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# Evidence of a global subsurface magma ocean in Io from Galileo’s magnetometer observations

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## Abstract

Theoretical models of tidal dissipation in Io’s interior have provided support for a global melt layer in the interior of Io. The extremely high temperature of the lava erupting on Io’s surface also hint at an extremely hot interior consistent with an internal magma ocean but no direct evidence has been available.

Using Jupiter’s rotating magnetic field as a sounding signal, we report evidence of a strong dipolar electromagnetic induction signature in Galileo’s magnetometer data from four different flybys. The signal is consistent with electromagnetic induction from large amounts of rock-melts in the asthenosphere of Io. Modeling of this signature shows that the induction response from a completely solid mantle model is inadequate to explain the magnetometer observations. However, we find that a layer of asthenosphere > 50 km in thickness with a rock melt fraction $\geq 20\%$ is adequate to accurately model the observed magnetic field. This work also places a stronger upper limit of 107 nT on the permanent equatorial surface dipole field that could be generated by a dynamo inside Io.

## 1. Introduction

The technique of electromagnetic induction has been used previously to identify liquid water oceans in the interiors of Europa, Ganymede and Callisto [1], [2], [3]. Recent high-temperature experiments on ultramafic rocks derived from the Earth’s mantle show that their electrical conductivity increase from 10-9 S/m at room temperature to ~ $10^{-3}$ S/m at 1200 °C and ~ $10^{-2}$ S/m at 1400 °C at pressures prevailing in Io’s upper mantle [4], [5], [6]. When the mantle rocks are heated beyond the solidus temperature, they attain conductivities in the range of $10^{-4}$ – 5 S/m depending on factors such as temperature, composition, melt fraction and melt connectivity [5], [6].

## 2. Modeling

The magnetic field near Io arises from three different sources. The largest contribution is from Jupiter’s internal dipole and its magnetosphere. Next in importance is the electromagnetic induction response from subsurface conductors such as a magma ocean. Finally, plasma interaction with Io’s atmosphere from high ionospheric conductivity and plasma pick-up also results in a substantial magnetic field. We modeled the magnetic field of Jupiter and its magnetosphere using spline fits on magnetometer data from closest approach after excising the data where contributions from Io are present. The plasma interaction field was obtained from 3-D MHD simulations from a model used successfully to simulate Ganymede’s internal field and its magnetosphere [7]. The response of conducting layers inside Io are modeled as three shells (crust, mantle and core) and the solutions to the electromagnetic diffusion equation for the multiple shell model are expressed in terms of Bessel functions [8]. The amplitude and phase responses are computed from the three main Jovian rotational harmonics (13 hrs and its multiples) and then summed. This technique was used on data from I24, I27, I31 and I32 passes. Here we show results of modeling for the I24 pass. In the presentation modeling from all four passes would be shown.

Figure 1 shows observations from the I24 pass in solid black curves. The modeled field from Jupiter and its magnetosphere is shown in green dashed lines. The contribution from MHD model (no induction) and the Jovian field is plotted with green solid lines. It can be seen that an MHD model does not adequately represent the observations. In the next set of models, we included the inductive field from a warm solid mantle at 1200 °C (conductivity = 0.002 S/m, dotted blue lines) and a hot solid mantle at 1400 °C (conductivity = 0.007 S/m, dashed blue lines). In these models a core of radius 900 km possessing infinite conductivity was also included. It can be seen that solid warm and hot models of the mantle are also inadequate to explain the observations. Finally, we included asthenospheric shells with a thickness of 50 km overlying the hot solid mantle and a 5% melt fraction (conductivity = 0.1 S/m), a 20% melt fraction (conductivity = 0.43 S/m), and a perfectly conducting shell located underneath the crust (solid red lines). As can be seen models with 20% melt fraction or higher provide excellent fits to the observations and provide the best evidence of a subsurface magma ocean in Io.

## 3. Figures

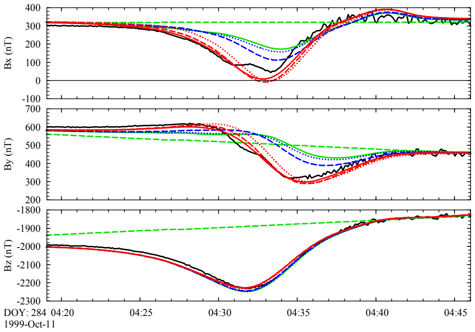

Figure 1: Observations (solid black curves) and model fields (colored lines) for the I24 pass. The green dashed line represents the Jovian background field near Io. The MHD model (no induction) is plotted with green solid lines. The MHD models that include the inductive field from: a warm solid mantle at 1200 °C (conductivity = 0.002 S/m, dotted blue lines), a hot solid mantle at 1400 °C (conductivity = 0.007 S/m, dashed blue lines), an asthenosphere with a 5% melt fraction (conductivity = 0.1 S/m) overlying a hot solid mantle (dotted red lines), an asthenosphere with a 20% melt fraction (conductivity = 0.43 S/m) overlying a hot solid mantle (dashed red lines) and a perfectly conducting shell located underneath the crust (solid red lines). Figure adapted from [9]

## 6. Summary and Conclusions

We have provided direct evidence of a magma ocean located under the crust of Io. It is required that the melt fraction of this asthenospheric layer exceed 20%. In addition, the magma layer thickness also exceeds 50 km. Future observations at harmonics longer than 13 hours are required to place stronger limits on the melt fraction and the thickness of the magma ocean.

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