CORE EVOLUTION IN ICY SATELLITES AND KUIPER BELT OBJECTS. William B. McKinnon and Michael T. Bland, Department of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University, St. Louis, MO 63130 (mckinnon@wustl.edu).

Introduction: Understanding the formation and evolution of icy satellite and Kuiper belt object (KBO) cores is one of the final frontiers of planetary science. Constraints are limited (mainly satellite densities and moments-of-inertia), but meteoritic analogues, petrological experiments, and theoretical models act as guides. Ever improving understanding of satellite formation also provides context [1]. The recent determination of Titan's moment-of-inertia (MOI) now orders Callisto, Titan, and Ganymede in terms of increasing degrees of ice-from-rock differentiation, with Ganymede apparently the only fully differentiated major icy satellite [e.g., 2]. Titan in particular has provoked a range of proposed internal structures, not all of which are mutually compatible, but all have important implications for Titan's atmospheric evolution, which is in itself a singularly valuable constraint. Here I examine some of the issues surrounding Titan's core composition and evolution, in particular whether a simple 2-layer icy mantle over rocky core is plausible.

Structural Models for Titan: Figure 1 illustrates a representative internal structure for Titan, based on the normalized moment-of-inertia (MOI) determined by [3], 0.342 ± 0.001, from the gravity flybys of Titan by Cassini, which is in turn based on the assumption of hydrostatic equilibrium in interpretation of the measured degree-2 gravity field. This MOI is intermediate to that determined for Ganymede and Callisto (0.311 and 0.355, respectively [4]), and because the mean densities (ice/rock ratios) of all three worlds are similar, implies that differentiation of rock from ice is incomplete on Titan. Incomplete in this case means imperfect separation of bulk rock from bulk ice, or water chemically bound in rock minerals, or both.

In Fig. 1 the rock mineralogy chosen is based on the thermochemical equilibrium calculations of [5] for rock condensed in the protojovian nebula. Although our ideas of satellite origin have evolved considerably, and it seems more probable that the rock component acquired by the moons of Jupiter and Saturn accreted in solar-orbiting planetesimals, which were then drawn into low-mass accretion disks about their parent planets (e.g., [6]), the rock model in [5] has the virtue of being hydrated and oxidized, and solar in composition.

The rock in [5], which includes silicates, oxides (magnetite) and sulfides (troilite and millerite), was modeled in [7] as "PF-rock." We have updated this rock mineralogy with the recommended abundances from [8]. The updated STP density is 3230 kg m^{-3}, which is notably more than that of typical hydrated carbonaceous chondrites (~2500 kg m^{-3}, accounting for porosity [9]). CI and CM chondrites also contain bound water, carbonates, hydrated sulfates (of possible terrestrial origin [10]), and of course, carbonaceous matter. Porosity should not persist at depth and at the high pressures pertinent to major icy satellite such as Titan. Likewise, hydrated sulfates and bound (as opposed to structural) water should not be stable at the several GPa levels in the rock core of Titan. Thus we retain the use of PF-rock as a reasonable average rock model for Titan. Alternatives are considered below.

Figure 1 is meant to be illustrative. The size of the inner rock+metal core depends on the rock mass fraction in the intermediate, mixed ice+rock layer. The figure illustrates a case in which the mixed layer has the same rock mass fraction as Titan as a whole [7]. Depending on how Titan's core forms, it may be larger or smaller, with corresponding adjustments to the rock mass fraction and thickness of the mixed layer. There are limits, however. Without any rock+metal core, the rock volume fraction in the mixed interior [3] rises past 60%, which suppresses any ice-mediated convection, and leads to a conductive thermal gradient and ice melting (differentiation). At the other extreme, a massive rock core and no mixed layer require the rock to be hydrated and low-density [11].

Low-density rock: It has been recently proposed that Titan's rocky core may be modeled as antigorite serpentine, with an STP density of 2750 kg m^{-3} [11-

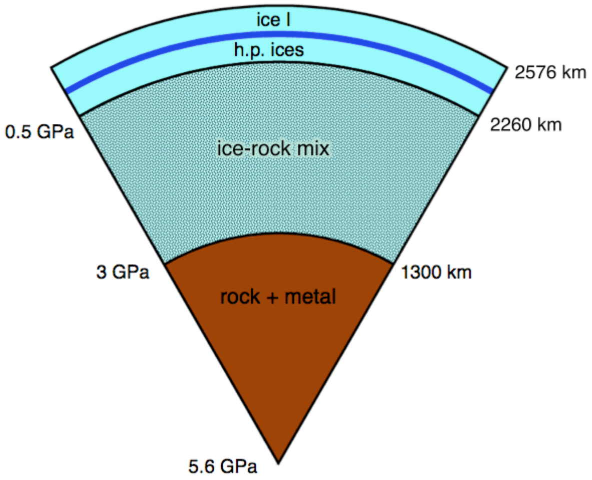


Fig. 1. Three-layer structural model for Titan based on [7] with updated abundances from [8]. Rock is solar in composition, hydrated, and oxidized. Pure water ice is assumed, with no explicit NH_3 or CH_4.

13]. These models presumably draw from the exploratory experiments of [14], in which antigorite, chlorite, and/or talc dominate solar-composition rock mineralogy at Ganymede and Titan core pressures. Serpentine and similar layer silicates certainly dominate CI chondrite compositions, and comprise the largest mass fraction of PF-rock (46 wt%), but assuming a single core mineral of this density is implicitly a non-solar composition model. The implied Mg/Fe ratio is 73/26, vs. a solar ratio of 55/45 [8]. The problem with these antigorite core models is that they simply do not include enough iron. Realistic core models are denser, and thus cannot match Titan's MOI constraint without some intermediate mixed ice-rock layer.

Nevertheless, it is important to reconsider the rock mineralogy in Fig. 1. The original PF-rock mineralogy included minor anhydrous framework silicates (5 wt %) and did not include carbon. If sufficient oxygen is available (from water), C will oxidize to CO_2, and form stable carbonate minerals at core pressures and moderate temperatures [14]. Using the abundances in [8], all of Mg and a majority of the Fe can form antigorite (with an Mg/Fe ratio of 68/32), and the remaining Fe and Ni can combine with sulfur to make pyrrhotite ($Fe_{0.9}S$) and NiS (based on mass balance). These dense sulfides comprise ~25 wt% of the total. The only important lower density minerals that appear plausible are calcite (taking up all available Ca) and kaolinite (taking up the Al, although realistically, Al will be hosted in chlorite [14]; in this thought experiment, however, the Mg has already been spoken for). At only a few wt%, these latter minerals cannot make up for the denser serpentine and major sulfide component.

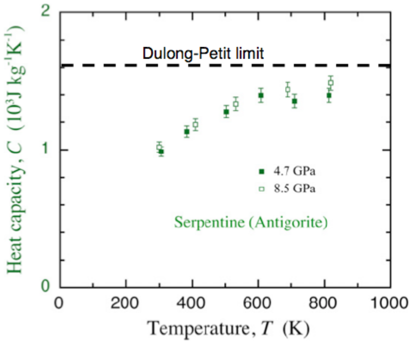
Additional caveats: 1) The stability of pyrrhotite at conditions as oxidizing as the hematite-magnetite buffer [14] is not expected from lower-pressure phase relations. These would predict either pyrite or sulfates such as anhydrite [15]. This issue is unresolved; 2) Any sulfate that might have formed earlier [12-13], say on a carbonaceous planetesimal, has presumably been reduced, or leached to the ice layers during core formation. The loss of this sulfate would increase the overall iron content of the core; 3) A core whose iron metal is solely in the form of sulfide will form a separate metallic inner core only with great difficulty, as the melting point of FeS increases smartly with pressure and no eutectic composition will exist. The existence of Ganymede's magnetic dynamo would seem to call for coexisting Fe or Fe_3O_4.

Dehydration: Explicit in the low-density antigorite core models is a requirement that the core not heat to the point of antigorite/chlorite/talc dehydration. Core thermal evolution depends on many factors, such as the timing of core formation (which determines when radiogenic heat can begin to accumulate – the more this is delayed the less ^{40}K can contribute), and the distribution of ^{40}K between the core and any primordial ocean (leached ^{40}K does not contribute to core evolution). The amount of radiogenic heat (from U, ^{40}K, Th) potentially available to the core is huge,

$$\left(\int_{4.5\,\mathrm{GYA}}^{0}\sum H_i e^{-t/\tau_i}\,dt\right)\Bigg/ C_{P,rock} \quad \approx \quad 2300\,\mathrm{K} \quad ,$$

for a nominal $C_{P,rock}$ of 1 kJ kg^{-1} K^{-1}. Initial core temperature is also important. If core formation is delayed due to initial formation of a rocky "carapace" [16], this carapace will have time to heat internally on its own, before infall.

Nevertheless, the most important physical parameters are likely to be the thermal conductivity and heat capacity of the core rock, which will be dominated by antigorite [11]. Antigorite is known to be a relatively poor conductor [17]. The heat capacity assumed in the models of [11,13], 2 kJ kg^{-1} K^{-1}, strongly suppresses the thermal evolution of the core. This heat capacity is also substantially higher (by up to a factor of 2) than experimental determined values [17, reproduced below], or even the high-temperature, thermodynamic Dulong-Petit limit. This overestimate all but guarantees that realistic Titan core models will reach dehydration temperatures early in their histories.



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