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Iron snow dynamo models for Ganymede

Ulrich R. Christensen

Max Planck Institute for Solar System Research, Göttingen, Germany

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ABSTRACT

Ganymede's internal magnetic field is dominated by the axial dipole. The measurements by the Galileo spacecraft only place an upper limit on the quadrupole moment. Ganymede's magnetic field has the lowest ratio of quadrupole power to dipole power for all known planetary dynamos, not only at the planetary surface but possibly also at the top of the dynamo region. The dynamo operates in a fluid iron core that probably contains a significant amount of sulfur. Crystallization of the core will then proceed from the top by formation of iron snow in a layer that develops a stable compositional gradient. Remelting of the snow at the bottom of this layer enriches the underlying fluid in iron and drives compositional convection. Here we explore the consequences for the dynamo process of this scenario by numerical modeling. Convection is driven by an imposed buoyancy flux at the top of a convecting core region that is surrounded by a conducting fluid shell with a strongly stabilizing density gradient. Only horizontal flow is allowed in the outer shell. It is shown that this is a valid approximation in the case where the stabilizing density contrast in the upper shell exceeds by far the unstable density contrast in the convecting region. We vary the basic control parameters, concentrating on the regime where the magnetic field is dominantly dipolar. Compared to reference cases without an extra layer above the dynamo, we find that a stable fluid conducting layer with a thickness of 100 km or larger reduces the ratio of quadrupole power R_2 to dipole power R_1 by a factor of at least four. With a stable outer layer R_2/R_1 is compatible with the Galileo observations for all tested dipolar models, whereas in the absence of such layer R_2/R_1 is too large or at best marginally compatible. For plausible values of the buoyancy flux the models reproduce Ganymede's observed dipole moment. A stable layer that is comparable in thickness to the unstable region is found to promote a hemispherical type of dynamo whose field in incompatible with observations. This may indicate that the snow layer in Ganymede's core has a moderate depth extent.

1. Introduction

Ganymede is the only satellite in the Solar System which presently has a dynamo-generated internal magnetic field (Kivelson et al., 1996). It is dominated by the dipole with a moment of order 700 nT × r_G^3 ($r_G = 2634$ km is Ganymede's radius) and a tilt of 4° relative to the rotation axis (Kivelson et al., 2002). In terms of additional internal field components, the Galileo magnetometer data are equally consistent with two different models (Kivelson et al., 2002). In one model the data are fitted by a combination of internal dipole and quadrupole components. The quadrupole contribution was found to be small in comparison to the dipole and most of it is described by the Gauss coefficient g_{21}. In the other model there is no quadrupole, but a time-variable induced field is assumed in addition to the dipolar dynamo field. The oscillation of Jupiter's field at Ganymede due to the tilt of Jupiter's dipole axis and the planet's rapid rotation leads to a significant induced field, provided the electrical conductivity inside Ganymede is high enough at a fairly shallow depth, most plausibly because of the existence of a salty water ocean below an outer ice shell. Kivelson et al. (2002) found a complete tradeoff, in the fit to the limited flyby data, between an induction signal and the g_{21}-term. Recently, independent evidence has been presented for the existence of a strong induced field component from Hubble space telescope observations of the time-variable location of auroral emissions on Ganymede, which are believed to indicate the location of the boundary between field lines that close in Ganymede and those that connect Ganymede with Jupiter (Saur et al., 2012). Therefore it is reasonable to consider the quadrupole moment obtained by the inversion of the Galileo magnetometer data in the model without induced field as an upper bound for Ganymede's actual quadrupole moment.

The hypothesis that Ganymede's dynamo might operate in a salty ocean has been rejected, because in order to reach a magnetic Reynolds number that would be sufficient for a dynamo, the flow velocity in the ocean must be implausibly large on the order of

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E-mail address: christensen@mps.mpg.de

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$1\ \mathrm{m\,s^{-1}}$ (Schubert et al., 1996). Therefore a metallic core is considered as the only possible environment in which a dynamo could work in Ganymede. Three-layer models of Ganymede that satisfy its mean density and moment of inertia, with a metallic core, a silicate mantle and an ice layer, find core radii between virtually zero and half of Ganymede's radius if a wide range of densities is allowed for each layer (Sohl et al., 2002; Hauck et al., 2006). Fixing the silicate and ice shell denities to plausible values and allowing for core compositions ranging from pure iron to pure FeS, Sohl et al. (2002) find core radii between 1/4 and 1/3 of Ganymede's radius. This may represent the most likely range, although other core sizes are possible.

The relative contribution of quadrupole components to the magnetic field can be quantified by the Mauersberger–Lowes power of the quadrupole, R_2, to that of the dipole (R_1), where

$$R_n = (n+1)\sum_{m=0}^{n}\left(g_{nm}^2 + h_{nm}^2\right), \tag{1}$$

with n spherical harmonic degree, m spherical harmonic order, and g and h the Gauss coefficients. Using the quadrupole coefficients in the model by Kivelson et al. (2002) without induced field component (their Table III) we find $R_2/R_1 = 0.0025$ at the surface of Ganymede. For a potential field of internal origin, the field strength at degree n varies with radius r proportional to $r^{-(n+2)}$, hence the ratio of dipole power to quadrupole power changes as $R_2/R_1 \propto r^{-2}$. Its value at the surface of the core, denoted here by R'_2/R'_1, is more meaningful to characterize the dynamo. Using $r_c = 0.25\,r_G$ for the radius of Ganymede's core, the quadrupole to dipole power R'_2/R'_1 is only 0.04. To put this into perspective, the value at the top of Earth's core in 2010 was 0.14. Making reasonable assumptions about the ratio between the radius of the conducting core to the outer radius of a planet, r_c/r_p, we find similar or higher values for most other planets with an active dynamo: 0.33 for Mercury with $r_c/r_p = 0.82$ (Anderson et al., 2011), 0.10 for Jupiter with $r_c/r_p = 0.85$ and 1.6 and 2.7 for Uranus and Neptune, respectively, with $r_c/r_p = 0.75$ (Russell and Dougherty, 2010). Only Saturn with $r_c/r_p = 0.6$ may have a lower $R'_2/R'_1 = 0.023$ (Cao et al., 2011). However, the value for Ganymede is probably smaller than 0.04. For a core with $r_c = 0.30\,r_G$ the ratio R'_2/R'_1 would drop to 0.028 and in view of the very likely presence of an induced magnetic field component all these numbers are upper bounds. We can conclude that Ganymede has an anomalously low quadrupole moment relative to its dipole moment. It may fortuitously hold only at the present epoch. However, this would require that all five independent quadrupole coefficients are simultaneously small by chance, which seems improbable. The main purpose of this work is therefore to study if properties of Ganymede's dynamo that may distinguish it from other planetary dynamos can be the cause for the weak quadrupole moment.

Putting mechanical forcing, e.g. by tidal or librational effects (Wicht and Tilgner, 2010), aside, flow in a metallic planetary core can be driven by thermal convection or by compositional convection. A condition for thermal convection to occur is that the heat flow out of the core is larger than the heat transported by conduction along an adiabatic temperature gradient. Taking as lower bound for the adiabatic gradient $(\partial T/\partial P)_S \geqslant 1.6\times10^{-8}$ K/Pa for an iron–sulfur alloy at a pressure of 6 GPa at the top of Ganymede's core (Williams, 2009) together with a thermal conductivity $k \geqslant 30\ \mathrm{W/(m^2\,K)}$ that is calculated from the electrical conductivity $>10^6$ S/m (Deng et al., 2013) using the Wiedemann–Franz law, a density of $\rho = 6500\ \mathrm{kg/m^3}$ and gravity $g = 1.3\ \mathrm{m/s^2}$, the adiabatic conductive flux is $>4\ \mathrm{mW/m^2}$. Thermal evolution models for Ganymede predict a present core heat flow in the range 2–4 $\mathrm{mW/m^2}$ (Hauck et al., 2006), hence pure thermal convection is not very likely to drive a dynamo in Ganymede. Kimura et al. (2009) concluded that thermal convection may be possible if Ganymede's core is rather big and sulfur-rich, however, their assumed value for the adiabatic conductive heat flux is very low. Compositional convection occurs when solidification is progressing in a core that contains alloying elements aside from iron, with sulfur being the favorite candidate in small planetary bodies. In the Earth's core solidification starts from the center because the melting point gradient is steeper than the adiabatic temperature gradient which is established in a convecting fluid. However, this cannot necessarily be considered as the prototype situation for smaller planets. Rather a variety of other scenarios are conceivable, e.g. crystallisation of iron at the top of the core or at some intermediate depth (Hauck et al., 2006). Williams (2009) pointed out that at the low pressures in the cores of small bodies the adiabatic temperature gradient could be steeper than the melting point gradient for a nearly pure iron composition. The addition of sulfur not only reduces the melting temperature T_M, but also leads to shallower pressure gradients dT_M/dP, particularly in the 6–10 GPa pressure range that is relevant for Ganymede's core (Chen et al., 2008; Buono and Walker, 2011). For compositions more sulfur-rich than ≈15 wt% sulfur, dT_M/dP even becomes negative. Sulfur is a volatile element and is probably more abundant in the outer Solar System where lower condensation temperatures have been reached in the protosolar nebula than in the region of the terrestrial planets. Hence Ganymede's core plausibly contains a significant amount of sulfur. The small or negative dT_M/dP implies that crystallization will start at the core–mantle boundary and proceed downward as the core cools.

Fig. 1 illustrates the top-down iron snow scenario for Ganymede, assuming arbitrarily an initial sulfur concentration of ≈15.5% in the core. In the top layer iron snow is formed and sinks gravitationally. The temperature gradient in this layer is set by the heat flux at the core–mantle boundary, which is controlled by the heat transport capability of the overlying shells and the thermal history. The temperature gradient at the top of the core is expected to be lower than the adiabatic gradient. As the core cools, the top layer becomes gradually more enriched in sulfur and the local sulfur concentration is regulated in such a way that the temperature is everywhere at the melting point. A stable gradient in concentration is set up in the

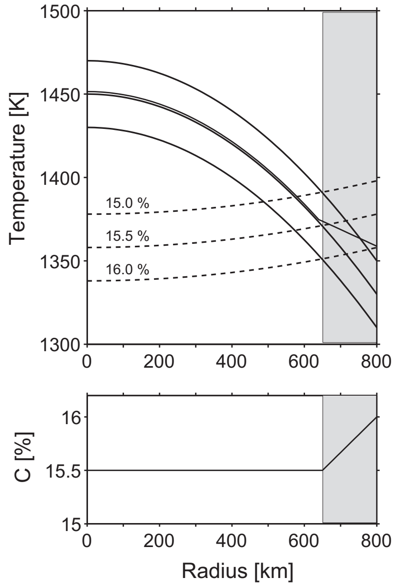

Fig. 1. Schematic illustration of the iron snow regime in Ganymede's core. Top panel: temperature vs. radius; thin full lines are adiabats, broken lines melting temperature for different sulfur concentrations, bold line is actual temperature. Bottom panel: sulfur concentration vs. radius. The iron snow region is shaded.