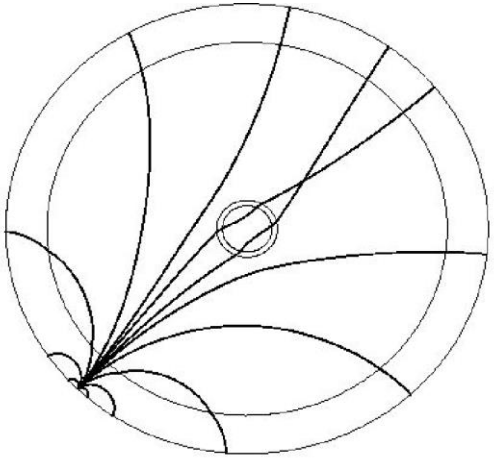
Observations

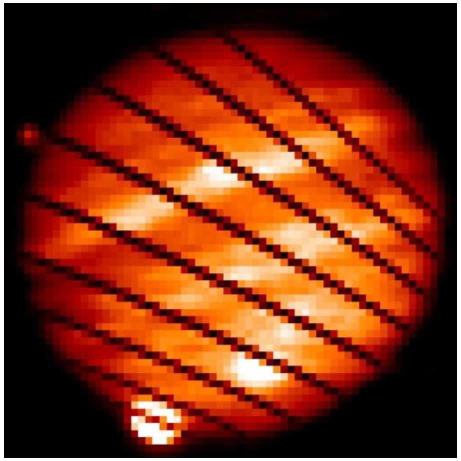
Technique	Instrument	Signal	Detection	1 m/s →
Doppler velocity	Sodium cell MOF	v	$\frac{\delta\Phi}{\Phi} = \frac{\mathrm{d}\ln I}{\mathrm{d}\ln\lambda}\frac{v}{c}$	50-100 ppm
Fourier seismometry	Mach-Zehnder	$\delta\varphi = 2\pi\,\sigma\Delta\,\frac{v}{c}$	$\frac{\delta\Phi}{\Phi} = 2\pi\,\sigma\Delta\,\frac{v}{c}$	~ 200 ppm
Visible photometry	CCD	$\delta r = \frac{c_s}{g}\,v$	$\frac{\delta\Phi}{\Phi} = \frac{2\,\delta r}{R}$	1 ppm → 70 ppm
Infrared photometry	IR detector	$\frac{\delta T}{T} = (1-\gamma)\,\frac{v}{c_s}$	$\frac{\delta\Phi}{\Phi} = \frac{hc}{\lambda k_B T}\frac{\delta T}{T}$	0.5 %

Gaulme et al. 2015, Seismology of Giant Planets
2014arXiv1411.1740G

Infrared photometry

Mosser et al. 1996,
Icarus 121, 331





First tentative observation: Deming et al. 1989

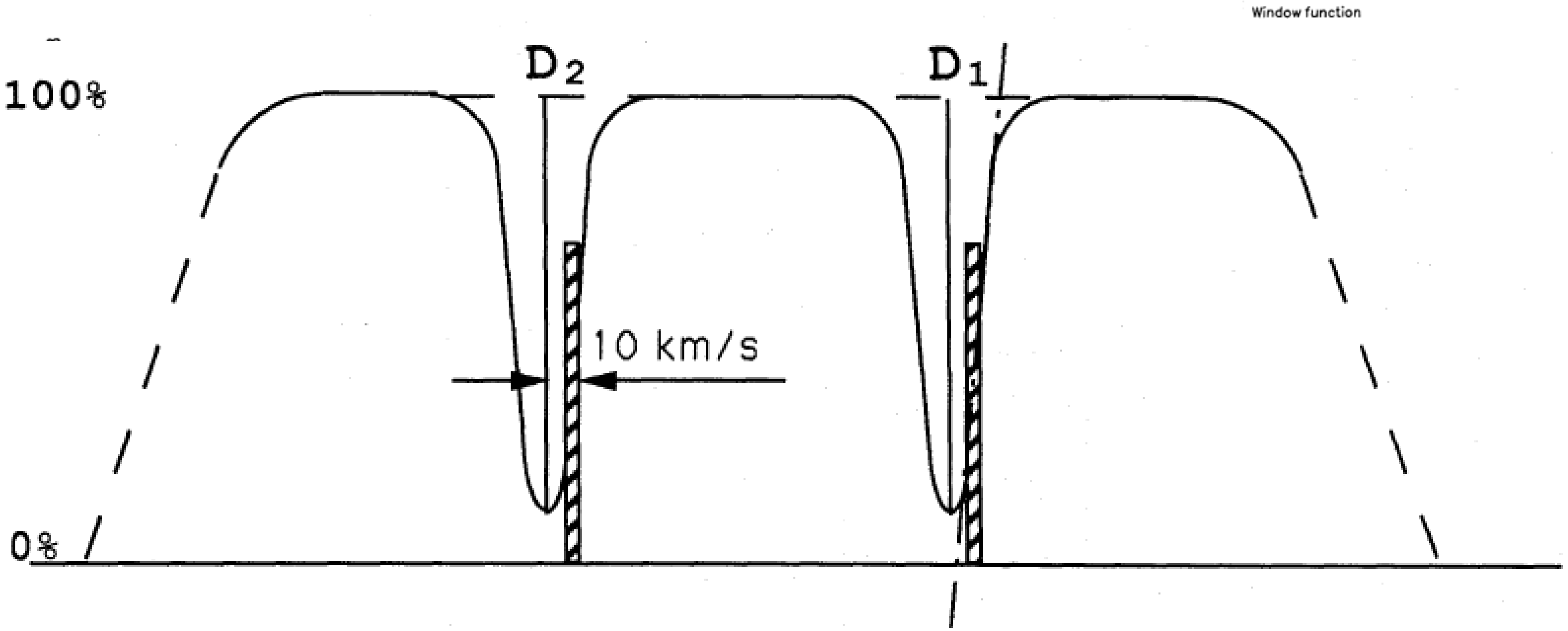
Observations of the Shoemaker-Levy 9 fragment impacts in July 1994

No detection → energy deposit < 2 10^{21} J
Strong impact → 10^{20} J → waves that probe the upper envelope
Very strong impact → 10^{21} J → excitation of pressure modes

In 1994, strongest impacts ~ 20 times too small to excite detectable waves
Today, new infrared detectors (small pixels, enhanced sensitivity)
→ much easier detection

Doppler measurements

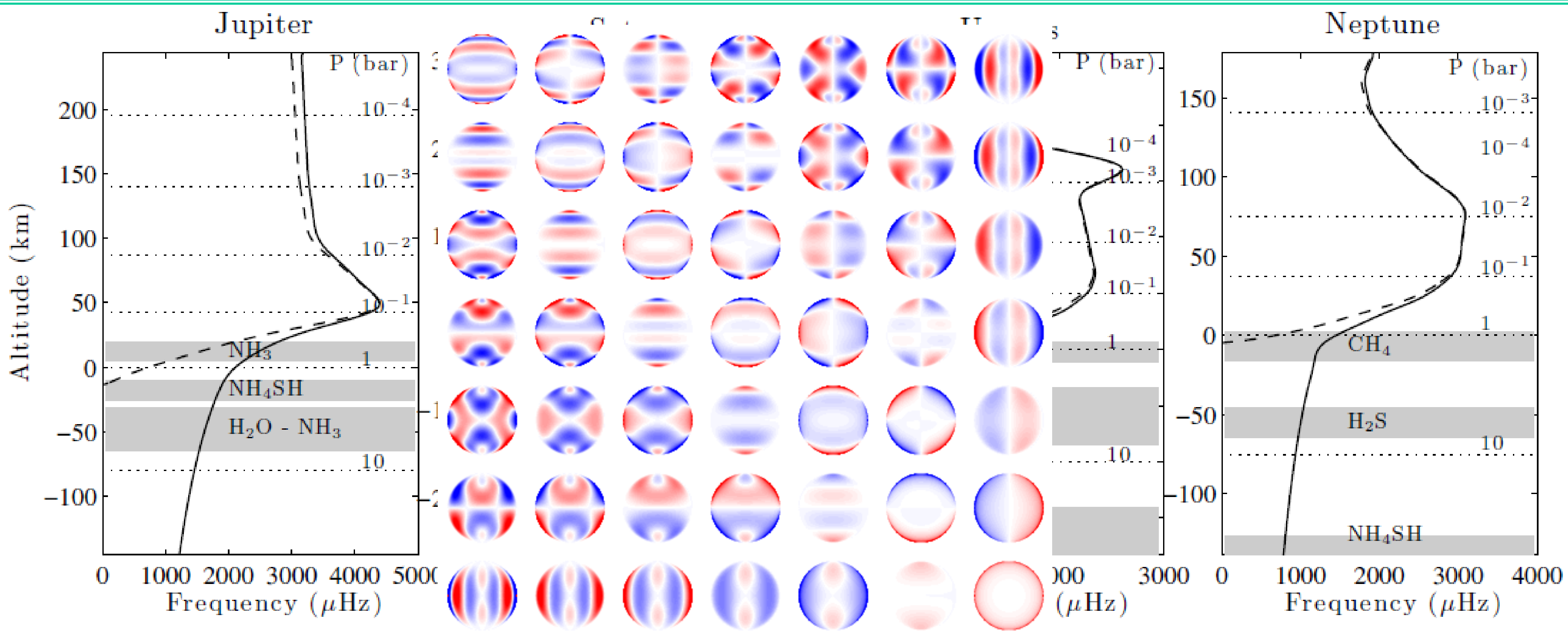
Schmider et al. 1991, A&A 248, 281



First tentative observation: Schmider et al 1991

Instrument = optical resonant sodium cell
Complex instrumental visibility due Jovian rotation
→ incorrect calibration of the oscillation amplitude

Visible photometry



No observation: JOVIS project = small mission, phase O-A funded by CNES

Low-Earth orbit, visible photometry

Cloud amplification → amplification of the signal by a factor of about 70

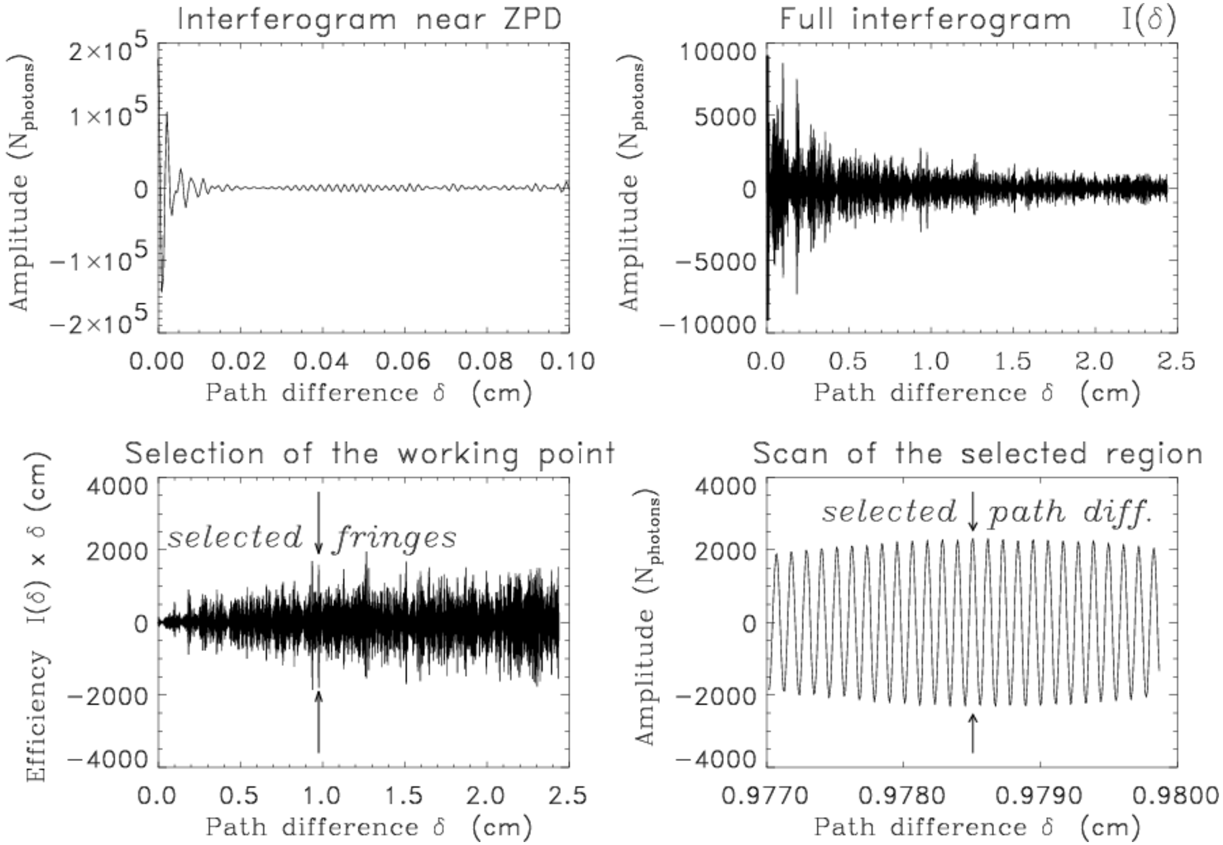
→ complicate visibility

Gaulme & Mosser 2005, Icarus 178, 84

Gaulme et al. 2015, Seismology of Giant Planets

Fourier seismometry

Mosser et al. 2003, PASP 115, 990
Mosser et al. 2000, Icarus 144, 104
Mosser et al. 1993, A&A 267, 604



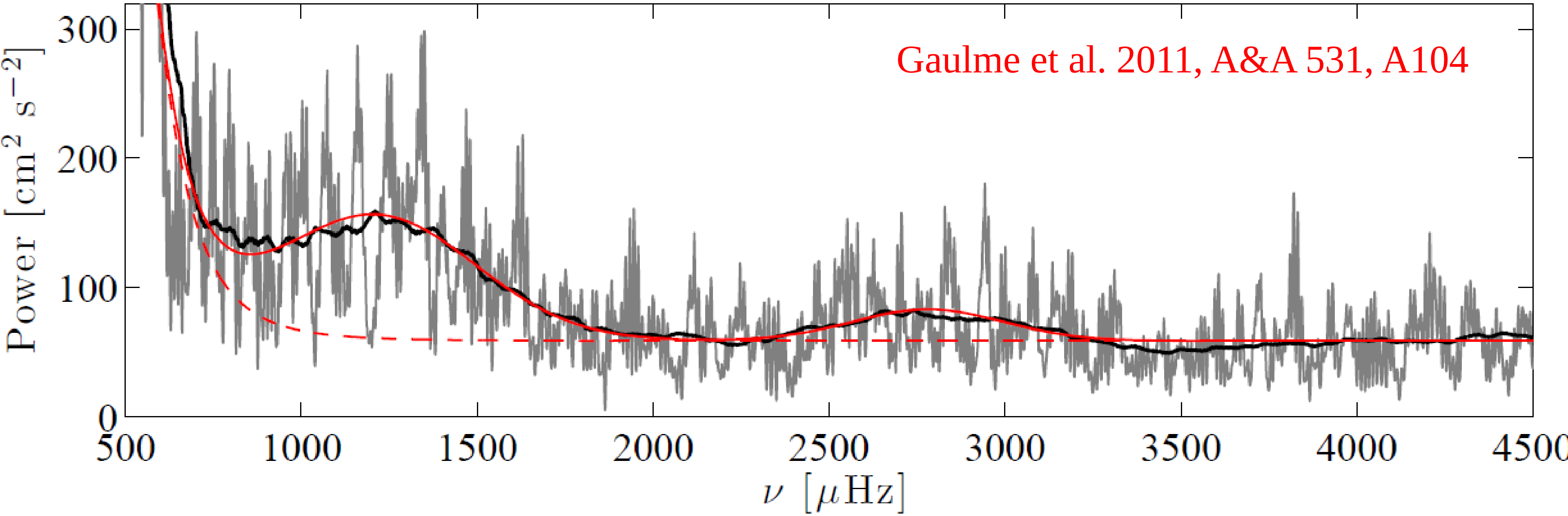
First tentative observation: Mosser et al 1993

Instrument = FTS / CFHT

1991: drift of the working point → reduced sensitivety

1996: new set-up → phase measurement → tentative observation

Fourier seismometry



Jupiter observed with the SYMPA in 2005 at Teide Observatory

SYMPA instrument: Fourier-transform imaging-spectrometer with fixed OPD
main optical device is a Mach-Zehnder interferometer [Schmider et al., 2007].

Accurate calibration of the instrument

→ ν_{max} = 1213 ± 50 μHz
→ $\Delta\nu$ = 155.3 ± 2.2 μHz
→ A = 49 ± 10 cm/s

Lessons from observations

Day-night alternance *must* be avoided

Photometric observations are noisier than Doppler measurements

Mode visibility is complicate

Observations have to deal with Jovian rotation

Imaging capability

+ image of the full Jovian disk
+ spatial resolution up to the degree $\ell = 20$

Accurate calibration is necessary

→ best compromise = imaging Fourier transform seismometry
(but dont forget IR photometry if a comets crashes into Jupiter)

18 april 2020 International weekly journal of science

nature

€ 10 www.nature.com/nature

Jovian oscillations reveal a 10-M_{Earth} solid core

Differential rotation stronger than expected

The hydrogen plasma-phase transition definitely ruled out

Asteroseismic relations now valid from $R_{\odot}$ /10 to 1000 $R_{\odot}$

Editor’s note: quem Jupiter vult perdere, prius dementat