FORMATION AND EARLY EVOLUTION OF AN UNDIFFERENTIATED TITAN. Robert I. Citron[1,2], Amy C. Barr[2,3], and Robin M. Canup[2,3], [1]Laboratory for Atmospheric and Space Science, University of Colorado, Boulder, CO 80309 (robert.citron@colorado.edu); [2]Center for Lunar Origin and Evolution, Southwest Research Institute, 1050 Walnut St. Suite 300, Boulder, CO 80302; [3]Department of Space Studies, Southwest Research Institute.

Introduction: The interior state of Titan is important to understanding the formation and evolution of the saturnian system [1,2]. Predictions about the amount of ice/rock separation in Titan during its formation and early evolution can guide future interpretations of its moment of inertia (MOI), when those data become available. We examine the conditions of Titan's formation, and ice/rock separation due to hypervelocity impacts during an outer solar system late heavy bombardment (LHB) predicted by recently proposed scenarios for the dynamical evolution of the outer solar system [3,4]. We show that Titan can accrete undifferentiated in a gas starved disk, even with modest amounts of ammonia mixed in with its ice, and that Titan can remain partially differentiated after an outer Solar System LHB [2].

Accretion: We calculate accretional temperature profiles for Titan by balancing radiation from its surface, heating of impacted material from its initial temperature (which we assume has the same temperature as the disk T_D), accretional heating, and ^{26}Al heating [1,2]. To determine whether melting and ice-rock separation occurs during formation, we compare accretional temperature profiles to the pressure-dependent melting point of water ice and ammonia-water ice mixtures. We find that a pure water ice Titan must finish forming no earlier than 4.26 Myr after CAI formation for T_D = 100 K to avoid melting [2], and that it must accrete slowly, in > 0.8 Myr. Such conditions are plausible in the Canup-Ward satellite origin model [5]. Small concentrations of ammonia, <15%, have a modest effect on the accretion timescale and endpoint needed for the formation of an unmelted Titan.

Late Heavy Bombardment: A leading theory for the origin of impactors onto Earth's moon during the Late Heavy Bombardment suggests that the event was triggered by early dynamical interactions between the outer planets and a disk of icy planetesimals [3,4]. An outer solar system LHB would also produce an intense bombardment of the saturnian satellites because of the gravitational focusing by Saturn. In an outer solar system LHB, Titan is hit with ~3×10^{23} g of cometary material with $\langle v_p \rangle$ ~ 10.5 km/s and $\langle r_p \rangle$ ~ 30 km [4,6,7]. The effect of an outer solar system LHB on the interior state of Titan remains unaddressed, but could affect its interior state and long-term thermal evolution.

Impact Induced Core Formation We use a numerical model developed by Barr and Canup [7] to simulate impact-induced core formation on Titan for a range of different LHB masses. The interior or Titan is represented by ~4×10^7 cubical elements with sides of 15 km, that initially contain a uniform volume fraction of rock, $\varphi_0=(\rho-\rho_i)/(\rho_r-\rho_i)$ with mean density ρ=1.8794 g/cm^3, rock density ρ_r=3.0 g/cm^3, and ice density ρ_i=1.4 g/cm^3 to account for solid/solid phase transitions and compression at depth.

For the several thousand impactors that hit Titan, a Monte Carlo approach is used to select random impact angle, position, v_i and r_p from a realistic distribution of impactors. Impact velocities are Rayleigh-distributed with the most likely value $\langle v_i \rangle$ = 10.5 km/s [6]. Because an outer solar system LHB is thought to populate Jupiter's Trojan asteroids [4], impactor radii are drawn from a double-power law size distribution constrained by that population: for small impactors, $dN_{sm}/dr \propto r^{-3}$, and for large impactors, $dN_{bg}/dr \propto r^{-6.5}$. We examine two cases where the division between large and small impactors occurs at absolute magnitude V=10, r_0=47 km, and at V=9, r_0=28 km, resulting in a mean projectile radius of 30 km and 20 km respectively.

Each hypervelocity impact drawn from the above distribution induces melting in a roughly hemispherical region beneath the impact site. The size and depth of burial of the melted region is constrained by numerical simulations of ice/ice impacts [7]. In locations where the volume fraction of the melt is >50% post-impact, the rock particles in the region to sink to the bottom of the melt pool [9], where they coalesce and rapidly sink to the core of the satellite within a few thousand years (much less than the duration of the LHB). We use the method described in [7] to sum the volume fraction of rock from impact-melted elements that is added to the core during each impact.

The transfer of rock mass from the outer mantle of the satellite to the core generates heat from the liberated gravitational potential energy. If the energy released by the impact-induced ice/rock separation is sufficient to melt the remainder of the satellite's ice, the process becomes energetically self-sustaining and will drive itself to completion (so-called "runaway differentiation") [10]. A simple estimate is that runaway differentiation occurs if $f_m = \Delta E_{gr}/(1-m_r)(1-x^3/\varphi_0) > 1$ where ΔE_{gr} is the difference in gravitational potential energy between the initial uniform-density and final differentiated states, φ_0 is the bulk volume fraction of the rock in the satellite's interior, and x is the fractional radius of the rocky core ($x \equiv R_{core}/R$). We calculate values of f_m using $E_{gr,f} = \int(Gm/r(m))dm$ based on the model satellite's final heterogeneous density structure, and $E_{gr,i} = -(3/5)GM^2/R$. For each LHB mass we calculate one hundred bombardment histories to determine the probability of runaway differentiation.

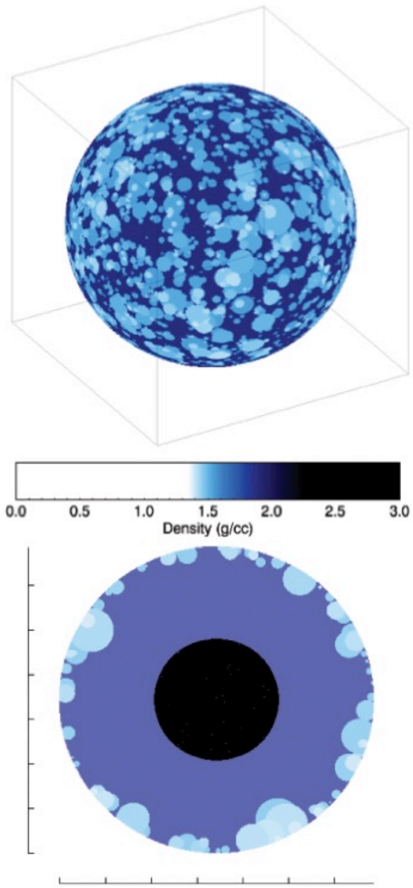

Figure 1. (top) Post-LHB density of Titan's surface as a function of latitude and longitude for our nominal ice/rock composition model and $\langle r_p \rangle$ = 30 km and M_D=20$M_\oplus$. Dark blue indicates ρ=1.88 g/cm^3, black indicates ρ=3.0 g/cm^3, and light blue indicates rock-free ice ρ=1.4 g/cm^3. (bottom) Slice through globe illustrating Titan's partially differentiated state post-LHB, with a rocky core (black), ice/rock mantle (blue), and ice-rich surface (light blue).

Results: Figure 2 illustrates that there is a > 99% probability Titan avoids runaway differentiation for $M^T_{LHB} \leq 4.8 \times 10^{23}$ g corresponding to a pre-LHB disk mass $M_D \leq 32 M_\oplus$ and initial disk mass $M_I \leq 56\ M_\oplus$. The conclusions are unchanged if the ice/rock densities are varied. This is well above the limit necessary to avoid completely differentiating Callisto ($M_D < 21\ M_\oplus$) [7].

We also compute the final moment of inertia of Titan for various initial disk masses (Figure 2). If Titan accretes undifferentiated and suffers a Nice-model outer solar system LHB (M_D = 20 $M_\oplus$), an upper limit on Titan's final MOI, not accounting for compression of ice and rock at depth, is 0.38. By analogy with the moment of inertia of Callisto, which has a similar size and mean density to Titan, we estimate that compression could reduce Titan's MOI by ~ 5% [11] to 0.36. Titan should have a rock core ≥ 0.4 R_{Titan}.

We find that a partially differentiated Titan is consistent with its formation in a gas starved disk and a LHB of the magnitude suggested by the *Nice* model.

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References: [1] Barr, A. C. & Canup, R. M., *Icarus,* 198, 163-177, 2008; [2] Barr, A. C. et al., *Icarus,* submitted, 2010; [3] Levison, H. F. et al., *Icarus,* 151, 286-306, 2001; [4] Gomes, R. et al., *Nature,* 435, 466-469, 2005; [5] Canup, R. M. & Ward, W. R., *Astron. J.* 124, 3404-3423, 2002; [6] Zahnle, K. et al., *Icarus,* 163, 263-289, 2003; [7] Barr, A. C. & Canup, R. M., *Nature Geoscience,* in press; [8] Canup, R. M. & Ward, W. R., *Nature,* 441, 834-839, 2006; [9] Reese, C. C. & Solomatov, V., S., *Icarus,* 184, 102-120, 2006; [10] Friedson, A. J. & Stevenson, D.J., *Icarus,* 56, 1-14, 1983; [11] McKinnon, W. B., *Icarus,* 130, 540-543, 1997.

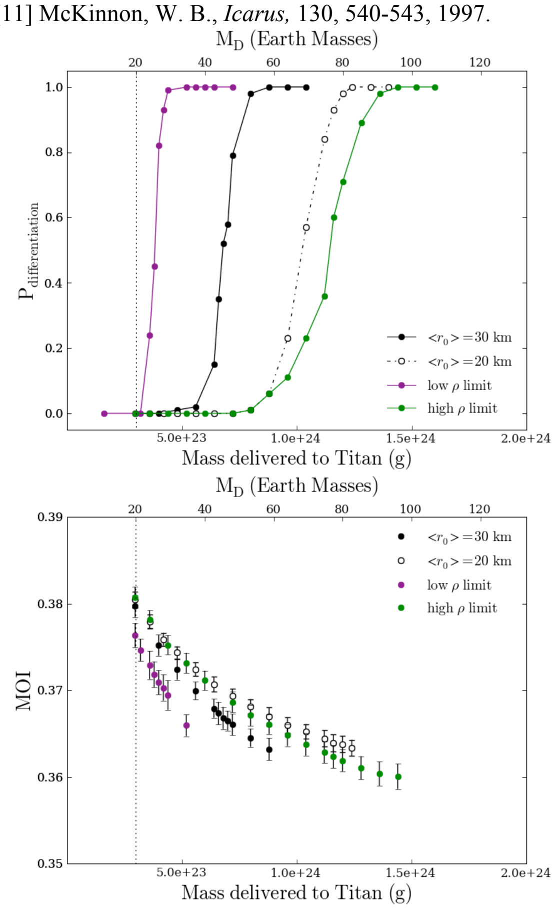

Figure 2. (top) Probability of runaway differentiation in Titan for $\langle r_p \rangle$=30 km, ρ_i=1.4 g/cm^3, and ρ_r=3.0 g/cm^3 (black), $\langle r_p \rangle$=20 km (gray), ρ_i = 1.2 g/cm^3 and ρ_r = 2.8 (purple), and ρ_i=1.5 g/cm^3, and ρ_r=3.8 (green). (bottom) Average MOI of Titan produced from partial differentiation during the LHB. Dotted line corresponds to the nominal Nice model LHB.