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The JOVIAL Project for Jovian Seismology

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Abstract. Jovian seismology is a unique tool to determine the internal structure of the giant planet. It could uncover the size and mass of the core, if any, the existence of a "plasma phase transition" between the molecular and the metallic hydrogen envelope, reveal the internal dynamic, and more generally address the formation and evolution of giant planets in the solar system giving a point of comparison for extra solar planets. Jovian seismology requires special observing tool. SYMPA (Schmider et al. 2007; Gaulme et al. 2008) was the first project specially designed for those objectives. A new type of instrument, a Doppler Imager, had been developed. The project permitted for the first time the measurement of the fundamental acoustic frequency of Jupiter (Gaulme et al. 2011). It also validated the principle of the instrument. However, several limitations appeared during the observations. The main one was the poor temporal coverage.

A new version of the Doppler Spectro Imager (DSI) has been studied extensively in the framework of the development of a space instrument for the JUICE mission. A prototype of this new device is presently developed in the laboratory (Soulat et al. 2011) and shows excellent sensitivity and stability. It will be tested on the sky in January 2014. The JOVIAL project foresees the installation of three similar instruments on three telescopes around the Earth (Japan, France, and USA) that will provide the necessary continuity in the observations. We expect to observe winds in the Jovian atmosphere with a precision better than 2 m/s and to detect modes with amplitude as low as 5 cm/s up to the degree $\ell = 10$ at least. The main objective of the project is the detection of the Jovian core.

1. Giant Planet Seismology

1.1. The Heritage from Asteroseismology

Fifty-years experience in helioseismology has permitted great success, as demonstrated during this conference. It allowed the measurement of the internal density and ro-

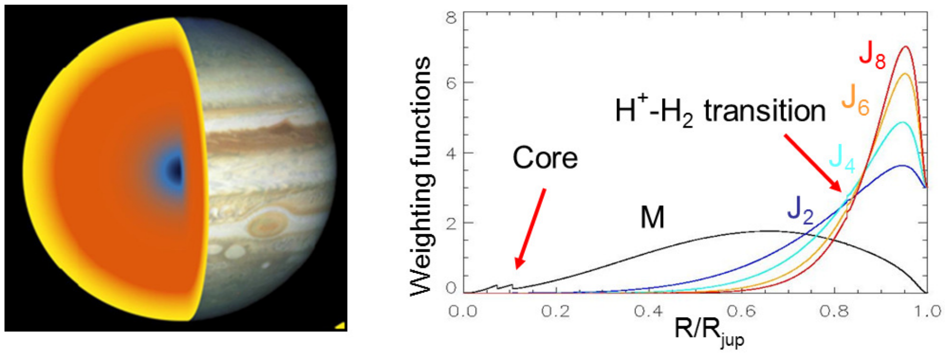

Figure 1. Left: Synoptic view of Jovian interior structure, with three layers: core, metallic hydrogen, molecular hydrogen. Right: Mass and gravitational moments up to J_8 as a function of the radius. (Courtesy: T. Guillot)

tation of the Sun with high precision. Both space and ground based measurements from IRIS, BiSON, GONG, GOLF (SOHO), LOI (SOHO), MDI (SOHO), HMI/SDO demonstrated that Doppler spectral imaging is the best method to detect and identify global oscillation modes.

More recently, asteroseismology has also been very successful. High precision spectroscopy from ground based observations permitted to observe low degree oscillation spectrum similar to the Sun. A real breakthrough was accomplished with space experiments *Convection Rotation and planetary Transits* (CoRoT) and *Kepler* that achieved very precise photometry. These missions observed oscillations on many type of stars, from solar-type stars to red giants and white dwarfs, and helped to understand the stellar evolution throughout the galaxy. Since the beginning of helioseismology, Vorontsov et al. (1976) has shown the interest in applying the same technique to giant planets. Gudkova et al. (1995) examined the physical problems that could be addressed by measuring oscillation frequencies for modes of different degrees.

1.2. Key Questions for Jovian Seismology

Giant planet internal structure is less understood than the solar one. This is mainly due to the high pressure at relatively low temperature inside the planets so the equations of state could not be studied at the laboratory and are badly known. Moreover, the formation and evolution mechanisms are still under debate. Two scenarios are proposed for giant planet formation: accretion of gas around a core of ice (rocks formed first) or a gravitational instability in the disk. The determination of the size and mass of the core of Jupiter as could be done by seismology will solve this question. Constraints to the internal structure of giant planets arise mainly from gravitational momentum. In a near future, the JUNO spacecraft will make great progress for the determination of the interior of Jupiter by radio sounding, mapping of the magnetic field and measurements of gravitational moments. However, the gravitational moments are mainly sensitive to the external part of the envelope (Figure 1). Determination of the core, in particular, relies on very uncertain equations of state. Present models for Jupiter and Saturn can fit the observation with a mass of the core between 0 and $10-15\ M_E$ (Guillot 2005). Only seismology is able to state the size and mass of the core, independent of the model.

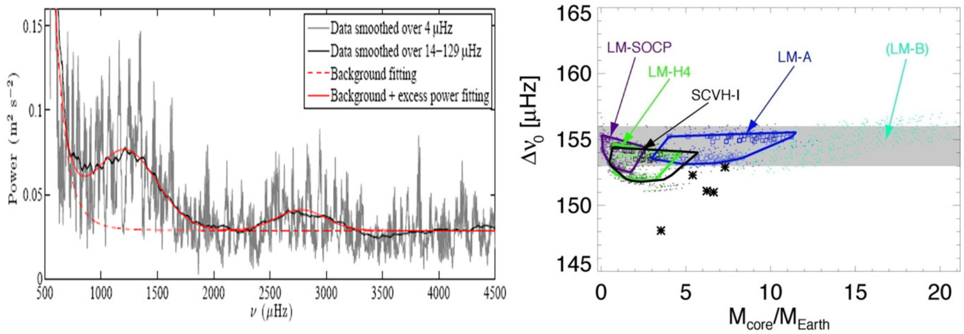

Figure 2. Left: Power density spectrum (PDS) of the Doppler signal for $\ell = 1$ mode obtained from 7 nights of observations. Right: Fundamental frequency as a function of the core mass for different models of the planet, as compared to the observed value (grey band). Reproduced from Gaulme et al. (2011) with permission from Astronomy & Astrophysics, © ESO

Seismology will also provide the rotation profile. It is expected that even in the outer region, seismology will provide a better radial resolution than gravitational moments.

2. Present State

Up to recently, detection claims of oscillations on Jupiter were uncertain. This is mainly due to the fact that previous observations had no access to angular resolution. The SYMPA (Seismographic Imaging Interferometer for Monitoring of Planetary Atmospheres) project (Schmider et al. 2007) was the first to develop an instrument dedicated to giant planet seismology. The instrument was an imaging Fourier transform tachometer, based on a Mach-Zehnder interferometer. It permitted ground-based observations of radial velocity maps of the Jovian surface with a resolution limited by the seeing. Data was processed with analysis techniques developed for helio and asteroseismology. Gaulme et al. (2011) performed a selection of antisymmetric modes $\ell = 1, m = 0$ and $\ell = 1, m = 1$ to avoid guiding effects and thermal drifts. The power density spectrum (PDS) of the corresponding time series reveals the presence of power excess in the range of 800 – 3000 μHz, where 20 individual peaks with mean amplitude of 30 ± 10 $cm/\ s$ could be identified. These peaks present a regular structure, with a mean spacing $\Delta\nu_0 = 154.5 \pm 1.5\,\mu$Hz, interpreted as the the fundamental frequency of Jupiter. This frequency is related to the mean density of the planet and proved to be in excellent agreement with most recent models. However, more precise parameters could not be found due to the low duty-cycle.

More recently, observations by *Cassini* of stellar occultations by Saturn rings reveals the presence of structure in the C-ring that could only be explained by the effect of f-modes of Saturn (Hedman & Nicholson 2013). This confirm the existence of oscillations in giant planets that make possible investigation of internal structure by seismology. It becomes a primary importance to set-up a dedicated project for giant planet seismology.

3. The JOVIAL Project

The Jovian Oscillations through radial Velocimetry ImAging observations at several Longitudes (JOVIAL) instrument uses a new Doppler Imager design with the same principle as SYMPA. The new instrument was studied for the JUICE (*JUpiter ICy moons Explorer*) mission with support of the French space agency CNES and will achieve a better sensitivity and better stability. A prototype has been tested at Nice observatory (Soulat et al. 2011) showing that a noise level as low as 10 $\mathrm{cm^2 s^{-2}\,\mu Hz^{-1}}$ could be obtained with a 1 m telescope. This will allow to detect all modes with amplitude larger than 5 cm/s of degree $\ell = 0$ to 10 on Jupiter and Saturn within 2 weeks of observations and observe zonal winds on Jupiter with a 2 m/s precision. However, the duty cycle is a critical conditions of these observations. The JOVIAL project foresees to observe simultaneously with three 1 to 2 m telescopes regularly placed around the Earth, in Japan, USA and France to solve this problem. The realization of the three instruments will take place in 2014 and 2015 and observations are foreseen for spring 2016 and 2017.

4. Conclusion

- The JOVIAL project offers a unique opportunity to fully investigate the internal structure and dynamics of Jupiter. In particular, it would definitively solve the question of the Solar System formation scenario. It will also provide a brand new view of the atmospheric dynamics.
- It inherits a robust 30-years experience in helio and astero-seismology, a technique that has recently proved its efficiency for the investigation of giant planets with the SYMPA project, and from the complete study of the Doppler Spectro Imager (DSI) prototype in the frame of the JUICE mission.
- It paves the way for a future space mission dedicated to giant planet seismology.

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References

Gaulme, P., Schmider, F.-X., Gay, J., Guillot, T., & Jacob, C. 2011, A&A, 531, A104
Gaulme, P., Schmider, F. X., Gay, J., Jacob, C., Alvarez, M., Reyes-Ruiz, M., Belmonte, J. A., Fossat, E., Jeanneaux, F., & Valtier, J.-C. 2008, A&A, 490, 859
Gudkova, T., Mosser, B., Provost, J., Chabrier, G., Gautier, D., & Guillot, T. 1995, A&A, 303, 594
Guillot, T. 2005, Ann. Rev. Earth Planetary Sci., 33, 493
Hedman, M. M., & Nicholson, P. D. 2013, AJ, 146, 12
Schmider, F. X., Gay, J., Gaulme, P., Jacob, C., Abe, L., Alvarez, M., Belmonte, J. A., Fossat, E., Gelly, B., Guillot, T., Jeanneaux, F., Mosser, B., & Valtier, J.-C. 2007, A&A, 474, 1073
Soulat, L., Schmider, F.-X., Robbe-Dubois, S., Appourchaux, T., Bresson, Y., Daban, J.-B., Gaulme, P., Gay, J., & Gouvret, C. 2011, in SPIE Conference Series, vol. 8172 of SPIE Conference Series, 18
Vorontsov, S. V., Zharkov, V. N., & Lubimov, V. M. 1976, Icarus, 27, 109