Planetary seismology: High risk, high return

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Except for specialists, planetary seismology refers first to Earth seismology, and stimulates thoughts about earthquakes, tsunamis, and all such rare and brutal events that everyone knows by experience and/or fears. According to etymology, seismology shakes and shocks our bodies and our minds. According to semantics, all languages make the difference between "superficial" and "deep" things, so that everyone turns out to be a seismologist, encouraged to prefer a deep to a superficial analysis, to get to the bottom of things, to look at an issue in more depth, to delve into something, to get to the root of the matter, to seek out the underlying issues. . .

We have basically a 2D topological experience of the Earth since we live on it and are attached to its surface. Of course, in tunnels and by plane, we are invited to explore the third dimension, a thin envelope in fact, so shallow with respect to the Earth radius. Even this Earth radius is an ethereal concept (sorry for the hiatus), since we lack normal circumstances where we can simply feel that the Earth is not as flat as a pancake. When the Earth was a pancake, there was a great debate about the nature of its edge. In a 3D spherical view, defining and measuring the Earth radius implies necessarily prospecting the medium between the surface and the center.

Hidden signatures

The favorite activity of a planetary seismologist consists in seeking to look well below the planetary surface, as done by Athanasius Kircher, a German Jesuit (1601–1680), in his model of the Earth's interior. Volcanoes were seen as outlets of the Earth's internal fires. Similarly, any trace on a planetary surface can be related to properties of the interior structure. On the Moon, the absence of surface faulting indicates tectonic inactivity. On Mars, the presence of huge volcanoes has the same consequence. However, this does not imply that the objects are seismologically inactive. On Jupiter, Saturn, and Neptune, the net flux radiating from the planet indicates a significant inner energy source (approximately equivalent to the solar flux), hence convection for extracting this energy, then possibly

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non-negligible seismic activity. These surface signatures are, however, not enough to scan the interior in detail. To do so, we need seismology.

The aim of seismology is, in essence, hidden. As a consequence, the paradigm of instrumentation for planetary seismology is demanding: Complex and sensitive devices are required, for mostly unknown results to be recorded in complex conditions. When an instrument is designed and built for, e.g., measuring various components in a planetary atmosphere with an unprecedented sensitivity, much information is available on this atmosphere. First of all, the existence of this atmosphere is certain, and many molecules just wait to be detected. When you aim to observe the Moon, Mars, or Jupiter with a seismometer, you need the most sensitive instrument, since you seek for tiny signals, and you pray for an efficient source of excitation, and the absence of noise.

Instrument and instrumental noise

The noise level of an efficient instrument must be as low as possible. As usual, this implies contradictory specifications. The white noise level of an *in-situ* seismometer with a suspended proof mass is inversely proportional to the square root of the product of the proof mass, the period, and the quality factor of the suspension (see Chapter 3 by Lognonné and Pike). Such seismometers are, basically, equivalent to instruments used on Earth. However, for use in space, mass is an issue. Mid-term solutions must be found for the quality factor too, since a high quality factor in favor of a noise-free instrument implies a narrow bandpass, hence an instrument efficient in only very limited cases.

Similarity with helioseismology is useful for defining the instrumental principle for seismic observations of a planet with a fluid surface. In order to retrieve a tiny seismic Doppler signal embedded in multiple much stronger Doppler-like signatures (differential rotation, convective movements), such an instrument has to simultaneously achieve imaging and high-resolution spectrometry. This requires a large number of photons to be detected, hence a large photon collector. The quality factor of the spectrometer has to be as large as possible, which goes against the first specification.

Having a single instrument for seismology is, as one can imagine, not appropriate. With one single instrument, the information to be recovered is highly degenerate. In the opposite case, reconstructing a precise tomographic view of an inhomogeneous body requires a large number of seismometers adequately distributed. For cases in between, the more instruments you have, the more informative the results can be. The single seismometer deposited on Mars by the Viking mission could not work in favorable conditions. For Jovian seismology, the first observations made without spatial resolution could only retrieve integrated signals. Current projects for Jovian seismology all consider an imaging instrument able to deliver seismic information on the whole visible hemisphere.

Excitation and signal

The question of excitation plays a central role. As seen above, for other bodies a tectonic origin as on Earth is unlikely. Identifying a phenomenon able to excite waves is tough;

quantifying the excitation is awfully complex. Apart from the Moon, which benefitted from multiple observations that led to the detection of various types of events (see Chapter 15 by Knapmeyer and Weber), the situation is unclear since we lack information. Obtaining this information would require seismology. . .

The examples of helio- and asteroseismology can be usefully exploited for understanding the possible excitation of oscillations in the fluid giant planets. Oscillations in these objects are called normal modes (according to the terminology used for solid planets) or global oscillations (according to the terminology used in helio- or asteroseismology). In practice, long-lived modes constructed by resonant pressure waves (P waves) are observed, not only transient waves. In such fluid media, shear waves (S waves), with transverse displacement, do not exist. Solar-like oscillations are seen in all stars showing an external convection envelope. Convective turbulent cells breaking just below the photosphere, responsible for the granulation seen on the Sun, stochastically excite waves. The levels of excitation are low, and the mechanism implies that the oscillations are embedded in a high background noise. Fortunately, the coherence of the long-lived oscillations allows their detection. A similar excitation is expected for the giant planets, except Uranus.

Results and prospects

So far, unique results have been obtained for the seismic Moon, benefitting from the multiple manned missions on the Moon from 1969 through 1977. Passive and even active seismometric observations were performed, and yielded various results, with the detection of waves generated by meteoroid impact, thermal waves, or deep Moonquakes. Mars' seismicity was monitored by the Viking mission, from 1976 through 1978. Only one seismic station was operative. The seismometer could not be deposited on the ground but was mounted on the lander to minimize the weight and complexity. It failed to produce any positive seismic detection, with all events certainly due to wind shifts. For Jovian planets, the best result, limited to the detection of seismic global parameters, was obtained with a dedicated ground-based instrument.

Even if seismology is a powerful tool for inferring information on the planetary (and stellar) interior structure, any other way to provide such information is good and should not be ignored. The gravitational moments of Jupiter, quickly measured by the NASA space probe Juno during its nearby flybys of the planet, can be used to relate the geometrical properties of the external gravitational field of the planet to its mass density distribution. However, such information corresponds to quantities integrated from the center to the surface of the planet and has no precision compared to seismic observations, which provide us with a differential view of the body. At the time of writing, we expect unique results from the ESA mission Rosetta. The lander Philae will carry much information on the structure of a comet core. Radar will perform tomography of the nucleus by measuring electromagnetic wave propagation between the Philae lander and the Rosetta orbiter through the comet nucleus. Other instruments are aimed at measuring physical properties of the outer layers of the comet.

Despite the high cadence of planetary probes traveling to Mars and landing on it, the seismic analysis of Mars is still to come. The situation will fortunately change with the NASA Discovery Program mission InSight (Interior Exploration using Seismic Investigations, Geodesy and Heat Transport). InSight aims to measure the size, composition, and physical state of the martian core. It is designed to determine the thickness and structure of the martian crust, the composition and structure of the martian mantle, the thermal state of Mars' interior, to measure the magnitude, rate and geographical distribution of Mars' internal seismic activity, and to measure the rate of meteorite impacts on the surface of Mars. The only way currently possible to provide more rapid results in planetary seismology should come from the NASA *Kepler* 2.0 mission. With photometry, this mission could lead to a major breakthrough in planetology by providing the first seismic observations of Neptune.

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Excerpt
More information

A bright outlook for helio- and asteroseismology

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As documented in the following, very substantial results have already been obtained from helio- and asteroseismology, based on huge observational projects, such as the GONG project, the helioseismic instruments on the Solar and Heliospheric Observatory (SOHO) and Solar Dynamics Observatory (SDO) satellites, and asteroseismology with the CoRoT and *Kepler* missions. But this is just the beginning. New asteroseismic projects are on the way, and there are also plans for new developments in observational helioseismology, including multi-wavelength observations (Hill *et al.*, 2013). For local helioseismology a potential breakthrough will come from ESA's Solar Orbiter mission (Gandorfer *et al.*, 2011), which will for the first time allow detailed investigations of the regions near the solar poles.

However, there is much to be done with the existing data, and much to be done further to develop the analysis techniques. The helioseismic data have been far from fully exploited, with the inverse analyses being typically based just on a small fraction of the available observations. In particular, the high-resolution observations from the Helioseismic and Magnetic Imager (HMI) instrument on SDO may provide reliable frequency data on high-degree modes, which would allow more detailed investigations of the thermodynamics of the region of helium ionization (e.g., Rabello-Soares *et al.*, 2000). Also, the base of the solar convective envelope certainly deserves further investigation, including an updated search for possible latitude variations (Monteiro and Thompson, 1998) and a follow-up to the hint of solar-cycle variations found by Baldner and Basu (2008). The helioseismic data on frequency splittings have been extensively used to study variations of solar internal rotation during the solar cycle (for a recent example, see Howe *et al.*, 2013). However, further work is certainly required on constraining the rotation of the solar core, where improvements in the inversion techniques may allow a better localization and balance between resolution and error. I note that Vorontsov and Jefferies (2013) are developing new techniques for the analysis and interpretation of helioseismic data which offer substantial promise for improved inferences on structure and rotation.

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Local helioseismology has the potential to provide information about the rapidly evolving subsurface structure and dynamics of the Sun. At present, and in the foreseeable future, the most detailed results are obtained from the HMI on the SDO satellite (Scherrer *et al*., 2012). These include daily images of active regions on the solar backside obtained with helioseismic holography (e.g., Lindsey *et al*., 2011, see http://jsoc.stanford.edu/data/farside/), the potential, not yet fully realized, of providing generally available maps of flow-field wave-speed perturbations several times a day, as well as synoptic maps of these quantities for each Carrington rotation (Zhao *et al*., 2012c). Such results clearly have great value for the study and potential understanding of solar activity, and for space weather analysis and prediction, and their availability and user friendliness should be further improved.

An extensive discussion of the state of helioseismology and its future development, including the very many open issues, was provided by Gough (2013).

For distant stars, inverse analysis, in the manner successfully applied to the Sun, is severely limited owing to the restriction of the observed modes to those of low degree (see also Thompson and Christensen-Dalsgaard, 2002). Analysis of low-degree solar data (Gough and Kosovichev, 1993) and simulated stellar data (Basu *et al*., 2002) indicates that some resolution of the structure may be possible in the core of solar-like stars. These techniques are based on linearizing the frequency differences between the star and a reference model; it has been found that such linearization may be inaccurate unless the reference model is already quite close to the star. A conceptually very different approach to structure inversion, which does not require linearization, has been proposed by Roxburgh and Vorontsov, based on phase matching (for a brief overview, see Roxburgh, 2010). This has yielded very promising results when applied to artificial data and was recently applied to observed data with encouraging results (Roxburgh, 2015). Inversion for stellar rotation has been attempted in a few cases, to obtain localized information about the core rotation in unevolved red giants, while inferences aimed at determining the near-surface rotation had some success in suppressing the unwanted contributions from the core. Further tests of these techniques, including use on artificial data, are also required.

As a complement to these detailed investigations of individual stars, further development is required of efficient and reliable techniques to analyse observations of large numbers of stars. An extensive analysis of main-sequence and subgiant stars was carried out by Chaplin *et al*. (2014) based on *Kepler* observations of global seismic parameters. However, the determination and fitting of individual frequencies still require substantial care and human intervention in the analysis. Even techniques that in principle provide an unbiassed best estimate of the fit and its statistical properties depend on appropriate assignment of weight to the frequencies, frequency combinations, and other observables which is difficult to make automatic. Also, work is still required on the proper implementation of error correlation in these fits. In the case of *Kepler*, detailed data are potentially available for a few hundred main-sequence and subgiant stars, and hence it is possible to invest considerable effort in the analysis of individual stars. For future missions we can expect such data for thousands of stars, and hence automated procedures become mandatory.

Given the huge number of stars observed with present and coming projects we also need to consider how best to make use of the data. Extensive modeling efforts will probably be confined to a relatively small number of "best" cases, with data of exceptional quality or otherwise presenting particularly interesting features. Thus we need to develop methods to identify such cases. For the bulk of the stars, ensemble studies will be carried out, to determine the dependence on global stellar parameters of the properties of the stars, including specific aspects of their internal structure. This also has the potential to provide a wide-ranging test of stellar modeling. Cases of clear discrepancies between the models and the observations will be obvious targets for more detailed investigation, to identify the reasons for the failure of the models. It is evident that reliable statistical information is required to ascertain whether the inferred discrepancies are indeed significant.

A key goal of these investigations is of course to improve our understanding of stellar structure and evolution, with emphasis on the physical processes controlling stellar properties. Stellar modeling is undergoing a substantial evolution, with the inclusion of increasingly realistic descriptions of effects of rotation and other instabilities, based in part on insights obtained from large-scale hydrodynamical simulations. We can expect a strong interaction between this improved modeling and the continuing improvements in the asteroseismic inferences.

Looking beyond the likely horizon of the present author, it is clear that a major limitation of present asteroseismology is the restriction to low-degree modes. For example, this essentially precludes any search for stellar analogues of the solar tachocline, which is expected to play a major role in the generation of the solar magnetic activity. Thus, observations able to detect oscillations of degree at least as high as 60 are highly desirable. This is one of the goals of the Stellar Imager (Carpenter *et al.*, 2009), a mission concept for interferometric stellar observations with rather high spatial resolution. Such a mission will require very considerable technical development and likely precursor missions to document technical feasibility. Should the full Stellar Imager be carried out, which I certainly hope, we would get an even closer relation between the seismology of the Sun and the distant stars.

Part I

Observation and space missions