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The generation of Ganymede's magnetic field

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Summary

Ganymede maintains a strong, intrinsically produced magnetic field [1], making it unique among the satellites of the Solar System. The field is likely generated by dynamo action within Ganymede's metallic core [2], but how a dynamo has been maintained into the current epoch remains unclear [3]. Using a coupled thermal-orbital model we investigate the physical conditions that might allow magnetic field production via thermal or compositional convection.

Introduction

Analysis of magnetometer data taken during Galileo's four closest flybys of Ganymede indicated the presence of a magnetic dipole field with equatorial field strength of 720 nT and orientation of 10^{o} to the spin axis [1]. The strength of the field and Ganymede's high degree of central condensation suggest that the field is generated via dynamo action within Ganymede's metallic core [2]. Production of a magnetic field requires that the available core power exceeds the power required to drive the dynamo. In the absence of inner core formation the dynamo power requirement is that the heat flux out of the core must exceed that which can be conducted along the adiabat (i.e., the core must be convecting) and that enough energy remains to overcome ohmic dissipation of the field. When inner core formation occurs, gravitational energy and latent heating due to Fe condensation are also available to drive the dynamo.

Testing the mechanisms of field production

Using a multi-layer, one-dimensional thermal model we investigate the physical conditions that permit dynamo action on Ganymede. We find that present-day magnetic field production cannot be driven by thermal convection alone. Thermal convection requires that the metallic core cools faster than 250 K Ga^{-1}; however, our models indicate that the current core cooling rate is less than 40 K Ga^{-1}, suggesting the core is cooling conductively.

Thus, convection driven by compositional buoyancy associated with inner core formation is the likely origin of the dynamo. If the sulphur content of Ganymede's core is low (i.e., less than 3%) an inner core will begin to form deep within the metallic core and Ganymede's dynamo can be powered analogously to the terrestrial dynamo. However, if the sulphur content of Ganymede's core is large (i.e., greater than ~3%) the Fe-S melting curve will intersect Ganymede's core adiabat at the core-mantle-boundary rather than deep in the core. Ganymede's inner core will then form via the rain-out of iron grains through the liquid core [4,5]. This mechanism of inner core formation has serious consequences for dynamo generation. While gravitational energy is still available to power the dynamo, the latent heat associated with Fe condensation at the core-mantle boundary will quickly be removed to the overlying mantle. This energy is therefore not available to power the dynamo. Because of the small size of Ganymede's core, the relative importance of latent heating to the core's energy balance is large. Without it, a dynamo cannot be maintained.

Figure 1 illustrates the importance of latent heating. For a core with low sulphur content (i.e., inner core formation proceeds in an Earth-like regime; panel A and C) the available core power exceeds the requirement for driving a dynamo, and maintaining a magnetic field until the present day appears plausible. However, for larger sulphur content (i.e., inner core formation via "iron snow"; panel B and D) the available core power does not exceed the dynamo requirement at present. In addition, we find that the silicate mantle, which ultimately controls the rate of core cooling, must

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cool rapidly for magnetic field generation to be possible. The rheological behaviour of the mantle is therefore constrained to be similar to wet olivine. Our modelling therefore indicates that present day magnetic field generation can occur via compositional convection, but only if a limited set of physical conditions are met: the core must have a low sulphur content, the core must have formed hot (consistent with the low S content), and the silicate mantle must be able to cool rapidly.

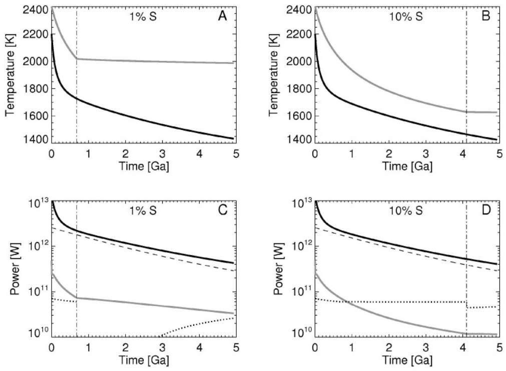

Figure 1: A. *The temperature of the silicates mantle (black line) and metallic core (grey line) as a function of time for a core with 1% sulphur by mass. The vertical dashed line indicates the onset of inner core formation.* B. *As in (A) but for a core with 10% sulphur by mass.* C. *The power out of the silicate mantle (black line) and metallic core (grey line) as a function of time. The power due to radiogenic sources is shown as a dashed line and the power requirement to drive a dynamo is shown as a dotted line. The vertical dashed line again indicates onset of inner core formation.* D. *As in (C) but for a core with 10% sulphur by mass.*

Because these conditions are not necessarily compatible with cosmochemical and physical models of the satellite, we have explored an alternate scenario in which passage through a Laplace-like resonance in Ganymede's past [6] enabled present-day magnetic field production [3,7]. During resonance passage, tidal dissipation in the silicate mantle prevents the metallic core from cooling. Once the satellites escape the resonance, dissipation ends and the hot silicate mantle and metallic core cool rapidly, triggering convection in the core and generating a magnetic dynamo. To test the feasibility of this scenario we couple our thermal model to an orbital model [6] of the Galilean satellites' evolution into the Laplace resonance, which permits investigation of passage through one or more Laplace-like resonances that cause tidal heating in Ganymede. We find that there are no physically plausible scenarios in which tidal dissipation within the silicate mantle is large enough to trigger a thermal runaway that buffers core cooling during the period of resonance passage. These results are robust to variations in the silicate rheology, variations in Jupiter's tidal Q, the structure of the ice shell, and the presence of partial melt within the mantle. We therefore feel confident that this attractive mechanism for maintaining Ganymede's dynamo is not feasible.

How can Ganymede's magnetic field be explained? Our modelling hints at several possibilities. Perhaps the conditions outlined above are actually met (i.e., the metallic core has a low S mass fraction). Alternatively, the possibility of remnant magnetization has not been completely ruled out [8]. Furthermore, if formation of a hot metallic core occurred late in Ganymede's history then present-day magnetic field generation would be greatly enabled. Finally, we note that there is much that is unknown regarding Ganymede's core and magnetic dynamo. Could oxygen be an important core component? Is there an interaction between Ganymede's dynamo and Jupiter's magnetic field? Greater understanding may await a new mission to the Jupiter system.

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