A 9.1 Probing the interiors of giant planets

A. Context and state of the art

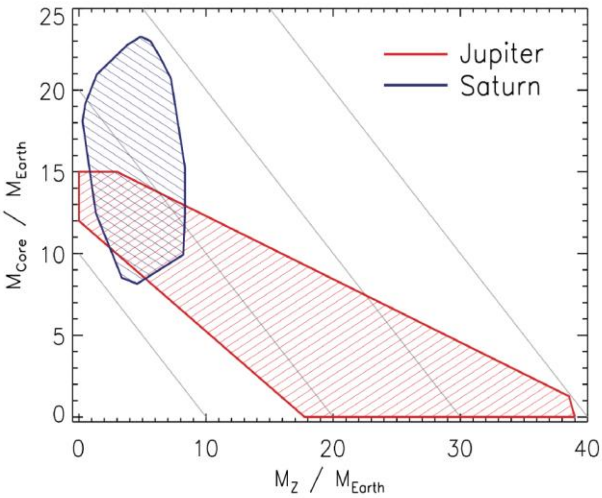

Figure 1. Possible core mass/ heavy element total mass for different models of Jupiter and Saturn compatible with the known parameters of the planets, including gravitational moments. Jackiewicz, adapted from Saumon & Guillot 2004, Fortney & Nettelman 2010

The composition, internal structure, and thermal evolution of Jupiter provide crucial insight into the history of the Solar System as a whole. Unfortunately, both the mass of heavy elements and their distribution throughout the interior remain extremely uncertain. Various estimates of the core mass range from 0 to 15 MEarth and the total mass of heavy elements from 10 to 40 MEarth (Saumon & Guillot 2004, Militzer et al. 2008, Nettelmann et al. 2008). Because any model of Jupiter's formation must account for the core mass, a definitive measurement would have profound implications for our understanding of planetary formation and evolution (e.g., Pollack et al. 1996, Ida & Lin 2005, Alibert et al. 2005). If mixing processes have distributed heavy elements unevenly through the interior, the thermal evolution of the planet would be profoundly affected (Stevenson 1985, Leconte & Chabrier 2012). New constraints on the interior structure allow a better understanding of the tidal dissipation in Jupiter and the resulting evolution of the Jovian moons (Ogilvie & Lin 2004; Wu 2005; Lainey et al. 2009; Remus et al. 2012).

We foresee that a revolution in our understanding of the interior of giant planets (and in particular Jupiter and Saturn) will result from two sets of new measurements: First, extremely accurate measurements of Jupiter's and Saturn's gravity (but also magnetic) fields will be done by the Juno and Cassini spacecrafts, respectively. Second, the recent discovery that these planets oscillate paves the way for seismological studies of these planets, with new possibilities in terms of detecting composition jumps, stable regions, etc. Our group is directly involved in the Juno mission as CoI and member of the scientific team, and as PI on the development of JOVIAL, which will build three Doppler imagers to detect the oscillations of Jupiter and Saturn through simultaneous observations from New Mexico, France and Japan.

Gravity measurements

In 2016, NASA's *Juno* mission will make key contributions to our understanding of Jupiter thanks to precise measurements of its gravity and magnetic fields and to its radiometric sounding of the deep atmosphere. The difficulty in constraining the interior structure through the gravitational harmonics is that the terms of the gravitational potential are primarily sensitive to the outer envelope of the planet. The core only weakly influences even the lowest order term, J_2. While Juno will provide decisive improvements in our knowledge of Jupiter, constraints on the core mass will remain intrinsically model-dependent (Guillot 2005).

Seismic observations

Since the very beginning of helioseismology, the possibility to apply the same techniques on giant planets has been contemplated (Vorontsov et al, 1976).

Several attempts to observe these oscillations have been made in the past. As for the Sun, the most promising method is the detection of periodic velocity variations at the surface of the planet. Schmider et al. (1991) and Mosser et al. (1993, 2000) observed excess oscillatory power in the expected frequency range for Jovian p-modes. The detection of a clear signature of free oscillations of the planet has finally been achieved with an instrument that was dedicated for Jovian seismology, SYMPA (Schmider et al. 2007). Indeed, a careful analysis of the data focused on low-degree modes, shows both this power-excess and a clear comb-like power spectrum with a mean separation of the modes of 154 μHz, identified to the Jovian fundamental frequency. The value was found in agreement with theoretical predictions (Gaulme et al. 2011) and mode amplitudes around 0.4 m s^{-1} compatible with theoretical expectations (Bercovici and Schubert, 1987).

In 2013, density waves observed in the C-ring of Saturn were identified as the resonant effect of Saturn f-modes (also called surface or tsunami modes). Such a behavior was predicted by Marley (Marley, 1991, Marley and Porco, 1993). The basic idea is that wave features in Saturn's C rings could be created by resonant interactions with internal oscillation modes, since these modes perturb the internal density profile and, therefore, the external gravity field. Six modes were identified and compared to theoretical values. Their peculiar structure conducted to the idea of a stable zone near the core of the planet and a coupling between f modes and g modes inside the stable layer (Fuller, 2014).

Both these detections of global oscillations by two fully different techniques on the two main giant planets of the Solar System open the window of a full study of the internal structure of the giant planets by seismology. *JOVIAL* will use observations of acoustic waves that can propagate all the way to the center of the planet and therefore directly contain information on the deep interior (Jackiewicz et al. 2012).

B. Current activity

The main objective of *JOVIAL* is the determination of the internal structure of Jupiter by seismic observations, and in particular the characterization of the size and mass of the Jovian's core. This will be achieved with the same technique that led to the successful observations by SYMPA.

Between 2009 and 2013, a new Doppler Seismo-Imager (DSI) instrument was developed to solve several issues of the SYMPA instrument and in view of a possible space mission. This new instrument was successfully tested at the laboratory, in Nice, showing performances in line with theoretical expectation.

In 2014, first test observations with the DSI prototype where obtained at the MEO telescope at Calern, confirming the performance obtained at the laboratory, and giving a noise level dominated by the photon noise around 5 cm/s/$\mu Hz^{1/2}$. The telescope interface included a tip-tilt mirror, actuated at 100 Hz, to avoid guiding errors and remove partially the atmospheric agitation.

At the end of the same year, our colleagues of NMSU obtained fund from the NASA/ESPCOR program for the JIVE project. JIVE consists into a duplication of the DSI prototype for its installation at Apache Point Observatory, led by NMSU. The main objective of the JIVE project is to provide a ground-based support for the JUNO mission.

In 2015, the *JOVIAL* project was funded by the ANR. *JOVIAL* will complete the network by enabling a full integration of the French contribution (in terms of observations, data analysis and theoretical studies) and the construction of a new versatile Doppler Imager that can be adapted to *any* telescope.

Instrument description

The *JOVIAL* instrument aims to detect periodic variations of the velocity field due to the acoustic oscillations of the planet. *JOVIAL* achieves this goal by the measurement of the Doppler shift of solar spectral lines reflected at the surface of Jupiter. As SYMPA (Schmider et al, 2007), *JOVIAL* is a modified Mach-Zehnder interferometer. The Doppler shifts of the solar lines reflected at the surface of the planets, is measured at any point of the surface by measuring the phase of the interferometric fringes.

SYMPA detected oscillations modes between 0.8 and 1.5 mHz with a mean amplitude of 30 cm/s. In the case of Jovian observations with *JOVIAL*, the theoretical noise level integrated over the whole disk is about 4 cm/s/μHz½ in the range of [0.5 – 4] mHz, where the oscillations are expected. Therefore we expect to detect all the modes with amplitudes larger than 10 cm/s with a SNR of 3.

Thermal fluctuations are minimized by a careful choice of material for the Mach-Zehnder (MZ) and a cautious thermal regulation with a stability of 0.1°C. The MZ is also placed in a vacuum ceiling to avoid OPD variations due to pressure and humidity variations. This is sufficient to ensure a noise level due to OPD variations well below the photon shot noise.

Guiding effects and atmospheric turbulence are important sources of uncertainties in the velocity field measurements, mainly because of the fast Jovian rotation of 12 km/s at the equator (and similar value on Saturn). This fast rotation is the cause of a spurious velocity signal associated with the displacement of the planet image in the field of the instrument. Moreover, fast atmospheric agitation as well as telescope drifts degrade the resolution of the images, reduce the contrast of the fringes and introduce bias in velocity measurement. Partial Adaptive Optics correction is feasible on a 1-arcmin field, larger than the isoplanetic angle, using an extended wave-front sensor, derived from solar Adaptive Optics (AO) system (Rimmele et al, 1998). Such an AO is presently developed at the C2PU telescope in the frame of CIAO project (see in this document), and will be included in the *JOVIAL* instrument design. It aims to reach an angular resolution better than 0.5 arcsec, or less than 2000 km at the surface of Jupiter, whatever the seeing conditions, in order to measure all the modes up to the degree *l*=25 at least.

Figure 2. View of the DSI instrument during integration phase. The Mach-Zehnder is inside the vacuum chamber on the left. The two output beams are splitted by polarizer cubes and folded onto the detector, that will take place above the mirrors, on the right.

DEVELOPMENT PLAN

The DSI prototype at Calern is now installed at C2PU 1-m telescope, where a Coudé focus is available. A dedicated Adaptive Optics system (CIAO) module is presently developed for this telescope. The design of this module allows its use on a relatively large field of 1 arcmin, sufficient for observations of Jupiter. This large field AO inherits from a technology developed for solar observations. It uses a Correlation Wave Front Sensor based on a Shack-Hartmann, providing average wave-front corrections over the whole field. This is particularly suitable for planetary observations, where correlation can easily be estimated.

The JIVE instrument is foreseen to be installed at Apache Point at the end of 2016. The building of the MZ has already started. The optical and mechanical interface with the 1-m telescope is presently under study. The DSI prototype, and the JIVE copy, is a bench instrument that should be placed at a stable place, like the Coudé focus of the MEO telescope or at the Nasmyth focus of the 1-m telescope at Apache Point observatory.

The recent funding of *JOVIAL* will allow the study of a fully new, compact version of the DSI instrument that could be placed at any telescopes around the world, with just a different optical adaptation for each telescope. In particular, this new design will allow the operation of the instrument in any thermal environment and any type of telescope focus (Coudé, Nasmyth, Cassegrain), gravity invariant or not, as opposite to the present prototype version that could only be operated on a horizontal bench in stable temperature conditions. This is particularly important to have access to the 1.88 m telescope at Okayama observatory, with a Cassegrain focus, but also for possible observations with larger telescopes, as the 3.5 m telescope at Apache Point Observatory, for instance. Indeed, getting a similar noise level on Saturn, twice as far as Jupiter, requires a 4 times larger telescope diameter. *JOVIAL* will permit such observations in the future.

The optical study of this compact version has already started. By the end of 2016, we should have a preliminary version of the optical schema, including AO, for any foreseen telescope in the network. We foresee a construction and integration of the new version in 2017 for it installation at the Okayama observatory at the beginning of 2018. After test at the laboratory and commissioning at the telescope, the instrument should be ready for a first observing run on Jupiter in May 2018.

C. Future steps

After a first period of observation of Jupiter, which would definitively solve the question of the Jovian's core, it would be interesting to continue the observations for every year to improve the internal structure model by a better precision on the frequencies. This will be very useful in view of the arrival of the JUICE mission in the Jovian system. Observations on several years of the atmosphere will also give clues to understand the physical mechanisms between the interior and the atmosphere.

In the future, if additional fund could be obtained, the same mechanical and optical modifications, including the addition of an AO module, could be applied to the JIVE version, for its use at the 3.5m telescope at Apache Point Obervatory for observations of Saturn.

A dedicated space mission would provide longer continuous observations with an unprecedented resolution. The first target foreseen for such a mission would be Saturn, in the frame of the Hera proposal. Ice giants, Uranus and Neptune, will remain very difficult targets for observations from the ground and could only be explored with a space mission. We are in the definition of a mission to Uranus. The present instrument has been designed in view of a space mission and could easily be adapted on any spacecraft either for long cruise observations with limited resolution or with a good resolution from a spacecraft in orbit around any of the giant planets of the Solar System.

D. International collaborations

Network observations rely on international collaborations. The development of the Echoes proposal for the JUICE mission permitted, not only to build a prototype of a new instrument, but also to establish strong collaboration between the science team in France and several groups in the USA, in particular with the JPL, Pasadena, and the group of Jason Jackiewicz at the New Mexico State University, Las Cruces. The JIVE project, presented by NMSU, was selected by NASA in 2014 to develop a copy of the Doppler Imager at Apache Point Observatory, to complete the JUNO mission. The instrument will operate at Apache Point Observatory in 2017.

The selection of the JOVIAL project by the ANR offered the possibility to develop a new axis of collaboration with Japan, a good place to set-up an additional instrument for a whole-Earth network, completing the instruments in France and in the USA in view of 24h/day observations. The science team in Japan is interested in the internal structure of giant planets for comparison with exoplanets and as a clue to understand the formation of the Solar System and of extrasolar systems.
Around the JOVIAL and the Juno mission, the collaboration extends to scientists involved in internal structure of Jupiter in Italy and USA, and specialists of giant planet's atmospheric dynamics, in particular in Spain and the USA.

E. List of people involved in the project

Permanent
Tristan Guillot, CNRS DR, F.X. Schmider, CNRS DR, J.P. Rivet, CNRS CR
Contact: guillot@oca.eu

Engineers
Yves Bresson, IE Optics, Julien Dejonghe, IE Mechanics, Olivier Preis, IE Project Management and Frédéric Morand, IE, Software

PhD
Ivan Gonçalves

F. Most significant publications of the team

Gaulme, P., Schmider, F.-X., Gay, J., Guillot, T., Jacob, C., Detection of Jovian seismic waves: a new probe of its interior structure, Astronomy and Astrophysics 531, A104 (2011)

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Helled, R. and Guillot, T. "Interior Models of Saturn: Including the Uncertainties in Shape and Rotation", *The Astrophysical Journal*, vol. 767, p. 113 (url) (2013)

Short CV of participants

F.X. Schmider, CNRS research director at Lagrange Laboratory. Development of instrumentation for High Angular Resolution and for asteroseismology. PI of the JOVIAL project.

Tristan Guillot, is CNRS research director. He is an expert of planetary interiors and planet formation. He is associate Editor of Astronomy & Astrophysics. Author of ~135 reviewed publications, with over 7,700 citations and an H-index of 45 (source ADS), he has been the recipient of the bronze medal of CNRS, of the Urey Prize of the Division for Planetary Sciences of the AAS, and of the Zeldovitch Medal of the Committee for Space Research.