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Time-varying interaction of Europa with the jovian magnetosphere: Constraints on the conductivity of Europa's subsurface ocean

Nico Schilling [*], Fritz M. Neubauer, Joachim Saur

Institut für Geophysik und Meteorologie, Universität zu Köln, Albertus-Magnus-Platz, 50923 Köln, Germany

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Abstract

We study the conductivity distribution inside Europa by using a time-dependent 3D-model of the temporal periodic interaction between Europa and the jovian magnetosphere. The temporal variations are caused by periodic variations of the magnetospheric plasma and magnetic fields at Europa. We develop a model which describes simultaneously the 3D plasma interaction of Europa's atmosphere with Jupiter's magnetosphere and the electromagnetic induction in a subsurface conducting layer due to time-varying magnetic fields including their mutual feedbacks. We find that inclusion of the magnetic field perturbations caused by the interaction with Jupiter's magnetospheric plasma is important for interpreting Galileo's magnetic field measurements near Europa. This leads to improved constraints on the conductivity and thickness of Europa's subsurface ocean. We find for the conductivity of Europa's ocean values of 500 $\mathrm{mS/m}$ or larger combined with ocean thicknesses of 100 km and smaller to be most suitable to explain the magnetic flyby data. In summary, this results in the following relation: electrical conductivity × ocean thickness $\geqslant 50\ \mathrm{S/m\,km}$. It is shown that the influence of the fields induced by the time variable plasma interaction is small compared to the induction caused by the time-varying background field, although some aspects of the plasma interaction are changed appreciably.

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1. Introduction

Galileo measurements of Europa's gravitational field and modeling show Europa to be a differentiated satellite consisting of a metallic core, a silicate mantle and a water ice–liquid outer shell. The minimum water ice–liquid outer shell thickness is about 80 km for plausible mantle densities (Anderson et al., 1998). High resolution data obtained with the Solid State Imaging (SSI) system show evidence of a young and thin, cracked and ruptured ice shell (e.g., Belton et al., 1996; Carr et al., 1998). The geological observations imply that warm, convecting material existed at shallow depths within the subsurface at the time of its recent geological deformation. Global-scale tectonic patterns can be explained by nonsynchronous rotation and tidal flexing of a thin ice shell above a liquid water ocean (Geissler et al., 1998; Greenberg et al., 2000). The water layer is likely comprised of three sub-layers: an outer, brittle/elastic ice layer, an underlying ductile layer of potentially convecting ice, and a lower layer of liquid. Estimates of the thickness of the ice layer (including the lower ductile layer) range from a few km to 60 km (e.g., Schenk, 2002; Hussmann et al., 2002). However, while the evidence for liquid water in the past is favorable, there is no unambiguous indication from spacecraft imaging that such conditions exist today (Pappalardo et al., 1999).

Thermal models indicate that a significant portion of the outer water shell could be liquid today (e.g., Squyres et al., 1983; Schubert et al., 1986; Spohn and Schubert, 2003). One energy source for maintaining a liquid water ocean is tidal heating caused by the three-body Laplace resonance with Io and Ganymede. This process could offset the freezing of the water ocean by subsolidus ice convection (e.g., Cassen et al., 1979). The major uncertainty in modeling is the rheology of ice (Durham and Stern, 2001). Also, the rate of freezing of the internal ocean depends on its composition, since the occurrence of minor constituents in the ice and ocean such as hydrated salt

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[*] Corresponding author. Fax: +49 221 4705198.
E-mail address: schilli@geo.uni-koeln.de (N. Schilling).

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minerals (McCord et al., 1998) and ammonia (Kargel et al., 1991; Deschamps and Sotin, 2001) effect the rheology of the ice and the freezing temperature of the ocean.

The strongest indication for a liquid water ocean at present time comes from the magnetic field observations (Kivelson et al., 1999, 2000; Khurana et al., 1998). Europa has no detectable permanent internal magnetic field (Schilling et al., 2004). The magnetic field data show evidence for electromagnetic induction taking place in the interior of Europa due to the time-varying external magnetic field (Neubauer, 1998a, 1998b; Khurana et al., 1998). Therefore, the observations support the idea, that a global subsurface conducting layer may be present. In addition, there are magnetic field perturbations owing to the interaction of Europa's atmosphere with the jovian magnetospheric plasma. These time-varying magnetic field perturbations are permanently there on top of the induction signature compromising their interpretation. While induction signatures are clearly visible in the data when Europa is well outside Jupiter's current sheet, the strong plasma interaction dominates and hides the induction effect when Europa is close to the center of the current sheet (Kivelson et al., 1999).

An atmosphere at Europa was detected by Hall et al. (1995) with the Hubble Space Telescope Goddard High-Resolution Spectrograph. The observations imply molecular oxygen column densities in the range of $\sim(2-14) \times 10^{18}\ \mathrm{m}^{-2}$ (Hall et al., 1998). The atmosphere of Europa is produced by the interaction of energetic charged particles with Europa's surface (e.g., Johnson et al., 2004). Shematovich et al. (2005) find by using a collisional 1D Monte Carlo model of Europa's atmosphere that the atmosphere is more strongly structured in the radial direction than previously assumed and that the near-surface region of the atmosphere is determined by both water and oxygen photochemistry. Recent images of Europa's atomic oxygen emission obtained with the HST Space Telescope Imaging Spectrograph (STIS) indicate that the surface is not icy everywhere, but that the composition varies with longitude (McGrath et al., 2004). Atomic Na and K are observed in the extended atmosphere (Brown and Hill, 1996; Brown, 2001). They occur in a ratio different from that at Io (Na/K is 25 for Europa and 10 for Io), and from meteoritic or solar abundance ratios (Brown, 2001; Johnson et al., 2002). Therefore a subsurface source of alkalis is suggested (Johnson et al., 2002; Leblanc et al., 2002). A recent review on Europa's atmosphere can be found in McGrath et al. (2004).

Kliore et al. (1997) detected an ionosphere on Europa by using Galileo radio occultation measurements. They derived a maximum electron density of about $10{,}000\ \mathrm{cm}^{-3}$ with a scale height of 240 km. By assuming a spherically symmetric ionosphere for each derived electron density profile, Kliore et al. (1997) found a strongly asymmetric ionosphere with maximum densities on the flanks and minimum densities downstream. The main source of Europa's ionosphere is electron impact ionization (Saur et al., 1998).

Zimmer et al. (2000) investigated the implications of the observed induced magnetic fields for the electrical structure of Europa's interior. By using a simple shell model they set bounds on the characteristics of the current carrying layer. Zimmer et al. (2000) find that the magnetic signature at Europa is consistent with more than 70% of the induced dipole moment expected for a perfectly conducting sphere. Therefore, currents are required which flow in a shell with conductivity of at least 60 mS/m and close to the surface (within a 200–300 km depth). Zimmer et al. (2000) argue that solid ice, an ionosphere or a conducting core cannot reproduce the amplitude of the observed magnetic perturbation. In addition, Zimmer et al. (2000) argue that it seems to be very unlikely that the magnetic signature can be explained by induction taking place in a conducting mantle only. They therefore support the idea of a subsurface ocean. However, they do not take into account the plasma interaction of Europa with the jovian magnetosphere, which we show to be important for the interpretation of Galileo's magnetic field measurements near Europa. Instead they treat magnetic field perturbations due to local plasma currents as a systematic error.

Previous models of Europa's interaction with the jovian magnetosphere considered either the plasma interaction only (Saur et al., 1998), included an intrinsic dipole moment as a free parameter but did not include the induced magnetic field self-consistently (Kabin et al., 1999; Liu et al., 2000), or they focused on the electromagnetic induction process inside Europa (Zimmer et al., 2000). For example, Kabin et al. (1999) included an intrinsic dipole moment as a free parameter, where they fitted their model results to the data of Galileo's first Europa flyby. Depending on their model parameters they find different values for the internal dipole moment. When rotating the plasma flow upstream of Europa by 20°, their intrinsic dipole moment is close to the direction of an induced dipole moment, but with a small magnitude of about 70% of that obtained by Kivelson et al. (1999).

In this paper we combine the electromagnetic induction process inside Europa and the interaction with the ambient magnetospheric plasma and consider their interdependency. This allows us to improve the results of Zimmer et al. (2000) and thus to further constrain the nature of the internal conducting layer. The time-dependent interaction between Europa and the jovian magnetosphere includes the local plasma interaction of Europa's atmosphere and ionosphere as well as the interaction of a potential internal ocean with the magnetosphere of Jupiter. Due to Jupiter's rotation with respect to Europa and the inclination of Jupiter's magnetic dipole moment, the magnetospheric plasma density and the background magnetic field vary at the position of Europa. The time-varying magnetic fields induce currents in an electrically conducting ocean below the Europan ice crust. These currents generate a time-varying induced magnetic field which influences the plasma interaction. In addition, the periodic variations of the magnetospheric plasma and the interaction with the atmosphere lead to a secondary induction effect. To study this time-dependent interaction, we develop, for the first time, a three-dimensional single-fluid MHD model which includes periodic magnetic fields from the interior of the Moon.

In Section 2, we give a basic overview of the "classical" electromagnetic induction problem applied to Europa. The induced magnetic fields derived in this section are part of our interaction model. In Section 3, we introduce our model of the

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