TIDAL HEATING: LESSONS FROM IO AND THE JOVIAN SYSTEM (REPORT FROM THE KISS WORKSHOP). R.S. Park[1], K. de Kleer[2], A. McEwen[3], C.J. Bierson[4], A.G. Davies[1], D. DellaGiustina[3], A.I. Ermakov[1], J. Fuller[2], C. Hamilton[3], C. Harris[5], H. Hay[3], R.A. Jacobson[1], J. Keane[2], L. Kestay[6], K. Khurana[7], K. Kirby[8], V. Lainey[1], I. Matsuyama[3], C. McCarthy[9], F. Nimmo[4], M. Panning[1], A. Pommier[10], J. Rathbun[11], G. Steinbrügge[12], D. Stevenson[2], V.C. Tsai[2], and E. Turtle[8], [1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109 (Ryan.S.Park@jpl.caltech.edu); [2]California Institute of Technology, Pasadena, CA 91125; [3]University of Arizona, Tucson, AZ, 58721; [4]University of California – Santa Cruz, Santa Cruz, CA 95064; [5]University of Michigan, Ann Arbor, MI 48109; [6]US Geological Survey, Flagstaff, AZ, 86001; [7]University of California – Los Angeles, CA 90095; [8]Applied Physics Laboratory, Johns Hopkins University, Laurel, MD 20723; [9]Columbia University, Palisades, NY 10964; [10]University of California – San Diego, La Jolla, CA 92093; [11]Planetary Science Institute; [12]University of Texas at Austin, Austin, TX 78705,

Introduction: The evolution of the interior of planets and satellites, as well as their potential habitability, are central questions in Planetary Sciences. Recent discoveries from spacecraft missions and telescopic programs have illuminated the central role that tidal heating plays in the evolution of many worlds across our Solar System and beyond. This fundamental process drives the orbital evolution of star–planet or planet–satellite systems as a whole, and shapes the surface environments and geological activity of planetary bodies, impacting the habitability of ocean worlds such as Europa and Enceladus. However, despite its broad ranging importance, there remain fundamental gaps in our understanding of tidal heating and coupled orbital evolution. For example: Where and how is tidal heat actually dissipated? How do we link physical measurements in the laboratory on crust and mantle analogues to planetary-scale observations of deformation or heat flow? How are subsurface oceans created and maintained?

While there are well-tested tools in place to study a variety of individual planetary processes, there is no established path forward for unraveling the interconnected roles of tidal heating and orbital evolution. Such investigations will require innovative approaches and new technologies that can pin down the orbital evolution and deformation of these worlds by integrating laboratory work, spacecraft and ground-based observations, and numerical models. To address pathways to these questions the Keck Institute for Space Studies (KISS) workshop entitled "Tidal Heating: Lessons from Io and the Jovian System" was held October 15–19, 2018. The central objective of this workshop was to integrate the numerous recent advances across the relevant fields, including laboratory studies, telescopic/spacecraft data, and instrumentation under development, to construct a coherent path forward for understanding tidal heating and its influence on the evolution of planetary systems. The combination of recent scientific advances as well as the forthcoming *Europa Clipper* and J*Upiter ICy moons Explorer* (*JUICE*) missions, the formation of the NASA Ocean Worlds program, potential New Frontiers-class missions to tidally heated worlds (*e.g.*, Io, Enceladus, and Titan) and potential ocean world landers and penetrators make it clear that now is a critical time for integrating what we know, identifying what we do not know, and creating a clear roadmap for the future science investigations/technologies that will be needed to optimize efforts in the coming decades.

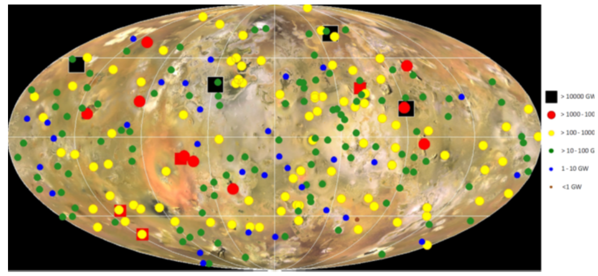

Figure 1: Thermal emission from Io's volcanoes. This Mollweide equal-area plot centered on 180 W longitude shows 250 active or recently active volcanoes that show measurable thermal emission, with the size and color of the symbol reflecting the magnitude of their heat flow contributions. The plot includes the locations of outburst eruptions at Surt, Tvashtar, Amirani, Pillan, Gish Bar Patera, Heno Patera, Rarog Patera and 201308C. Because of their transient nature outbursts are shown as black or red squares. From Davies et al. (2015) [1], using data from Veeder et al. (2012; 2015) [2-3].

Five Key Questions about Tidal Heating: We identified five key questions to drive future research and exploration:

Q1: What do volcanic eruptions tell us about the interiors of tidally heated bodies? Volcanism provides information about interiors that are otherwise inaccessible, as well as evidence that there is sufficient internal energy to melt the interior (see Fig. 1). When combined with laboratory experiments under controlled pressure and temperature, eruptive products can constrain temperature and pressure with depth. Measurements of eruptive temperature, heat flow, and eruptive style are greatly desired to distinguish between compositions.

Q2: How is tidal dissipation partitioned between solid and liquid materials? Io's intense volcanism is a clear sign of tidal dissipation but where the dissipation occurs is still up for debate. If dissipation concentrates in the deep mantle, tidal heating would preferentially occur at the poles. If dissipation instead concentrates in the asthenosphere, tidal heating would occur at low latitudes, with minima at the poles. Laboratory and modeling efforts are needed to better interpret the observations, particularly in consideration of possible end-

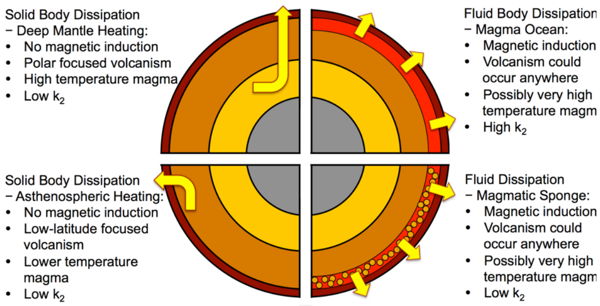

Figure 2: Illustration of the structure of Io's interior, with arbitrary layer thicknesses, considering end-member tidal dissipation scenarios within a solid interior (left panels) versus how dissipation processes would be affected by either a magma ocean, or globally extensive high-partial melt layer (*i.e.*, a magmatic sponge). Adapted from Hamilton et al. (2018) [4].

member tidal dissipation scenarios within a solid interior vs. dissipation affected by a global melt layer or interconnected melt phase (see Fig. 2).

<u>Q3: Does Io have a melt-rich layer, or "magma ocean", that mechanically decouples the lithosphere from the deep interior?</u> Images of Io from *Voyager* and *Galileo* clearly show distributed and extensive volcanism that is likely driven by tidal heating. However, to understand the dynamics, it is important to know if the melt is interconnected or if it is presented as isolated pockets. A tool to probe melt in the interior would be via magnetic induction. A magma ocean beneath Io's surface can be modeled as a conducting layer. The natural time variation in Jupiter's magnetic field induces eddy currents in this layer, producing an observable secondary magnetic field. The depth, thickness, and electrical conductivity of Io's magma ocean can be constrained by inverting the secondary magnetic field measured by satellite magnetometers [5]. Electrical laboratory measurements can be used to interpret the field signals in terms of melt fraction [6].

<u>Q4: Is the Jupiter/Laplace System in equilibrium?</u> The Io–Europa–Ganymede system is a complex and delicately built tidal engine that powers Io's extreme volcanism and warms water oceans in Europa. Io's gravity generates a tidal bulge within Jupiter, whose dissipation transfers some of Jupiter's rotational energy into Io's orbit, moving it outwards and deeper into a 2:1 eccentricity resonance with Europa. This increases Io's eccentricity, resulting in enhanced tidal heating. Ultimately, Jupiter's rotational energy is converted into a combination of gravitational potential energy and heat via dissipation in both Jupiter and the satellites. Two possible resonance scenarios have been proposed: one in which total heat produced is constant and one with heat production varying around a long-term equilibrium, with eccentricities also varying. These questions can be answered by measuring how orbits are changing, measuring heat flow, and understanding isotope geochemistry for long-term evolution.

<u>Q5: Can stable isotopes inform long-term evolution?</u> A major obstacle to our understanding of tidal heating is our almost complete lack of knowledge about the long-term evolution of tidally-heated systems in the Solar System. The questions of whether these satellites are currently in equilibrium, what their orbital and tidal energy dissipation histories have been over their lifetimes, and how long they have been geologically active are all central to interpreting current signatures, yet are areas of major uncertainties and debate [7]. An intrinsic difficulty in determining the long-term history of tidally-heated worlds is that their tidally-powered geological activity rapidly resurfaces them and alters visible signatures. Isotope ratios, which are insensitive to many of these alteration processes and hence preserve long-term records of processes, provide a potential window into these otherwise-inaccessible periods of these objects' histories.

Avenues for Progress: The most promising avenues to address these questions include a new spacecraft mission making close flybys of Io, missions orbiting and landing on ocean worlds such as Europa and Enceladus, technology developments to enable advanced techniques, closer coupling between laboratory experiments and tidal heating theory, and advances in Earth-based telescopic observations, especially for exoplanets. An Io mission should: characterize volcanic processes to measure passive heat flow and/or high-spatial-resolution broad-wavelength-coverage by infrared cameras on spacecraft (Q1); test interior models via a set of geophysical measurements coupled with laboratory experiments and theory (Q2 and Q3); measure the total heat flow from Io as well as the rate of Io's orbital migration (*i.e.,* to complement similar measurements expected at Europa and Ganymede) to measure the total energy production of the Jovian system (Q4); and measure stable isotopes in Io's atmosphere and plumes (Q5). No new technologies are required for such an Io mission following advances in radiation design and solar power realized for *Europa Clipper* and *JUICE*. In the longer-term, seismology is a promising avenue for future exploration, and interferometric synthetic aperture radar could be revolutionary, but requires advanced power systems and lower mass for future Solar System operations.

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