REVEALING THE INTERNAL STRUCTURE OF EUROPA WITH A BAYESIAN APPROACH TO MAGNETIC INDUCTION STUDIES.

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Introduction: Over the past three decades, spacecraft exploration has revealed that many planetary bodies in the outer solar system possess large subsurface reservoirs of liquid water [1]. Determining the composition, evolution, and habitability of these ocean worlds is a key goal of upcoming missions [2]. Observations of induced magnetic fields by a spacecraft magnetometer provide a powerful probe into the interior of these bodies, allowing for the detection and characterization of their subsurface oceans. Here, we present a new Bayesian approach for inverting magnetic measurements to determine the internal structures of planetary bodies. This approach has the advantages of (1) providing robust confidence intervals for retrieved parameters; (2) incorporating *a priori* constraints, enabling quantitative incorporation of physical constraints and complementary datasets; and (3) quantifying degeneracies between model parameters such that the estimates for model parameters include the non-uniqueness of the solution. We demonstrate how this technique can be used to estimate the ability of the Europa Clipper Magnetometer (ECM) to constrain the thickness of Europa's ice shell and the thickness and conductivity of its ocean.

Magnetic Induction at Europa: Jupiter's rotation and the orbital motion of Europa result in a time-varying magnetic field at Europa. In a conductor, such as a saltwater ocean, these fields generate eddy currents, which in turn produce a secondary magnetic field. The largest amplitude oscillation is caused by the ~10° tilt of the Jovian dipole axis relative to Jupiter's rotation axis, resulting in ~200 nT variation at the ~11.2 hr synodic period. The Galileo mission's detection of an induced response at this period revealed the presence of Europa's subsurface ocean [3, 4]. However, measurement of the induction response at a single frequency alone cannot produce a unique solution for Europa's interior [e.g., 5].

Jupiter's quadrupole moment as well as Europa's orbital eccentricity, inclination, and precession produce additional magnetic oscillations that are sufficiently large to yield detectable induction responses [e.g., 6] (Fig. 1). A key goal of ECM is to measure these induced fields with the precision necessary to break degeneracies in the interior model, yielding constraints on Europa's ice shell thickness, ocean thickness, and ocean conductivity. Using a Bayesian approach, we assess ECM's ability to meet these objectives for a range of plausible Europan interiors.

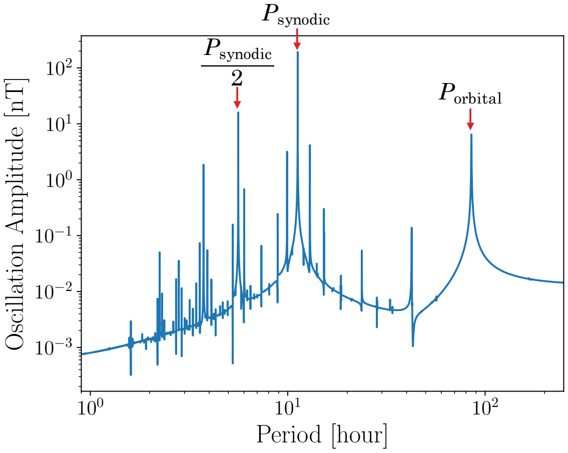

Fig. 1. Spectrum of time-varying Jovian field at Europa determined from a Jovian magnetosphere model [10] and JPL ephemerides. Magnetic oscillations at the synodic period, its second harmonic, and the orbital period may all produce detectable induced fields.

Inferring Europa's Interior Structure: In Bayesian inference, retrieval model parameters are described by probability distributions. An initial (prior) probability distribution describes our belief about the values of model parameters. New observations are then combined with the prior to generate a new (posterior) distribution (Fig. 2). We sample the posterior using Markov Chain Monte Carlo (MCMC) methods, which can efficiently explore the model parameter space, evaluating how well a given choice of retrieval model parameters matches the observations [7, 8]. Our retrieval model has three components. The local Jovian field is modeled as a constant field plus seven oscillating components at the highest amplitude frequencies found in Fig. 1. We adopt a spherically symmetric three-layer internal structure model for Europa: a non-conducting rock and iron core, a conductive liquid water layer, and an outer non-conducting ice shell [9]. In conjunction with the Jovian field model, this interior model is used to calculate the induced magnetic field at the seven driving frequencies. Finally, we include a model of sensor jitter and offsets.

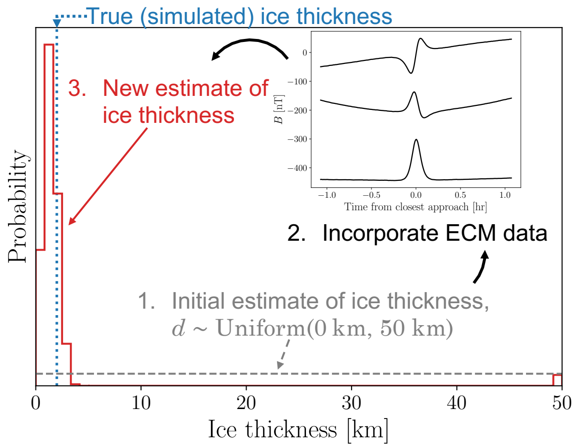

Fig. 2. Illustration of Bayesian inference. A broad initial estimate of the ice thickness (gray) is updated with simulated ECM data (black), resulting in a new probability distribution of ice shell thickness (red). The retrieved ice shell thickness distribution captures the value used to generate the simulated ECM data (blue dashed line).

Evaluation of ECM. To estimate the performance of ECM, we generated synthetic datasets for a range of plausible Europan interiors and then employed the Bayesian approach described above. The synthetic datasets were generated using a high-fidelity model that is distinct from the retrieval model used in inversion. The local field model used in retrieval was replaced with a model of the Jovian magnetosphere [10]. The induction response was calculated for ~10^4 frequencies assuming a three-layer model of Europa's interior [9]. Finally, we used a detailed sensor and spacecraft noise model which includes multiple systematic noise sources.

We considered six possible Europan interiors, with ice thicknesses of 2–30 km, ocean thicknesses of 50–168 km, and conductivities of 0.1–28 S m^{-1}. We considered an inversion successful if the true value of a parameter falls within the 95% confidence interval of the retrieved distribution, marginal if it is not but is within the 99.7% interval, and unsuccessful otherwise. In all scenarios, we found that the synthetic ECM data are sufficient to recover the ocean conductivity, ocean thickness, and ice shell thickness within at least the 99.7% interval, with thicker and more conductive oceans producing more accurate retrievals (Fig. 3). We note that these results assume that magnetic perturbations produced by moon-plasma interaction can be removed with the help of magnetohydrodynamic (MHD) simulation. Work on the effect of incomplete removal of these plasma effects is ongoing.

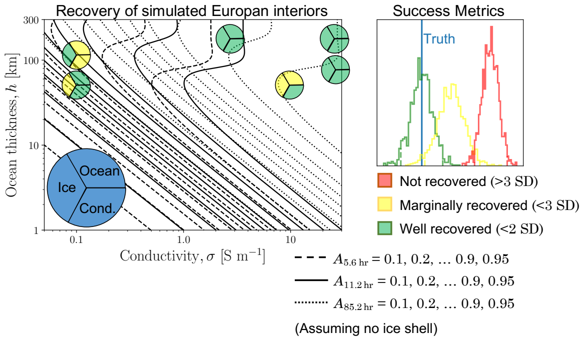

Fig. 3. Evaluation of Bayesian inversion technique on simulated ECM data for six possible Europan interiors. Left: A pie chart for each scenario considered is plotted in ocean thickness and ocean conductivity space. Pie charts indicate whether the ice thickness, ocean thickness, and ocean conductivity were successfully recovered for that scenario. Black contour lines show efficiency of the induction response ($B_{\mathrm{induced}}/B_{\mathrm{driving}}$) at three key periods (5.6 hr, 11.2 hr, and 85.2 hr) for reference. Right: Metrics for recovery evaluation.

Revisiting Galileo. We also apply our approach to archival data from the Galileo mission. We performed preliminary inversions using data from the E4, E14, E15, and E26 flybys with moon-plasma interaction fields removed from the E4 and E15 flybys using MHD simulations. The initial results are consistent with prior analyses [e.g., 5, 9] and are the subject of ongoing work.

Conclusions: We have developed a technique for characterizing the interiors of icy moons using magnetic induction and Bayesian inference. By applying this technique to synthetic ECM data, we find that ECM should usefully constrain Europa's ice shell thickness, ocean thickness, and ocean conductivity. These properties in turn constrain the composition of the ocean and the flux of chemical energy available for biology, key parameters for assessing Europa's habitability [11]. Finally, our approach also shows promise for extracting new insight from the Galileo data and for use in future missions to other possible ocean worlds [e.g., 12].

Acknowledgments: This work was supported by NASA through the Europa Clipper Project.

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