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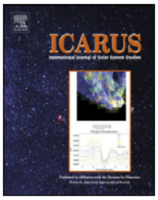

The production of Ganymede's magnetic field

Michael T. Bland [a,*], Adam P. Showman [a], Gabriel Tobie [b,c]

[a] Department of Planetary Sciences, Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA
[b] Université Nantes Atlantique, Laboratoire de Planétologie et Géodynamique de Nantes, 2, rue de la Houssiniére, 44322 Nantes cedex 03, France
[c] CNRS, UMR-6112, 2, rue de la Houssiniére, 44322 Nantes cedex 03, France

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ABSTRACT

One of the great discoveries of NASA's Galileo mission was the presence of an intrinsically produced magnetic field at Ganymede. Generation of the relatively strong (750 nT) field likely requires dynamo action in Ganymede's metallic core, but how such a dynamo has been maintained into the present epoch remains uncertain. Using a one-dimensional, three layer thermal model of Ganymede, we find that magnetic field generation can only occur if the sulfur mass fraction in Ganymede's core is very low ($\lesssim 3\%$) or very high ($\gtrsim 21\%$), and the silicate mantle can cool rapidly (i.e. it has a viscosity like wet olivine). However, these requirements are not necessarily compatible with cosmochemical and physical models of the satellite. We therefore investigate an alternative scenario for producing Ganymede's magnetic field in which passage through an eccentricity pumping Laplace-like resonance in Ganymede's past enables present day dynamo action in the metallic core. If sufficient tidal dissipation occurs in Ganymede's silicate mantle during resonance passage, silicate temperatures can undergo a runaway which prevents the core from cooling until the resonance passage ends. The rapid silicate and core cooling that follows resonance escape triggers dynamo action via thermal and/or compositional convection. To test the feasibility of this mechanism we couple our thermal model with an orbital evolution model to examine the effects of resonance passage on Ganymede's silicate mantle and metallic core. We find that, contrary to expectations, there are no physically plausible scenarios in which tidal heating in the silicates is sufficient to cause the thermal runaway necessary to prevent core cooling. These findings are robust to variations in the silicate rheology, tidal dissipation factor of Jupiter (Q_J), structure of the ice shell, and the inclusion of partial melting in the silicate mantle. Resonance passage therefore appears unlikely to explain Ganymede's magnetic field and we must appeal to the special conditions described above to explain the presence of the field.

1. Background

Ganymede is unique among the satellites of the Solar System in that it has an intrinsic magnetic field (Kivelson et al., 1996; Gurnett et al., 1996; Williams et al., 1997) while other large satellites do not. Analysis of magnetometer data taken during the Galileo spacecraft's four close Ganymede flybys suggest that the field consists of a Ganymede-centered dipole tilted 10° with respect to the rotation axis (Kivelson et al., 1996). With an equatorial surface-field strength of 750 nT, the field creates a mini-magnetosphere ~2 Ganymede radii in extent within Jupiter's larger magnetosphere (Kivelson et al., 1996, 1997, 1998).

The strength of the observed field and Ganymede's high degree of central condensation [$C/MR^2 = 0.3115$ where C is the axial moment of inertia, and M and R are the satellite mass and radius respectively (Anderson et al., 1996; Schubert et al., 2004)] suggest that dynamo action within a metallic core generates the magnetic field (Schubert et al., 1996; Sarson et al., 1997). Other field producing mechanisms are largely inconsistent with observations. The strength of the field, which is significantly greater than Jupiter's field at Ganymede's location, makes production by induction [the mechanism that produces the fields of Europa and Callisto (Khurana et al., 1998; Kivelson et al., 1999, 2000; Zimmer et al., 2000)] unlikely (Schubert et al., 1996). Ganymede's observed field may, in fact, include an induced field component generated in a conducting layer (likely an ocean) at ~150 km depth; however, modeling indicates that this component is small (Kivelson et al., 2002). Additionally, the unrealistically high fluid velocities ($1\ \mathrm{m\,s^{-1}}$) required to produce a dynamo in a thick, electrically conducting ocean make such a mechanism unfeasible (Schubert et al., 1996). Furthermore, producing the observed field via remnant magnetization of Ganymede's rocky mantle requires making rather favorable assumptions regarding the magnetic properties of the rocky materials and requires that a strong dynamo-generated field existed earlier in Ganymede's history (Crary and Bagenal, 1998).

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[*] Corresponding author. Now at: Department of Earth and Planetary Science, Washington University, St. Louis, MO 63130, USA. Fax: +1 (314) 935 7361.
E-mail address: mbland@levee.wustl.arizona.edu (M.T. Bland).

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While we cannot eliminate the mechanism entirely, it seems less plausible than a dynamo generated magnetic field (Schubert et al., 1996).

The dynamo mechanism for magnetic field production requires that fluid motions occur within an electrically conducting medium such as a fluid metallic core. In a planetary dynamo, buoyancy driven convection provides this motion [Malkus (1963) and Vanyo et al. (1995) have also suggested that precession can drive motion within a fluid core, however its relevance to dynamo generation is debatable (e.g. Rochester et al., 1975; Loper, 1975)]. In the absence of an inner solid core, thermal buoyancy alone must drive convection. The requirement for convection in this case is simply that the heat flux out of the core (F_{total}) is greater than the maximum heat flux that can be carried conductively ($F_{\mathrm{cond,ad}}$) (i.e. the heat flux conducted along the core adiabat). Thus, for convection (Stevenson, 2003)

$$F_{\mathrm{total}} > F_{\mathrm{cond,ad}} \equiv k_c \frac{\alpha_c g_c T_{\mathrm{cmb}}}{c_{p,c}}, \qquad (1)$$

where k_c is the thermal conductivity, α_c is the thermal expansivity, $g_c \approx 1.3\ \mathrm{m\,s^{-2}}$ is the local gravitational acceleration (cf. Sohl et al., 2002), T_{cmb} is the temperature at the core–mantle boundary, and $c_{p,c}$ is the specific heat at constant pressure. Equating the minimum required heat flux (Eq. (1)) to the cooling rate of the core yields a minimum cooling rate required to maintain thermal convection

$$\left(\frac{\mathrm{d}T}{\mathrm{d}t}\right)_{\mathrm{min}} = \frac{3k_c\alpha_c g_c T_{\mathrm{cmb}}}{R_c\rho_c c_{p,c}^2}, \qquad (2)$$

where R_c and ρ_c are the radius and density of the core respectively. For parameters appropriate to Ganymede (Table 1) and $T_{\mathrm{cmb}} = 2000$ K, the minimum required cooling rate is $\sim$250 $\mathrm{K\,Ga^{-1}}$. If we assume secular cooling of Ganymede's core associated with the decline in radiogenic heating over the age of the Solar System, the present cooling rate falls well short of the minimum requirement (see Section 3) and a dynamo driven by present-day thermal convection appears unlikely.

To maintain a planetary dynamo, it is necessary but not sufficient that fluid motion occurs in a planetary core. In addition, a self-sustained planetary dynamo requires that convection can supply sufficient power to overcome losses due to ohmic dissipation of the field (e.g. Stevenson et al., 1983; Buffett, 2002). The ohmic dissipation Φ can be approximated by (Buffett, 2002)

$$\Phi = \left(\frac{\eta \bar{B}^2}{\mu_\circ L^2}\right)\frac{4}{3}\pi R_c^3, \qquad (3)$$

where $\eta \sim 2\ \mathrm{m^2\,s^{-1}}$ is the magnetic diffusivity, $\bar{B}$ is the average strength of the field at the core–mantle boundary, $\mu_\circ = 4\pi \times 10^{-7}\ \mathrm{N\,A^{-1}}$ is the magnetic permeability, and L is the length scale for convection (a free parameter). Assuming a core radius of 700 km, and a convective length-scale equal to $\sim$10% of the core radius we find $\Phi = 10^8$ W, consistent with the strength of Ganymede's magnetic field extrapolated to the core–mantle boundary. Because of the uncertainty in the radius of Ganymede's core and the length scale for convection, Φ may vary by an order of magnitude. Such variations do not affect our basic conclusions. The power requirement (W) for sustaining a dynamo is then (Stevenson et al., 1983)

$$P_B = 4\pi R_c^2 \frac{k_c\alpha_c g_c T_{\mathrm{cmb}}}{c_{p,c}} + \frac{\Phi}{\epsilon} - \left(\frac{E_G}{\epsilon} + L_{Fe}\right)\frac{\mathrm{d}m_{ic}}{\mathrm{d}t}, \qquad (4)$$

where ϵ is a Carnot-like efficiency factor ($\sim$0.05; Buffett et al., 1996), E_G is the gravitational energy per unit mass released by inner core formation, L_{Fe} is the latent heat of iron, and $\mathrm{d}m_{ic}/\mathrm{d}t$, is the rate at which the mass of the inner core increases. The first term on the right-hand side of Eq. (4) is simply the power lost from the core by conduction as given in Eq. (1); the second term is the additional power required to overcome ohmic dissipation; the third term is the power provided by compositional convection (see below) and is zero in the absence of an inner core.

Whether thermal convection can occur or not, cooling of the core can lead to the formation of a solid inner core. Inner core growth provides an additional source of energy and buoyancy in the core as heavy elements (e.g. Fe/Ni) freeze out, releasing latent heat, and light elements (e.g. sulfur) are expelled upward, releasing gravitational energy. Earth's magnetic dynamo appears to require such compositionally driven convection (e.g. Verhoogen, 1961; Braginsky, 1963; Gubbins, 1977; Loper, 1978a, 1978b; Lister and Buffett, 1995; Buffett et al., 1996; Gubbins et al., 2004), and it may play a similar role in driving Ganymede's core dynamo (Kuang and Stevenson, 1996; McKinnon, 1996; Hauck et al., 2006). Sulfur is a likely candidate for the light alloying material in Ganymede's core (e.g. McKinnon, 1996; Scott et al., 2002; Schubert et al., 2004). While elements such as oxygen are also plausible components (e.g. McKinnon and Desai, 2003), the inclusion of such a complex core chemistry is beyond the scope of the present work.

Equation (4) indicates that inner core formation relaxes the power requirements on the dynamo. However, whether compositional convection can account for Ganymede's dynamo remains unclear. In a detailed investigation of compositional convection's impact on the evolution of Ganymede's core, Hauck et al. (2006) used scaling arguments to calculate the magnetic Reynolds number ($Re_m = u\mathcal{L}/\eta$ where u is the flow velocity and $\mathcal{L}$ is the thickness of the convecting layer) associated with compositional convection. When one accounts for the fact that the inner core is $\sim$50% of the total core radius after 4.6 Ga (see Hauck et al., 2006), then Re_m due to compositionally driven convection in Ganymede is $\approx$35. However, numerical investigations indicate that convectively-driven, self-sustained dynamos require a magnetic Reynolds number of 40 to 50 (Olson and Christensen, 2006; Christensen and Aubert, 2006). Compositional convection's ability to maintain Ganymede's dynamo over geologic time therefore appears marginal.

Furthermore, inner core formation on Ganymede may occur in a novel way relative to the Earth. In contrast to melting relations in the Fe–FeS system at high pressures (e.g. Boehler, 1996; Usselman, 1975), experimental work at low pressures (<14 GPa) indicate that, for sulfur concentrations greater than $\sim$3%, the melting curve is less steep than Ganymede's expected core adiabat (i.e. $(\mathrm{d}T_{\mathrm{melt}}/\mathrm{d}P) < (\mathrm{d}T/\mathrm{d}P)_{\mathrm{ad}}$), and for even larger sulfur concentrations the melting temperature can decrease with increasing pressure (i.e. $(\mathrm{d}T_{\mathrm{melt}}/\mathrm{d}P) < 0.0$; Fei et al., 1997). These observations imply that, for sulfur concentrations greater than 3%, Fe will first condense at Ganymede's core–mantle boundary (i.e. at the top of the liquid core), rather than at the inner-core/outer-core boundary as occurs on Earth (Kuang and Stevenson, 1996; McKinnon, 1996; Hauck et al., 2006). The relatively dense Fe condensed at the top of the liquid core is buoyantly unstable and will sink downward to form an inner core, releasing gravitational energy (Hauck et al., 2006). Hauck et al. (2006) have argued that such compositional convection is sufficient to drive Ganymede's dynamo. However, because condensation of Fe occurs at the core–mantle boundary rather than deep in the core, the latent heat released by Fe condensation might not contribute to the convection that drives the dynamo because this heat is immediately removed from the core to the cooler mantle above. The removal of the latent heating term from Eq. (4) severely limits the ability of compositional convection to power the dynamo. This is especially true in Ganymede's small core where the gravitational energy release is relatively small (see Section 2.1.2). Furthermore, while the gravitational energy re-