INTERNAL STRUCTURES OF THE GALILEAN SATELLITES: WHAT CAN WE REALLY TELL?

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Introduction: The internal structures (e.g., core size and composition) of the Galilean satellites cannot be uniquely determined by density and moment-of-inertia values alone. Assumptions about composition, chemistry, and thermal structure must be made, and differences in these assumptions account for, in part, the sometimes different conclusions reached to date [1,2]. Here we show how different oxidation states, completeness of metal-from-rock differentiation, Mg number, and non-hydrostatic gravity affect internal structure determinations. We argue that solar composition is compatible with the chemistry of all 4 satellites, and that strong Fe/Si enrichment or depletion with respect to solar values [1,2] is not required.

Io: Io has been fiercely tidally heated, possibly for 4.5 Gyr [3], and appears anhydrous. Its density of 3527.8 ± 2.9 kg m^{-3} [4] is less than solar composition anhydrous rock [5] or the closet volatile-depleted meteoritic analogue, H-chondrites [6], at STP. Obviously, though, Io's internal temperatures are quite high (based on eruption temperatures), and for any appreciable sulfur content, the core indicated by the moment-of-inertia factor (0.37685 ± 0.00035 [4]), must be molten [7]. These factors make the densities of solar composition rock and Io nearly coincident, but for the EOS we adopt for molten Fe-S-O, exact equivalence requires that the silicate mantle contain a lower density layer, i.e., a crust and/or partially molten asthenosphere.

Others have concluded that Io's Fe/Si ratio is subsolar, based on a either multilayer and generally non-solar mantle compositions [1] or on a pure forsterite/fayalite mantle [2]. In the first case the core composition and density is fixed, whereas in the second it is based on the solid densities of high-pressure polymorphs of Fe and FeS. In contrast, we use liquid densities based on experimental values for Fe-O-S [8,9], and for pressure effects on FeS, the high-temperature polymorph FeS V [10], with modest density decrement upon melting of 250 kg m^{-3} (the same as for pure iron). The oxidation state of Io's mantle has been determined to be similar to that of the Earth's mantle [e.g., 11], consistent with earlier arguments that Io was not formed from a metal-bearing assemblage [12] (that is, Io either accreted from material with a higher oxidation state or underwent oxidation during hydrothermal alteration, with H_2 vented and lost). Thus our preferred cores are sulfur-rich (on the FeS side of the eutectic) and oxygen bearing, which accounts for their relatively low densities and large sizes (>60% of Io's radius for high mantle Mg numbers, decreasing with increasing crust/asthenosphere thickness).

Europa: Europa's density and moment-of-inertia [13] cannot be met by an ice+water layer overlying an anhydrous but undifferentiated interior of solar composition (the moment-if-inertia factor is too large), unless the interior is solid and reduced (metal-bearing). The latter seems unlikely to obtain given Io's oxidation state, whereas radiogenic heating alone inevitably leads to metal and sulfide melting and core formation [14]. We therefore focus on 3-layer models: ice/water over a silicate mantle over a molten Fe-S-O core.

Figure 1 illustrates the variation of Europa's moment-of-inertia factor (MOI) as a function of mantle Mg#, for different adiabatic potential temperatures and assumptions about oxidation state and degree of differentiation. The models are based on the ICYMOON structural code [5], which can handle multiphase ice layers (including oceans) as well as metal-bearing cores.

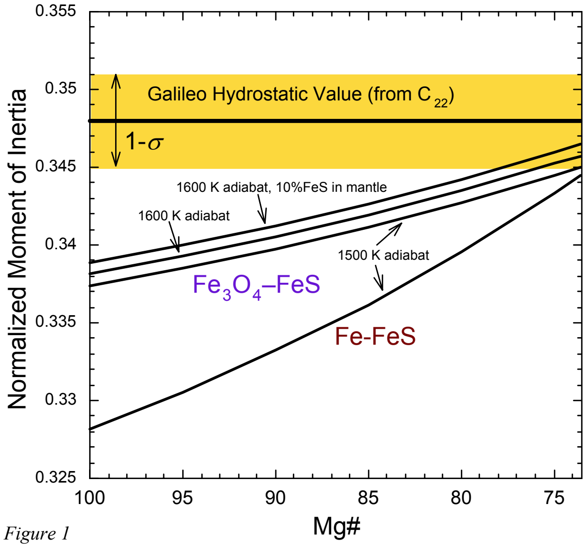

Figure 1

If all Fe and S is in the core (an extreme assumption), then the MOI is too low to be compatible with the Galileo-derived limit (note that the latter [13] has been updated to a radius of 1560.7 ± 0.65 km [15]). As the interior is oxidized (Fe → FeO in olivine and pyroxene), the model MOI becomes formally compatible with the Galileo 1-σ limit. Compatible models have low Mg# (similar to that inferred for the martian mantle [16]) and close to pure FeS cores [17].

Greater degrees of oxidation (above QFM) stabilize magnetite and ferrosilite at the expense of fayalite, which leads to an increase in core mass as Fe_3O_4 *is a core phase* (e.g., it has a eutectic melting relationship with FeS [18]). The upper curves in Fig. 1 represent a limiting case, in which the Mg# of all mantle phases are the same. The internal temperature of the mantle and core has a modest effect on the models. A similar effect accrues to incomplete melting of FeS (i.e., if internal temperatures never exceed the ~1600 K necessary at pressure [7]). Fig. 1 illustrates this effect for the case where 10% of the total FeS remains as a solid mantle phase. An even greater effect may be expected due to incomplete drainage of FeS due incomplete wetting, but this is not a factor for oxidized melts [19].

In summary, solar composition internal models for Europa are possible. Unfortunately, such models are not definitive, as Europa may have a silicate crust (which would lower its model MOI) as well as a modest non-hydrostatic contribution to its gravity signature (which causes the MOI derived from the Radau-Darwin relation to be too high). As can be seen, a non-hydrostatic contribution to C_{22} smaller than the error in Fig. 1 can have a large effect on the derived Mg# and core size. The inferences in [1,2] for subsolar Fe/Si for Europa appear based, as for Io, on a different (denser) EOS for the core.

Ganymede: The density and MOI of Ganymede are compatible with a fully rock-from-ice differentiated interior [20], but if the rock is anhydrous and of solar composition the match is good without invoking further separation of metal from rock [5]. A metal-rich core is necessary to explain Ganymede's magnetic field [e.g., 21], and even though Ganymede's MOI is less sensitive to metallic core formation (compared with Europa or Io), formation of the core takes the model MOI out of formal agreement with Galileo gravity data.

For Ganymede, however, the possibility of a non-hydrostatic contribution to the gravity field must be taken seriously. Non-hydrostatic contributions are non-negligible for all the terrestrial planets, and of the Galilean satellites considered so far, slowly rotating and non-tidally heated Ganymede offers the best prospect for a contribution from its rock+metal interior that cannot be ignored in comparison with the main (hydrostatic) signal.

Unnormalized C_{22} values for Mercury, Venus, Earth, the Moon, and Mars are 1×10^{-5}, 5.5×10^{-6}, 1.6×10^{-6}, 2.2×10^{-5}, and 6.3×10^{-5}, respectively [22-26]. The non-hydrostatic mass distributions responsible are due to a number of causes (descending slabs, mascons, Tharsis, etc.), but whatever the cause, the values approximately follow "Kaula's Rule," in which C_{22} scales as $\sim g^{-2}(r/R)^{5/2}$, where g is gravitational acceleration at the level of anomaly support, r, and R is the surface radius [see 5]. The minimum value this set of values predicts for Ganymede is $\sim 7 \times 10^{-6}$. Only twenty percent of this value ($\sim 1.5 \times 10^{-6}$), coupled with a low Mg# mantle, is required to reconcile the model and observed MOI for Ganymede. We note that that there appears to be unmodeled power in the Galileo gravity field (J.D. Anderson and R.A. Jacobson, pers. comm.), consistent with some contribution from non-hydrostatic sources.

Callisto: Callisto's MOI indicates that it is only partially differentiated [27], if it is in hydrostatic equilibrium, which means that any rock model can be used for its interior. It is interesting to note that three-layer solar composition models [5] put the boundary between the ice layer and the primitive rock+ice layer right at the pressure of the ice I-ice III-water triple point (where an ocean would lie), which may not be a coincidence.

Summary: Solar composition (in terms of the rock+metal) structural models for the Galilean satellites can be constructed. Fractionation of Fe from Si (up or down) is not required, nor is it implied in new satellite formation models [28].

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