TIDAL HEATING: LESSONS FROM IO AND THE JOVIAN SYSTEM (REPORT FROM THE KISS WORKSHOP). H. Hay[1], K. de Kleer[2], A. McEwen[1], R.S. Park[3], C.J. Bierson[4], A.G. Davies[3], D. DellaGiustina[1], A.I. Ermakov[3], J. Fuller[2], C. Hamilton[1], C. Harris[5], R.A. Jacobson[3], 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[3], A. Pommier[10], J. Rathbun[11], G. Steinbrügge[12], D. Stevenson[2], V.C. Tsai[2], and E. Turtle[8], [3]University of Arizona, Tucson, AZ, 85721 (hhay@lpl.arizona.edu); [2]California Institute of Technology, Pasadena, CA 91125; [3]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109; [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: Recent spacecraft missions and telescopic programs have illuminated the role of tidal heating in the evolution of many worlds across our Solar System and beyond. Tidal dissipation can control how and where energy is transferred between the icy and liquid-water regions of ocean worlds, directly impacting their habitability. This fundamental process also drives the orbital evolution of these bodies. Despite its broad ranging importance, there remain fundamental gaps in our understanding of tidal heating and coupled orbital evolution. To address this, the Keck Institute for Space Studies (KISS) workshop "Tidal Heating: Lessons from Io and the Jovian System" was held in late 2018. The objective of the workshop was to integrate recent advances in laboratory studies, telescopic/spacecraft data, and instrumentation under development, to construct a path forward for understanding tidal heating as a physical process and its influence on the evolution of planetary systems.

Four Key Questions about Tidal Heating: We identified four key questions about tidal heating relevant to water-ice ocean worlds to drive future research:

<u>Q1: What do (cryo)volcanic eruptions tell us about the interiors of tidally heated bodies?</u> Volcanism provides information about interiors that are otherwise inaccessible. Combined with laboratory experiments, observations of cryovolcanic activity can help constrain temperature and pressure with depth. This information can then further inform rheological models which are vital in tidal heating calculations.

<u>Q2: How is tidal dissipation partitioned between solid and liquid materials?</u> The three-dimensional distribution of tidal heating can control the evolution of ice thickness in the ice shell and mantle through melting/freezing. This may impact the dynamical and chemical behavior of the ocean through the introduction of gradients in temperature and salinity. Measuring passive heat flow allows us to identify where most tidal heating occurs as each interior layer produces a unique heating pattern. Tidal deformation of the ice shell causes heating at high latitudes, while the mantle focuses heating towards the equator [1, 2]. In contrast, ocean tide dissipation produces significantly different patterns of heat flow than that in the solid regions [3].

<u>Q3: Is the Jupiter/Laplace System in equilibrium?</u> Tidal heating in the Io–Europa–Ganymede system is exquisitely coupled and driven by the Laplace resonance. The resonance excites the moons' eccentricities, while tidal heating circularizes the orbits. In order to understand the long-term evolution of any of the moons, we must therefore investigate each of them. By measuring how their orbits expand, their surface heat flow, and their isotope geochemistry, we can further understand the long-term evolution of these moons.

<u>Q4: Can stable isotopes inform long-term evolution?</u> 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 the otherwise-inaccessible periods of these objects' histories.

Avenues for Progress: The most promising avenues to address these questions include a mission with close flybys of Io (where the signatures of tidal heating are the strongest), missions orbiting and landing on ocean worlds such as Europa and Enceladus, closer coupling between laboratory experiments and tidal heating theory, and advances in Earth-based telescopic observations. Future missions should measure passive heat flow using broad-wavelength infrared cameras (Q1, Q2); test interior models via geophysical measurements, laboratory experiments, and theory (Q2); measure the orbital migration of Io, Europa, and Ganymede, to determine if the Laplace resonance is in equilibrium (Q3); and measure stable isotopes in atmospheres and plumes (Q4).

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