TITAN'S ACCRETION AND LONG TERM THERMAL HISTORY. P. R. Estrada and I. Mosqueira, *Carl Sagan Center, SETI Institute, Mountain View CA 94043, USA, (Paul.R.Estrada@nasa.gov)*.

Abstract: We investigate Titan's long-term thermal evolution starting with its accretion history in the context of the SEMM regular satellite formation model [1-3]. Our formation model allows for a size distribution of impactors with upper size cut-off constrained by Hyperion's size and a variable power-law exponent [4]. The sources of heating include short and long-lived radioactive decay, latent heat of melting, accretional heating and satellite differentiation, *i.e.*, rock sinking and water-melt upwards percolation (e.g., [5]). The satellite cools radiatively into the subnebula. The thermal and rheological properties of the satellite such as conductivity, specific heat, thermal expansivity and viscosity are functions of temperature (and pressure) and of the phase diagram of ice and ice-silicate mixtures. The values for these quantities are taken to be those measured for ice I and higher ice polymorphs (when available). We find (1) that melting in the interior takes place well before the satellite reaches its final size, leading to the formation of an ocean overlying a silicate carapace. However, (2) as a result of its cold accretion coupled with the stiffness of the higher-phase ice viscosities present in the deep interior, rock settling may occur in a timescale comparable to Titan's lifetime. Therefore, proper understanding of Titan's present state of differentiation will require a detailed investigation of core overturn instabilities.

Introduction: Recent Cassini radio tracking data has provided a normalized moment of inertia for Titan of 0.34 [6]. Given that the quadrupole field is consistent with hydrostatic equilibrium, a two-layer interior model may imply incomplete differentiation with a 700 km water-ice shell and an undifferentiated ice and rock-metal interior. Such an internal structure is difficult to reconcile with the formation of a satellite of Titan's size. This is because it is difficult to avoid melting during accretion. Other workers attempt to circumvent this issue by forming these large moons from dust-sized particles (e.g., [7-8]), so that the energy of accretion is placed at the satellite surface where it can be efficiently radiated away. However, this scenario is not only unrealistic, but it fails to account for Titan's partially differentiated state. Indeed, whether differentiation takes place during accretion or during the LHB [8], one must still contend with melting and possibly runaway differentiation and core formation (e.g., [9]). Thus, accreting Titan unmelted, far from providing an explanation for the observations, simply postpones the problem that needs to be addressed. Here we consider the far more plausible scenario that these moons formed from a population of satellitesimals with a range of sizes, and that heat burial must therefore be treated.

Accretion and differentiation models of Titan: Our simulations are carried out using the ACCTHERM code developed by the authors, which will be described in detail elsewhere. The temperature T at radius r and time t satisfies the spherically symmetric time-dependent heat diffusion equation with heat sources. The temperature profile is obtained using an implicit finite difference scheme. Solution of this equation employs an

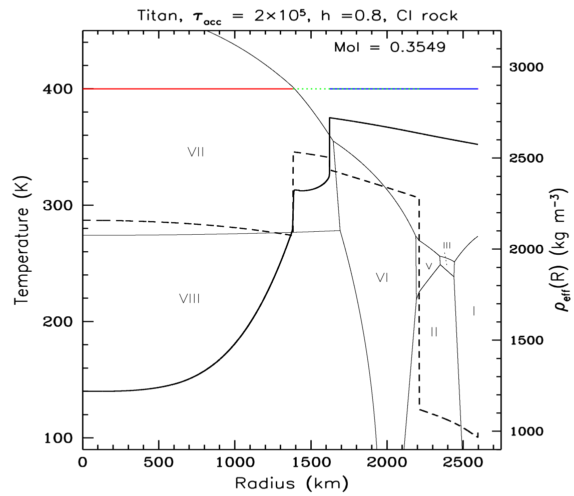

Figure 1: Titan immediately following accretion for a model using CI rock, and 80% of the heat is buried at depth. Plotted as a function of r is the temperature (bold solid curve), overlying the water-ice phase diagram (solid curves). Also plotted is the density as a function of depth (bold dashed curve). Red: undifferentiated. Blue: ocean. Green: carapace. Titan's moment of inertia at this time is indicated.

outer boundary condition involving an energy balance between surface deposition of impact energy, heat conducted to the surface and radiation into space (e.g., [10]). Heat transport can occur through conduction or convection. For the latter, we use parameterized liquid and a selection of solid-state convective schemes available in the literature (e.g., [5,11-12]).

We assume that a small constant fraction of the energy of accretion is deposited at the surface, and the rest is buried in the satellite interior to a depth that depends on the impact speed but is generally of order of the size of the impactors [13]. Our model allows for a size distribution of impactors with upper size cut-off chosen to be $\sim$ 100 km. Such objects are expected to form in the outer circumplanetary disks and drift in a timescale that sets the time for accretion of the satellites [2,3]. In the model of [2,3], Hyperion can be interpreted as an outer disk satellitesimal that drifted-in due to gas drag and became captured into resonance, which prevented it from accreting onto Titan. Since accreting objects would have undergone a collisional cascade as a result of gravitational stirring by the proto-satellite, it is reasonable to use Hyperion as a representative case of the upper-end of typical impactors during the accretion of full-sized satellites [4].

Generally, melting in the interior takes place well before the satellite reaches its final size, resulting in an ocean overlying a silicate carapace (see Fig. 1). While accretional heating and the sinking rock component deposits most of the energy in the top $\sim 100 - 200$ km, a key issue is the degree to which energy released by the sinking rock can lead to additional melting and possibly runaway differentiation (e.g., [9]). In this regard, Titan's moment of inertia of 0.34 [6] casts doubt on the idea that differentiation must necessarily proceed to completion, and motivates a more detailed look both at the physics of en-

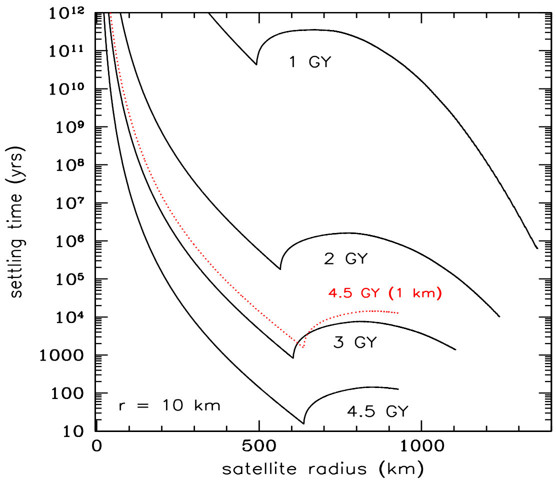

Figure 2: Plot of the settling time for a 10 km "rock particle" at different epochs in the evolution of Titan. In this simulation, the base of the carapace reaches the melting temperature in < 1 GY, and begins to sink as more of the interior reaches the melting temperature. Each curve extends from the deep interior to the base of the carapace at the time indicated. Results for a 1 km particle are plotted for comparison.

ergy deposition (e.g., [10]), radiation into space (including the likely presence of an atmosphere [14], and surface hot-spots), and the settling of solids in the interior (e.g., [15]).

In our models, we consider a range of parameters such as the degree of hydration of the rock component, the fraction of the impact energy that is deposited at the surface of the satellite, and accretion times. But we do not yet consider the effects of small admixtures of contaminants such as ammonia. Here we begin to investigate the poorly understood role that the settling of silicates plays in satellite differentiation.

Results: In Figure 1 we plot the internal structure of Titan at the end of accretion. For this run accretion is taken to begin 4 Myr after CAIs and last for 2×10^5 years after that. The background temperature for radiation and the temperature of satellitesimals is 100 K. A fraction $h = 0.8$ of the energy accretion is deposited in the satellite interior, and the remainder is placed on the surface of the satellite. The plot includes the internal T as a function of r, the water-ice melt and solid-solid phase curves, and the satellite density as a function of radius. The differentiated and undifferentiated regions of the satellite are indicated in the plot caption. As shown, at the end of accretion there is a rocky carapace over an undifferentiated interior, and a substantial water-ocean (overlain at later times in the satellite's evolution by a relatively thin ice shell).

It is common practice to calculate Rayleigh-Taylor instability timescales [16] using a viscosity of about $10^{13} - 10^{14}$ Pa sec corresponding to a temperature of ~ 230 K at the base of the silicate carapace following satellite accretion. However, this neglects to treat the much higher viscosities in the deep interior of the satellite. In addition, the gravity is determined by the mass inside a given radius r, which decreases (roughly with r) as we approach the center of the satellite. Therefore, the timescale computed using the conditions at the bottom of the carapace should not be used to infer the timescale for core overturn to take place. Instead, we compute the non-Newtonian viscosities [17] using the semi-local conditions at a given radial location using the heuristic differential stress (which ignores thermal contributions) $\sigma \sim \Delta\rho g l_0$ (typically ~ 1 MPa), where $\Delta\rho$ is the density contrast between the undifferentiated core and the rocky carapace at maximum filling fraction, g is the local gravity, and l_0 is the semi-local rocky overburden computed as the distance over which the viscosity changes by a factor of e. We then calculate local viscosities using $\eta = (1/3)A^{-1}\sigma^{1-n}e^{Q^*/R_g T}$, where the factor A and the activation energy Q^* depend on the ice phase [see 17]. This in turn allows us to find the time $t_{set} \approx 9\eta r/2g\Delta\rho R_0^2$ for a nominal $R_0 \sim 10$ km "rock particle" to settle to the core as a function of r and t after accretion.

In Figure 2 we plot the settling time beneath the carapace for different evolution times up to the present day (4.5 GY). Because the carapace sinks over time (due to melting at the base), the curve end-points are located progressively deeper in the interior. After accretion, all of the ice beneath the carapace is either ice VII or VIII, for which no viscosity data exists. Instead, we use the values for ice VI for now [17]; however, deeper ice-phases may prove stiffer than ice VI, which would make this assumption a conservative one. The artificial-looking kink in the curves is due to the fact that sufficiently close to the core $l_0 > r$ so that at this radial location we replace l_0 with r in the heuristic differential stress equation.

Conclusions: It is often argued that for a Titan-sized satellite core overturn takes place in < 1 GY. However, so far our ongoing work indicates that following accretion Titan's cold $T \sim 100$ K interior heats up and approaches the melting point temperature of $T \simeq 475$ K (at $r = 0$) in a time comparable to the decay time of the principal radiogenic isotopes. We find that a cold interior (large η) can hinder runaway differentiation unless radiogenic heating can thaw the deep interior. This can work because energy transport by conduction into the satellite interior is inefficient, and the settling time of rock in the deep interior can be comparable to the lifetime of Titan. Our preliminary results based on an admittedly heuristic treatment of silicate settling suggest that significant effort will need to be devoted to the dynamics of core overturn in the deep interior before we can gain confidence in our interpretation of Titan's state of differentiation based on its present MOI. We leave a more rigorous treatment of this problem for future work.

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