The Librations, Tides, and Interior Structure of Io

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Abstract The melt zone in the volcanically active satellite Io plays a key role in diverse processes such as volcanism, heat transfer, tidal dissipation, and the orbital evolution of the Galilean satellites in the Laplace resonance. Information on the melt distribution, the degree of partial melt, and the possible existence of a global magma ocean has been derived from Galileo magnetic induction measurements, volcanic eruption temperatures, and Hubble Space Telescope auroral spot observations but is currently inconclusive. Here, we calculate the libration amplitude of Io for a diverse set of internal structure models and show that Io’s libration can provide insight into the existence of a global magma ocean and into the thickness and rigidity of the crust above it. The diurnal libration amplitude of Io is several times larger if Io has a magma ocean instead of a partial melt asthenosphere and can reach values of above 1 km, making it easily observable for spacecraft flying close by Io on multiple occasions. It also strongly increases with decreasing crustal thickness and increases significantly with increasing rigidity. We demonstrate that the combination of observations of the libration amplitude and the tidal Love number $k_2$ will allow estimating the rigidity and thickness of the crust separately, which is impossible with only one of the quantities observed.

Plain Language Summary Io, one of the large satellites of Jupiter, is the volcanically most active body in the Solar System. Observations with the Galileo spacecraft and the Hubble Space Telescope indicate that Io’s silicate rock mantle must be partially molten and that possibly a layer of fully molten rock, a magma ocean, exists. The characteristics of the melt zone are not well understood but are important for understanding the dynamics and evolution of Io. Here, we show that variations in the rotation rate of Io can provide insight into the existence of a global magma ocean and into the thickness and rigidity of the crust above it. Those rotation variations are much larger if a magma ocean is present than if only partial melt occurs and can easily be observed by future missions to Io. Such missions can also observe the tides of Io, and we demonstrate that the combination of tidal and rotational observations can be used to determine both the thickness and the rigidity of the crust above the magma ocean.

1. Introduction

The massive amount of volcanic activity is a clear indication of molten rock in Io. Galileo magnetometer data suggest that Io has an at least partially molten asthenosphere beneath its surface, if not a fully molten magma ocean (Khurana et al., 2011). Tidal deformation measurements by the Io Volcano Observer (IVO) mission (McEwen et al., 2019) could differentiate between full and partial melt (Bierson & Nimmo, 2016). Here, we show that observations of libration, the variations in the rotation rate of Io at its orbital period, are a complementary tool to determine the status of Io’s melt region. Libration may be accurately measured by future spacecraft such as IVO during multiple flybys of Io by imaging and using a geodetic control network and precise orbit reconstruction as has been done for Enceladus (Thomas et al., 2016).

Io’s rotation is synchronous with the orbital motion, as is the case for all large satellites in the Solar System, meaning that orbital and rotational periods are equal. Io is expected to have reached that equilibrium state shortly after its formation as a result of tidal friction. The gravitational torque of Jupiter causes small deviations, or librations, about the stable equilibrium rotation. At short time scales, the largest libration has a period equal to that of the orbital period of 1.77 days. As illustrated in Figure 1, this diurnal libration can be described by an oscillation of the long axis of Io around its equilibrium orientation, corresponding to synchronous motion, in such a way that the long axis is always pointing further away from Jupiter than
the direction to the empty focus (e.g., Tiscareno et al., 2009). At perijove and apojove, the long axis points toward Jupiter and the amplitude of libration, or the angular deviation of the orientation of the long axis with respect to its equilibrium orientation, is equal to zero, as is the torque. For mean anomalies between $0^\circ$ and $180^\circ$, Io's long axis lags behind the direction to Jupiter, in the sense of the rotational and orbital motion. The gravitational torque exerted by Jupiter therefore tends to speed up Io's rotation. For mean anomalies between $180^\circ$ and $360^\circ$, it decelerates the rotation. As a consequence, Io’s rotation will be slowest at perijove and fastest at apojove. Because Io is rotating slower than the mean synchronous rotation for mean anomalies between $0^\circ$ and $90^\circ$, its long axis will lag behind the equilibrium orientation (Figure 1). This lag angle, the libration, increases with increasing mean anomaly, even though Io’s rotation is accelerating, to reach a maximum libration lagging behind the equilibrium orientation at a mean anomaly of $90^\circ$. The accelerating effect of Jupiter’s torque on Io’s rotation causes the libration to decrease to zero at apojove. In the second part of the orbit, the long axis leads the equilibrium orientation. The maximum leading libration is reached at a mean anomaly of $270^\circ$, where Io’s rotation rate is equal to the equilibrium rotation rate.

The amplitude of the diurnal libration signal depends on how Io responds to the gravitational forcing. Here, we calculate the diurnal libration amplitude for a large set of interior structure models of Io and assess the influence on it of a subsurface magma ocean and of the rigidity and viscosity of the crust. In Section 2, we briefly review Io’s interior and describe the set of internal structure models used. In Section 3, the diurnal libration of Io is calculated for two cases: first for Io having a partial melt zone but no global melt and second for Io with a global magma ocean. We show that Io’s libration amplitude strongly depends on the thickness and rigidity of the crust. In Section 4, we discuss other librations than the one at 1.77 days that are due to changes in the Keplerian orbit of Io. We present our conclusions in Section 5 and demonstrate that if both libration amplitude and tidal Love number $k_2$ can be measured, both the thickness and the rigidity of the crust can be constrained.

2. Io’s Interior

The low-degree gravity coefficients of Io, determined from radio-tracking the Galileo spacecraft during five close flybys of Io, shows that Io’s mass distribution satisfies the ratio $J_2/C_{22} = 10/3$, which is consistent with
3. Libration

3.1. Asthenosphere

We first study the libration of Io assuming that Io has no global magma ocean. Although partial melt is present, in terms of the rotational motion, the entire silicate shell will behave as one solid. Comstock and Bills (2003) and Noyelles (2013) determined the libration amplitude assuming that Io has infinite rigidity and obtained values of about 245 m and between 270 and 286 m, respectively. Only Noyelles (2013) included a liquid core. Here, we also include the effect of tidal deformation of Io. We define the libration angle $\gamma = \phi - M_0$, where $\phi$ is the rotation angle of Io and $M_0$ the mean anomaly. Writing the libration at orbital period of 1.77 days as $\gamma = \sin(M_0 + \pi)$, we can express the libration amplitude $\gamma_{\text{solid}}$ for an entirely solid (no magma ocean) and elastic Io as (Van Hoolst et al., 2013).
Rigidities are $6 \times 10^{10}$ Pa (crust), $2 \times 10^9$ Pa (asthenosphere), and $4 \times 10^{10}$ Pa elsewhere. Values with deformation included are shown in blue and are below those for rigid solid layers (green).

The fact that deformation reduces the libration amplitude can be understood from an energy argument or from a dynamical point of view by considering how tidal deformation changes the gravitational torque of Jupiter on Io. From the point of view of energy, the gravitational interaction of Jupiter with Io leads to an increase in the elastic energy through deformation and an increase in the gravitational energy related to the forcing libration period and therefore negligibly affects the libration amplitude. Compared to an infinitely rigid Io, for which we confirm the values obtained by Noyelles (2013), deformation for an Io with finite rigidity decreases the libration amplitude by up to 15 m (Figure 3).

To study the deformation effect from the dynamical point of view, we consider explicitly that tidal deformation of an entirely solid satellite Io will only be reduced at the level of a few percent by deformation. In the lowest energy state, this ratio shows that most of the energy increase will be gravitational and that the libration amplitude is between 266 and 275 m.

Figure 3. Amplitude of the libration for a partially molten asthenosphere. Rigidities are $6 \times 10^{10}$ Pa (crust), $2 \times 10^9$ Pa (asthenosphere), and $4 \times 10^{10}$ Pa elsewhere. Values with deformation included are shown in blue and are below those for rigid solid layers (green).

\[
\mathcal{R} = \frac{32\pi}{5} \frac{1 + \nu}{5 + \nu} \left( \frac{1 + k_f^2}{k_f} \frac{\mu dR^3}{GM^2} \right)
\]

(Goldreich & Mitchell, 2010). Here, $\mu$ is the rigidity, $\nu$ the Poisson ratio (values taken between 0.1 and 0.4), and $d$ the thickness of the shell. Assuming an entirely solid satellite (taking shell thickness $d$ to be equal to the radius of Io), the ratio is approximately 25 for the interior models considered. Because nature tends to the lowest energy state, this ratio shows that most of the energy increase will be gravitational and that the libration of an entirely solid satellite Io will only be reduced at the level of a few percent by deformation. In the next subsection, we show that this conclusion is not valid if Io has a magma ocean and that deformation has a much stronger effect because the crust can then be considered as decoupled from the deeper interior.

\[
g_{\text{solid}} = 6\frac{\bar{B} - \bar{A}}{C} \frac{en^2}{n^2 - \omega_f^2} \approx 6e \frac{\bar{B} - \bar{A}}{C},
\]

where $\omega_f$ is the free frequency of libration

\[
\omega_f = \frac{k_f}{k_f - k_2}
\]

and $\bar{B} = B(k_f - 5k_2/6)/k_f$, $\bar{A} = A(k_f - 5k_2/6)/k_f$ and $\bar{C} = C + 4k_2R^2/9G$ (Van Hoolst et al., 2013). Here, $G$ is the universal gravitational constant. The mean motion of Io’s orbit is denoted by $n$, $e$ is the orbital eccentricity (we choose an average value of 0.004151, Lainey et al., 2006, see also Section 4), $k_2$ the classical potential Love number, and $k_f = 4C_{22}/q = 1.304$ the fluid Love number with $q = n^2R^3/(GM) = 1.7138 \times 10^{-3}$. We refer to Van Hoolst et al. (2013) for the slightly modified equations for the case of a liquid core, which are used to calculate the values reported below. For rigidities of $2 \times 10^9$ Pa in the asthenosphere and $6 \times 10^{10}$ Pa in the crust, the libration amplitude is between 266 and 275 m. The Love number $k_2$ is between 0.051 and 0.083 (see also Bierson & Nimmo, 2016) and depends mainly on the radius of the liquid core. The free libration period is between 13.32 and 13.50 days and is close to the period for an infinitely rigid Io (equal to 13.28 days, by setting $k_2 = 0$ in the above equations) because $\bar{C} \approx C$ and the ratio of Love numbers in Equation 2 is close to 1. The free period is much longer than the forcing libration period and therefore negligibly affects the libration amplitude. Compared to an infinitely rigid Io, for which we confirm the values obtained by Noyelles (2013), deformation for an Io with finite rigidity decreases the libration amplitude by up to 15 m (Figure 3).
The second periodic tidal bulge is oriented along an axis 45° ahead, in the direction of rotation, of the orientation of the static bulge (Van Hoolst et al., 2013). Because of the alignment with the static tidal bulge, the first periodic tidal bulge increases the torque and thus the libration amplitude. The torque on the second, misaligned periodic tidal bulge is in the opposite direction of the two other torques, as can be seen from the schematic in Figure (1). Because the angular separation between the tidal bulge and the direction to Jupiter is much larger for the misaligned tidal bulge than for the first bulge aligned with the long axis—it is about 45° for the former and twice the orbital eccentricity at most (e.g., Murray & Dermott, 1999) for the latter—the total effect of the torques on the periodic tidal bulges, and thus deformation, is to decrease the net total torque, and thus libration. From the decomposition of the tidal potential into its static and periodic components, the total gravitational torque can be shown to decrease with respect to an infinitely rigid Io by a factor \((k_f - k_3)/k_f\) (Van Hoolst et al., 2013). For an entirely solid Io without magma ocean, this ratio is between 0.94 and 0.96, explaining the about 5% reduction in libration amplitude compared to a rigid Io. This Love number ratio and libration amplitude reduction is almost insensitive to the choice of the rigidity of the crust within the range \([10^{10}, 6 \times 10^{10}]\) Pa. Also, changes in the rigidity of the asthenosphere within two orders of magnitude of the nominal value of \(2 \times 10^9\) Pa do not significantly change the libration amplitude.

### 3.2. Magma Ocean

A magma ocean strongly affects the rotational dynamics of Io by decoupling the libration of the layer above the magma ocean from that below it. In addition, deformation will have a much larger effect. The libration amplitude of the crust \(g_c\) can be well approximated by (Van Hoolst et al., 2016)

\[
g_c \approx \frac{4eK_1}{C_c(n^2 - K_1/C_c)} \quad (4)
\]

Here, \(C_c\) is the polar moment of inertia of the crust and \(K_1\) is the effective strength of the total forcing torque exerted on the crust at the orbital period. It essentially consists of the sum of the gravitational torque exerted by Jupiter and of the associated pressure torque exerted by the magma ocean, both on the static shape of the shell of Io and the tidal bulge of the crust (see Van Hoolst et al., 2013, for explicit expressions), other terms contributing well below 1%. The libration model does not take into account that the core is liquid because it has a negligible effect when a liquid layer (the magma ocean) exists close to the surface (Baland & Van Hoolst, 2010). It also does not include the possible effects of tidally forced inertial modes in the magma ocean. Although they can contribute to the dissipation in the magma ocean (Tyler et al., 2015) through the development of internal shear layers (Ogilvie, 2009), their additional pressure coupling on the solid crust above is expected to be small (Rovira-Navarro et al., 2019) and to have a negligible effect on the libration of the crust (Rekier et al., 2019). Equation 4 is similar in form to Equation 1 and expresses the libration amplitude essentially as a ratio of the effective torque divided by the moment of inertia of the librating layer. Although the total torque on the crust is a factor 1.6 to 16 times smaller (from thick to thin crust) than the total gravitational torque on an entirely solid Io without magma ocean, the polar moment of inertia of the crust is 4 to 71 times smaller than the polar moment of inertia of the whole satellite. The rotational response of the crust of Io is, therefore, larger than that of Io without a magma ocean, demonstrating that a magma ocean strongly increases the libration amplitude (Figure 4). For the thickest crusts considered, this ratio explains the fact that the libration amplitude is about a factor 2.5 times larger than for an entirely rigid Io.

Equation 4 shows that the libration amplitude is further increased by a resonance with a free mode (Figure 4). Two free libration modes exist if Io has a global magma ocean: (1) a librational motion of the solid region below the magma ocean and crust in phase and (2) a libration in which the motion of the interior beneath the magma ocean is out of phase with that of the crust (Van Hoolst et al., 2013). The period of the first mode is between 58 and 109 days, depending mainly on the size of the core, and is almost
unaffected by deformation. This period range applies to our set of models in which we neglected any density jump at the interface between the magma ocean and the underlying mantle. Consideration of such a density difference, expected to be small, will decrease the period. The period is much larger than the orbital period $2\pi/n$, justifying that we neglect the square of its frequency with respect to $n^2$, as done in Equation 4. We note that also for the entirely solid Io, a resonance with such a free mode can be neglected (see Equation 1). The period of the second mode is given, in an excellent approximation, by $2\pi\sqrt{C/C_f}$. The period of the second mode is 2 to 3 days shorter than for an elastic crust and closer to the forcing frequency, contributing to a larger resonant amplification and a larger libration amplitude for a rigid crust (Figures 4 and 5).

The dependence of the libration amplitude on the thickness of the crust is striking if a global magma ocean is present and is reminiscent of the behavior of the libration amplitude of Enceladus (Thomas et al., 2016), although the reducing effect of deformation is much larger than for Enceladus. For an infinitely rigid crust, the period of the second free mode is 2 to 3 days shorter than for an elastic crust and closer to the forcing frequency, contributing to a larger resonant amplification and a larger libration amplitude for a rigid crust (Figures 4 and 5). Also, the total torque on the crust, represented by $K_3$ in Equation 4, increases by a factor 1.6 to 16 when considering infinite crust rigidity, further contributing to a larger libration for a rigid crust. Compared to a crust with infinite rigidity, tidal deformation decreases the libration amplitude by a factor of 2 and more for crustal thicknesses below 60 km. Figures 4 and 5 also show that other parameters of the interior, such as the thickness of the magma ocean, have a negligible effect on libration for a fixed rigidity profile. We, nevertheless, note that we do not consider any density difference between the magma ocean and the crust or mantle in the Io models. Density differences of a few hundred kg/m³ between those layers can lead to differences in the libration amplitude of up to 10%.

We now provide further insight into the large reducing effect of tidal deformation on the libration amplitude and evaluate the effect of rigidity and viscosity on the libration amplitude. We focus on the rigidity and viscosity of the crust because these quantities of the layers beneath the magma ocean have a negligible effect on the libration of the crust of Io due to the much smaller tidal displacement and libration amplitude of those layers compared to the crust.

Io's large topography indicates that the crust must have a significant rigidity (Schenk & Bulmer, 1998). Rigidities of the crust are chosen between $10^{10}$ Pa and $6 \times 10^{10}$ Pa, although realistic rigidity values for Io's crust are likely to be between $3 \times 10^{10}$ Pa and $6 \times 10^{10}$ Pa. The smallest value is only considered as an extreme limit case to be able to set strong lower bounds on the libration amplitude. Our assumption of a single rigidity value for Io's crust is a somewhat simplified description. In reality, rigidity will depend on at least temperature, melt fraction, forcing frequency, and composition. Torsional oscillation experiments on olivine polycrystals show that the rigidity decreases from 50–70 GPa at 1,000°C to ≤10 GPa at 1,300°C (Jackson et al., 2004). The rigidity is further reduced as the melt fraction increases, with a dependence that is approximately linear up to some critical melt fraction (Mavko, 1980). Because Io's crustal temperature structure is dominated by advection, it is expected to be cold apart from a thin boundary layer at the base (O'Reilly & Davies, 1981). As a result, a vertically averaged crustal rigidity less than roughly 30 GPa would be a very surprising result. As we will show in the concluding section, strong constraints on the rigidity of the crust can be obtained by combining measurements of the diurnal libration with those of tides.

As is well known for the large icy satellites (Jara-Orué & Vermeersen, 2014; Van Hoolst et al., 2013), the libration amplitude decreases with decreasing crustal rigidity because tidal deformation of the crust increases with it (Figure 6). For crustal rigidities between $3 \times 10^{10}$ Pa and $6 \times 10^{10}$ Pa and thicknesses

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**Figure 5.** Period of the out-of-phase free libration in the case of a magma ocean for inclusion (blue) or not (green) of deformation.
between 5 and 100 km, the libration amplitude is 2 to 6 times larger than the amplitude for Io without a magma ocean. It reaches an amplitude of 1.5 km for the thinnest crust and largest rigidity considered. For the smallest rigidity considered, the libration amplitude is close to that of an entirely solid Io.

The libration behavior of Io is intermediate between that of large icy satellites as Ganymede and Europa, and that of the much smaller Enceladus. For large icy satellites, the crust almost deforms as a layer in hydrostatic equilibrium and its shape conforms to that of the response of the liquid layer beneath, resulting in a small libration. In terms of its tidal deformation, the ice shell of the large icy satellites can be considered to be soft (Beuthe, 2018). Likewise, the crust of Io is soft for the lowest crust rigidities considered here. At the higher realistic rigidities, the surface deformation is significantly different from that of a liquid, as is also the case for Enceladus. Enceladus’ ice shell can be considered to be hard, in the sense that its tidal deformation is determined by its elastic properties only, not by the deformation of the subsurface ocean. An approximate criterion to distinguish between soft and hard shells is given by the quantity:

$$Q = \frac{1 + \nu}{5 + \nu} \frac{\mu d}{R}$$

being smaller or larger than 1 (Beuthe, 2018). Here, $\mu = \mu / (\rho g R)$ is the nondimensional rigidity of the crust with density $\rho_c$, and $g$ is the gravitational acceleration at the surface. For the nominal case with $\mu = 6 \times 10^{10}$ Pa, $Q \approx 0.64(d/100 \text{ km})$. As it is close to 1, the deformation of the crust is not only determined by the elastic crust properties, as is approximately the case for small satellites like Enceladus, but also by the magma ocean. Alternatively, the ratio between the elastic energy of deformation of the crust and the gravitational energy (Equation 3) can be considered to estimate the importance of tidal deformation on libration (Goldreich & Mitchell, 2010). Because $\mathcal{R} \approx 1.44(d/100 \text{ km})$ for the nominal case, Io’s libration is intermediate between the two limiting cases and is significantly reduced by the tidal deformation of the crust but still is much larger than for the case that Io has no magma ocean. For the smallest crustal rigidity considered, $Q \approx 0.1$ and $\mathcal{R} \approx 0.2$, an order of magnitude smaller than 1. The crust then behaves as a soft crust dominated by elastic energy of deformation and the libration amplitude decreases strongly to values comparable to that of an entirely solid satellite, as is the case for the large icy satellites of the Solar System like Ganymede, Titan, and Europa (Figure 6).

The crust is thought to have formed by downward motion of cooled previously erupted material (O’Reilly & Davies, 1981). Beneath it, and above a magma ocean, a transition region may exist with some degree of partial melt and a much lower rigidity. To estimate the effect of such a transition layer on the libration, we separate the crust into a top layer with a high rigidity and a lower transition region with a lower rigidity of $2 \times 10^9$ Pa, representative of a partial melt asthenosphere. We varied the thickness of this layer between 10% and 50% of the total crustal thickness. The introduction of the transition layer makes the total crust softer and reduces the libration amplitude. For the thinnest crusts considered (5 km), the amplitude diminishes by about 9.5% per increase in transition zone thickness by 10% of the total crust thickness. For the thickest crusts considered (100 km), the reduction is about 5% for similar increases in the thickness of the transition zone.

Viscosity of the crust reduces the libration amplitude (Jara-Orué & Vermeersen, 2014). We include visco-elastic deformation in the libration model by calculating the tidal deformation and Love numbers for a Maxwell rheology. The complex, frequency-dependent rigidity $\mu_c$ of the crust is expressed by

$$\mu_c(n) = \frac{\mu \eta n}{\eta n - i \mu}$$

where $i$ is the imaginary number, $\mu$ the elastic rigidity of the crust, and $\eta$ the crustal rock viscosity (e.g., Vermeersen & Sabadini, 2004). For low (<30%) degrees of partial melt, Io is expected to have a mantle
viscosity $>10^{18}$ Pa s (Bierson & Nimmo, 2016), and top crust viscosity values can be orders of magnitude larger than that for the Earth's upper mantle. Postglacial rebound shows that the viscosity of the Earth's upper mantle is about $10^{21}$ Pa s (Velicogna & Wahr, 2002). For this range of viscosity values, and for higher values, the effect of viscosity on the libration amplitude can be neglected. This can be understood from the value of the Maxwell timescale, separating elastic from fluid behavior, which is larger than 0.5 years for the viscosity and rigidity values considered. Because it is two orders of magnitude longer than the libration period, the crust behaves essentially elastically. Unrealistically, lower viscosity values must be considered to reduce the libration amplitude of Io through visco-elastic effects in a uniform crust. Even in a possible transition zone with partial melt, the viscosity is not expected to be below $10^{18}$ Pa s. We nevertheless considered values in a bottom transition zone with viscosity values down to $10^{15}$ Pa s. For the standard model with a top crust rigidity of $6 \times 10^{10}$ Pa and a rigidity of $2 \times 10^9$ Pa in the transition zone, the libration amplitude is significantly reduced due to viscosity only for the unrealistic lowest viscosity values. Because those viscosity values are many order of magnitude below representative values for Io’s crust, we do not expect that more advanced rheology models such as the Andrade model, which leads to more dissipation than the Maxwell model (e.g., Bierson & Nimmo, 2016), will change our results and conclude that viscosity has a negligible effect on Io’s libration.

4. Librations Due to Orbital Perturbations

The orbital motion of Io is not purely Keplerian and changes over time (Lainey et al., 2006). Those orbital perturbations lead to changes in the gravitational torque of Jupiter on Io with respect to the mean Keplerian orbital motion and therefore to additional librations (Henrard, 2005). The main effect on Io’s librations is due to changes in the mean longitude, which is measured approximately (Io’s obliquity is very small, $\lesssim 0.002^\circ$, Baland et al., 2012; Bills, 2005) in the same plane as the rotation angle. We tested that variations in eccentricity, longitude of the pericenter, semimajor axis, longitude of the node, and orbital inclination have a secondary effect on Io’s librations. The orbital perturbations are mainly due to the motion of the other Galilean satellites and are strongly connected with the Laplace resonance. Two effects are particularly relevant here for librations at time scales much longer than the orbital period. First, the combination of the mean longitudes $\lambda_1 - 3\lambda_2 + 2\lambda_3$, where subscripts 1, 2, and 3 indicate Io, Europa, and Ganymede, oscillates around $180^\circ$ (“the Laplace resonance libration,” note that the word libration here refers to the oscillatory motion of the combination of orbital elements, not to the physical libration of Io). Second, the 2:1 resonances among Io-Europa and Europa-Ganymede are only approximately satisfied (“the great inequality”). Together with the precession of the perijoves of the satellites, this leads to orbital perturbations, and associated librations, at periods of 463 days, 482 days, 5.64 years, 486 days, and 404 days for the largest perturbations (in decreasing order of the magnitude of the perturbations in mean longitude equal to 39.74 arcsec, 20.04 arcsec, 18.55 arcsec, 11.42 arcsec, and 8.63 arcsec, Lainey et al., 2006). The next largest long-period perturbation in mean longitude has a period equal to the orbital period of Jupiter of 11.86 years and an amplitude of 7.69 arcsec (Lainey et al., 2006). In addition, short-period perturbations arise due to differences in the mean longitudes of Io, Europa, and Ganymede, with the two largest of these perturbations having approximately the diurnal frequency (1.763 days) and half the diurnal frequency (3.525 days, Lainey et al., 2006).

At long period, longer than the two eigenperiods, the rotation angle of Io approximately follows the variations in the mean longitude so that the libration amplitude is close to the amplitude of the orbital variations in mean longitude. This behavior is typical for an oscillator forced at longer periods than the eigenperiods and has also been shown to apply to the long-period librations of the icy Galilean satellites and Enceladus in a libration model assuming rigid solid layers (Rambaux et al., 2010, 2011). It implies that Io approximately keeps its long axis into the direction of Jupiter at those long periods. The libration amplitudes as measured on the surface of Io are therefore approximately 351, 177, 164, 101, 76, and 68 m in decreasing order of amplitude. The deviation with respect to the forcing amplitudes is at the percent level of the forcing because of their long period, and the relative dependence of long-period librations on the interior structure of Io is therefore much less than for the diurnal libration. Because these librations are much longer in period than, and incommensurate with, the diurnal libration signal, they are unlikely to affect the ability of any future spacecraft mission to retrieve the diurnal libration amplitude. We tested that assuming an uncertainty of the order of 20% on the amplitudes of the main long-period librations (which is larger than those
therefore are unlikely to degrade measurements of the diurnal libration. Similarly to any harmonic oscillator forced at periods much shorter than the eigenperiods, the variations in rotation angle at the diurnal frequency range are expected to be much smaller than the forcing amplitude. For the nearly diurnal libration related to orbital perturbations, the variation in the rotation angle is accordingly found to be about an order of magnitude smaller than the forcing of 92 m. The libration at 3.525 days, however, is closer to the out-of-phase eigenperiod (Figure 5) and is therefore less reduced in amplitude and can be of the order of the forcing amplitude of 81 m when Io has a magma ocean. Although its amplitude is much smaller than the diurnal libration amplitude, this libration might have some potential in helping to constrain Io’s interior as it also depends on Io’s internal structure.

5. Discussion and Conclusions

We calculated the librations of Io to study the potential of libration observations to constrain the interior of Io. Our results show that a global magma ocean strongly increases the diurnal libration amplitude. Without a magma ocean, the libration amplitude is about 266 to 275 m. With a magma ocean, the libration is several times larger, with values up to 1,580 m for a crust rigidity of $6 \times 10^{10}$ Pa. The diurnal libration of the solid interior beneath the magma ocean is about 10 m, measured on the surface of the mantle beneath the magma ocean. Physically, a magma ocean decouples the crust from the deeper interior, and the much smaller moment of inertia of the crust compared to that of the total satellite leads to a larger rotational response, and thus larger libration. For an infinitely rigid crust, the libration amplitude can be larger than 5 km for a crust thinner than 25 km (Figure 4). The finite rigidity of the crust limits the libration amplitude because the large deformation of the crust increases the elastic energy of it so that less energy is available for rotational variations. The libration amplitude strongly increases with decreasing thickness of the crust and with increasing crustal rigidity.

The large effect of a magma ocean on the diurnal libration makes libration an ideal tool to study the possible presence of a magma ocean in Io. The next missions to Jupiter, ESA’s JUICE mission (Grasset et al., 2013) and NASA’s Europa Clipper (Howell & Pappalardo, 2020), unfortunately will not fly close to Io, making libration observations of Io extremely challenging if not impossible. Multiple flyby missions of Io like IVO (McEwen et al., 2019), selected for further study by NASA in February 2020, can accurately determine libration by observing the same surface features at different mean anomalies, allowing study of Io’s melt zone and thickness and rigidity of the crust.

Long-period librations due to orbital perturbations caused by the other Galilean satellites depend much less on the interior structure of Io and their amplitudes can be approximated by those of the variations in the mean longitude of Io’s orbit in future analyses of libration observations by flyby missions like IVO. They therefore are unlikely to degrade measurements of the diurnal libration. Short-period, orbital-induced librations significantly depend on the interior but are much smaller in amplitude than the diurnal libration. The largest such libration has a period of 3.525 days and a maximum amplitude of the order of that of the forcing of 81 m. Besides those short-period librations related to orbital perturbations, we also note that for the mean Keplerian orbit, other libration signals exist at higher harmonic frequencies $kn$, where $k$ is an integer value. With respect to the diurnal libration amplitude, their amplitudes scale according to eccentricity $e$ as $e^{k-1}$, and they can therefore be considered to be negligible for future observational studies.

In addition to libration, IVO will also measure the surface tidal displacement and tidal changes in the external gravitational field of Io (characterized by $k_2$). In Figure 7, we show the amplitude of the diurnal libration versus the Love number $k_2$ for a set of rigidity and thickness values of the crust. As discussed above, both observable quantities increase with decreasing thickness of the crust. Tidal deformation increases because the magma ocean is then closer to the surface. To balance the tidal force, pressure gradients in the magma ocean require more deformation than shear stresses do in the solid crust. Libration also increases mainly because of the smaller polar moment of inertia of the crust. Crustal rigidity has opposite effects on $k_2$ and libration. Tidal deformation increases for lower rigidities and therefore the libration amplitude decreases. Conversely, the increased deformation results in a larger $k_2$. The different dependencies of $k_2$ and diurnal libration amplitude on crustal thickness and rigidity allow both these
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**Acknowledgments**

As a final word of caution, we remind the reader that our calculations of the tidal response have assumed a spherically symmetrical structure and those of the librations a triaxial ellipsoidal shape in agreement with hydrostatic equilibrium. In reality, lateral variations in heat production on Io may give rise to significant lateral variations in lithospheric thickness (Spencer et al., 2020; Steinke et al., 2020). Calculating the full effect of these lateral variations on the tidal and librational response is beyond the scope of this manuscript. However, we can appeal to similar calculations performed for the tides of Ganymede (A et al. 2014; Beuthe, 2018). These results show that lateral variations of Ganymede's shell thickness of the order of 25% lead to a change in the Love number $k_2$ well below 1% compared with the spherically symmetric equivalent. To quantify the effect of lateral variations on the librations, we changed the hydrostatic value of the equatorial flattening of the interface between the magma ocean and the crust to introduce variations in the thickness of the crust above the magma ocean. We considered crustal thickness variations of the order of several km in agreement with variations in the conductive crust obtained by Steinke et al. (2020). The lateral variations only change the libration when the density between the crust and magma ocean is different. Considering a density difference of 250 kg/m$^3$, the diurnal libration amplitude is modified by lateral variations by up to 10% with respect to the hydrostatic reference models for mean crustal thickness larger than 20 km. The differences increase with decreasing crustal thickness and can reach several 10% for crusts much thinner than 20 km. The differences increase with decreasing crustal thickness and can reach several 10% for crusts much thinner than 20 km.

These results, however, overestimate the effect of lateral variations. First, a large density jump at the interface between the magma ocean together with a large variation in the crustal thickness can only exist if gravitationally compensated elsewhere to satisfy the observationally determined values of the degree-two gravitational coefficients, which are suggestive of hydrostatic equilibrium. Second, without compensation at the top of the crust, the considered lateral variations induce large stresses in the crust that can exceed the about 10 MPa tensile strength of rocks for thin crusts with large density contrasts. Fracturing within the crust then dilutes or wipes out the bottom topography. Although further work is clearly needed, these libration results and the Ganymede analogy for tides suggest that lateral variations are unlikely to invalidate our proposed method to test for a magma ocean. For crustal density contrasts up to 250 kg/m$^3$, lateral variations only slightly degrade the possibility to constrain the thickness and rigidity of the crust for thicknesses above 20 km. Lateral variations can have a more significant effect for crusts thinner than 20 km or with larger density contrasts, but as noted above, it is not obvious that such variations can be maintained.

**References**


