EVOLUTION AND INTERIOR STRUCTURE OF TITAN. G. Mitri[1], R. T. Pappalardo[2], and D. J. Stevenson[1], [1]Division of Geological and Planetary Sciences, California Institute of Technology (mitri@gps.caltech.edu), [2]Jet Propulsion Laboratory, California Institute of Technology.

Introduction: Doppler data tracking from four flybys of the Cassini spacecraft was used by Iess et al. (2009) to determine the second-degree gravitational coefficients J_2 and C_{22} [1]. Here we model the accretion, evolution and interior structure of Titan, using the gravity data as constraints.

Two-Layer Model: The gravitational constant G times mass M of Titan is $GM = 8.97819\cdot10^{12}$ m^3 s^{-2}, the mean satellite radius is $R_T = 2{,}575$ km, and the mean density is 1,881 kg m^{-3}. We use the value of the axial moment of inertia as inferred by the gravity coefficients and hydrostatic equilibrium theory [1] as our primary constraints. We consider a two-layer model with an inner and an outer layer mainly composed of water in liquid and solid phases. The high pressure polymorph ices that might form at the base of the outer layer have phases III, V and VI. The model considers the pressure dependence of the ices I, III, V and VI, and of liquid water, and the possibility that ammonia might be present in a subsurface liquid layer. We find that the deep interior layer has radius of ~2,050 km and has a relatively low density of ~2,600 kg m^{-3}. Such low density enhances the hypothesis that the deep interior is composed of a mixture of rocks and water ices, indicating the partial differentiation of the interior [cf. 2]. If Titan is partially differentiated, then the interior must avoid melting of the ice and desegregation of rock from water during its evolution.

Accretion: We model accretional heating of a growing Titan to determine the formation conditions that can permit a partially differentiated interior. The gravitational binding energy, $E = (3/5)(GM^2/R_T) \sim 2.8\cdot10^{29}$ J, gives a first order estimate of the total amount of energy involved during the accretion of Titan. If all the binding energy is transformed into thermal energy, then the heat produced during the accretion is larger than the required heat to melt Titan's interior $\sim 4\cdot10^{28}$ J, assuming a latent heat of melting equal to that of the water ice ($3\cdot10^5$ J kg^{-1}). However, just a fraction of the accretional energy is transformed into heat: part of the accretional energy is released from Titan's surface as radiant energy. The release of accretional energy by radiation is facilitated if Titan's accretion occurred on a long timescale, as shown in other accretion models [e.g. 3,4].

Titan is likely formed by a large number of impact events. The resulting heat is transported in the growing Titan at a characteristic length $l \sim \sqrt{\kappa\tau_{accr}}$, where κ is the thermal diffusivity (~10^{-6} m^2 s^{-1}) and τ_{accr} is the time scale of accretion. In the range of the accretion times 10^4 yr < τ_{accr} < 10^6 yr, the heat is transported at a characteristic length scale 1 km < l < 6 km. Because of the small heat characteristic length l, we can neglect the dependence on time of the interior temperature during the accretion. Then we can write the energy balance in a growing Titan with radius $r = r(t)$ as

$$\rho c_p\left(T_r - T_{disk}\right)\frac{dr}{dt} = (1-h)\frac{4}{3}\pi G\rho^2 r^2\frac{dr}{dt} - \varepsilon\sigma\left(T_r^4 - T_{disk}^4\right) \quad (1)$$

where ρ is the density; c_p is the specific heat (~1,500 J kg^{-1} K^{-1}); G is the gravitational constant; t is time; T_r is the surface temperature of the growing Titan; and T_{disk} is the temperature of the proto-Titan nebula (T_{disk} ~100 K [5]). The parameter h is introduced to account for the impact energy distributed on the surface and in the interior layers [6]. A plausible range for the values of h are between 0 and 0.5 [7]; for h = 0 the kinetic energy after the impacts is uniformly distributed on a superficial thin layer. Eq. 1 considers that part of the binding energy which is radiated from the surface, is equal to $\pi r^2\sigma T_r^4$, and that part from the accretional disk of Titan radiates with an energy equal to $\pi r^2\sigma T_{disk}^4$, where σ is the Stefan-Boltzmann constant. ε is the surface thermal emissivity. For a body without an atmosphere, ε ~1.

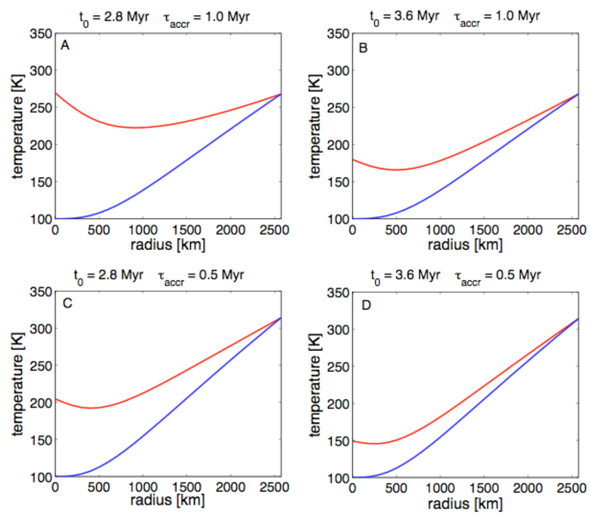

Fig. 1. *Temperature profile of Titan's interior after accretion for different values of the start time of accretion t_0 and the accretion time τ_{accr}. The time t = 0 is the time of the onset of the calcium-aluminum-rich inclusions (CAIs). The blue curves are the temperature profile for a model without radiogenic heating and the red curves include radiogenic heating. The model considers that the energy after impacts is uniformly distributed on a superficial thin layer (h = 0).*

Radiogenic decay will contribute to heat within the interior of Titan during accretion. In particular, short-lived radioisotopes ^{26}Al and ^{60}Fe could have provided large amounts of heating during the early period of Titan's evolution. The internal temperature (T_i) variation is given by

$$T_i = T_r + \frac{1}{c_p}\int_{t_0+\Delta t_r}^{t_0+\tau_{accr}} H(t)\,dt \quad (2)$$

where Δt_r ($0 \le \Delta t_r \le \tau_{accr}$) is the amount of time after the start time of accretion (t_0) and the growing Titan has radius r ($0 \le r \le R_T$). We consider the radiogenic heating rate $H(t)$ for CI chondrite with isotopes ^{238}U, ^{235}U, ^{232}Th, ^{40}K, ^{26}Al and ^{60}Fe. The time t_{CAI} = 0 represents the onset of the calcium-aluminum-rich inclusions (CAIs), and t_0 is the start-time of the accretion.

Fig. 1 shows the interior temperature of Titan at the end of accretion for model with radiogenic heating (red curves) and without (blue curves). Panel A is for $\tau_{accr} = 1 \cdot 10^6$ yr and $t_o = 2.8 \cdot 10^6$ yr; Panel B is for $\tau_{accr} = 1 \cdot 10^6$ yr and $t_o = 3.6 \cdot 10^6$ yr; Panel C is for $\tau_{accr} = 0.5 \cdot 10^6$ yr and $t_o = 2.8 \cdot 10^6$ yr; and Panel D is for $\tau_{accr} = 0.5 \cdot 10^6$ yr and $t_o = 3.6 \cdot 10^6$ yr. Fig. 1 shows that increasing the start time of accretion (t_0) decreases the total power of heat produced by radiogenic decay, thereby cooling the interior of Titan. An inspection of Fig. 1 shows that increasing the total accretion time (τ_{accr}) (neglecting the radiogenic heating; blue curves), increases the energy radiated from the surface, which would have a cooling effect on Titan. However, increasing the total accretion time (τ_{accr}) also increases the total power of heat produced by radiogenic decay (Eq. 2), thereby resulting in an overall heating of the interior of Titan (red curves). We found that Titan can avoid melting of the interior if it was formed relatively late $t_0 \geq 2.6 \cdot 10^6$ yr to avoid the presence of short-lived radioisotopes (^{26}Al), and the accretion occurred on timescale $\tau_{accr} \geq 1 \cdot 10^5$ yr.

Thermal Evolution: In the previous paragraph we discussed how Titan might avoid melting and differentiation during accretion. Even if the radiogenic heating declines over time, the interior might undergo a significant increase of its temperature after accretion, if the heat generated in the interior is not efficiently transported to the surface. This could potentially produce melting and differentiation. The interior temperature (T_i) during interior evolution can be described by solving the differential equation

$$\rho c_p V \frac{dT_i}{dt} = \rho V H(t) - 4\pi R_i^2 F(t) \qquad (3)$$

where V is the volume of the interior, $H(t)$ is the radiogenic heating, and $F(t)$ is the heat flux through the surface of the deep interior layer with radius R_i. The heat flux F is given by $F = K(\Delta T / R_i) Nu$, where K is the thermal conductivity, ΔT is the difference of temperature across the layer, and Nu is the Nusselt number. We adopt the scaling law for thermal convection as in [8]. For a high Rayleigh number (>10^8), the heat flux is given by

$$F = 0.52K \left(\frac{RT_i}{1.2Q}\right)^{4/3} \left(\frac{\alpha \rho g}{\kappa \eta_i}\right)^{1/3} \qquad (4)$$

where R is the gas constant, Q is the activation energy of ice (~60 kJ mol^{-1}), α is the thermal expansivity, and g is the gravity at the surface of the deep interior layer. Note that the heat flux for a high Rayleigh number does not depend on the difference of temperature ΔT and the radius R_i. The temperature T_i is the adiabatic temperature of the convective sublayer of the deep interior layer of Titan, and η_i is the viscosity in the interior. We consider that diffusion creep is the dominant creep mechanism of water ice. In a mixture of ice and rock, the impurities within the water ice prevent the movement of dislocations. Macroscopically this will produce an increase of viscosity given by

$$\eta_i = \eta_0 \left(1 + 2.5\Phi + 10.05\Phi^2 + 0.00273 e^{16.6\Phi}\right) \qquad (5)$$

where Φ is the rock's volume fraction and η_0 is the viscosity of pure water ice [9].

Fig. 2 shows the evolution of the interior temperature T_i from the end of accretion to 4.6 Gyr (Panel A). The simulation in Fig. 2 adopts as an initial temperature the interior temperature at the end of accretion, as in Fig. 1. The total power of radiogenic heating is shown in Panel B. The interior temperature reaches a maximum of ~275 K at ~0.3 Gyr after accretion; this is below the melting temperature of high pressure ices. Then the interior cools down, until a temperature of 240 K is reached at the present, for a total radiogenic power of ~0.3 TW.

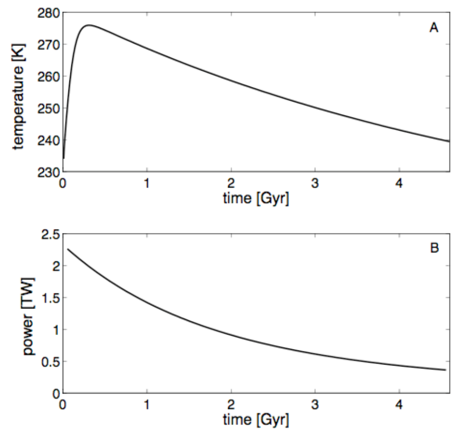

Fig. 2. *Panel A is the evolution of the interior temperature of Titan after accretion to 4.6 Gyr. Panel B is the evolution of the radiogenic heating power.*

Conclusions: The moment of inertia as inferred by gravity data [1] indicates that Titan might be partially differentiated with a deep interior layer of radius ~2,050 km, composed of a mixture of rock and ice. If Titan is partially differentiated, in order to avoid melting and complete desegregation of rock and ice, we have shown that the icy satellite must be formed relatively late $t_0 \geq 2.6 \cdot 10^6$ yr after the calcium-aluminum-rich inclusions (CAIs), and the accretion must have occurred on a timescale $\tau_{accr} \geq 1 \cdot 10^5$ yr. We also show that post-accretion, Titan can undergo significant heating of the interior, potentially producing melting and differentiation. Nevertheless, we show that under a range of conditions Titan can avoid melting during all of its evolution.

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