INTERNAL STRUCTURE AND MECHANISMS OF CORE CONVECTION ON GANYMEDE.

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Introduction: We model the thermal state of the non-ice interior of Ganymede, giving special attention to the role of an alloying element in the core, such as sulfur, on the internal structure and core melting relationships. This approach provides the opportunity to outline the range of conditions that may be consistent with the present generation of a magnetic field. This work may in turn help tighten bounds on the internal structure and the bulk sulfur content of the satellite's core. In addition, the overlap between pressures in Ganymede's core (< 20 GPa) and those in laboratory experiments [1] provides an opportunity to investigate the potential mechanisms of chemical convection that may drive magnetic field generation.

Background: Flybys of Jupiter's largest moon, Ganymede, by NASA's Galileo spacecraft have provided useful constraints on its internal structure and dynamics [e.g., 2-4]. The non-dimensional polar moment of inertia (C/MR^2) is 0.3105 ± 0.0028. This low value indicates that Ganymede is the most centrally concentrated, largely solid body known in the Solar System [2], suggesting complete global differentiation and the formation of a metallic core. The detection of an intrinsic magnetic field [3] places an additional constraint on internal structure; either there is a layer with significant remanant magnetization [e.g., 5] or the field is generated by convection in an electrically conducting fluid, likely a liquid portion of the metallic core [4].

The constraints provided by the C/MR^2 value and the bulk density (~1936 kg/m^3 [2]) do not uniquely determine internal structure, although a three-layer model (ice, rock, and metal) appears to be the most consistent with observations [2, 4]. All other things being equal, the radius of the core varies inversely with density to the 1/3 power, which is a function of composition of any alloying elements such as sulfur. Therefore, any constraints that can be placed on core composition would help refine internal structure models. As the melting temperature is a strong function of sulfur content in the Fe-FeS system [e.g., 1, 6], thermal evolution models may allow us to place bounds upon the amount of sulfur in the core to values consistent with the present-day magnetic field.

Considerable effort has gone into modeling heat transfer within the outer ice shell of the Galilean satellites and the implications of subsurface liquid layers [e.g., 7-12]. The non-ice portion of the planet, however, is comparable in size to the Earth's moon, although it is likely more dense. If Ganymede's intrinsic magnetic field is the product of dynamo action or magnetoconvection [4], then we assume that convection (thermal and/or compositional) occurs in the core. These convective motions are driven (in the absence of heat-producing elements in the core) by cooling from above, which is regulated by the heat transfer through the overlying silicate mantle.

Convection within the silicate mantle is a possibility during at least some portion of Ganymede's history. Convection could manifest itself in the stagnant-lid regime, in which the cold, rigid, outer layer does not participate in the convection, or in some sort of lithospheric-recycling mode facilitated by the pervasive availability of H_2O near the silicate-ice interface. The latter is certainly more conjectural, but either or both of these modes of mantle convection may have operated at some time during the past and affected the current thermal state of the core.

Given the unconstrained composition of Ganymede's core, any compositional convection could be driven in several different ways [e.g., 13]. First, at low sulfur contents, nominally pure, solid Fe might precipitate to form an inner core and expel the lighter constituent, which would rise within the outer core. Second, for a sulfur-rich composition, FeS might precipitate deep within the core, buoyantly rise, and remelt at higher levels. Alternatively, because of the decrease in eutectic temperature in the Fe-FeS system with increasing pressure within the pressure interval relevant to Ganymede's core, solids might rain down from higher levels in the core at compositions with sub-eutectic sulfur content, only to remelt at deeper levels.

Modeling: We start with a suite of three-layer, internal structure models that are consistent with the non-dimensional polar moment of inertia and bulk density [2], where the core density is constrained by the assumed sulfur content [e.g., 14, 15]. The densities of the ice and rock layers are similarly unknown, but a range of values can be investigated.

These structural models provide input for thermal evolution models of the silicate mantle and metallic core. Convection within the ice layer is not modeled, but the ice-rock interface temperature is constrained by the melting temperature of ice at high pressures. The abundance of heat-producing elements is also unconstrained, but a CI chondritic composition may be a reasonable starting assumption. However, recent structural models using equations of state and physical properties of likely icy satellite constituents as potential constraints suggest that a composition similar to L or LL chondrites may be representative of Ganymede's non-ice interior [16].

We model planetary thermal evolution via a parameterized convection scheme, including core cooling and inner core formation [e.g., 17, 18]. These calculations exploit a one-dimensional (radial) model of convection in one or more spherical shells overlaying a spherical core. Convection is parameterized with a relationship between the Rayleigh and Nusselt numbers, which non-dimensionally characterize convective vigor and heat transfer, respectively [e.g., 19]. Recent scaling relationships for stagnant-lid convection may be appropriate [e.g., 20]; however, because of the possibility of free water to lubricate faults at the ice-silicate interface, we cannot *a priori* rule out that some sort of lithospheric recycling has occurred. Our model of inner core formation for Fe-rich cores follows the methodology of [17], but the phase relationships in the Fe-FeS system have been updated by the results of recent, high-pressure experimental studies [1].

Results: We have investigated a subset of end-member structural models (i.e., ρ_{ice} = 1000 kg/m^3, ρ_{rock} = 3100 kg/m^3; ρ_{ice} = 1300 kg/m^3, ρ_{rock} = 3600 kg/m^3, etc.) for a range of core sulfur contents (ρ_{Fe} = 8000 kg/m^3 and ρ_{FeS} = 5100 kg/m^3 [14]). Heat production within the silicate mantle is specified by CI chondritic abundances for K (550 ppm), U (8 ppb), and Th (29 ppb) [21]. For the sake of generality, we also examine models with twice and half these abundances, which also encompasses the heat productivity of L and LL chondrites. Generation of heat within the core is neglected, and the ice-silicate interface is assumed to be isothermal. As the timing of differentiation or any tidal heating due to passage through and capture into resonances [10] is uncertain, our initial models start with a fully differentiated planet at ~4.5 Ga [8], yet we recognize that this state may have been reached at a later epoch. We assume that the viscosity of the silicate layer can be approximated by that for an olivine rheology [22] that may be dry or wet and Newtonian (stress-independent) or non-Newtonian.

Initial results reveal two aspects of the structure and evolution of Ganymede's core. First, among compositions more Fe-rich than eutectic, the maximum sulfur content that admits a compositional mechanism for convection over a range of possible structures and mantle heat source compositions is ~15-18 wt % (the minimum sub-eutectic sulfur content for an entirely liquid core) for a wet, non-Newtonian, olivine rheology. This result is important because the extraction of heat from the core by the mantle alone is less than the ~6 mW/m^2 that can be conducted along an adiabat.

Second, because of the decrease in eutectic melting temperature with pressure up to ~14 GPa [1], it is possible that instead of Fe solidifying at high pressures within the core leading to growth of a solid, inner core, iron might precipitate at lower pressures within the core, rain down to deeper levels, and (possibly) remelt. This process could drive chemical convection within the core for bulk core sulfur contents greater than 6 wt % and less than the eutectic sulfur fraction(~18-22 wt %, depending upon pressure). Our initial results, however, indicate that even at bulk core sulfur contents less than 6 wt %, any ongoing chemical convection in Ganymede's outer core would be affected by this rain process because of the increased concentration of sulfur in the outer core (due to earlier growth of an iron inner core. Furthermore, at these low sulfur contents, solid inner core growth proceeds by 4.5 Gyr to the point where the ratio of the inner core to outer core radii is greater than 0.7; in such a thin shell, dynamo action may not be preferred [e.g., 23, 24].

An alternative to be investigated is that the composition of Ganymede's core lies on the S-rich side of the Fe-FeS eutectic, and that the buoyant rise of FeS precipitates (and potential remelting at lower pressures) may drive core convection. Our initial results nonetheless suggest that the driving mechanism for Ganymede's internal magnetic field could be quite different from the mechanism of solid inner core growth that is likely a contributor [e.g., 25] to magnetic field generation in the Earth.

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