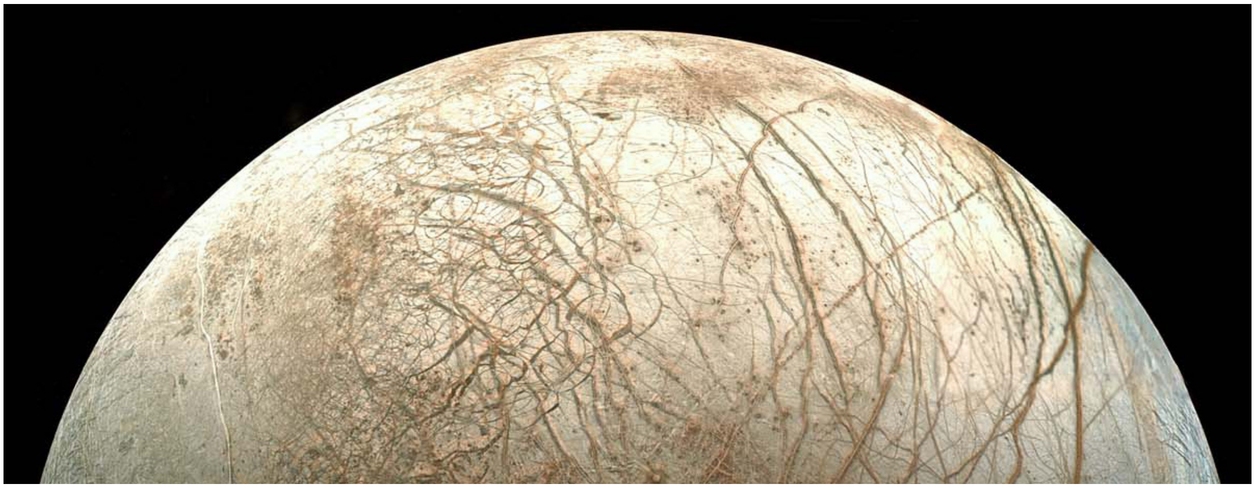
Astro2020 Science White Paper

Structure of terrestrial planets and ocean worlds



Jupiter's icy moon Europa is thought to have a subsurface ocean whose volume may be a few times larger than all of Earth's oceans combined.

Thematic science area: Planetary Systems

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1 Scientific context

1.1 Background

Profound developments in our understanding of the Earth, Moon, Mercury, and other bodies have been enabled by rotation studies [e.g., Munk and MacDonald, 1960, Lambeck, 1980, Wahr, 1988, Dickey et al., 1994, Margot et al., 2007, Thomas et al., 2016]. Munk and MacDonald [1960] summarized the indelible impact of rotation studies on the field:

> The diversity of the subject is appalling. It touches on every branch of geophysics. By the time it is covered, information will have been gained concerning wind and air masses, atmospheric, oceanic and bodily tides, sea level, rigidity and anelasticity of the Earth's mantle, and motion in its fluid core.

High-precision planetary rotation measurements open up new and exciting opportunities in planetary geophysics (Fig. 1). In particular, they can illuminate fundamental properties and processes related to Venus and the Galilean satellites.

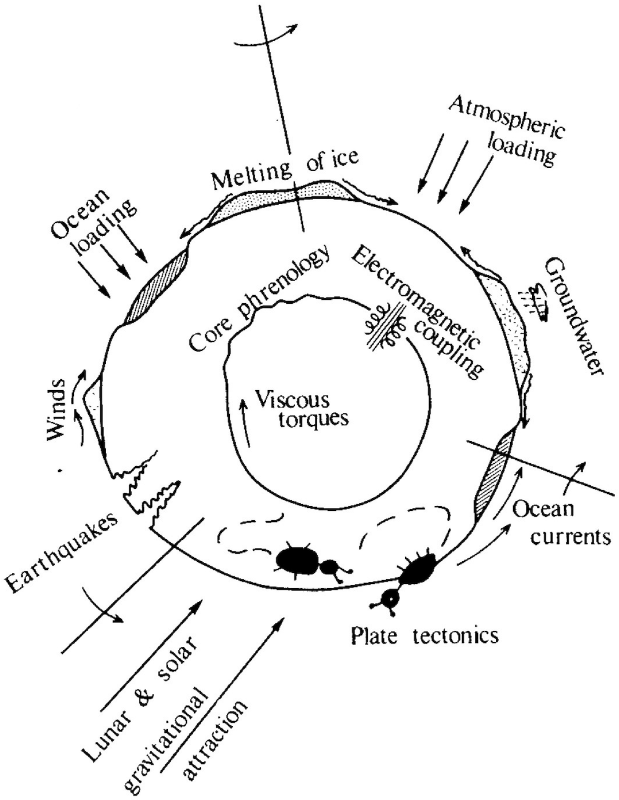

Figure 1: Schematic illustration of the forces that perturb the Earth's rotation. Core phrenology refers to the bumps on the core-mantle boundary that have been proposed by R. Hide as a mechanism for coupling the core and mantle. The beetles are T. Gold's representation of continental drift. Figure and caption from Lambeck [1988].

1.2 Venus

Venus is Earth's closest analog in the Solar System in terms of mass, radius, and density. Kepler results indicate that there are likely billions of Venus- and Earth-like planets in the Galaxy [e.g., Borucki, 2016]. However, Venus remains enigmatic on a variety of fundamental levels: The size of its core is unknown; whether the core is solid or liquid is uncertain [e.g., Dumoulin et al., 2016]; the length of day varies with frequencies and amplitudes that are not well known [Margot et al., 2012]; its atmospheric superrotation, 60× faster than the solid body, is not understood [e.g., Read and Lebonnois, 2018]; and the atmosphere exhibits distinctive planetary-scale features that are stationary with respect to the solid body [Fukuhara et al., 2017]. High-precision measurements of the spin state of Venus with radar have the potential of providing key advances in all of these areas. First, a measurement of the spin precession rate ($\approx 2'' \, \mathrm{yr}^{-1}$) will yield a direct measurement of the polar moment of inertia, which is unknown [Yoder, 1997]. The moment of inertia provides an integral constraint on the distribution of mass in a planetary interior. Apart from bulk density, it is arguably the most important quantity needed to determine reliable models of the interior structure of Venus, including the size of its core. Second, a time history of length of day (LOD) variations at the 10 ppm level will identify the geophysical forcings responsible for spin variations, which Margot et al. [2012] have attributed primarily to angular momentum exchange between the atmosphere and solid planet. Radar measurements of the instantaneous spin rate of Venus between 2004 and 2016 reveal a total excursion in LOD of $\sim$66 ppm. The observations cannot be reconciled with the Magellan $\sim$500-day-average spin period of 243.0185 ± 0.0001 days [Davies et al., 1992], nor with a $\sim$16-year-average estimate of 243.023 ± 0.002 days [Mueller et al., 2012], nor with any other constant spin period. A continuation of LOD measurements will allow us to quantify daily, seasonal, and secular variations. They will also enable tests of hypotheses related to the dynamics and superrotation of the atmosphere and angular momentum exchange, including the hypothesis that mountain torques affect the spin period of Venus [Fukuhara et al., 2017, Navarro et al., 2018].

1.3 Ocean Worlds

Ocean worlds such as Europa, Ganymede, Titan, and Enceladus are capturing the attention of planetary scientists and astronomers because the presence of oceans strongly affects the geochemistry, geophysics, geology, and perhaps biology of these worlds, and because there may be tens or hundreds of billions of such worlds in the Galaxy. Europa is the primary target of the two-billion-dollar Europa Clipper mission [Pappalardo et al., 2017], NASA's next flagship mission. Ganymede is the primary target of the Jupiter Icy Moon Explorer (JUICE), a billion-dollar spacecraft mission selected by the European Space Agency [Grasset et al., 2013]. Both missions are slated for launch in the early 2020s. The latest NRC Planetary Decadal Survey states that Europa is "one of the most important targets in all of planetary science."

The exploration of Europa is of great interest because this Galilean satellite may be hospitable to certain life forms [National Research Council, 1999, Joint Jupiter Science Definition Team, 2010]. Several lines of evidence suggest that a subsurface ocean exists beneath an ice shell [e.g., Kivelson et al., 2004, Greeley et al., 2004, Nimmo and Pappalardo, 2016], but there is considerable debate about the thickness of the shell [Greenberg, 2008], which impacts Europa's astrobiological potential. As in the case of Mercury [Margot et al., 2018] and Enceladus [Thomas et al., 2016], it is possible to use dynamical considerations to determine whether an outer shell is decoupled from the interior and to evaluate the shell thickness by measuring the amplitude of forced longitude librations [Peale, 1976].

A detection of librations would provide a breakthrough similar to that at Mercury [Margot et al., 2007] or Enceladus [Thomas et al., 2016], enabling the first measurements of the shell's moment of inertia and placing definite constraints on the rheology and thickness of the shell.

Measuring Europa's obliquity will allow us to conclusively rule out a fully solid interior, which is one of Clipper's primary science objectives. The dynamical evidence for a decoupling between the outer shell and the interior would provide a completely independent line of evidence supporting the existence of a global subsurface ocean.

Obliquity measurements can reveal the nature of the shell-interior coupling and also explain striking surface features. The distribution and orientation of surface features (cycloids, lineaments, and strike-slip faults) are thought to be related to patterns of tidal stress [Hoppa et al., 1999], which are affected by the obliquity. For instance, Hurford et al. [2009] found that an obliquity of $\sim 0.1^\circ$ could explain the observed latitude offsets of some angular cycloids, as well as the presence of equator-crossing cycloids. Rhoden et al. [2011] found that an obliquity of $\sim 1^\circ$ could explain observed deviations from the expected pattern of fault slip directions (only left-lateral above 35° N latitude, only right-lateral below 35° S latitude). Rhoden and Hurford [2013] examined the azimuthal directions of lineaments on Europa and argue that their formation is consistent with an obliquity of $\sim 1^\circ$. Obliquity measurement will enable tests of hypotheses related to the formation of tectonic features.

Measuring the obliquities of the Galilean satellites is also crucial to enable tidal heating calculations. Wisdom [2008] has derived expressions for tidal heating of synchronous satellites with arbitrary orbital eccentricities and obliquities.

2 Scientific opportunities: Radar Speckle Tracking

Planetary radar provides an inexpensive and powerful tool for monitoring planetary spin states via observations of the "speckle displacement effect", a technique also known as "radar speckle tracking" [Margot et al., 2007]. Radar echoes from solid bodies exhibit spatial irregularities in the wavefront caused by the constructive and destructive interference of waves scattered by the irregular surface. The corrugations in the wavefront, i.e., speckles, are tied to the rotation of the target body. When the trajectory of the wavefront corrugations is parallel to a roughly east-west antenna baseline, echoes received at two receiving stations display a high degree of correlation. The time of day and value of the time delay at the correlation peak are directly related to the orientation and magnitude of the spin vector of the body. For typical Solar System observations, the speckle size ($\sim R\lambda/D$, for a target at range R, observing wavelength λ, and diameter D) is on the order of 1 km and the high-correlation condition lasts for approximately 30 s.

Previous measurements with the Goldstone Solar System Radar (GSSR) and the Green Bank Telescope (GBT) yielded instantaneous spin rate measurements at the 10 ppm level with X-band transmission from the GSSR and reception at Goldstone and the GBT. The accuracy of the measurements scales as $\sim \lambda/B$, where B is the length of the telescope baseline, such that higher frequencies and longer baselines yield the best measurements. For example, with observations obtained between 2002 and 2012, the orientation of Mercury's spin axis has been measured with $5''$ precision, and measurements of the amplitude of longitude librations have revealed that Mercury has a molten core [Margot et al., 2007, 2012]. The accuracy of these measurements has been validated at the 1% level by independent measurements obtained by the MESSENGER spacecraft during its four-year mission duration [Margot et al., 2018].

With a single telescope baseline, it is possible to obtain one measurement per day when the stringent geometry and signal-to-noise (S/N) requirements are satisfied. However, measurements accumulate at a slow rate because each measurement requires simultaneous scheduling on two large radio antennas, successful transmission during the appropriate 30-second window, and successful reception at both antennas during the relevant 30-second windows. In order to fully constrain the spin axis orientation, it is imperative to secure observations at a variety of baseline orientations, which typically takes several years. For Venus, it is possible to schedule sessions at specific times on consecutive days during favorable seasons that last a few weeks each year. For ocean worlds, the opportunities are rare and far between. Due to S/N requirements, the optimal seasons occur every 12 years when the Earth-Jupiter distance is minimized. During these seasons, scheduling requirements are similar to those of Venus observations.

Continued observations of Venus throughout the next decade will enable (1) improved determination of the spin axis precession and therefore moment of inertia and core size; and (2) improved quantification of the amplitude of LOD variations on daily, seasonal, and secular timescales, providing strong constraints on the dynamics of the atmosphere and its interactions with the solid planet, illuminating a regime that may be common on exoplanets.

Continued observations of ocean worlds throughout the next decade will enable (1) improved determination of obliquities, which can provide confirmation of the presence of a subsurface ocean and illuminate the nature of the shell-interior coupling; and (2) attempts to measure the amplitude of longitude librations, which would place bounds on the moment of inertia of the outer shell and therefore shell thickness.

3 Key advances necessary for completion

Progress over the next decade in internal structure of Solar System bodies requires a powerful planetary radar using 8 GHz or higher frequencies, such as NASA's 70 m antenna at Goldstone (DSS-14), and a large single-dish receiving telescope located at least 1000 miles away from the transmitter in a roughly East or West direction, such as the 100 m Green Bank Telescope. **The radar speckle tracking observations are not possible with any other configuration, which means that the availability of the ground-based assets used in other astronomical applications directly affects the ability to conduct the measurements described in this white paper**. We are submitting this white paper to the Astro2020 decadal survey because the Astronomy and Astrophysics Decadal Survey will make impactful recommendations about the necessary facilities.

Because radar speckle tracking observations can only be conducted at specific times of day during relatively short seasons, the ability to schedule both telescopes with fixed-time observations is essential. With the reduction in "Open Skies" observations at the GBT, scheduling of fixed-time observations has become very difficult. We recommend that telescope scheduling policies facilitate the scheduling of fixed-time observations to enable the science described in this white paper.

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