Magnetic field induced by convective flow in Europa's subsurface ocean

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SUMMARY

The electromagnetic (EM) methods played a crucial role in detecting the subsurface oceans in the interior of Europa, Callisto, and Ganymede. On Europa, the time-varying primary magnetic field generated by Jupiter induces a secondary magnetic field, which was measured by the Galileo probe at the synodic period. The comparison with the numerically modeled secondary field indicates that Europa's shell is conductive, which supports the presence of highly conductive salty sea water in the subsurface ocean. In that case, the ocean flow generates an additional magnetic field, the so-called ocean-induced magnetic field (OIMF), which has been overlooked so far. A notable exception is the study of Vance et al (2021). They predicted the OIMF ≤ 20 nT using a simplified scaling relation in which they inserted typical values of the primary field, electrical conductivity, and flow velocity according to the flow model of Soderlund (2019). Here, we revisit their results using a full EM induction solver. Besides, we rely on our flow model to systematically study the geometry estimates proposed for Europa.

Keywords: Europa, motional induction, ocean dynamics

FLOW PATTERNS IN EUROPA'S OCEAN

The flow model is based on the Boussinesq approximation controlled by three non-dimensional numbers: the Rayleigh (Ra), Ekman (Ek), and Prandtl (Pr) numbers. As the computationally feasible values of Ek and Ra are orders of magnitude different from the realistic values (Gastine et al, 2016), we built a dataset to establish an appropriate scaling law to extrapolate the results. Previous studies have shown that Europa's subsurface ocean is influenced but not dominated by the Coriolis force (Soderlund, 2019; Gastine et al, 2016). We show that two modes of convection can exist in this setting. Mode I is dominated by prograde zonal flow at the equator with negligible radial and meridional flows. Mode II is characterized by Hadley-like meridional circulation cells in both hemispheres and prograde zonal flows occurring closer to the polar regions (see Fig. 1). The scaling analysis based on our dataset strongly indicates that Mode II is appropriate for Europa's ocean. The proposed scaling of velocities yields values around 20 cm/s, which is well aligned with energy estimates (Jansen et al, 2023) but at least five times lower than predicted by Soderlund (2019).

EUROPA'S OCEAN-INDUCED MAGNETIC FIELD

We calculate Europa's OIMF using the time-domain EM induction solver ElmgTD (Velímský, 2013; Velímský and Martinec, 2005). Compared to the frequency-domain approach, the time-domain solution naturally contains all, not only the selected periods (e.g., synodic). The ElmgTD solver uses the vector spherical harmonic functions (Varshalovich et al, 1988) in the lateral directions and piecewise-linear 1-D finite elements in the radial direction. ElmgTD can work with 3-D conductivity distribution (Šachl et al, 2019), but the lateral conductivity variations in Europa's interior are unknown. In all presented calculations, we consider a layered conductivity model. The conductivity is constant in each layer, representing (top to bottom) ice, ocean, silicate mantle, and iron-nickel core. In such a case, the EM induction problem is decoupled for individual spherical harmonics, which allows us to use high resolution (1 km) in the radial direction at low computational expense. Our calculations suggest that the magnitude of Europa's OIMF forced by the flow in Mode II (see the first paragraph) is approximately 1 nT (see Fig. 2). Thus, Europa's OIMF is more than one order of magnitude weaker than predicted by Vance et al (2021). The discrepancy is primarily caused by more sluggish ocean flow and the correct treatment of EM induction. We obtain three times smaller OIMF if we use flow and conductivity models that mimic the setup of Vance et al (2021). On top of that, Europa's OIMF is affected by the conductivity and thickness of ice and ocean, which we demonstrate in a parametric study.

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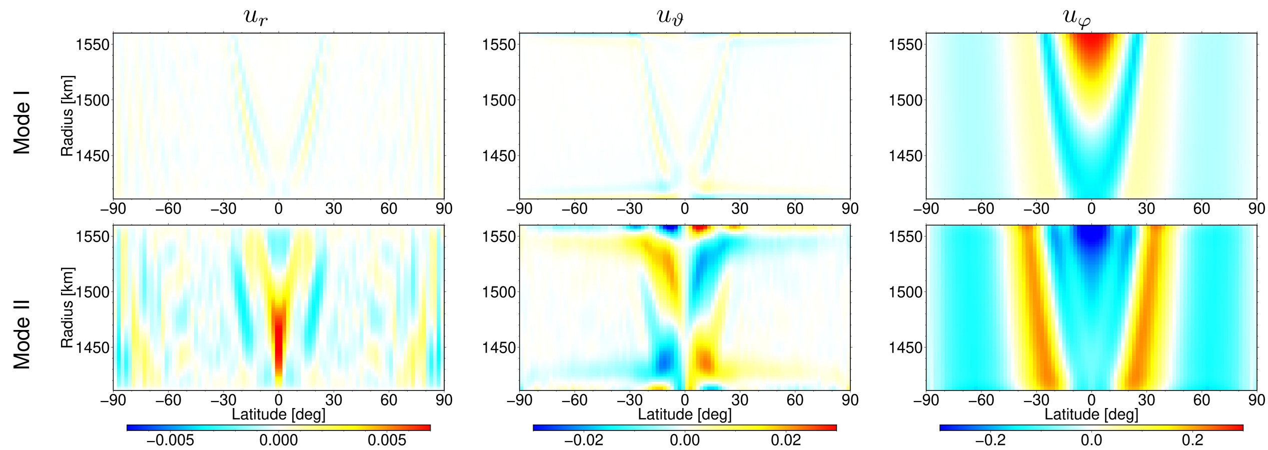

Figure 1: Two possible flow configurations in the ocean under a mild influence of the Coriolis force. Values are in m/s.

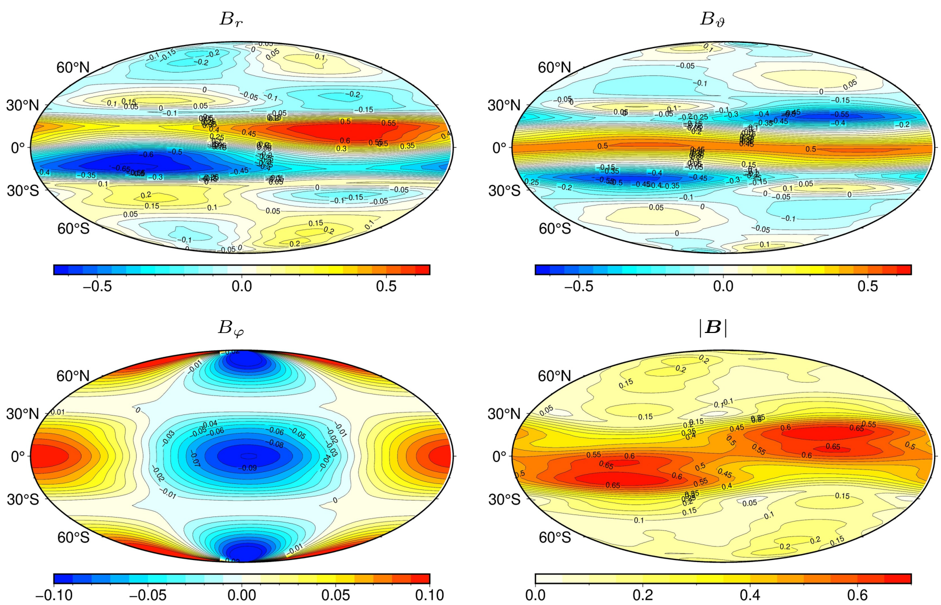

Figure 2: Europa's OIMF in nT four hours after the one-year spin up. Ice and ocean thicknesses are 1 km and 124 km, respectively.