Recent advances in magnetic induction from asymmetric ocean worlds. Marshall J. Styczinski[1], Steven D. Vance[2], Corey J. Cochrane[2], and Erika M. Harnett[1]. [1]University of Washington, Seattle (mjstyczi@uw.edu), [2]Jet Propulsion Laboratory, California Institute of Technology

Introduction: Magnetic induction sounding provides the primary evidence for a present-day subsurface ocean in Europa, and possibly also in Callisto [1, 2]. Additional magnetic field measurements by the *Europa Clipper, JUICE,* and *Juno* missions might be able not only to confirm the presence of oceans in Jupiter's large icy moons, but also determine the ocean thickness and salinity, through close flybys sampling the range of orbital position and System III longitude. Such experiments to analyze the symmetric dipolar induction response might also be able to infer the radial conductivity, thus aiding in efforts to understand the ocean thermal and compositional evolution [3, 4]. In addition to the symmetric response, an asymmetric component may also exist, due to the triaxial shape of the moons which implies non-uniform ice thickness [5], or due to non-uniform tidal heating [6]. At Callisto, asymmetry in the ionosphere presents a particular problem, confounding the interpretation of the induction signal [7].

Magnetic induction might also be applied to the large moons of Uranus and Neptune, where dipole and quadrupole variations in the planetary magnetic fields provide multiple excitation frequencies sampling a range of depth-dependent amplitude and phase responses [8, 9]. However, in these moons, lessons from detailed reconnaissance of Enceladus suggests a possibly more important role of asymmetry; the moon's surface geology, librational heating [10], and gravity and topography measurements from *Cassini* indicate strong lateral variations in ice thickness from $5{-}35\,\mathrm{km}$ [11, 12]. The heavily modified uranian moon Miranda is similarly sized to Enceladus, and both moons may have undergone a similar orbital evolution that caused them to pass through strong resonances that caused internal tidal heating [13, 14]. Owing to this heating, extant oceans within the uranian moons may persist to the present day. Future missions to the Uranus system must account for asymmetry in detecting oceans through magnetic sounding, as departure from spherical symmetry can confuse or mask signals that may be measured by a magnetometer [15]. Until now, it has not been possible to assess the impact of asymmetric structures on the induced magnetic field.

Effects of asymmetry: Induced magnetic fields result from flow of electric currents in conducting material in response to a magnetic field, in accordance with Maxwell's laws. The shape of the conducting material affects where currents can flow, thereby affecting the spatial structure of the induced magnetic field. For example, magnetic moments observed by a spacecraft passing near a moon with an asymmetric ice–ocean boundary like the one in Fig. 1 will appear stronger near the equator and weaker near the poles than would be observed with a spherically symmetric boundary with $r(\theta,\phi)=a$.

A Taylor expansion of boundary shapes in terms of spherical harmonics yields the solution. The induced magnetic moments B^i_{nm} for degree n and order m induced from a moon can be summarized as

$$B^i_{nm} \sim B^e_{nm}\mathcal{A}^e_{nm} + \frac{\varepsilon}{R}\mathcal{A}^\star_{nm}\sum_{n',m'}\Xi^{nm}_{n'm'}B^e_{n'm'}, \quad (1)$$

where B^e_{nm} are the excitation moments applied by the parent planet, $\mathcal{A}$ are complex amplitudes asymptotic to $(1+0i)$ for a perfectly conducting ocean, ε is the maximum deviation from spherical symmetry for the outer conducting boundary of radius R, and Ξ is a mixing coefficient constructed from Clebsch–Gordan coefficients. The exact form of Eq. 1 for arbitrary conducting oceans is the subject of a manuscript in preparation.

The spherically symmetric version of Eq. 1 is recovered by setting $\varepsilon=0$. In that case, $B^i_{nm}=B^e_{nm}\mathcal{A}^e_{nm}$. Of special note, the $\Xi^{nm}_{n'm'}B^e_{n'm'}$ terms link each excitation moment to induced moments of differing n and m. The strength of this coupling depends on the precise shape of the boundary (which impacts Ξ) and the overall departure from spherical symmetry ε. The farther from symmetric, the stronger the signal.

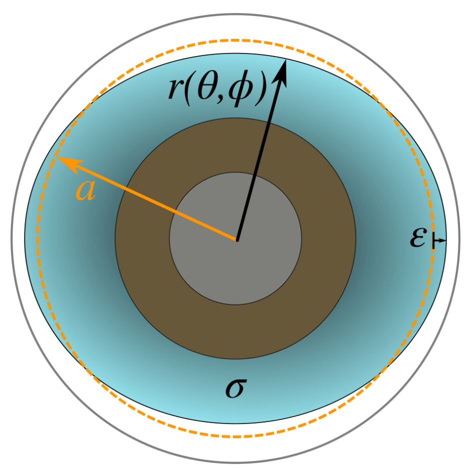

Figure 1: Cross-sectional diagram indicating a non-spherical ice–ocean boundary $r(\theta,\phi)$. The mean radius of the boundary is a, indicated by the dashed circle. The induced field will appear stronger near the equator and weaker near the poles than for an ocean with $r(\theta,\phi)=a$.

Consequences on induction: ε/R for the ice–ocean boundary of Enceladus is about 0.078 [12], implying the modification to the spherically symmetric signal for a body with similar asymmetry may be as much as 7%. The similarities between Enceladus and Miranda encourage comparison. Indeed, there is evidence to suggest that tidal heating concentrated in the ice shell of Enceladus-sized bodies may be expected to result in pronounced lateral asymmetry [16]. Uranus hosts a complicated intrinsic field [17], with high-degree moments and a large inclination relative to its rotation axis. Miranda and the other large moons orbit close to the uranian equator, so they see large magnetic oscillations—of order $300\,\mathrm{nT}$ for Miranda at its synodic period with Uranus [9]. If Miranda is home to a dramatic asymmetry in its subsurface ocean akin to that of Enceladus, efforts to detect an ocean there through a magnetic investigation may be thwarted or supported by modeling the effect of that asymmetry on the induced magnetic field. The strength of asymmetric effects may be as much as $23\,\mathrm{nT}$ at the surface, and the effect on magnetic measurements at altitude may be further enhanced due to phase rotation by the complex nature of the induction amplitudes $\mathcal{A}^e$ and $\mathcal{A}^\star$.

Until recently [15], all prior work investigating the interior structure of ocean worlds through magnetic induction has assumed each layer is spherically symmetric. It is also customary to assume the excitation field is uniform across the body, which is reasonable as most moons are small compared to the distance scales of variation in magnetic fields of the giant planets. The primary consequences of these assumptions are that the induced field of the moon is purely dipolar, and degenerate with conductivity and thickness of the ocean [18, 19]. Under these assumptions, spacecraft data are typically analyzed by a least-squares fit to a dipole moment. Oscillating quadrupole and higher moments will skew fitted results based on flyby geometry, orbital and true anomaly conditions, and the interior model considered. These are effects we are working to quantify in ongoing investigations. Past studies have also typically supposed the phase delay is not resolvable [e.g. 2, 18], producing physically inconsistent results. A full consideration of the known geophysical relationships can reduce uncertainty in the calculated results, offering the potential for better understanding and constraining interior structure models [4]. Including asymmetric effects through the products of this work supports a better quantification of our uncertainty.

Other applications: There are a number of promising avenues for enhancing magnetic sounding investigations by including the effects of asymmetry. Callisto is observed to have an induced magnetic field [2], but past studies have been unable to conclusively determine whether a liquid ocean is responsible, or if the observed signals are consistent with an ionosphere alone [7, 20]. Because the ionosphere is closer to a spacecraft at altitude, and there is an expected day–night asymmetry in the ionospheric conductance at Callisto [21], a strongly conducting ionosphere that would be necessary to explain the observed signals should also exhibit characteristics of marked asymmetry. In contrast, asymmetry in a strongly conducting subsurface ocean would be less pronounced, because self-gravity will smooth out the variations somewhat and because the quadrupole-and-higher magnetic moments will decay more rapidly with distance. Modeling possible asymmetry in the Callisto ionosphere therefore provides an opportunity to settle the question of whether there is a conducting ocean present.

Statistical methods are an implicit requirement to considering the wide parameter space of asymmetric structures within ocean moons. Many sources of asymmetry are expected, and these can be used to narrow the set of interior models to consider, but more powerful constraints may be obtained through Bayesian inference. In future work, we intend to study the effects each of these considerations has on magnetic sounding investigations.

Acknowledgments: This work was supported by NASA Headquarters under the NASA Earth and Space Science Fellowship Program - Grant 80NSSC18K1236.

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