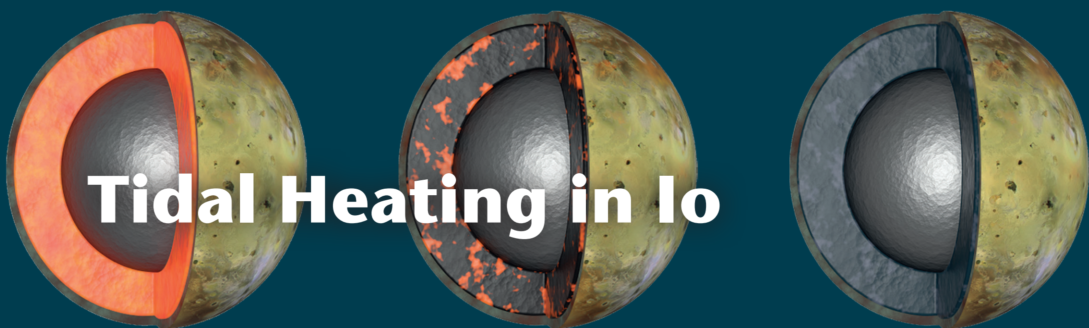

Tidal Heating in Io

Isamu N. Matsuyama[1], Teresa Steinke[2], and Francis Nimmo[3]

Image credit: Chuck Carter and James Tuttle Keane / Keck Institute for Space Studies.

1811-5209/22/0018-0374$2.50 DOI: 10.2138/gselements.18.6.374

Io experiences strong, periodic, gravitational tides from Jupiter because of its close distance to the planet and its elliptic orbit. This generates internal friction that heats the interior, a naturally occurring process in the Solar System and beyond. Io is unique in our Solar System because it gets most of its internal energy from this tidal heating, providing an ideal laboratory for improving our understanding of this fundamental process that plays a key role in the thermal and orbital evolution of the Moon, satellites in the outer Solar System, and extrasolar planets.

Keywords: tides; Io; Jupiter; deformation; heating; orbits

INTRODUCTION

The deformation of an object in response to an external time-varying force generates frictional energy that heats its interior. This is a naturally occurring process in satellites where the driving force is the gravitational pull of the parent planet, and is commonly referred to as tidal heating, tidal energy dissipation, or tidal friction. For example, the Moon's gravitational force causes Earth's water to bulge out on the side closest to the Moon and the side farthest from the Moon (high tides). The work done by the gravitational force is dissipated in the oceans, producing the dominant contribution to Earth's tidal heating (Munk 1997).

Just as the Moon exerts a gravitational pull on the Earth, the Earth exerts a gravitational pull on the Moon, causing tidal heating inside the Moon. The Earth–Moon and Jupiter–Io orbital distances are similar, and Jupiter's mass is about 300 times that of the Earth; therefore, the gravitational forcing of Io by Jupiter is also larger than the gravitational forcing of the Moon by the Earth by the same degree. The strong gravitational forcing combined with a hot deformable interior makes Io the most tidally deformed and tidally heated satellite in the Solar System. Peale et al. (1979) predicted that strong tidal heating should melt a large fraction of the interior, likely producing widespread active volcanism at the surface. This prediction was confirmed by *Voyager 1* observations revealing active volcanic plumes and widespread volcanic features (Davies and Vorburger 2022 this issue).

Tidal heating is a fundamental process in the Solar System, playing an important role in the thermal and orbital evolution of satellites, including the formation of subsurface oceans in satellites around giant planets. Beyond the Solar System, tidal heating also plays a key role in the thermal and orbital evolution of extrasolar planets orbiting close to their stars. In this paper, after discussing the origin of the time-varying gravitational forces driving tidal heating, we describe classical formulations of tidal heating and how tidal heating patterns can be used to probe the interior of Io. We also discuss recent advances in theoretical models of tidal heating.

TIDAL DEFORMATION

The Moon, Io, and many satellites in the outer Solar System are in a state of synchronous rotation, a natural outcome of gravitational forces slowing down the rotation of a satellite to a state where the rotational period is synchronized with the orbital period. Extrasolar planets orbiting close to their stars are also expected to be in this state because of the strong gravitational forces from the star. Pluto and Charon are in a dual synchronous state, the final state of tidal evolution where the rotational periods of both Pluto and Charon are equal to the orbital period. In synchronous rotation, a satellite always shows the same face to the planet it is orbiting. In a reference frame fixed to the satellite and rotating at the same synchronous rotation rate, the planet remains stationary if the orbit is perfectly circular (Fig. 1A). Therefore, the planet can only exert a constant, time-independent gravitational pull on the satellite. This forcing can produce permanent deformation (a permanent "tidal bulge") along the line connecting the centers of Io and Jupiter (the tidal axis), but it cannot provide the periodic deformation needed to generate continuous tidal heating.

Jupiter's innermost moons, Io, Europa, and Ganymede, are in a resonant state (a Laplace resonance) where Io completes two orbits around Jupiter for every one orbit completed by Europa, and four orbits for every one completed by Ganymede. This resonant configuration produces periodic gravitational pulls between the satellites, helping maintain non-circular orbits that result in periodic variations in the satellite–planet distance. In the same reference frame assumed above (i.e., fixed to a satellite and rotating at the same synchronous rotation rate), the planet is no longer stationary and instead moves around the stationary point

1 Lunar and Planetary Laboratory
University of Arizona
Tucson, AZ, USA
E-mail: isa@lpl.arizona.edu

2 Faculty of Aerospace Engineering
Delft University of Technology
Delft, the Netherlands
E-mail: teresa.steinke@me.com

3 Department of Earth and Planetary Sciences
University of California
Santa Cruz, CA, USA
E-mail: fnimmo@ucsc.edu

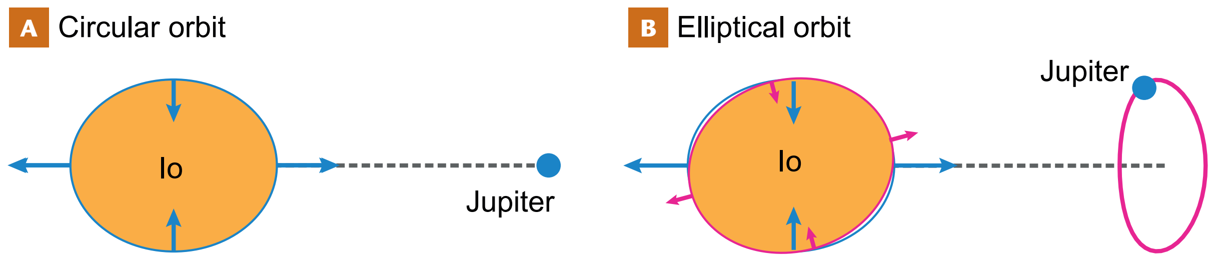

FIGURE 1 Motion of Jupiter as seen in a reference frame centered on Io and rotating with Io's synchronous rotation rate for (**A**) a circular orbit and (**B**) an elliptical orbit. For purposes of illustration, the amplitude of Jupiter's motion in (**B**) is exaggerated. Io's deformation is primarily determined by its response to the static component of Jupiter's gravitational pull and produces a permanent bulge (blue arrows). A dynamic bulge, which is the source of tidal heating, arises in an eccentric orbit and results in a modulation of the permanent bulge (magenta arrows).

for a circular orbit (FIG. 1B). The amplitude of these variations and the corresponding tidal heating increases as the orbit becomes more elliptical. Because of the time-varying distance and direction of Jupiter, the size and direction of the moon's tidal bulge also varies, resulting in tidal heating.

Satellite deformation in response to forcing by gravitational tides depends on its interior structure. A satellite can be more deformable, increasing tidal heating, owing to several factors. A lower material rigidity in the interior increases satellite deformation. A satellite with a more uniform interior density structure is also more deformable because a differentiated interior structure, with higher density near the center of the satellite, provides more gravitational binding. Several icy satellites in the outer Solar System contain interior water oceans beneath an outer icy shell, and Io may contain an interior magma ocean beneath a rocky shell (Khurana et al. 2011; Breuer et al. 2022 this issue). The presence of an internal liquid layer decouples the outer shell from the interior, increasing tidal dissipation in the shell and decreasing it in the inner regions (Tobie et al. 2005).

TIDAL HEATING IN SOLID REGIONS

In solid regions, part of Io's deformation in response to Jupiter's forcing is purely elastic and determined by the elastic moduli of the interior layers. The other part is anelastic and determined by the relaxation of materials in the interior layers, with a larger anelastic response associated with stronger energy dissipation. The anelastic component of the deformation and corresponding energy dissipation can be characterized in terms of the phase lag, δ_μ, between a periodic forcing and the deformation in response to it. This is commonly quantified by the material quality factor, Q_μ, defined as $Q_\mu \equiv 1/\tan(\delta_\mu)$. A shorter relaxation time as a result of stronger anelasticity corresponds to a larger phase lag, a smaller Q_μ, and stronger energy dissipation. The anelastic behavior of a material can be measured in laboratory experiments; however, such experiments have focused on the response to forcing with smaller stress amplitudes than those of tidal forcing in satellites (de Kleer et al. 2019).

In analogy with the material quality factor, Q_μ, it is possible to define an effective quality factor for the satellite as a whole, $Q \equiv 1/\tan(\delta)$, using the phase lag δ of the tidal bulge. The anelasticity of the satellite as a whole depends on how the anelasticity is distributed in the interior. The effective quality factor can be found given the material quality factor of the interior layers, although one must carefully account for the effect of self-gravity (Zschau 1978). As discussed above for the material quality factor, larger anelasticity, and the stronger energy dissipation associated with it, corresponds to a larger phase lag and a smaller effective tidal quality factor. The phase lag of the satellite deformation as a whole can, in principle, be measured by observing the satellite shape and gravity field. In Io's case, the time-varying part of the tidal bulge has an expected amplitude of about 50 m, depending on the rheological assumptions.

For real geological materials, the degree of anelasticity is a function of (at least) temperature and the forcing frequency (Karato and Wu 1993). The simplest useful model of a viscoelastic material is the Maxwell model, which depends on two parameters: rigidity and viscosity. These two quantities can be combined to produce the characteristic Maxwell time of the material, which determines whether the material responds to a periodic forcing in a mostly viscous or mostly elastic fashion. For the Earth's mantle, the Maxwell time is about 300 years; thus, at the seismic forcing period (~1 s), the mantle behaves elastically, while on timescales of millions of years, the mantle responds like a viscous fluid.

An important aspect of the Maxwell model is that tidal heating is maximized (Q is minimized) when the forcing period is comparable to the Maxwell time. At much shorter forcing periods, the body responds elastically (no

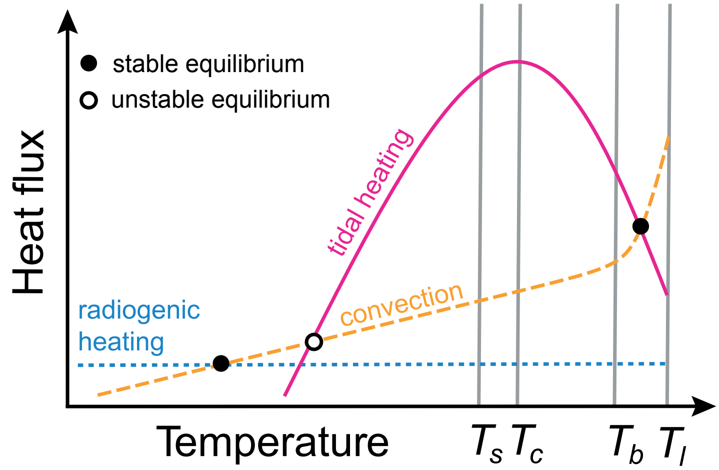

FIGURE 2 Depiction of possible thermal equilibria between heat production resulting from tidal heating and radiogenic heating and heat transport resulting from convection. Radiogenic heating produces the same heating regardless of temperature. At a critical temperature (T_c) slightly above the solidus (T_s), the shear modulus and tidal heating decrease rapidly. At the breakdown temperature (T_b), the solid matrix loses coherence, reducing the tidal heating. Convective heat transport increases with temperature as the viscosity decreases, with a rapid increase upon approaching the liquidus temperature (T_l). AFTER MOORE ET AL. (2007). Heat production is equal to heat transport at *equilibrium* states. In stable equilibrium (solid circles), if the temperature is disturbed slightly, then it returns to its original equilibrium state. In unstable equilibrium (open circle), the temperature continues to move away from its original equilibrium state.

dissipation); at much longer periods, the body behaves like a low-viscosity, and thus low-dissipation, fluid.

Because viscosity, and thus the Maxwell time, is a strong function of temperature, the rate of tidal heating in a body like Io will also depend on temperature. In practice, it will also depend on whether melt is present, as partial melt reduces the effective viscosity and shear modulus of the solid. As shown in FIGURE 2, as temperature increases, tidal heating increases to a point just beyond the solidus, after which the heating rate decreases again. Because heat transport is also likely to be a strong function of temperature, several equilibrium points likely exist, where heat transport and heat production are equal.

The viscoelastic behavior of geological materials can be measured by torsion experiments (Jackson and Faul 2010). Unfortunately, the Maxwell model does not provide an adequate description of the experimental results at frequencies similar to the tidal forcing frequency, and so other, more complicated deformation models are sometimes employed (e.g., Bierson and Nimmo 2016; Rovira-Navarro et al. 2021; Kervazo et al. 2022). An even more serious problem is that the behavior of partially molten materials, which very likely describes the mantle of Io, is not well characterized experimentally. This lack of experimental data limits our ability to develop accurate tidal heating models.

If Io's mantle consists of a partially molten mush, tidal forcing may cause relative motion between the melt and the solid. This relative motion could provide an additional source of dissipation, just as a dry sponge bounces when dropped, while a wet sponge (being more dissipative) does not. The physics of such a tidally driven, poro-viscoelastic problem has been examined for the case of water and rock (Rovira-Navarro et al. 2022), but not so far for solid and melt.

TIDAL HEATING IN A MAGMA OCEAN

Going back to the analogy of the Earth–Moon system, the Moon's gravitational force acting on Earth deforms both the oceans and the solid regions. For the Earth, tidal heating in the solid regions is significantly smaller than tidal heating in the oceans (Munk 1997; Egbert and Ray 2001). Therefore, if Io contains a subsurface magma ocean (Khurana et al. 2011), one might also expect strong tidal heating in this magma ocean (Ross and Schubert 1985; Tyler et al. 2015), although the effect of an overlying solid shell must be considered (Matsuyama et al. 2018).

Tidal heating in fluid regions is driven by the same gravitational forces deforming the solid regions. However, the response to gravitational forcing, and the corresponding tidal heating, can differ significantly in fluid regions because it can involve large horizontal fluid motions. Tidal heating in fluid regions depends on the nature of these horizontal fluid motions and their damping mechanisms. The damping of fluid motions occurs as a result of viscous dissipation within the fluid occurring at solid–fluid interfaces (commonly referred to as bottom friction for Earth's oceans) and in the interior of the ocean.

TIDAL HEATING PATTERNS

Tidal heating can occur in all interior regions, and the pattern of heat flow observed at the surface depends on how tidal heating is partitioned in the interior. The surface tidal heating pattern inferred from the spatial distribution of Io's hot spots (FIG. 3) must be related to the tidal heating distribution in the interior, providing a probe for the interior structure of Io. The expected surface tidal heating pattern can be found by integrating the dissipated energy

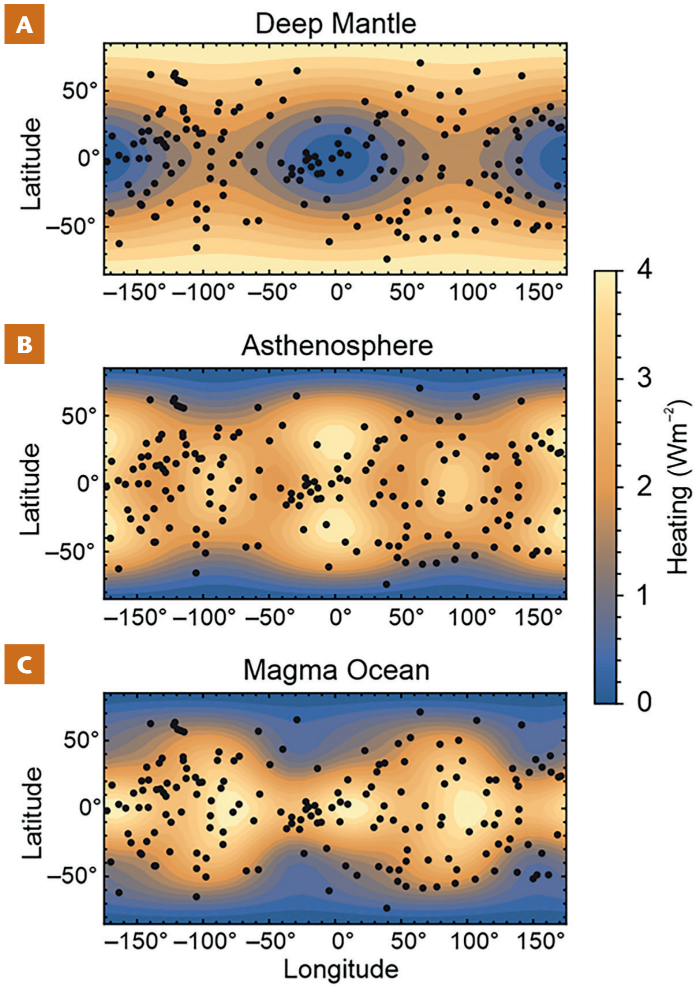

FIGURE 3 Io's predicted surface tidal heating patterns for three endmember Io models, including solid dissipation in (**A**) a deep mantle or (**B**) an asthenosphere or (**C**) fluid dissipation in a magma ocean. Solid dissipation is computed using the method of Segatz et al. (1988). Magma ocean dissipation is computed using the method of Matsuyama et al. (2018). Black circles show the locations of observed hot spots (Hamilton et al. 2013).

in the interior layers and assuming that heat is transported radially to the surface. FIGURE 3 shows the expected surface tidal heating patterns for three endmember models for tidal heating inside Io (Breuer et al. 2022 this issue). Tidal heating in the deep mantle results in polar regions that are preferentially heated (FIG. 3A). In contrast, tidal heating in the asthenosphere, a region beneath the outer rigid shell that is much more deformable than the overlying shell, results in equatorial regions that are preferentially heated (FIG. 3B). If the partial melt fraction in the asthenosphere is larger than ~30%, dissipation associated with volume changes modifies the surface tidal heating pattern, but equatorial regions remain preferentially heated (Kervazo et al. 2022). Tidal heating in a subsurface magma ocean also produces preferentially heated equatorial regions, but unlike asthenospheric tidal heating, the pattern is not symmetric around the tidal axis (0° and 180° longitude) (FIG. 3C).

There is no obvious correlation between the surface tidal heating pattern inferred from Io's hot spots and the pattern predicted by endmember Io models (FIG. 3). Combinations of endmember models (Segatz et al. 1988; Hamilton et al. 2013; Bierson and Nimmo 2016; Kervazo et al. 2022) or recent advances in modeling efforts (Steinke et al. 2020; Spencer et al. 2021) may reconcile this discrepancy. It is worth noting that Io's hot spots may not be representative of the surface heat flow pattern because the obvious hot spots can only account for about half of Io's heat flow, with the other half distributed in an unknown pattern throughout the surface (Veeder et al. 2015).

TIDAL HEATING WITH LATERAL VARIATIONS

As the surface tidal heating patterns in FIGURE 3A–3C show, tidal heating in a spherically symmetric interior is laterally non-uniformly distributed. With the amount of tidal heat generated exceeding radiogenic heating by several orders of magnitude, the non-uniform heat source represents a special characteristic of Io's interior. Whether this non-uniform heat source causes large-scale variations in Io's interior properties and variations in Io's surface heat flow depends on where tidal dissipation takes place in the interior and how the produced heat is transported to the surface. Mantle convection blurs the lateral variations produced by tidal heating (Tackley 2001). A thinner convective layer is associated with stronger heat transport by magma and stronger variations of mantle temperature and surface heat flux that remain from the non-uniform heating (Steinke et al. 2020). Scenarios with mixed heating (i.e., with heat coming from the deep mantle heating and the asthenosphere) and with mantle convection in the whole mantle, show no significant spatial variations in the surface heat flux, just as suggested for a magma ocean (de Kleer et al. 2019). Significant lateral variations in the interior, which could also be recognizable at the surface, remain for an asthenospheric heating endmember (FIG. 3B) with a separate convection system in the asthenosphere.

As previously explained, the amount and distribution of tidal heating depends on the viscosity and, therefore, on the temperature and melt distribution. The question arises as to how a tidally induced heterogenous viscosity distribution in Io's asthenosphere would affect the distribution of tidal heating. The feedback between rheology-dependent, non-uniform tidal heating and tidal-heating-dependent rheology explored by Běhounková et al. (2021) for Europa revealed small to moderate effects, with enhancement of melt production at high latitudes. However, these results cannot be directly applied to Io's thin (~100 km) asthenosphere with likely large melt fraction variations. Incorporating a tidally induced heterogenous melt distribution in the asthenosphere (Steinke et al. 2019) leads to differences in the heating pattern compared with the pattern shown in FIGURE 3B. Besides the effect of increased tidal heating in regions with increased melt fraction, an asymmetry in the tidal dissipation pattern with respect to the line connecting Io and Jupiter is induced, similar to the asymmetry resulting from dissipation in a magma ocean (FIG. 3C).

TIDAL HEATING EFFECTS ON THE LITHOSPHERIC THICKNESS

It is generally assumed that areas with greater tidal heating will result in greater melt production. How these spatial variations affect other surface characteristics like topography is, however, not as obvious. This is partly because Io is unique, in that the primary way it transports heat in the near-surface is neither via conduction nor convection, but by *advection*: hot magma ascends to the surface, where it cools to space. This "heat-pipe" mechanism was first described by O'Reilly and Davies (1981) and allows Io to rid itself of large amounts of heat while still maintaining a cold upper layer—the lithosphere (Keszthelyi et al. 2022 this issue). This lithosphere is probably tens of kilometers thick, based on the existence of large mountains on Io.

How the lithospheric thickness depends on the tidal heating beneath is not clear. Spencer et al. (2021) developed a model for Io heat transport in which porous flow in the deeper interior gives way to macroscopic flow (e.g., through dikes) in the lithosphere. In this model, some fraction of the melt does not reach the surface but is intruded into the lithosphere, modifying its temperature structure. If the intrusion rate is independent of the total rate of melt production, then higher tidal heating rates produce a locally thicker lithosphere (FIG. 4A). Conversely, if the intrusion rate scales with the total melt production rate, the lithospheric thickness stays constant (FIG. 4B).

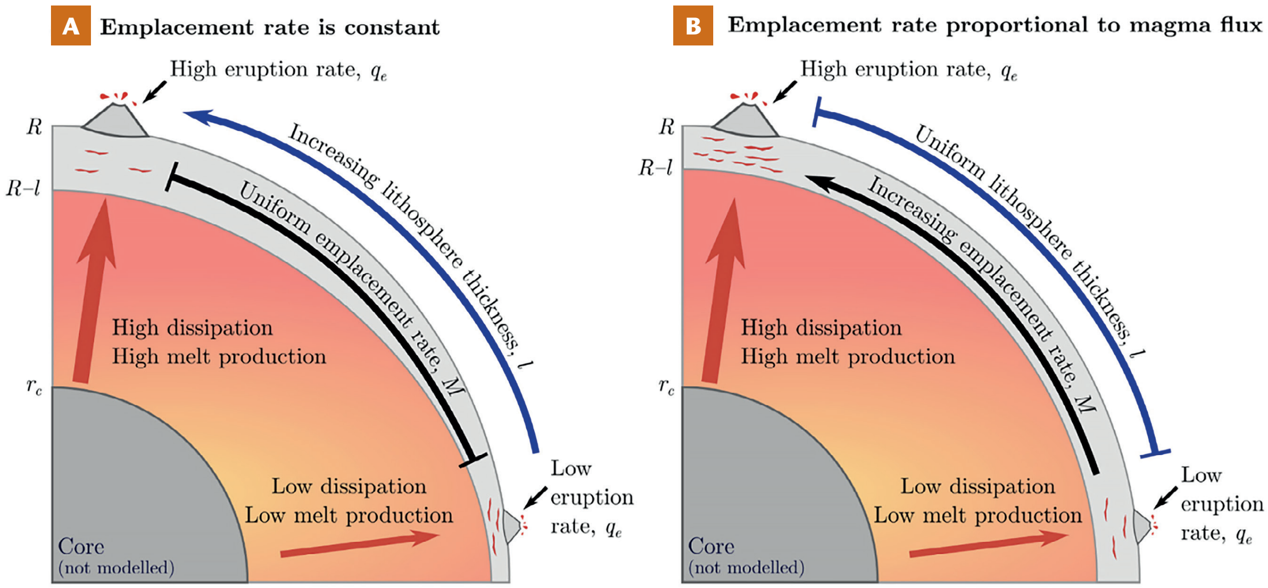

FIGURE 4 Depiction of how the lithospheric thickness depends on tidal heating beneath two endmember models of magmatic intrusion: (**A**) constant intrusion rate and (**B**) intrusion rate proportional to the melt production rate. FROM SPENCER ET AL. (2021).

If there are lithospheric thickness variations, they will lead to topographic variations. The lithosphere, being dense, will produce small (~0.1 km) depressions where it is thickest. However, this is assuming that there is no compositional difference between the lithosphere and the underlying mantle. In reality, lower melting temperature materials will likely be concentrated in the near-surface. Because such materials tend to also be low density, the lithosphere may be compositionally distinct from, and less dense than, the mantle. In that case, areas of thicker lithosphere would give rise to elevated regions; because compositional density variations can be much larger than thermally induced variations, the amplitude of the resulting topography is expected to be larger. Although the available topographic data (White et al. 2014) are imperfect, they suggest long-wavelength swells having an amplitude of ~1 km. In the Spencer et al. (2021) model, these larger amplitudes would suggest a lithosphere that is compositionally distinct from the mantle beneath.

SUMMARY

Io provides an ideal laboratory for studying tidal heating, which is a fundamental process in the Solar System and beyond. Recent tidal heating models address the effects of more complicated deformation models, a subsurface magma ocean, large melt fractions in the asthenosphere, mantle convection, and feedbacks between tidal heating and the interior structure. However, these models are ultimately limited by the lack of experimental data constraining the anelastic behavior of likely materials composing Io under realistic conditions. In particular, the response to forcing with stress amplitudes similar to those of tidal forcing and the effects of partial melt are not well characterized.

ACKNOWLEDGMENTS

We thank Marc Rovira-Navarro, Gabriel Tobie, and an anonymous reviewer for their thorough and constructive reviews.

REFERENCES

Běhounková M and 6 coauthors (2021). Tidally induced magmatic pulses on the oceanic floor of Jupiter's moon Europa. Geophysical Research Letters 48: e2020GL090077, doi: 10.1029/2020GL090077

Bierson CJ, Nimmo F (2016) A test for Io's magma ocean: modeling tidal dissipation with a partially molten mantle. Journal of Geophysical Research: Planets 121: 2211–2224, doi: 10.1002/2016je005005

Breuer D, Hamilton CW, Khurana K (2022) The internal structure of Io. Elements 18: 385-390

Davies AG, Vorburger AH (2022) Io's volcanic activity and atmosphere. Elements 18: 379-384

de Kleer K and 35 coauthors (2019) Tidal heating: lessons from Io and the Jovian system. Final Report for the Keck Institute of Space Studies. Lead PIs: de Kleer K, Park R, McEwen A, pdf: www.kiss.caltech.edu/final_reports/Tidal_Heating_final_report.pdf

Egbert GD, Ray RD (2001) Estimates of M_2 tidal energy dissipation from TOPEX/Poseidon altimeter data. Journal of Geophysical Research: Oceans 106: 22475-22502, doi: 10.1029/2000jc000699

Hamilton CW and 7 coauthors (2013) Spatial distribution of volcanoes on Io: implications for tidal heating and magma ascent. Earth and Planetary Science Letters 361: 272-286, doi: 10.1016/j.epsl.2012.10.032

Jackson I, Faul UH (2010) Grainsize-sensitive viscoelastic relaxation in olivine: towards a robust laboratory-based model for seismological application. Physics of the Earth and Planetary Interiors 183: 151-163, doi: 10.1016/j.pepi.2010.09.005

Karato S-I, Wu P (1993). Rheology of the upper mantle: a synthesis. Science 260: 771-778, doi: 10.1126/science.260.5109.771

Kervazo M, Tobie G, Choblet G, Dumoulin C, Běhounková M (2022). Inferring Io's interior from tidal monitoring. Icarus 373: 114737, doi: 10.1016/j.icarus.2021.114737

Keszthelyi LP, Jaeger WL, Radebaugh J (2022) The cycles driving Io's tectonics. Elements 18: 393-398

Khurana KK and 5 coauthors (2011) Evidence of a global magma ocean in Io's interior. Science 332: 1186-1189, doi: 10.1126/science.1201425

Matsuyama I, Beuthe M, Hay HCFC, Nimmo F, Kamata S (2018) Ocean tidal heating in icy satellites with solid shells. Icarus 312: 208-230, doi: 10.1016/j.icarus.2018.04.013

Moore WB, Schubert G, Anderson JD, Spencer JR (2007) The interior of Io. In: Lopes RMC, Spencer JR (eds) Io after Galileo: A New View of Jupiter's Volcanic Moon. Springer Berlin, Heidelberg, pp 89-108, doi: 10.1007/978-3-540-48841-5_5

Munk W (1997) Once again: once again—tidal friction. Progress in Oceanography 40: 7-35, doi: 10.1016/S0079-6611(97)00021-9

O'Reilly TC, Davies GF (1981) Magma transport of heat on Io: a mechanism allowing a thick lithosphere. Geophysical Research Letters 8: 313-316, doi: 10.1029/GL008i004p00313

Peale SJ, Cassen P, Reynolds RT (1979) Melting of Io by tidal dissipation. Science 203: 892-894, doi: 10.1126/science.203.4383.892

Ross MN, Schubert G (1985) Tidally forced viscous heating in a partially molten Io. Icarus 64: 391-400, doi: 10.1016/0019-1035(85)90063-6

Rovira-Navarro M, van der Wal W, Katz RF, Liao Y, Nimmo F (2022) The tides of Enceladus' porous core. Journal of Geophysical Research: Planets 127: e2021JE007117, doi: 10.1029/2021JE007117

Rovira-Navarro M, van der Wal W, Steinke T, Dirkx D (2021) Tidally heated exomoons around gas giants. The Planetary Science Journal 2: 119, doi: 10.3847/psj/abf6cb

Segatz M, Spohn T, Ross MN, Schubert G (1988) Tidal dissipation, surface heat flow, and figure of viscoelastic models of Io. Icarus 75: 187-206, doi: 10.1016/0019-1035(88)90001-2

Spencer DC, Katz RF, Hewitt IJ (2021) Tidal controls on the lithospheric thickness and topography of Io from magmatic segregation and volcanism modelling. Icarus 359: 114352, doi: 10.1016/j.icarus.2021.114352

Steinke T, Hu H, Höning D, van der Wal W, Vermeersen B (2020) Tidally induced lateral variations of Io's interior. Icarus 33: 113299, doi: 10.1016/j.icarus.2019.05.001

Steinke T, van der Wal W, Vermeersen BL (2019) Modelling the feedback of Io's tidally induced heterogeneous interior on tidal dissipation. In: AGU Fall Meeting Abstracts 2019: P51A-07

Tackley PJ (2001) Convection in Io's asthenosphere: redistribution of nonuniform tidal heating by mean flows. Journal of Geophysical Research: Solid Earth 106: 32971-32981, doi: 10.1029/2000je001411

Tobie G, Mocquet A, Sotin C (2005) Tidal dissipation within large icy satellites: applications to Europa and Titan. Icarus 177: 534-549, doi: 10.1016/j.icarus.2005.04.006

Tyler RH, Henning WG, Hamilton CW (2015) Tidal heating in a magma ocean within Jupiter's moon Io. The Astrophysical Journal Supplement Series 218: 22, doi: 10.1088/0067-0049/218/2/22

Veeder GJ and 5 coauthors (2015) Io: heat flow from small volcanic features. Icarus 245, 379-410, doi: 10.1016/j.icarus.2014.07.028

White OL, Schenk PM, Nimmo F, Hoogenboom TA (2014) A new stereo topographic map of Io: implications for geology from global to local scales. Journal of Geophysical Research: Planets 119: 1276-1301, doi: 10.1002/2013JE004591

Zschau J (1978) Tidal friction in the solid earth: loading tides versus body tides. In: Brosche P, Sündermann J (eds) Tidal Friction and the Earth's Rotation. Springer Berlin, Heidelberg, pp 62-94, doi: 10.1007/978-3-662-40203-0_7 ■