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The effect of Jupiter oscillations on Juno gravity measurements

Daniele Durante[a,*], Tristan Guillot[b], Luciano Iess[a]

[a] Sapienza University of Rome, Dipartimento di Ingegneria Meccanica ed Aerospaziale, Via Eudossiana 18, 00184 Rome, Italy
[b] Université de Nice-Sophia Antipolis, Observatoire de la Côte d'Azur, CNRS UMR 7293, 06304 Nice Cedex 4, France

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ABSTRACT

Seismology represents a unique method to probe the interiors of giant planets. Recently, Saturn's f-modes have been indirectly observed in its rings, and there is strong evidence for the detection of Jupiter global modes by means of ground-based, spatially-resolved, velocimetry measurements. We propose to exploit Juno's extremely accurate radio science data by looking at the gravity perturbations that Jupiter's acoustic modes would produce. We evaluate the perturbation to Jupiter's gravitational field using the oscillation spectrum of a polytrope with index 1 and the corresponding radial eigenfunctions. We show that Juno will be most sensitive to the fundamental mode ($n = 0$), unless its amplitude is smaller than 0.5 cm/s, i.e. 100 times weaker than the $n \sim 4-11$ modes detected by spatially-resolved velocimetry. The oscillations yield contributions to Juno's measured gravitational coefficients similar to or larger than those expected from shallow zonal winds (extending to depths less than 300 km). In the case of a strong f-mode (radial velocity ~ 30 cm/s), these contributions would become of the same order as those expected from deep zonal winds (extending to 3000 km), especially on the low degree zonal harmonics, therefore requiring a new approach to the analysis of Juno data.

1. Introduction

Arriving at Jupiter on 4 July 2016, NASA's Juno mission will complete 37 orbits around the planet, revealing details of its interior structure and composition (Bolton, 2010). A radio science experiment will measure Jupiter's gravity field with extremely high accuracy, thereby providing constraints on the planet's interior density profile and differential rotation (Guillot, 2005; Hubbard, 1999; Kaspi et al., 2010). Juno's orbit is polar and highly eccentric ($e = 0.95$), with a period of about 14 days. The perijove altitude is about 4000 km above the reference 1 bar level (which corresponds to 71,492 km at the equator). The pericenter latitude precesses from 5° N to 35° N over the nominal one-year and a half mission. The longitude of the node is controlled by means of orbital maneuvers. During pericenter passes Juno is tracked from ground at Ka band (32–34 GHz) to obtain the spacecraft range rate to accuracies of a few micron/s over time scales of 1000 s (see Asmar et al., 2005). The low pericenter altitude and the very accurate radio system provide excellent sensitivities to the gravity field of the planet (Finocchiaro, 2013; Finocchiaro and Iess, 2010).

Another method to probe the interior of the planet is through the determination of Jupiter's acoustic normal modes. While these oscillations are certainly a potential source of information on the radial density profile, they may also complicate the interpretation of Juno's gravity data. Jupiter's normal modes displace large masses that may perturb the spacecraft motion to levels that can be measured by Juno's extremely accurate Doppler system.

Theoretical studies of Jupiter's seismology were first performed in the mid 1970s (Vorontsov et al., 1976). They were subsequently revised and extended to include the effect of Jupiter's rotation and flattening (Mosser, 1990; Vorontsov and Zharkov, 1981), atmosphere (Mosser, 1995), and to infer consequences for Jupiter's interior models (Gudkova and Zharkov, 1999; Jackiewicz et al., 2012).

Over the past decades, several attempts to observe Jovian global modes have been carried out with different methods: thermal infrared photometry (Deming et al., 1989), optical resonance spectrophotometry (Schmider et al., 1991), using a Fourier transform spectrometer (Mosser et al., 1993), and finally with SYMPA (Seismographic Imaging Interferometer for Monitoring of Planetary Atmospheres), a Fourier tachometer whose principle is based on the spectro-imaging of the full planetary disk (Schmider et al., 2007). Analyzing data acquired with the latter instrument, Gaulme et al. (2011) detected an excess power between 800 and 2100 μHz and a secondary excess power between 2400 and 3400 μHz, as well as a characteristic splitting of the peaks of

* Corresponding author.
E-mail addresses: daniele.durante@uniroma1.it (D. Durante), tristan.guillot@oca.eu (T. Guillot), luciano.iess@uniroma1.it (L. Iess).

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155.3 ± 2.2 μHz, all of these compatible with frequencies of acoustic oscillations predicted by interior models of Jupiter.

In parallel, Hedman and Nicholson (2013) confirmed that waves observed by the Cassini spacecraft in Saturn's rings cannot be caused by satellites and therefore must result from global oscillations in Saturn, as had been proposed by Marley and Porco (1993). In this case, the very accurate determination of mode frequencies allows to directly probe the interior structure. The modes observed are f-modes, i.e., they correspond to the fundamental ($n = 0$) mode of acoustic oscillations. Fuller (2014) proposed that the observed frequency splitting results from a mixing mechanism between f-modes and g-modes (i.e., non-acoustic waves for which the restoring force is gravity), which requires the existence of a deep thick stable stratified region within the interior of Saturn.

It is thus clear that both Jupiter and Saturn oscillate (to some degree) and that a large fraction of the mass of these planets is involved in these oscillations. We aim to determine whether these oscillations have consequences for Juno, both for our ability to properly estimate the gravitational moments and then to provide constraints on the characteristics of those oscillations.

The article is organized as follows: In Section 2, we describe the simplified acoustic oscillation spectrum of Jupiter adopted as a basis for our calculations. In Section 3, we explain how we model gravitational perturbations arising from the oscillations. The consequences for Juno's measurements are presented in Section 4. The last section summarizes our findings.

2. Jupiter's acoustic oscillation spectrum

As first demonstrated by Vorontsov et al. (1976), Jupiter's atmosphere reflects acoustic waves if their frequency is smaller than about 3 mHz. These waves may propagate into the planetary interior, down to the core for some of them. At some well-defined frequencies, these waves resonate constructively and can reach non-negligible amplitudes. These frequencies depend on the structure of the planet. As long as a precise determination of the wave frequencies is not required, we estimate them by using simple models. The amplitudes of the waves depend on several unknown factors: the structure of the planet but also excitation and damping mechanisms. At this stage it is hard to identify a clear excitation mechanism. In terms of damping in the absence of other mechanisms yet to be determined, radiative damping in the atmosphere will yield a slow decay of waves with a timescale of about 300 years at 1 mHz to 10 days at 3 mHz (see Mosser, 1995 and Gaulme et al., 2015).

Following Hubbard (1977) (see also Guillot, 2005), we choose to approximate Jupiter's interior structure by a simple polytropic model of polytropic index equals to 1. The simplicity of this model does not compromise the results and the conclusions of this paper. The spectrum of mode frequencies surely differs from those predicted by more sophisticated model, but for our purposes, slightly different frequency values do not change substantially the overall picture of the gravitational signature of Jupiter acoustic modes. The same is true if the radial eigenfunctions are slightly changed. Indeed, our goal is simply an assessment of the effect of normal modes on Juno's gravity measurements. As a reference, frequencies obtained with the polytrope for low-degree, low-radial-order modes differs by about 5% with respect to those reported by detailed models (e.g., Gudkova and Zharkov, 1999). From a geophysical point of view this aspect is crucial, but not for the purpose of this paper. Eigenfrequencies and eigenfunctions can then be easily computed for the polytropic model. As we comment later in Section 3.1, gravity measurements does not allow us to consider modes of degree 0 and 1. The frequencies of the first few low degree, low-radial-order modes are reported in Fig. 1, starting from $l = 2$.

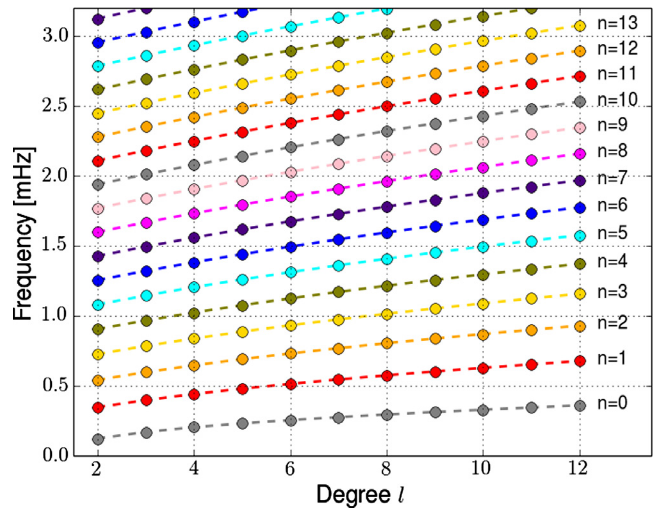

Fig. 1. Frequencies for low degrees and low radial order acoustic modes.

The period of the modes plays a crucial role in Juno's measurements. Due to the high eccentricity of Juno's orbit, the measurement sensitivity to the harmonics of gravity field is higher near perijove, and decreases sharply as the spacecraft altitude increases (gravity measurements are carried out at about +/− 4 h, corresponding to ∼ 5.8 R_{jup}, from closest approach). Fundamental modes have periods of about one hour, to a maximum value of 2 h for the $l = 2$ mode. Higher radial order modes have progressively shorter periods. The modes detected by SYMPA have periods between about 5 to 20 min and would correspond to $n \sim 4$ to 11 modes for $l = 2$ modes. Therefore the timescale of these phenomena falls within Juno's sensitivity window, set by the duration of a perijove pass (8 hours).

Jupiter radial eigenfunctions are reported in Fig. 2. On the left, eigenfunctions for fundamental modes ($n = 0$), affecting the whole planet, are reported for $m = 0$ and increasing degree, whereas modes with degree $l = 2,\ m = 0,$ and increasing radial order are shown on the right. Eigenfunctions are normalized to be unity at Jupiter reference radius.

We can notice on the left panel of Fig. 2 that, as the degree of the spherical harmonic increases, the fundamental modes move towards the surface, and the perturbation influences a limited portion of the planet (the outer layers). Similarly (right panel on Fig. 2), when the radial order increases, the oscillation period decreases, and the corresponding eigenfunction reaches values close to unity only near the surface. High radial order oscillation modes influence the Jupiter upper layers, whereas low radial order modes penetrate deeper in the planet. It is a very well known aspect of acoustic modes: they probe different region of the interior of a planet (or a star) according to its degree and radial order.

3. Gravity perturbation modeling

3.1. Basics

In order to evaluate the perturbation to Jupiter gravitational field produced by acoustic modes, we start from the harmonic expansion of the gravitational potential:

$$U(r, \theta, \varphi) = -\frac{GM}{r}\left\{1 + \sum_{l \geq 2} \sum_{-l \leq m \leq l} \left[\left(\frac{R}{r}\right)^{l} U_{l,m}\, Y_{l,m}(\theta, \varphi)\right]\right\} \tag{1}$$

With the usual convection, R is the reference Jupiter radius, r is the radial coordinate, θ is the colatitude, and φ is the longitude

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