GIANT PLANETS SEISMOLOGY

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Abstract. The giant planets Jupiter and Saturn belong to the interesting category of possible goals for remote seismic analysis. Their first seismic observations and their analysis were attempted in 1987 and 1991 respectively, under Philippe Delache's initiative. The theoretical analysis of giant planets seismology reveals the strong signature of the dense planetary core and the tiny one of the hydrogen plasma phase transition. The asymptotic formalism makes possible to obtain pertinent information for the observation of planetary oscillations and for their analysis. Specific observational techniques were developed to detect the seismic signature of giant planets. However, the first observations (Schmider *et al.* 1991, Mosser *et al.* 1993) of Jovian oscillations remain tentative. Even if the Jovian origin of the signal is beyond doubt, the interpretation in terms of Jovian global modes remains speculative. The collision of comet SL9 onto Jupiter provided an unexpected and unique opportunity to search for oscillations excited by the cometary impacts (Mosser *et al.* 1996). Seismic observations of Saturn remain negative so far. Therefore, this review focuses on Jupiter. Finally, the almost 10-years long experience of seismic observations of Jupiter and Saturn has not yet provided new constraints for planetary interior models. However, guidelines for future observational projects dedicated to Jovian seismology can be drawn. The different techniques of observation are compared, and observational requirements are precisely described.

1. Introduction

A complete review of giant planets seismology was already given by Mosser (1994). The theoretical aspects of giant planets oscillation were described exhaustively, as well as the current status of what is known about the

J. Provost and F.-X. Schmider (eds.), Sounding Solar and Stellar Interiors, 251-264.

Jovian interior. The current review focuses on observational aspects, and try to determine the manner to optimize further seismic observations of Jupiter.

A survey of the papers dealing with giant planets seismology is presented in Section 2. The Jovian standard interior model is described in Section 3. Properties of the planetary pressure modes oscillation pattern estimated with the asymptotic theory are briefly presented, in order to provide information for observational work. Section 4 presents past observations, with a tentative comparative study of their performance. Perspectives are proposed in Section 5.

2. Historical review

Giant planets seismology is a recent field of interest. The first paper devoted to Jovian oscillations was published in 1976 by Vorontsov *et al.* The first tentative observations were reported by Deming *et al.* (1989). It is possible to define three periods in the past twenty years.

- First, Vorontsov *et al.* provided a very complete set of theoretical papers dealing with the specific problems of Jovian seismology.
- Then, the first observations of Jovian oscillations were attempted. In parallel, various theoretical papers were published.
- In July 1994, the collision of comet Shoemaker-Levy 9 provided a unique opportunity to search for Jovian oscillations. One third of the papers in Jovian seismology are devoted to this event.

Figure 1 presents an histogram of all papers published between 1976 and 1996 in journals with an international audience and lecture committee. The three periods mentioned above appear clearly. The first theoretical papers (Vorontsov *et al.* 1976, 1989, Vorontsov & Zharkov 1981, Vorontsov 1981, Vorontsov 1984a,b), even if covering the main theoretical aspects of the subject, remained isolated (except Bercovici & Schubert 1987), and giant planets seismology was still a confidential field. However, the successes in helioseismology opened new horizons.

Observations made in 1987 (Deming *et al.* 1989, Schmider *et al.* 1991) correspond to beginning of the second period. Philippe Delache played a very important role, making possible theoretical, instrumental and observational progresses. Synergy between planetologists and seismologists was highly fruitful. Independently of the observational results, the potential obtention of new constraints on the planetary interior structure induced further works (Marley 1991, Marley & Porco 1993, Lee 1993).

The collision of comet Shoemaker-Levy 9 fragments with Jupiter opened a new period. Several groups proposed or achieved observations for monitoring the seismic consequences of the impacts (Kanamori 1993, Deming

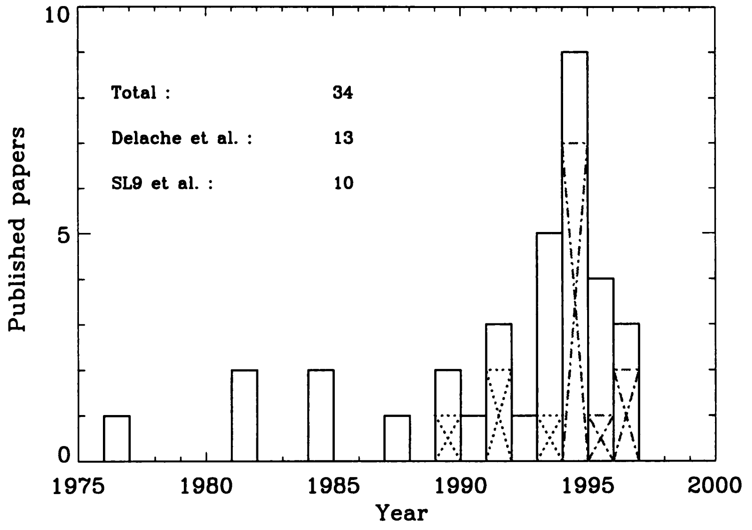

Figure 1. Histogram of papers dealing with Jovian seismology in the past two decades. Papers reporting new observational results are indicated by dotted lines. Philippe Delache, even if he does not explicitly appear in the author lists, was at the origin of 13 papers, among whose can be the first possible detection of Jovian oscillations.

1994, Gough 1994, Lee & Van Horn 1994, Lognonné *et al.* 1994, Marley 1994, Cacciani *et al.* 1995). Searching for the seismic signature of the cometary impacts was considered as a "high risk, high return" operation. This period will remain a short parenthesis, and giant planets seismology confined to very few groups, if future observations remain unable to provide new constraints on the Jovian interior structure.

3. Giant planets interior models and seismology

3.1. STANDARD MODEL

The Jovian standard interior model is based on the following assumptions:

- The gravitational moments, measured by the Voyager spacecraft (Campbell & Synnot 1985), imply a planetary core of heavy elements.
- Convection, measured in the upper troposphere, is needed to extract the interior heat of the planet. That induces an adiabatic structure.
- The composition is supposed to be homogeneous. In the fluid envelope, the mass fraction are respectively X = 74%, Y = 24% and Z = 2%, according to the Galileo probe (von Zahn & Hunten 1996).
- The transition between the molecular and metallic phases of hydrogen (plasma phase transition, PPT) occurs at the 1.2 Mbar pressure level (Chabrier *et al.* 1992).

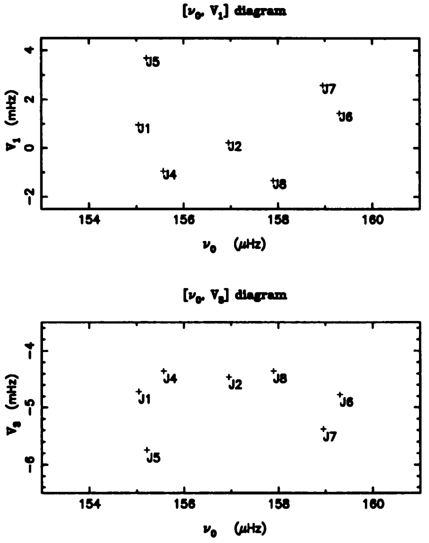

Figure 2. Asteroseismic HR diagram: comparison of different Jovian interior models, based on parameters of the oscillation pattern: ν_0 is the characteristic frequency, V_1 and V_3 the second-order frequencies (Provost *et al.* 1993). Despite the fact that all these standard models satisfy the gravitational constraints, their seismic properties are very different.

Different interior models were constructed following this scenario . When displayed in a seismic HR diagram (Christensen-Dalsgaard 1988), they prove to be very different (Fig. 2). The gravitational moments, integrated quantities of the mass distribution, do not provide a precise determination of the interior. Furthermore, the previous assumptions are denied by the non-standard point of view:

- The core may be more or less diluted in the envelope (Stevenson 1985)
- Condensation of heavy elements, or non-miscibility in the metallic phase imply an inhomogeneous composition.
- The PPT remains a theoretical construction.
- A possible radiative window, near the 2000 K temperature level, should modify completely the whole interior adiabat (Guillot *et al.* 1994).

The discrepancies between the standard Jovian interior models constrained by the gravitational moments, as well as the comparison of the standard and non-standard descriptions of the Jovian interior structure, defines the minimum output expected from giant planets seismology: constraints on the core size, existence and location of the PPT, mass distribution within the planet.

3.2. OSCILLATION PATTERN

3.2.1. *Asymptotic analysis*

The asymptotic analysis, derived from Tassoul (1980) and adapted to the Jovian interior with a dense core, is valid for low degree and high radial order modes of the non-rotating planet (Provost *et al.* 1993):

$$\nu_{n,\ell} = \left[n' + \frac{L^2 V_1 + V_2}{4\pi^2 \nu_{n,\ell}} - \frac{\varepsilon}{\pi} \sin \alpha_{n,\ell} - \frac{\varepsilon^2}{\pi} \frac{N-2}{2N} \sin 2\alpha_{n,\ell} \right] \nu_o$$

$$\text{with} \quad \alpha_{n,\ell} = 2\pi \left(\frac{n'}{N} - \frac{\ell}{2} - \frac{L^2 V_3 + V_4}{4\pi^2 \nu_{n,\ell}} \right) \quad \text{and} \quad n' = n + \frac{\ell}{2} + \frac{n_e}{2} + \frac{1}{4}$$

and where n and ℓ are the radial order and the degree of the degenerated mode; n_e is the polytropic index at the surface, ν_0 is the main characteristic frequency while $V_{1\to4}$ are the second order frequencies, ε and N represent respectively the amplitude and the period of the core modulation. The PPT occurs at a too-high level in the envelope to have any signature on low degree modes. On the other side, the modulation due to the dense core cancels the regularity of the pattern developed by the asymptotic theory (Tassoul 1980). All the conclusions based on the asymptotic results are confirmed by numerical calculations (Vorontsov *et al.* 1989, Lee 1993, Provost *et al.* 1993, Gudkova *et al.* 1995).

3.2.2. *Rotation*

For low degree high frequency modes, the planetary rotation can be treated as a perturbation (Mosser 1990), despite its relative importance: $\nu_{\text{rot}}/\nu_0 \simeq 1/5$ for Jupiter, compared to about 1/300 for the Sun. The rotational removal of degeneracy is given by

$$\nu_{n,\ell,m} = \nu_{n,\ell} \left[1 + E(e,n,\ell) \left(\frac{1}{3} - \frac{m^2}{\ell(\ell+1)} \right) \right] - m\,\nu_{\text{rot}}$$

This result agrees with the numerical analysis made by Lee (1993) taking into account the coupling between the modes. The small correction E is of the same order as the planetary oblateness $e = 6.5\%$. The additive term $-\, m\, \nu_{rot}$ is due to the rotating frame. The relative weight of the correction due to oblateness is high enough to completely cancel the regularity of the Zeeman-like multiplet. The frequency differences in a $\ell = 2$ multiplet with $\nu \simeq 2$ mHz vary between 14 and 42 μHz, whereas $\nu_{\text{rot}} = 28$ μHz. Inside a given multiplet, the eigenfrequencies of opposite azimuthal orders satisfy to:

$$\nu_{n,\ell,-m} - \nu_{n,\ell,m} = 2\, m \times \nu_{\text{rot}}$$

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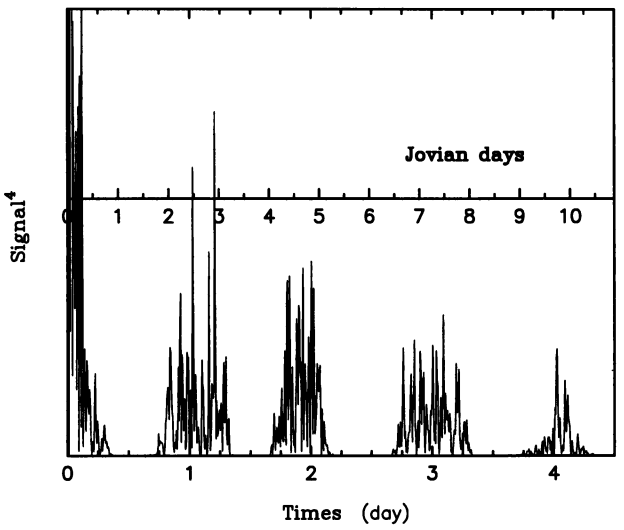

Figure 3. Spectrum of the spectrum recorded at CFHT in 1991, with the signature of the rotational splitting.

This equation, which expresses that the difference between two unknown eigenfrequencies remains a well known term, gives an important clue for the detection of an oscillating signal. The identification of doublets separated by an even multiple of the rotation frequency represents the signature of an oscillating phenomenon affected by the rotation. In the spectrum of the spectrum, this signature will consist of a series of peaks multiple of half the period of rotation (Fig. 3).

It must be emphasized that this signature is not a photometric effect, provided it appears at frequency much higher than the rotational frequency. The contamination of the spectrum by photometric inhomogeneities was examined by Lederer *et al.* (1995), and concluded that the spectrum range over 0.5 mHz is exempted from spurious photometric signal.

3.2.3. *Ray tracing*

The ray tracing theory was used by Bercovici & Schubert (1987) in order to obtain in a simple way the oscillation diagram, and by Mosser *et al.* (1988) to put in evidence the influence of the planetary core on the Jovian seismic pattern. However, this approach is too crude to describe precisely the core influence. A ray not propagating in the core simply ignores its existence, whereas the evanescent behaviour of a Jovian mode in the central region of the planet will seriously influence its eigenfrequency.

On the other hand, the ray tracing method was adequate for describing the propagation of very high frequency waves generated by the impacts of

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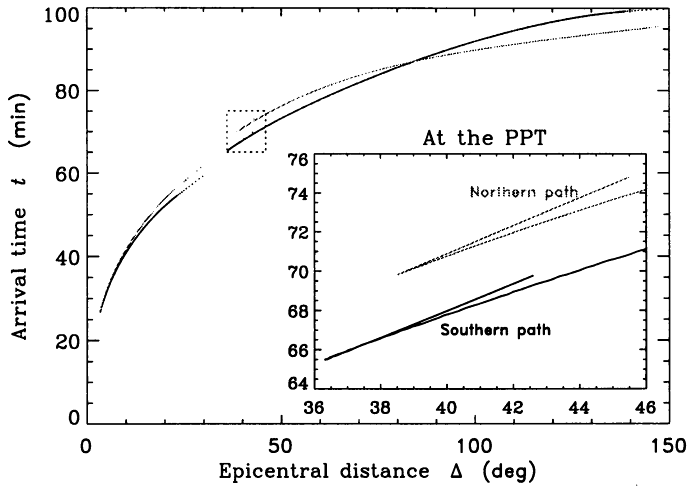

Figure 4. Arrival time versus epicentral distance for a Jovian interior model with PPT. The epicentral distance is the angular distance between the impact point and the region where the wave reaches the troposphere again. Due to the planetary oblateness, the north and south paths are not synchronized. The zoom shows the signature of the PPT, namely the shadow zone occurring about 1 hour after the impact.

comet SL9 fragments in the Jovian fluid envelope (Fig. 4). This event provided a unique opportunity to search for the signature of the PPT (Gudkova *et al.* 1995).

3.3. ENERGETICS

It is doubtless that Jupiter oscillates. The planet is fluid, mostly convective, and emits more energy than received from the Sun. Waves with frequency less than 3.1 mHz are trapped below the tropopause (Mosser 1995). However, the amplitude of the oscillations remains unknown. Theoretical predictions are currently unable to predict any amplitude level, just because the Jovian interior remains too mysterious. The mechanism proposed for the excitation of solar pressure modes by turbulent convection seems to be not efficient in Jupiter, since it gives very low amplitude (Deming *et al.* 1989). On the other side, the latent heat at the PPT should provide a powerful possible excitation. In fact, observations are the only way to solve the problem.

Jovian oscillations may be solar-like. In that case, Jovian and solar oscillation pattern should be similar, due to the equality between the free fall characteristic frequency $\sqrt{\mathcal{G}M/R^3}$ of Jupiter and the Sun. The modulation due to the planetary core and the different cutoff frequencies make

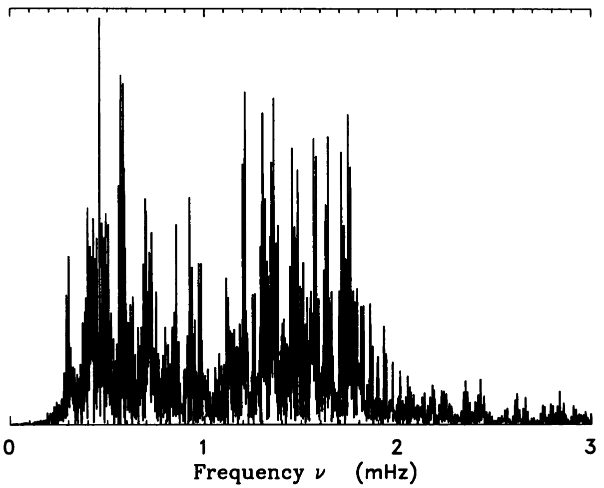

Figure 5. Fourier spectrum of the data recorded at OHP in 1987. The most evident signature is due to non-continuous observations. Many doublets separated by two times the rotational frequency (28 μHz) can be detected.

the global aspect of the theoretical spectra very different.

4. Observations

4.1. RESONANCE SEISMOMETRY

Full disk observations of Jupiter with a sodium cell resonance were performed at the Observatoire de Haute-Provence, in november 1987, during 6 nights close to the planetary opposition (Schmider *et al.* 1991). The Doppler shifts of the solar sodium line reflected by the planet are analyzed by the local sodium reference. The relative variations are related to a velocity change by the factor $2.10^{-5}/(\text{m.s}^{-1})$. The detection of the signature of the rotational removal of degeneracy acts in favor of the detection of the pressure mode signal (Mosser *et al.* 1991). Various tests showed that this signature was unambiguous, and not related to photometric changes, despite a non-favorable duty cycle.

4.2. FOURIER TRANSFORM SEISMOMETRY

The principle of Fourier Transform seismometry (Mosser *et al.* 1993, Maillard 1996) consists of searching for the Doppler signal in the interferogram of the planetary spectrum. Working in the Fourier space makes possible to benefit of the multiple advantage. The Jovian spectrum exhibits at 1.1 μm a complex rotational-vibrational pattern, due to the $3\nu_3$ methane band. More than 40 lines appear around σ_0=9100 cm^{-1}, and induce strong signatures in the interferogram at path differences near 1 cm. The pattern at a selected path difference δ is sensitive to the velocity v and develops schematically as:

$$I(\delta) \propto \cos 2\pi\sigma\delta = \cos 2\pi\sigma_0\delta \left[1 + \frac{v}{c}\right]$$

Stability of the method is provided by the metrologic He-Ne laser of the Fourier Transform Spectrometer based at the CFH 3.6-m telescope. The method was employed first on Jupiter. This mono-site observation provided results in agreement with the one of Schmider *et al.* (1991). Intensity changes at a zero crossing of the interferogram were registered (Mosser *et al.* 1993).

$$dI = I_{\max}\, 2\pi\sigma_0\delta\, \frac{dv}{c}$$

The field of view being limited to 12" (1/4 of the Jovian diameter at planetary opposition), it was therefore necessary to cancel out the guiding errors. Due to the fast planetary rotation, 1" drift on the planet is equivalent a velocity shift about 0.5 km.s^{-1}. A rapid modulation parallel to the Jovian axis of rotation permitted this. Furthermore, this modulation cancelled out the contribution of telluric water. However, this method appeared to be very sensitive to any modification of the working point.

In order to increase the performance of the detection, the principle of the observation was changed into a phase measurement. New InGaAs detectors permitted to increase the quantum efficiency of the detection and to obtain a 24" field of view. This new method was used in July 1996. A sample of the phase determination is given in Fig. 6.

$$d\varphi = 2\pi\sigma_0\delta\, \frac{dv}{c}$$

This second method presents great advantages compared to the first one. First it is not contaminated by photometric changes, since the determination of the phase and the amplitude are independent. Second the sensitivity is no longer affected by unavoidable low frequency drifts of the working point. Furthermore, it makes possible an absolute calibration of the signal. The calibration factor is simply $c/2\pi\sigma_0\delta$, $\simeq$ 5 km.s^{-1}

4.3. IR PHOTOMETRY

The previous methods are sensitive to the velocity field of the oscillation. IR monitoring of the Jovian disk allows the measurement of temperature

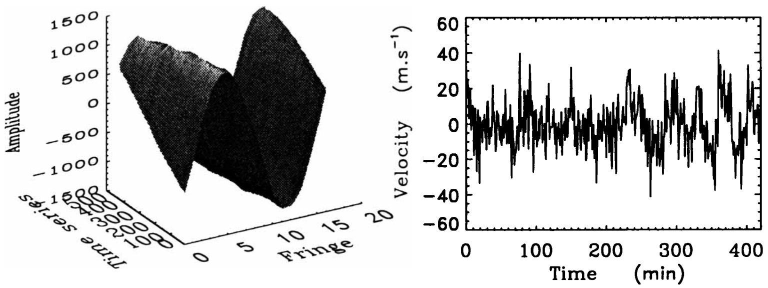

Figure 6. Registration of the phase of the scanned portion of the interferogram, and traduction in terms of Doppler velocity

variations associated to the adiabatic wave (Deming *et al.* 1989). The temperature perturbation of an adiabatic wave is related to its velocity by

$$\frac{\mathrm{d}T}{T} = (1-\gamma)\,\frac{\mathrm{d}v}{c_{\mathrm{S}}}$$

where c_{S} is the local sound speed, about 0.8 km.s^{-1} in the Jovian troposphere, and γ the adiabatic exponent (about 1.4). When sounding the Jovian troposphere in the 10-μm region, sensitive to the tropospheric levels around $T_0 \simeq 135$ K, the relative flux variations are related to the thermal variations by:

$$\frac{\mathrm{d}\Phi}{\Phi_0} \simeq 12\,\frac{\mathrm{d}T}{T_0}$$

Finally, the relative flux variations are related to a Doppler term by the ratio 5.10^{-3} / m.s^{-1}. This method was first investigated by Deming *et al.* (1989), but unsuccessfully. The detector was a 20-element linear array, limiting the sensitivity of the observations to only zonal high-degree modes ($|m| = \ell \geq 10$). Other attempts conducted with a 20×64 pixels camera (Fisher 1994) were also unsuccessful.

Observations made in July 1994, during and after the collision of comet Shoemaker Levy 9 with Jupiter, used this technique. Daytime observations are possible, what was necessary for the recording of the SL9 events, that occurred in the daytime when Jupiter was far from opposition. Spatial

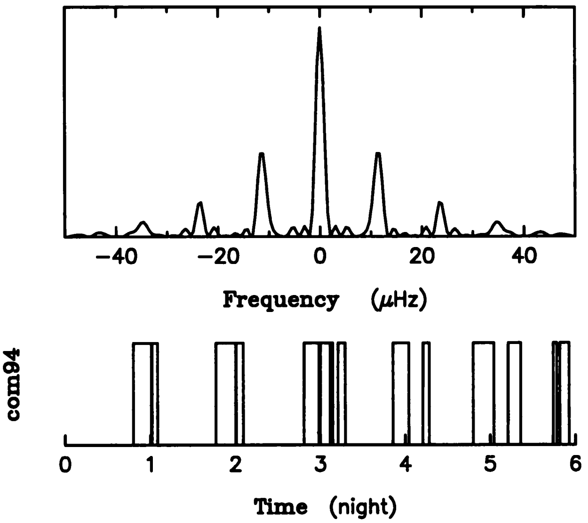

Figure 7. Window function of the 3 runs conducted with IR cameras in July 1994 after the SL9 impacts. The duty cycle is about 34%.

resolution is related to the number p of pixels along the Jovian diameter. It is theoretically equal to $p/2$. Multi-site observations were conducted, from the Canary Islands, Chile and Hawaii (Fig. 7). On the contrary to Doppler measurements, this method offers no internal stable reference. Each visible feature on the Jovian thermal map has a non-negligible contribution to the signal. The flux variation between two neighbour pixels is about 1/100 the mean flux, as high as the typical rms noise level.

TABLE 1. Comparison of observational techniques

	Na cell seismometry OHP 1987	FT seismometry CFH 1996	IR photometry ESO 1994
stability	atomic line	He-Ne laser	×
sensitivity ($1/\mathrm{m.s}^{-1}$)	2.10^{-5}	3.10^{-5}	5.10^{-3}
noise level (1σ, 1 min integration)	25 $\mathrm{m.s}^{-1}$	15 $\mathrm{m.s}^{-1}$	3 $\mathrm{m.s}^{-1}$
corrected for photometry	yes	yes	×
multi-site (1996)	yes	no	yes
high ℓ modes	no	no	yes

5. Perspectives

5.1. COMPARISON OF OBSERVATIONAL METHODS

According to the results summarized in Table 1, it seems that IR photometry presents multiple advantages. First, it is intrinsically the most sensitive technique. Second, it permits to achieve the lowest noise level. Third, it is sensitive to high degree modes, on the contrary to non-imaging techniques. IR observations may eventually be made during daytime, as was done during the SL9 events. Last but not least, the existence of many IR cameras makes it possible to achieve multi-sites observations, contrary to FT seismometry, currently limited by the number of available instruments.

However, IR photometry is, of course, sensitive to photometric changes, not only to the one due to oscillating terms, contrary to other methods which are corrected for photometric contamination. Only the careful analysis of existing data, not yet completed, can confirm the overall performance of this technique. The complexity due to the inhomogeneous thermal field has not yet been completely solved. Further IR observations should be conducted with a filter selecting atmospheric regions where the Jovian thermal map is the most uniform.

In fact both photometric and spectrometric observations have advantages. IR imaging techniques are necessary for the possible detection of the plasma phase transition of hydrogen, whereas full disk observations, as made with current spectrometric techniques, are of prime interest for the determination of the core structure (Mosser 1994). In both cases, the duty cycle of the observations must be as long as possible.

5.2. OBSERVATIONAL PROJECTS

The observational results are not satisfying. Even if the detection of the signature of the rotational splitting implies the detection of waves in the frequency range [1, 2 mHz], no new constraint has been carried out by seismology. On the other hand, the seismic interest concerning Jupiter, with all the potential constraints it implies, has induced many other works. A new generation of Jovian interior models (Guillot *et al.* 1994, 1995) was constructed, including up to date equations of state, based on rigorous physical assumptions, and numerically more robust than the previous generation. Some techniques proposed for the monitoring of the Jovian oscillations proved to be not convenient (Mosser 1992); on the other hand, Fourier-transform seismometry is directly applicable for asteroseismology (Maillard 1996).

Finally, it is possible to define guidelines for future observations:

- At least 4 nights observation with multi-sites observations providing a duty cycle better than 50% are necessary to infer physical results from the oscillation pattern.
- The field of view of either imaging techniques or spectrometric observations must accept the entire planetary image.
- Spectrometric measurements must include the correction for photometry.
- "Exotic" technique of detection must not be excluded, such as proposed by Marley & Porco (1993) for Saturn, considering the possible resonance between fundamental modes and gravitational perturbations in the planetary rings.
- Observations from space provide two major requirements for seismology: excellent duty cycle, stable photometry. Jupiter is a secondary objective of the spatial project Corot (Catala *et al.* 1995).

Acknowledgments

I wish to thank Philippe Delache and Daniel Gautier, who introduced me to giant planets seismology, and all the colleagues involved in the progress of this new topic.

This work has been supported by the Programme National de Planétologie from the Institut National des Sciences de l'Univers (INSU) and by the Groupement de Recherches 'Structure interne des étoiles et des planètes géantes' from the Centre National de la Recherche Scientifique (CNRS).

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