

# Excitation mechanisms for Jovian seismic modes

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## ABSTRACT

Recent (2011) results from the Nice Observatory indicate the existence of global seismic modes on Jupiter in the frequency range between 0.7 and 1.5 mHz with amplitudes of tens of cm/s. Currently, the driving force behind these modes is a mystery; the measured amplitudes are many orders of magnitude larger than anticipated based on theory analogous to helioseismology (that is, turbulent convection as a source of stochastic excitation). One of the most promising hypotheses is that these modes are driven by Jovian storms. This work constructs a framework to analytically model the expected equilibrium normal mode amplitudes arising from convective columns in storms. We also place rough constraints on Jupiter's seismic modal quality factor. Using this model, neither meteor strikes, turbulent convection, nor water storms can feasibly excite the order of magnitude of observed amplitudes. Next we speculate about the potential role of rock storms deeper in Jupiter's atmosphere, because the rock storms' expected energy scales make them promising candidates to be the chief source of excitation for Jovian seismic modes, based on simple scaling arguments. We also suggest some general trends in the expected partition of energy between different frequency modes. Finally we supply some commentary on potential applications to gravity, Juno, Cassini and Saturn, and future missions to Uranus and Neptune.

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## 1. Introduction

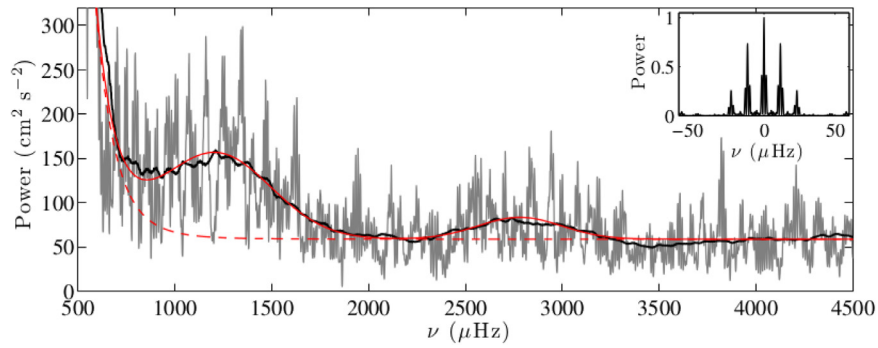
Jupiter is the largest planet in the solar system, and our most accurate nearby representation of thousands of exoplanet analogues which seem to be equally or more massive, and comprised of approximately the same material. Understanding Jupiter's formation history, then, is of great importance for understanding how planetary systems form in general. Understanding Jupiter's interior is an essential part of modeling mechanisms for its formation; for example, the most popular explanation for Jupiter's formation would suggest that the embryo Jupiter was a rocky planet early in its formation history, and we can perhaps expect a many Earth mass core to exist as a relic of that time (Pollack, 1996). Additionally, there is an abundance of information about thermodynamics and materials physics to be learned by probing the detailed structure of Jupiter's deep interior. Current methods of constraining Jupiter's interior (e.g., gravity and magnetic field measurements) are valuable, but cannot uniquely determine the internal structure. Therefore seismology will be an indispensable tool as we continue to try to study Jupiter's interior (Gaulme, 2014). Techniques applied to Jupiter can also be generalized to other planetary systems, and the scientific commu-

nity has already expressed interest in applying similar techniques to Uranus, Neptune (Turrini, 2014; Elliot, 2017), and even Venus (Stevenson, 2015; Lognonne and Johnson, 2015).

In 2011, a team from the Nice Observatory released a paper which claimed to have detected normal modes from Jupiter using an interferometer called SYMPA to perform Fourier transform spectroscopy (Schmider, 2007; Gaulme, 2008; 2011). SYMPA measures line of sight Doppler shifts, so the detected displacements are primarily radial. For modes within the frequency range of sensitivity (high order p-mode overtones with frequencies above about 700  $\mu$ Hz), SYMPA detected peak oscillation velocities on the order of 50 cm/s. As outlined in Section 3.6, this value is the result of the superposition of multiple modes, and the velocity amplitudes of individual modes may be lower by a factor of 2 or 3. To put this in perspective, compare this to the maximum velocity amplitude in any single mode found in the Sun, around 15 cm/s (Christensen-Dalsgaard, 2014). The total peak velocities measured on the Sun can be substantially higher, because the solar observatory's exquisite spatial resolution allows them to resolve much higher spherical order modes, and therefore more of an effect from superposition. Apparently the surface velocity amplitudes of both bodies are of similar orders of magnitude. It should be noted that since SYMPA's measurements were limited to eight nights without continuous observations, and because the instrument has low spatial resolution, that these measurements are only relevant to low spherical order, high frequency modes (overtones of global

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**Fig. 1.** The observed power spectrum obtained by Gaulme (2011).

scale modes). The power spectrum for the SYMPA measurements is found on Fig. 1.

This result is encouraging because it means the signal is sufficiently strong that meaningful measurements can be taken from Earth. It is puzzling, however, because it requires an excitation mechanism on Jupiter that is fundamentally different from what happens in the Sun. We can conduct a simple order of magnitude calculation to enumerate the problem here. Since each normal mode behaves as a simple harmonic oscillator, its total energy is equal to its maximum kinetic energy. If its eigenfunction is described by displacement vector eigenfunction  $\xi$  (further discussed in Section 2 and illustrated in Fig. 3) normalized to a magnitude of unity at the surface, then integrating over the whole body yields the total energy contained within a given normal mode.

$$E_{\text{mode}} = \frac{1}{2} v^2 \iiint \rho |\xi|^2 dV \quad (1)$$

where  $v$  is the velocity amplitude,  $\rho$  is the spatially dependent density.  $\iiint \rho |\xi|^2 dV$  is called the *modal mass* (Christensen-Dalsgaard, 2014). The order of magnitude behavior of the eigenfunctions in the Sun and in Jupiter should be similar, so we can neglect that factor since it is not a significant distinction between Jupiter and the Sun. That is, for similar eigenfunction structure  $\xi$ , one can approximate the modal mass  $\iiint \rho |\xi|^2 dV \sim fM$  to zeroth order—that is, the modal mass scales approximately linearly with the mass of the body (Christensen-Dalsgaard, 2014). We can therefore derive a zeroth order scaling relation of the form

$$E_{\text{mode}} \sim Mv^2 \quad (2)$$

where  $M$  is the mass of the body. Of course, this simplistic analysis ignores relevant details. The density contrast between the shallow and deep parts of the Sun is much more extreme than for Jupiter; this affects both the modal mass and the excitation efficiency. Still, as a zeroth order first approximation to introduce the problem, we can place an order of magnitude estimate on the efficiency with which energy is injected into this normal mode by comparing the squared velocity amplitude to the luminosity per unit mass. The luminosity per unit mass in the Sun is about  $2 \text{ erg g}^{-1} \text{ s}^{-1}$ , and for Jupiter it's about  $2 \times 10^{-6} \text{ erg g}^{-1} \text{ s}^{-1}$  (Stevenson, 2016). The problem then becomes immediately apparent. In order to produce the observed normal modes on Jupiter, the mechanism for injecting energy into the modes and retaining energy within the modes must be millions of times more efficient on Jupiter than on the Sun. This excitation is computed in more detail in Section 5.1. At the moment, this disparity is not understood. The focus of this paper is to attempt to identify mechanisms which could deposit energy into Jupiter's normal modes orders of magnitude more efficiently than the Sun.

Helioseismology revolutionized our understanding of the Sun. Studying the Sun's seismic modes definitively answered questions ranging from the solar neutrino problem, the Sun's convective

and radiative zones, the existence of deep jet streams, the age of the Sun, and its differential rotation (Deubner and Gough, 1984). Today, many fundamental questions about Jupiter may be answered with the same treatment. DiOSEISMOLOGY (an alternative word with equivalent meaning to Jovian seismology, first used by Mosser, 1994) could illuminate a condensed or diffuse core. It could provide more detailed information about the physical properties of liquid metallic hydrogen, and reveal the existence of regions of static stability or exotic chemical cloud decks deep below the visible surface. With so much to gain from dioseismology, it is a worthwhile endeavor to understand.

Unfortunately, the existing data for normal modes has rather low signal to noise ratio and is regarded by some as suspect, in part because we lack an understanding of how the modes could be excited. If we can develop a more quantitative understanding of their excitation and dissipation, then we could corroborate the possibility of their existence and motivate future observational programs. Such insights would be useful diagnostic tools to design space-based seismometers for future missions to Jupiter, as well as other planets in the solar system.

The 1994 comet strike of Shoemaker–Levy sparked much interest into the possibility of Jovian seismic mode excitation by the cometary impact. Competing calculations made contradictory predictions at the time. Dombard and Boughn (1995) did not predict measurable amplitudes, but others such as Lognonne et al. (1994) predicted measurable amplitudes for a sufficiently energetic impact. As it turns out, the seismic modes associated with SL9 were never detected (Mosser, 1996). In this work, we generalize the framework constructed by Dombard and Boughn (1995) for the expected seismic response to the impact of Shoemaker–Levy with Jupiter, as well as the work for the Sun and other stars made by Goldreich and Keeley (1977), Goldreich and Kumar (1994), to try to propose any plausible candidates for Jovian seismic mode excitations. These mechanisms should be both explanatory and predictive; if a certain model explains the observed results, it can also predict what amplitudes should be expected in frequency ranges which have not yet been detected. Future measurements, then, can provide support or refutation for different models proposed here.

This paper will begin with an introduction to our model of Jupiter and the treatment of its normal mode displacement eigenfunctions. We will then outline some general mathematical tools to abstractly model and parameterize different types of excitation sources. Next we will investigate a few important dissipation mechanisms to try to place some constraints on Jupiter's modal  $Q$ . We will then apply all these tools to some potential physical excitation sources, to try and estimate an order of magnitude for what velocity amplitudes these mechanisms might excite. Finally we will discuss our findings, with some brief remarks on potential applications of these findings to Jupiter and other planets.

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