RESEARCH ARTICLE
PLANETARY SCIENCES

Earth and Planetary Physics
8: 703–710, 2024
doi: 10.26464/epp2024043

Prospects for Jovian seismology with the Lenghu planetary telescope

YiQing Zou[1,2], Fei He[1,2*], ShanShan Zheng[3], Lei Yu[3], ZhongHua Yao[1,2], ZhaoJin Rong[1,2], and Yong Wei[1,2]

[1]Key Laboratory of Earth and Planetary Physics, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China;

[2]College of Earth and Planetary Sciences, University of Chinese Academy of Sciences, Beijing 100049, China;

[3]Anhui Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Hefei 230031, China

Key Points:

- Seismology is powerful to investigate the structure of Jupiter's interior.
- A interferometer polarization imager is designed to capture Jovian oscillation signals.
- The seismologic imager will be applied to the Lenghu planetary telescope.

Citation: Zou, Y. Q., He, F., Zheng, S. S., Yu, L., Yao, Z. H., Rong, Z. J., and Wei, Y. (2024). Prospects for Jovian seismology with the Lenghu planetary telescope. *Earth Planet. Phys.*, *8*(5), 703–710. http://doi.org/10.26464/epp2024043

Abstract: Jupiter is one of the top priorities for deep space exploration in China and other countries. The structure of Jupiter's interior, in particular, is a crucial but still unclear scientific topic. This paper discusses current scientific understanding of Jupiter's interior by summarizing the history of past and current exploration and data analysis. We review recent space-based and ground-based observation methods and analyze their feasibility. To gain new insight into the internal structure of Jupiter, we propose to study Jupiter's innards by planetary seismology. Ground-based observation, namely the Jupiter Seismologic Interferometer Polarization Imager (SIPI) in Lenghu, will be developed to obtain the Doppler velocity distribution on the surface of Jupiter and identify oscillation signals. Lenghu has observation conditions that are not only exceptional in China but even in the world, capable of providing novel insight into the interior of Jupiter. This will also be the first study in China of the interior of Jupiter using asteroseismology, which has significant implications for China's plans to explore Jupiter via spacecraft-mounted instruments.

Keywords: Jupiter seismology; Jupiter's interior; Jupiter model; Jupiter Seismologic Interferometer Polarization Imager (SIPI)

1. Introduction

Jupiter is the planet in the Solar System with the largest mass, the strongest magnetic field, the most energy, and the most abundant natural satellites. Exploring the interior of Jupiter can help us unveil the formation of the entire galaxy, including the origin of the Solar System and the growth of the planets. Despite hundreds of years spent studying the swirls and streaks of Jupiter's surface via telescopes, we still understand little about the substance that lies behind the clouds that cover the planet, preventing us from observing its interior. Learning more about its composition might help us comprehend the early development of the Solar System, the formation of Jupiter's magnetic field, and perhaps even the possibility of extraterrestrial life (Handler et al., 2013).

Since the dawn of the space age, scientists have studied the interiors of other planets by placing instruments on their surfaces, similar to the seismographs on the Earth. Seismic waves propagate through the planet, their velocities influenced by the density, temperature, and composition of the materials they pass through. Seismic tomography is then used to analyze the seismic waves recorded at multiple seismographic stations. Thus, the relationship between wave speed and depth can be obtained, and the characteristics of planetary structure and composition can be inferred. This has become a classic way to study solid Solar System bodies such as the Moon and Mars.

Jupiter is a gas giant; it is obviously impossible to place seismographs on its surface. It must be observed remotely, via satellites or ground telescopes. Traditional methods (e.g., studying the planet's gravitation and magnetic field) are insufficient to characterize the interior of Jupiter, making seismology a promising approach (Mosser, 1997). Although the Sun's interior and Jupiter's interior cannot be equated, it is possible to draw lessons from helioseismology.

The Sun is a massive rotating gas star, and its internal structure has been studied by analyzing the various waves occurring on the Sun. These waves are excited in the subsurface turbulent convective boundary layer. They propagate through the interior of the Sun, and, as they travel, they are affected by the properties of the material through which they pass (Gough et al.,1996a). Helioseismic waves are created when vibrations generated at each point

First author: Y. Q. Zou, kiwizou@mail.iggcas.ac.cn
Correspondence to: F. He, hefei@mail.iggcas.ac.cn
Received 17 AUG 2023; Accepted 15 JUN 2024.
First Published online 14 AUG 2024.

on the Sun's surface propagate in all directions. Correspondingly, vibratory motion at any point on the surface is a superposition of the waves generated at that point and propagating in all directions. The observed helioseismic waves have different frequencies, different wavelengths, and different vibration modes (Christensen-Dalsgaard, 1997; Appourchaux et al., 2010). By inverting the different waves, researchers have obtained information about the Sun's inner structure and have imaged the solar backside. Helioseismic waves can be categorized into different modes based on different restoring forces (Figure 1):

(1) G-mode, for which the restoring force is the buoyancy due to density fluctuations and gravity. G-mode waves are transverse and low frequency, and are confined to the inner part of the Sun. They propagate below the troposphere; when they reach the surface, they have significantly less amplitude than P-mode waves. For the Sun, typical periods of G-mode waves are several hours; the shortest recorded period is longer than 35 min (Stix, 2002; Fossat et al., 2017).

(2) P-mode, waves for which the restoring force arises from the pressure gradient. The P-mode can also be interpreted as pressure or acoustic waves. The P-mode has so far been the most often observed mode, with periods of a few minutes (Stix, 2002; García and Stello, 2015).

The oscillations seen on the solar surface are caused by the superposition of surface gravity waves and acoustic waves, or mixed modes with P and G properties. The oscillation frequency range is from 2–5 mHz, corresponding to periods ranging from 3 to 8 minutes. Maximum amplitude is observed at about the 5 minute mark, giving rise to the term of *5-minute solar oscillations* (Lubow et al., 1980; Deubner and Gough, 1984; Fossat et al., 2017).

Analyzing the frequencies of the Sun's oscillatory modes is one way to infer its internal structure. We can study the eigenfunctions of the oscillations, and the propagation of the wave components that constitute those eigenfunctions in a particular region of the Sun (Gough et al., 1996b). By measuring the motions of the atmosphere to identify their characteristics, it is possible to gain information relating to the whole volume through which the waves have traveled (Gough et al.,1996b). Different wave frequencies are interpreted to yield different information about the Sun's interior.

Jupiter, a gas giant planet, has a fluid structure similar to that of the Sun, suggesting that it should be possible to study its interior through similar interpretations of observations of Jupiter's free oscillations (Gaulme et al., 2011; Pallé et al., 2015). When waves in a fluid reach a density interface, they are reflected and turn into standing waves by superimposing with the previous wave, which is visually represented as free oscillations. Therefore, Jovian seismology observations can potentially be used to reveal the internal structure of Jupiter. However, differences between the Sun and Jupiter make Jovian seismology observations more difficult, for the following reasons.

(1) The Sun has a convective outer envelope that is highly active, and a radiative inner region that is strongly and stably stratified. Jupiter's interior, however, despite possibly having weak stable stratification layers (the helium rain region and the dilute core) is nearly on a single adiabat (Proctor, 2004; Guillot et al., 2004).

(2) As a typical stellar object, the Sun is much more centrally concentrated (indicated by a higher effective polytropic index) than Jupiter, which means that Jupiter possesses a more considerable relative radial density variation in its outer region. Effectively, all P-modes in Jupiter penetrate much more shallowly from its surface to the interior, in fractional radius, compared with the Solar P-modes of the same degree and order. In Doppler velocities, individual modes on the Solar surface have amplitudes of 10 cm/s or even lower, and their superposition leads to a total oscillatory signal of about 1 km/s (Harvey, 1995; Thompson, 2004; García et al., 2005), while on Jupiter it is just 0.01–1.0 m/s (Bercovici and Schubert, 1987). Observations of greater accuracy are required.

(3) The Sun is rotating much more slowly than Jupiter. Jupiter is rotating so fast that its spin frequency is comparable to its dynamical time scale (or the free-fall time scale). The Coriolis force and the related dynamical coupling effects in seismological modes become strong enough to make observations of Jovian seismological modes much more difficult than in helioseismology.

To get precise results, helioseismology requires nearly continuous

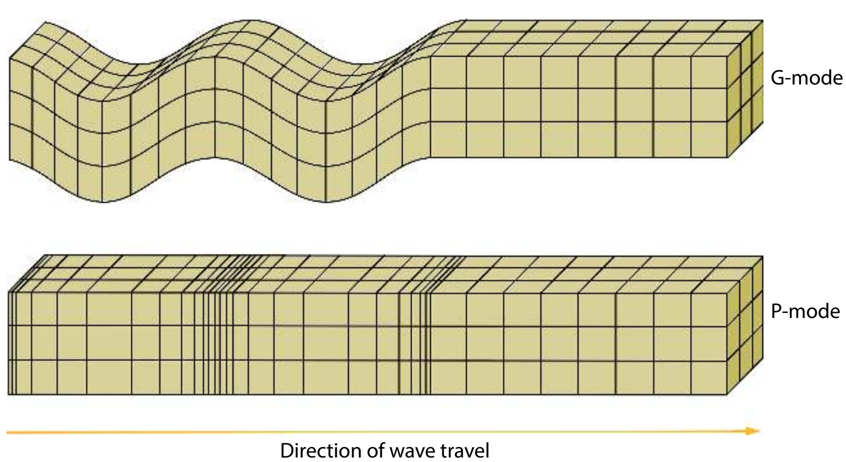

Figure 1. Illustration of G-mode and P-mode oscillations. (top) G-mode: oscillation is perpendicular to the direction of wave travel. (bottom) P-mode: oscillation is parallel to the direction of wave travel.

observations of oscillations on the surface of the Sun over a long period of time (Leibacher, 1999). Thus, in Jovian seismology, too, the duration of observations and the duty cycle will be critical to its success. While there are many technical challenges in translating the technique from the Solar case to that of Jupiter, several scientific achievements of Jovian oscillation detection in the acoustical regime have been achieved, as described in the next section.

This paper reviews previous observations and investigations of Jupiter's free oscillations. We then introduce China's first instrument focused on investigating the deep structure of Jupiter by imaging the planet's free oscillations.

2. Past Investigations of Jupiter's Interior

Jupiter played a pivotal role in the formation of the Solar System as we know it today, since it was so massive and formed so quickly. Our knowledge of Jupiter has been built from very few fundamental facts. Similar to the composition of the Sun, Jupiter contains mainly hydrogen and helium. The composition of Jupiter includes 89.8 ± 2.0% hydrogen, 10.2 ± 2.0% helium, and 0.4% of other elements (Mauri, 2010).

The common perception of Jupiter's interior is that Jupiter is a hydrogen-helium planet with hydrostatic equilibrium. Its temperature inside is 20,000 K (Hemley, 1995). Jupiter consists of an expanding gas cloud whose gravitational energy is converted into heat as it contracts (Hubbard and Smoluchowski, 1973; Guillot et al., 2004).

Jupiter is contracting at a rate of 3 cm per year, while its interior is cooling at a rate of 1 K per million years (Guillot et al., 2004). The cooling and contraction appear to generate a huge intrinsic energy flux, resulting in more energy emission from Jupiter than it receives from the Sun. This flux is assumed to drive most of the planet's internal convection currents and to generate the observed magnetic field through the dynamo mechanism (Guillot et al., 2004). If these theories hold, it should be possible to derive the composition of the planet directly from determination of the elemental abundances in its atmosphere, and to model Jupiter's interior by performing high-pressure laboratory experiments on the gas mixture (mainly hydrogen and helium), the equation of state, the boundary conditions, and the planet's energy flux. However, Jupiter's interior is undoubtedly much more complicated than this.

Understanding how the Solar System developed depends on determining each planet's precise elemental composition and how those elements are distributed within and around the planet. Jupiter's interior holds important traces of substances other than hydrogen and helium, including neon and water. Knowledge of Jupiter's atmosphere will thus not yield sufficient information to determine its interior structure. It is a challenge for us to pry into the interior of Jupiter because the coulombic interaction between electron degeneracy and ions can lead to phase transitions or phase separation of elements (Guillot et al., 2004; Nettelmann et al., 2008). Typically, models of planetary interiors based on gravity field measurements generally require that the planet have a dense core whose mass and composition reflect how the planet formed. To answer the most fundamental questions about the innards of Jupiter, and any clues they might suggest regarding the origin of the Solar System, a different approach to describing this important planet's interior is required.

2.1 Space-based Detections

Scientific knowledge of Jupiter has made great progress since the first Jupiter flyby of Voyager-I in 1979, aided by significant advances in technology, especially in detection methods that have made it possible to collect data on the internal pressure state, stratification characteristics, core characteristics, chemical composition, etc., of extraterrestrial bodies (Lindal et al., 1981). Planetary data collection can be space-based, ground-based, or both when observations can be synchronized; the detection techniques used vary, of course, depending on how the data are acquired. In the case of Jupiter, however, data relevant to the planet's internal structure remain insufficient.

In the half century since the question of Jupiter's interior was first addressed, tentative answers have progressed from straightforward to nuanced, from uniform to layered. As more information and data have been collected, models of Jupiter have become more detailed (Figure 2).

In 1972, the Pioneer 10 mission was launched; its observations led to the first insight into Jupiter's shape, and basic information about its atmospheric structure and temperature (Smoluchowski and Smoluchowsky, 1975). The Voyager-1 flyby of Jupiter in 1979 allowed the gravity field of Jupiter to be measured with higher precision, and preliminary constraints on the planet's internal model were achieved (Figure 2a). Given the satellite and detection technology at that time, data collected were insufficient to differentiate Jupiter's inner layers. Only a very vague conclusion could be drawn: helium was thought to be more abundant in the metallic layer than in the molecular layer (Smoluchowski and Smolu-

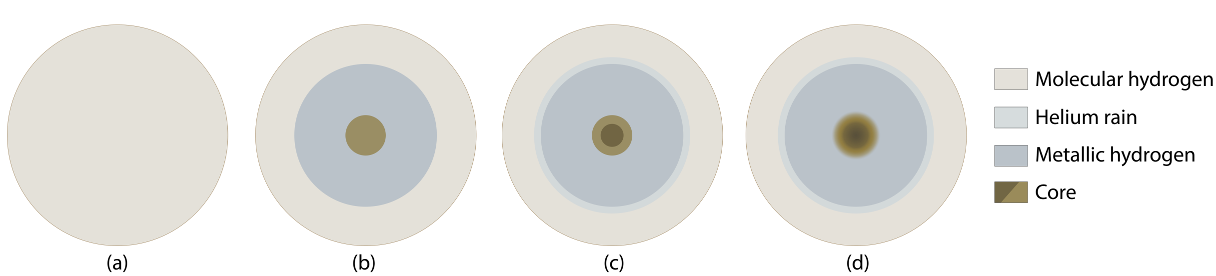

Figure 2. Structure models of Jupiter. (a) Homogeneous model; (b) Three-layer model: molecular hydrogen-metallic hydrogen-core; (c) Five-layers model: molecular hydrogen-helium rain-metallic hydrogen-ice core-rock core; (d) Diluted model: molecular hydrogen-helium rain-metallic hydrogen-diluted core.

chowsky, 1975).

Since then, researchers have gradually deepened their insight into the interior of Jupiter, especially through the measurements made during the Galileo and Cassini missions, which achieved more precise observations of the shallow parts of Jupiter. One of the three specific objectives of the Galileo mission was the Jovian atmosphere; the probe carried a series of instruments into the atmosphere, including a helium abundance detector (HAD) to measure the abundance ratio He/H_2 with high accuracy (Von Zahn et al., 1998). After Galileo measured Jupiter's external gravitational field and its atmospheric helium abundance, it was possible to set new limits on the composition and structure of the planet (Guillot et al., 1997).

Traditionally, the interior of Jupiter has been modeled as a three-layered structure: from inside to outside, Jupiter is modeled as having a core, a helium-rich metallic hydrogen envelope, and a helium-poor molecular hydrogen envelope (Figure 2b) (Guillot et al., 1997; Guillot, 1999).

This classic assumption that Jupiter's interior can be divided into three major layers persists, but it is almost certain to be more complicated than this. One of the difficulties is that we cannot pinpoint the region where helium decomposition occurs. This inhomogeneous region is likely to be very narrow and to occur in low-pressure metal hydrogen; the separation of helium from hydrogen may require higher pressure (Guillot et al., 2004). The observational data obtained by the Galileo and Juno spacecraft missions support the view that Jupiter's interior is neither homogeneous nor isentropic (Gudkova and Zharkov, 1999a; Brygoo et al., 2021), so more complex models are needed, and conclusions cannot be drawn with reference only to current models. A more detailed model has been proposed, dividing the Jovian structure into five layers: 1) an external hydrogen-helium molecular envelope; 2) an internal hydrogen-helium envelope; 3) a metallic hydrogen-helium envelope; 4) a layer of sedimentated helium; and 5) an ice-rock core (Figure 2c) (Gudkova and Zharkov, 1999b). If the structure of the core is not bilayer, but gradually diluted, then the estimate of the mass of the core will be low.

The Juno spacecraft, launched in 2011, was the second Jupiter orbiting satellite. Its scientific goals focused on Jupiter's atmosphere, magnetic field, and internal structure (Bolton et al., 2017). The Juno mission's mapping of Jupiter's gravitational field is the latest and provides the highest accuracy to date. The current structural model of Jupiter, which matches the Juno gravity data, indicates that deep inside Jupiter is an extended region rich in heavy elements; the planet's nucleus is thought to be gradually diluted or dispersed, rather than a compact core (Figure 2d) (Wahl et al., 2017).

According to gravity simulations, the outer surface of Jupiter's core is located between 0.3 and 0.5 of the planet's radius and is gradually becoming less dense (Müller et al., 2020; Durante et al., 2022). To explore the cause of the diffuse core, the authors ran a simulation of a head-on energetic collision between a giant planetary embryo and a proto-Jupiter. Their simulation showed that such a collision could produce a diluted core, mixing heavy elements into the inner layer, which is consistent with the findings of the current study (Liu SF et al., 2019) and supports the conjecture that Jupiter's diluted core may have been caused by a massive collision.

2.2 Ground-based Observations

Ground-based observations yielding data relevant to the internal structure of Jupiter have all relied on optical telescopes. Internal structure information is obtained by inversion of Jupiter's free oscillations. One of the most straightforward methods to analyze Jupiter's internal structure is using optical remote sensing since Jupiter has a global oscillation analog to the Sun (Bercovici and Schubert, 1987; Gaulme et al., 2015). Acoustic waves excited by turbulence, storms, and/or asteroid impacts in interplanetary space propagate into the interior of Jupiter (Goldreich and Keeley, 1977), and the acoustic modes are locked within Jupiter's layers (Figure 3).

An acoustic ray enters the interior of Jupiter obliquely from the surface; as the ray decreases, the velocity of sound becomes faster (Lee, 1993). This forces the ray to keep deflecting laterally until it moves along the tangent of the minimum radius, and then returns to the planet's surface (Rogers, 1995; Bagenal et al., 2007). As an acoustic ray approaches the top of Jupiter's stratosphere, the mode below the acoustic cutoff frequency is limited by Jupiter's minimum elevation. Because of Jupiter's low viscosity, these acoustic modes are preserved in Jupiter's interior, in which case the resonator becomes effective (Bercovici and Schubert,

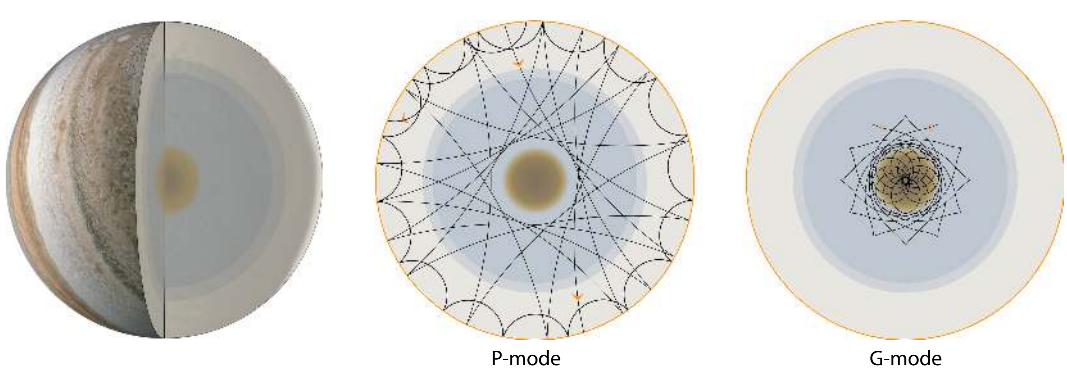

Figure 3. Propagation of acoustic waves in Jupiter. (left) Illustration of the layered model of Jupiter; (middle) P-mode: presenting in most area of Jupiter except the core; (right) G-mode: existing in the depths of Jupiter.

1987; Guillot et al., 2004; Markham and Stevenson, 2018). Thus, various acoustic wave frequencies and their oscillation modes reflect the layered structure and material state of Jupiter's interior, making their study a key technique for analyzing the interior of Jupiter. Our understanding of the giant planet's interior will significantly advance as we improve our observations of this gas planet's free oscillations. This can be demonstrated by the great contribution of helioseismic findings to the solar model.

At present, few clearly identified mechanisms have been proposed that can excite the vibrations of Jupiter to detectable levels. Turbulent convection is thought to be responsible for solar oscillations (Goldreich and Kumar, 1988), but Jupiter's convection amplitudes are far smaller than the Sun's (Deming et al., 1989). Application of the turbulent convection model to ground-based observations has produced some promising results, but instrument limitations and window effects, as well as complex atmospheric properties, have severely limited those results (Schmider et al., 1991; Lederer et al., 1995); Mosser et al. (2000), however, were able to establish a 0.6 m/s upper limit for modal amplitude.

In order to verify Jupiter seismology, we need improved observations from the telescopes on Earth. Scientists have designed Seismographic Imaging Interferometer for Monitoring of Planetary Atmospheres (SYMPA), the first imaging instrument developed to use imaging interferometry to monitor a giant gas planet's seismology (Schmider et al., 2007, 2008; Gaulme et al., 2008). The sensitivity of measuring the radial velocity will not be affected by the rapid rotation of Jupiter by using such a spatially resolved spectroscopic interferometric imager (Schmider et al., 2005; Schmider et al., 2007). The goal of SMYPA was to identify the vibrational modes of Jupiter. However, due to accuracy issues and other complicating factors, the observations have been unsatisfactory.

It remains challenging to gather data that would help elucidate Jupiter's interior. Spacecraft can gather data relevant to the interior of Jupiter by radio detection, magnetic field mapping, and gravitational moment measurements. The most direct constraints on Jupiter's interior structure comes from the measurements of gravitation moments (e.g., Militzer et al., 2016, Guillot et al., 2018). However, the gravitational moments are mainly sensitive to external part of Jupiter's interior structure and can provide limited information to the deep structure (Schmider et al., 2005).

Other candidate methods, such as observations of Jovian seismology via Earth-bound telescopy, could potentially advance our understanding of the layered structures below the atmosphere. This is a long-term program, and first we need to validate our instrument on the ground. After verifying the observation instruments, we will design an optical instrument to be carried by spacecraft, enabling additional observations from space. There is little observational research on Jupiter's free oscillations, because of inadequate accuracy of the instruments that have been available, and because of discontinuities in the observational data that have been available; these are the main scientific bottlenecks to be broken. We are quite prepared to try the approach presented below, at multiple qualified astronomical sites; with the cooperation of other investigators, we are confident that significant progress will be made.

3. Seismological Observations at Lenghu

In 2020, the Institute of Geology and Geophysics, Chinese Academy of Sciences established the Lenghu Observatory for Planetary Sciences, located in Saishiteng Mountain, Lenghu Town, Qinghai Province, which enjoys exceptionally favorable conditions for astronomical observation. We are constructing at Lenghu an optical system of high-precision, a polarization interferometric imager, for observing Jupiter. We expect continuous observation of Jupiter at Lenghu to make it possible to identify different oscillation modes and to invert the planet's internal structure. For optical observations, factors such as darkness at night, dust in the atmosphere, and fluctuations in atmospheric water vapor usually need to be taken into account in order to achieve observation accuracy and to avoid telescope interference as much as possible. A good natural seeing is essential for optical operations, especially for large-aperture telescopes; night viewing times must be free of light pollution. The effects of the aforementioned factors will be less noticeable the higher and further away from any city a site is.

Lenghu is one of the few locations worldwide that can support scientific investigation of Jupiter's optical imaging (Deng et al., 2021; Zhao et al., 2022). The Lenghu site provides outstanding astronomical seeing and pleasant weather for nighttime observation, according to data collected during three years of monitoring the optical viewing conditions there. Lenghu had >70% clear nights over those three years; its median nighttime temperature was 2.4 °C with little variation; precipitable water volume was 2 mm during winter — all of which indicate that Lenghu's air was very favorable and stable. The median seeing of the telescope at Lenghu can be up to 0.75 arcsec, ~75% of the time being less than 1 arcsec, ~10% of the time being better than 0.5 arcsec. These values are comparable to those of other first-class sites such as Mauna Kea and La Palma (Deng et al., 2021), confirming that Lenghu has great potential to support near-surface optical systems.

The Lenghu telescope is located on a summit of Saishiteng Mountain near the town of Lenghu in Qinghai Province, China. The telescope has a 1.8 m diameter Cassegrain optical system, 0.25′′ pixel resolution, and a spectral range of 370 to 1800 nm (He et al., 2021). One of the tasks of the telescope is to study Jovian free oscillation using long-term observation data to invert its internal structure. A seismologic interferometer polarization imager (SIPI) will be equipped at the focal plane of the telescope to image the Doppler signals due to the Jovian free oscillations. Similar to SYMPA, the SIPI contains a Mach-Zehnder interferometer and a Wollaston prism operating at 519 nm wavelength, which is at approximately the peak of solar radiation and will thus ensure the efficiency of the imaging. A diagram of the preliminary optical design of SIPI is shown in Figure 4. Using the SIPI, we can obtain four simultaneous images of Jupiter with even brightness, each with a phase difference of $\pi/2$. The timing of the two cameras will be controlled within milli-seconds. These four images will allow us to determine the phase of the velocity field and retrieve the interferogram mode's phase.

According to the theoretical analysis by Schmider et al. (2007), the

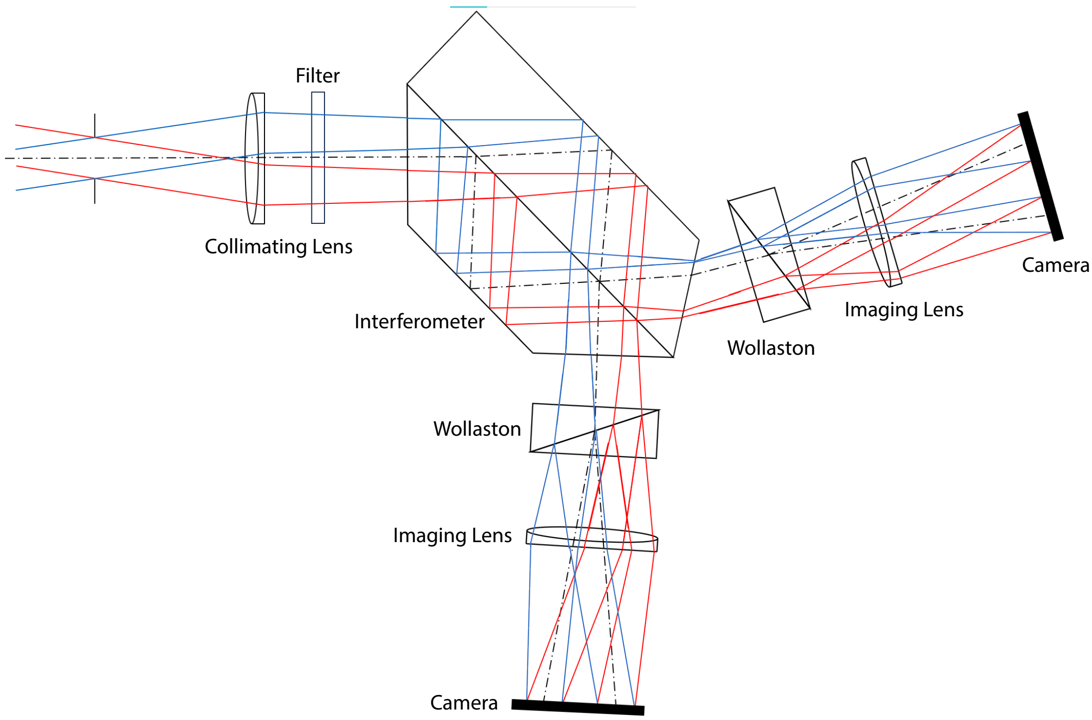

Figure 4. Optical scheme of the SIPI.

standard deviation of the velocity variations (δv) can be estimated by

$$\delta v = \frac{c}{2\pi\lambda_0\Delta\gamma\sqrt{2N}},$$

where c is the light speed, λ_0 is the central wavelength of the bandwidth, Δ is the optical path difference (OPD), γ is the contrast of the fringes, and N is the number of photons collected at the detector. Obviously, if we can increase N, we can reduce the standard deviation.

The number of collected photons is determined by several factors, such as the diameter of the telescope, the atmospheric transmission at the site, and the optical efficiency of the telescope (reflectivity, transmission, and quantum efficiency). For a telescope at the Lenghu site, at an elevation of 4200 m, the atmospheric transmission at 519 nm can reach 90% during a photometrically clear night, based on the atmospheric transmission (MODTRAN) model (Berk et al., 2014), assuming moderate resolution; this is significantly higher than the atmospheric transmission at the site used by SYMPA (Schmider et al., 2007). The 1.8-meter diameter of the Lenghu telescope is slightly larger than the 1.52-meter Carlos Sanchez telescope at Teide observatory. Also, compared with SYMPA, the OPD of SIPI will be significantly increased. These differences lead us to expect that the standard deviation of the velocity variation will be reduced when Lenghu data become available. Detailed analysis of the observation efficiency of SIPI will be done once the final design of SIPI is completed.

The most promising model of Jupiter's interior predicts theoretically that the fundamental frequency will prove to be approximately 153 μHz, and that the different modes can be separated at approximately this frequency or at a multiple of this frequency (Gudkova and Zharkov, 1999b). However, different models of the Jovian interior have suggested that the fundamental frequency might have other values, so those models must also be tested. However, background noise and data incompleteness may weaken the identification of P-mode features and specific structures, so we will continue to focus also on this issue in our future work, investigating Jupiter's oscillations with higher quality data.

4. Summary

This paper provides a concise overview of past efforts to understand Jupiter's interior; it also reviews the history of exploratory missions to the planet and of the models of Jupiter's interior. We suggest that asteroseismology can play a significant role in efforts to understand Jupiter better, and that the Lenghu Astronomical Telescope, too, has tremendous potential to advance future studies of Jupiter, which are likely to advance human understanding of the origins of our galaxy and of our own planet, Earth. Although many questions remain to be answered about the interior of Jupiter, the growing number of spacecraft and telescopes capable of providing rich new data to researchers suggest that the speed with which these questions are answered will soon accelerate; we can be confident that the day is coming when we on Earth will be able to map Jupiter's interior accurately.

In China, the study of Jupiter's interior is in its early stages. Our immediate goal is to construct the SIPI in order to observe Jupiter's free oscillations at Lenghu. The best conditions for observing Jupiter's radial velocity are now present. We can extract the doppler velocity distribution on Jupiter's surface, recognize the oscillation signal, and ascertain the oscillation's order by processing the data now becoming available. Eventually the telescopes at the Lenghu Observatory for Planetary Sciences will be used for other scientific purposes, such as tracking comets and other tiny objects, and observing the geological activities of

Jupiter's moons.

Although the plan described here, to apply asteroseismology to data from ground optical telescopes as a way to study the interior of Jupiter, is initially limited to China, which is suboptimal, we look forward to international cooperation, which will greatly improve results. After verifying the SIPI instrument at Lenghu, we will encourage colleagues in other countries to install SIPI instruments distributed evenly in geographic longitude (e.g., Lenghu, Hawaii, Chile, Spain). By deploying four telescopes with similar diameters in such a pattern, such an array, compared to a single telescope, has the potential, at times when all stations enjoy favorable weather conditions, to reach a duty cycle of observations close to 100%. This approach would enable long-term continuous monitoring of Jovian seismology and would thus significantly enhance the investigation of Jupiter's interior.

The primary advantage of ground-based observation is its long-term nature. However, ground-based optical remote sensing encounters challenges such as atmospheric interference, limitations in spatial resolution, and signal-to-noise ratio issues due to the considerable distance to Jupiter, atmospheric seeing, and weather variability. To overcome these limitations, the most efficient approach is to conduct observations from Jupiter's orbit, in addition to observations from Earth. Currently, China is planning the Tianwen-4 mission to explore the Jovian system. We propose equipping the Tianwen-4 spacecraft with instruments like SIPI, or other imagers based on similar optical principles, to capture Jovian free oscillations with unparalleled resolution and precision. This initiative not only stands to significantly advance our understanding of Jupiter's internal structure but also to provide crucial data for the study of Jupiter's atmospheric science.

Acknowledgments

This work is based on the following support: the National Natural Science Foundation of China (42222408), the Youth Innovation Promotion Association of the Chinese Academy of Sciences (Y2021027), and the Key Research Program of the Institute of Geology and Geophysics, CAS (Grant IGGCAS- 201904).

References

Appourchaux, T., Belkacem, K., Broomhall, A. M., Chaplin, W. J., Gough, D. O., Houdek, G., Provost, J., Baudin, F., Boumier, P., … Turck-Chièze, S. (2010). The quest for the solar g modes. *Astron. Astrophys. Rev.*, *18*(1), 197–277. https://doi.org/10.1007/s00159-009-0027-z

Bagenal, F., Dowling, T. E., and McKinnon, W. B. (2007) *Jupiter: The Planet, Satellites and Magnetosphere*. Cambridge: Cambridge University Press.

Bercovici, D., and Schubert, G. (1987). Jovian seismology. *Icarus*, *69*(3), 557–565. https://doi.org/10.1016/0019-1035(87)90024-8

Berk, A., Conforti, P., Kennett, R., Perkins, T., Hawes, F., and van den Bosch, J. (2014). MODTRAN®6: a major upgrade of the MODTRAN® radiative transfer code. In *2014 6th Workshop on Hyperspectral Image and Signal Processing: Evolution in Remote Sensing (WHISPERS)* (pp. 1-4). Lausanne, Switzerland: IEEE. https://doi.org/10.1109/WHISPERS.2014.8077573

Bolton, S. J., Lunine, J., Stevenson, D., Connerney, J. E. P., Levin, S., Owen, T. C., Bagenal, F., Gautier, D., Ingersoll, A. P., … Thorpe, R. (2017). The Juno Mission. *Space Sci. Rev.*, *213*(1-4), 5–37. https://doi.org/10.1007/s11214-017-0429-6

Brygoo, S., Loubeyre, P., Millot, M., Rygg, J. R., Celliers, P. M., Eggert, J. H., Jeanloz, R., and Collins, G. W. (2021). Evidence of hydrogen−helium immiscibility at Jupiter-interior conditions. *Nature*, *593*(7860), 517–521. https://doi.org/10.1038/s41586-021-03516-0

Christensen-Dalsgaard, J. (1997). Lecture notes on stellar oscillations, 8th edition. Institut for Fysik og Astronomi, Aarhus Universitet. https://phys.au.dk/~jcd/evolnotes/

Deming, D., Mumma, M. J., Espenak, F., Jennings, D. E., Kostiuk, T., Wiedemann, G., Loewenstein, R., and Piscitelli, J. (1989). A search for p-mode oscillations of Jupiter-Serendipitous observations of nonacoustic thermal wave structure. *Astrophys. J.*, *343*, 456. https://doi.org/10.1086/167719

Deng, L. C., Yang, F., Chen, X. D., He, F., Liu, Q. L., Zhang, B., Zhang, C. G., Wang, K., Liu, N., … Pan, J. (2021). Lenghu on the Tibetan Plateau as an astronomical observing site. *Nature*, *596*(7872), 353–356. https://doi.org/10.1038/s41586-021-03711-z

Deubner, F. L., and Gough, D. (1984). Helioseismology: Oscillations as a diagnostic of the solar interior. *Annu. Rev. Astron. Astrophys.*, *22*(1), 593–619. https://doi.org/10.1146/annurev.aa.22.090184.003113

Durante, D., Guillot, T., Iess, L., Stevenson, D. J., Mankovich, C. R., Markham, S., Galanti, E., Kaspi, Y., Zannoni, M., … Bolton, S. J. (2022). Juno spacecraft gravity measurements provide evidence for normal modes of Jupiter. *Nat. Commun.*, *13*, 4632. https://doi.org/10.1038/s41467-022-32299-9

Fossat, E., Boumier, P., Corbard, T., Provost, J., Salabert, D., Schmider, F. X., Gabriel, A. H., Grec, G., Renaud, C., …Lazrek, M. (2017). Asymptotic g modes: Evidence for a rapid rotation of the solar core. arXiv:1708.00259. https://doi.org/10.1051/0004-6361/201730460

García, R. A., Turck-Chièze, S., Boumier, P., Robillot, J. M., Bertello, L., Charra, J., Dzitko, H., Gabriel, A. H., Jiménez-Reyes, S. J., … Ulrich, R. K. (2005). Global solar doppler velocity determination with the GOLF/SoHO instrument. *Astron. Astrophys.*, *442*(1), 385–395. https://doi.org/10.1051/0004-6361:20052779

García, R. A., and Stello, D. (2015). Asteroseismology of red giant stars. In V. C. H. Tong, et al. (Eds.), *Extraterrestrial Seismology* (pp. 159-169). Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9781107300668.014

Gaulme, P., Schmider, F. X., Gay, J., Jacob, C., Álvarez, M., Reyes-Ruiz, M., Belmonte, J. A., Fossat, E., Jeanneaux, F., and Valtier, J. C. (2008). SYMPA, a dedicated instrument for Jovian Seismology. II. Real performance and first results. *Astron. Astrophys.*, *490*(2), 859–871. https://doi.org/10.1051/0004-6361:200809512

Gaulme, P., Schmider, F. X., Gay, J., Guillot, T., and Jacob, C. (2011). Detection of Jovian seismic waves: a new probe of its interior structure. *Astron. Astrophys.*, *531*, A104. https://doi.org/10.1051/0004-6361/201116903

Gaulme, P., Mosser, B., Schmider, F.-X., and Guillot, T. (2015). Seismology of giant planets. In V. C. H. Tong, et al. (Eds.), *Extraterrestrial Seismology* (pp. 189-202). Cambridge: Cambridge University Press. http://doi.org/10.1017/CBO9781107300668.017

Goldreich, P., and Keeley, D. A. (1977). Solar seismology. II-The stochastic excitation of the solar p-modes by turbulent convection. *Astrophys. J.*, *212*, 243–251. https://doi.org/10.1086/155043

Goldreich, P., and Kumar, P. (1988). The interaction of acoustic radiation with turbulence. *Astrophys. J.*, *326*, 462–478. https://doi.org/10.1086/166108

Gough, D. O., Leibacher, J. W., Scherrer, P. H., and Toomre, J. (1996a). Perspectives in Helioseismology. *Science*, *272*(5266), 1281–1283. https://doi.org/10.1126/science.272.5266.1281

Gough, D. O., Kosovichev, A. G., Toomre, J., Anderson, E., Antia, H. M., Basu, S., Chaboyer, B., Chitre, S. M., Christensen-Dalsgaard, J., … Vorontsov, S. V. (1996b). The seismic structure of the Sun. *Science*, *272*(5266), 1296–1300. https://doi.org/10.1126/science.272.5266.1296

Gudkova, T. V., and Zharkov, V. N. (1999a). Models of Jupiter and Saturn after Galileo mission. *Planet. Space Sci.*, *47*(10-11), 1201–1210. https://doi.org/10.1016/S0032-0633(99)00044-6

Gudkova, T. V., and Zharkov, V. N. (1999b). The free oscillations of Jupiter. *Planet. Space Sci.*, *47*(10-11), 1211–1224. https://doi.org/10.1016/S0032-0633(99)00045-8

Guillot, T., Gautier, D., and Hubbard, W. B. (1997). New constraints on the composition of Jupiter from galileo measurements and interior models. *Icarus*, *130*(2), 534–539. https://doi.org/10.1006/icar.1997.5812

Guillot, T. (1999). A comparison of the interiors of Jupiter and Saturn. *Planet.*

Space Sci., *47*(10-11), 1183–1200. https://doi.org/10.1016/S0032-0633(99)00043-4
Guillot, T., Stevenson, D. J., Hubbard, W. B., and Saumon, D. (2004). The interior of Jupiter. In *Jupiter: The Planet, Satellites, and Magnetosphere* (pp. 35-57). Cambridge: Cambridge University Press.
Guillot, T., Miguel, Y., Militzer, B., Hubbard, W. B., Kaspi, Y., Galanti, E., Cao, H., Helled, R., Wahl, S. M., … Bolton, S. J. (2018). A suppression of differential rotation in Jupiter's deep interior. *Nature*, *55*, 227–230 https://doi.org/10.1038/nature25775
Handler, G. (2013). Asteroseismology. In T. D. Oswalt, et al. (Eds.), *Planets, Stars and Stellar Systems* (pp. 207-241). Dordrecht: Springer. https://doi.org/10.1007/978-94-007-5615-1_4
Harvey, J. (1995). Helioseismology. *Phys. Today*, *48*(10), 32–38. https://doi.org/10.1063/1.881453
He, F., Yao, Z. H., and Wei, Y. (2021). Optical remote sensing of planetary space environment. In M. Marghany (Ed.), *Recent Remote Sensing Sensor Applications-Satellites and Unmanned Aerial Vehicles (UAVs)*. London: IntechOpen. https://doi.org/10.5772/intechopen.98427 (pp.55-78).
Hemley, R. J. (1995). Sound and fury in Jupiter. *Science*, *269*(5228), 1233–1234. https://doi.org/10.1126/science.7652568
Hubbard, W. B., and Smoluchowski, R. (1973). Structure of Jupiter and Saturn. *Space Sci. Rev.*, *14*(5), 599–662. https://doi.org/10.1007/BF00166644
Lederer, S. M., Marley, M. S., Mosser, B., Maillard, J. P., Chanover, N. J., and Beebe, R. F. (1995). Albedo features and Jovian seismology. *Icarus*, *114*(2), 269–277. https://doi.org/10.1006/icar.1995.1061
Lee, U. (1993). Acoustic oscillations of Jupiter. *Astrophys. J.*, *405*, 359–374. https://doi.org/10.1086/172368
Leibacher, J. W. (1999). The Global Oscillation Network Group (GONG) project. *Adv. Space Res.*, *24*(2), 173–176. https://doi.org/10.1016/s0273-1177(99)00497-4
Lindal, G. F., Wood, G. E., Levy, G. S., Anderson, J. D., Sweetnam, D. N., Hotz, H. B., Buckles, B. J., Holmes, D. P., Doms, P. E., … Croft, T. A. (1981). The atmosphere of Jupiter: An analysis of the voyager radio occultation measurements. *J. Geophys. Res.: Space Phys.*, *86*(A10), 8721–8727. https://doi.org/10.1029/JA086iA10p08721
Liu, S. F., Hori, Y., Müller, S., Zheng, X. C., Helled, R., Lin, D., and Isella, A. (2019). The formation of Jupiter's diluted core by a giant impact. *Nature*, *572*(7769), 355–357. https://doi.org/10.1038/s41586-019-1470-2
Lubow, S. H., Rhodes, E. J. Jr., and Ulrich, R. K. (1980). Five minute oscillations as a probe of the solar interior. In H. A. Hill, et al. (Eds.), *Nonradial and Nonlinear Stellar Pulsation* (pp. 300-306). Tucson: Springer. https://doi.org/10.1007/3-540-09994-8_28
Markham, S., and Stevenson, D. (2018). Excitation mechanisms for Jovian seismic modes. *Icarus*, *306*, 200–213. https://doi.org/10.1016/j.icarus.2018.02.015
Mauri, D. (2010). Mechanical design of an IR camera optical bench for Juno mission. Milano: Politecnico di Milano.
Militzer, B., Soubiran, F., Wahl, S. M., and Hubbard, W. (2016). Understanding Jupiter's interior. *J. Geophys. Res.: Planets*, *121*, 1552–1572. https://doi.org/10.1002/2016JE005080
Mosser, B. (1997). Giant planets seismology. *Symp.-Int. Astron. Union*, *181*, 251–264. https://doi.org/10.1017/S0074180900061192
Mosser, B., Maillard, J. P., and Mékarnia, D. (2000). New Attempt at Detecting the Jovian Oscillations. *Icarus*, *144*(1), 104–113. https://doi.org/10.1006/icar.1999.6271
Müller, S., Helled, R., and Cumming, A. (2020). The challenge of forming a fuzzy core in Jupiter. *Astron. Astrophys.*, *638*, A121. https://doi.org/10.1051/0004-6361/201937376
Nettelmann, N., Holst, B., Kietzmann, A., French, M., Redmer, R., and Blaschke, D. (2008). Ab initio equation of state data for hydrogen, helium, and water and the internal structure of Jupiter. *Astrophys. J.*, *683*(2), 1217–1228. https://doi.org/10.1086/589806
Pallé, P. L., Appourchaux, T., Christensen-Dalsgaard, J., and García, R. A. (2015). Helioseismology: Observations and space missions. In V. C. H. Tong, et al. (Eds.), *Extraterrestrial Seismology* (pp. 25-35). Cambridge: Cambridge University Press. https://doi.org/10.1017/cbo9781107300668.005
Proctor, M. R. E. (2004). Solar convection and magnetic fields. *Astron. Geophys.*, *45*(4), 4.14–4.20. https://doi.org/10.1046/j.1468-4004.2003.45414.x
Rogers, J. H. (1995). *The Giant Planet Jupiter*. Cambridge: Cambridge University Press.
Schmider, F. X., Mosser, B., and Fossat, E. (1991). Possible detection of Jovian global oscillations. *Astron. Astrophys.*, *248*, 281–291.
Schmider, F. X., Jacob, C., Fossat, E., Abe, L., Gay, J., Valtier, J. C., Guillot, T., Provost, J., Mosser, B., and Gaulme, P. (2005). JISCO: Jovian interferometric seismometer at concordia observatory. *EAS Publ. Ser.*, *14*, 285–290. https://doi.org/10.1051/eas:2005045
Schmider, F. X., Gay, J., Gaulme, P., Jacob, C., Abe, L., Álvarez, M., Belmonte, J. A., Fossat, E., Gelly, B., … Valtier, J. C. (2007). SYMPA, a dedicated instrument for Jovian seismology I. Principle and performance. *Astron. Astrophys.*, *474*(3), 1073–1080. https://doi.org/10.1051/0004-6361:20067019
Schmider, F. X., Gay, J., Gaulme, P., Jacob, C., Abe, L., Alvarez, M., Belmonte, J., Fossat, E., Gelly, B., Guillot, T., … Valtier, J. (2008). SYMPA, a dedicated instrument for Jovian seismology II. Real performance and first result. *Astron. Astrophys.*, *490*, 859–871. https://doi.org/10.1051/0004-6361:200809512
Smoluchowski, R., and Smoluchowsky, R. (1975). Jupiter 1975: The spectacular successes of the Pioneer 10 and 11 missions have brought Jupiter to the forefront of planetary studies today. *Amer. Sci.*, *63*(6), 638–648.
Stix, M. (2002). The Sun: An introduction (2nd edition). Heidelberg: Springer Berlin. https://doi.org/10.1007/978-3-642-56042-2
Thompson, M. J. (2004). Helioseismology and the Sun's interior. *Astron. Geophys.*, *45*(4), 4.21–4.25. https://doi.org/10.1046/j.1468-4004.2003.45421.x
Von Zahn, U., Hunten, D. M., and Lehmacher, G. (1998). Helium in Jupiter's atmosphere: Results from the Galileo probe helium interferometer experiment. *J. Geophys. Res.: Planets*, *103*(E10), 22815–22829. https://doi.org/10.1029/98JE00695
Wahl, S. M., Hubbard, W. B., Militzer, B., Guillot, T., Miguel, Y., Movshovitz, N., Kaspi, Y., Helled, R., Reese, D., … Bolton, S. J. (2017). Comparing Jupiter interior structure models to *Juno* gravity measurements and the role of a dilute core. *Geophys. Res. Lett.*, *44*(10), 4649–4659. https://doi.org/10.1002/2017GL073160
Zhao, Y., Yang, F., Chen, X.D., Zhang, X., Ma, J.F., Kong, X.H., Fu, X.T., Li, R.Y., Wei, Y., … Deng, L.C. (2022). Long-term variations in precipitable water vapor and temperature at Lenghu site. *Astron. Astrophys.*, *663*, A34. https://doi.org/10.1051/0004-6361/202243735