**Note**

**Origin of a partially differentiated Titan**

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**Abstract**

Accretional temperature profiles for Saturn’s large moon Titan are used to determine the conditions needed for accretion to avoid global melting as a function of the timing, duration, and nebular conditions of Titan’s accretion. We find that Titan can accrete undifferentiated in a “gas-starved” disk even with modest quantities of ammonia mixed in with its ices. Simulations of impact-induced core formation are used to show that Titan can remain partially differentiated after an outer Solar System late heavy bombardment capable of melting its outer layers, permitting some of its rock to consolidate into a core.

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**1. Introduction**

Titan’s interior state is important to interpretation of radio tracking data (less et al., 2010), its spin state (Stiles et al., 2008, 2010; Bills and Nimmo, 2008), and its atmospheric composition (Tobie et al., 2006). Here, we use recent models of satellite formation (Canup and Ward, 2002, 2006; Barr and Canup, 2008) to assess whether Titan can avoid fully differentiating while it accretes. We use geophysical models of impact-induced core formation in icy satellites (Barr and Canup, 2010) to assess whether Titan can remain partially differentiated after an outer Solar System late heavy bombardment (LHB) predicted by recently proposed scenarios for the dynamical evolution of the outer Solar System (Levison et al., 2001; Tsiganis et al., 2005; Gomes et al., 2005).

**2. Titan can accrete undifferentiated**

Historically, satellite formation models focus on the evolution of a minimum-mass nebula sub nebula (MMSN), wherein the masses of the currently observed satellites are combined with gas to create a massive solar-composition disk around the parent planet. MMSN models predict dense, gas-rich protosatellite disks and rapid formation of satellites whose interiors are heated close to, or well above their melting points (Stevenson et al., 1986, Schubert et al., 1986; Squyres et al., 1988; Canup and Ward, 2002; Barr and Canup, 2008; Canup and Ward, 2002) instead proposed satellite growth in a “gas-starved” disk supplied by the slow inflow of gas and <1 m-sized rock and ice particles from solar to planetary orbit. In the Canup and Ward model, the jovian and saturnian satellites form during the waning stages of gas accretion by the planets, implying that the observed satellites form in much lower-density disks than the MMSN, and that the satellites accrete in $10^{-6}$ to $10^{-5}$ yr, at a rate controlled by the supply of ice/rock solids to the disk from the solar nebula (Canup and Ward, 2002, 2006, 2009; Barr and Canup, 2008).

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mid-way between the density of Prim-Feegley rock and Cl chondrite, two endmember compositions for the rocky component of Callisto used by Mueller and McKinnon (1988). The ice density, \( \rho_i = 1.4 \text{ g/cm}^3 \), is chosen to represent the compressed densities of the water ice phases V-VII, whose densities at atmospheric pressure range from 1.2 to 1.5 g/cm\(^3\) (Hobbs, 1974), which may exist deep in Titan's interior. With these densities, Titan has \( m_r = 0.48 \). The specific heat, \( C_p \approx m_r C_{p,i} \approx (1 - m) C_{p,i} = 1.429 \times 10^7 \text{ erg/g K} \), where the specific heat of rock \( C_{p,i} = 7 \times 10^6 \text{ erg/g K} \) and the specific heat of ice \( C_{p,i} = 2.1 \times 10^7 \text{ erg/g K} \).

To determine whether melting occurs, we compare accretional temperature profiles generated using Eqs. (1) and (2) to the pressure-dependent melting point of water ice, \( T_{\text{m}} \). Data from Hobbs (1974) are used to construct \( T_{\text{m}}(P) \) as a function of depth in the satellite (Barr and Canup, 2008), and the interior pressure \( P \) at radius \( r \) from the satellite's center is calculated assuming the unmelted satellite has a uniform density, \( \rho(r,t) = (\Sigma A_i) 3^{1/3} G (r^2 - r_0^2) / (2 \pi r_0^2) \), where \( T_0 = 273.2 \text{ K} \), \( A = -7.95 \times 10^{-8} \text{ K} \) if Poise, \( B = -9.6 \times 10^{-8} \text{ K} \) if Poise\(^2 \), \( C = 53.8 \), \( D = 650 \), and \( 0 < X < 1 \) is the ammonia concentration by mass. During accretion, the satellite is heated at its surface by impacts, the temperature increases as a function of radius and is highest at the surface. Thus, melting is most likely to occur first at the ice l–III phase boundary at a depth of \( \approx 100 \text{ km} \) in Titan, and we do not include the effect of ammonia on the melting points of the high-pressure ice phases (Grasset and Pargamin, 2005). We check for melting by comparing \( T(r) - T_d \) to the pressure-dependent melting curves in the satellite after the accretion of each layer. We then identify conditions necessary to avoid melting during accretion and yield an initially undifferentiated Titan.

2.2. Results

Solution of Eq. (1) in the absence of radiogenic heating (Barr and Canup, 2008).

\[
\tau_{\text{acc,min}} = \frac{\rho_i}{(1 - m) C_{p,i} / C_0 + \rho_r G p^2 - C_r (T_d - T_r)} \frac{3 \pi G m_r}{3 \pi G m_r + 3 \pi G m_r}
\]

to give the absolute minimum accretion time scale for formation of an undifferentiated Titan, \( \tau_{\text{acc,min}} \). For Titan to avoid accretional melting, \( T_d \geq 253 \text{ K} \) at a depth of \( 1000 \text{ km} \) when it reaches its final radius \( R_s = 2575 \text{ km} \) (i.e., \( r_s = 2475 \text{ km} \)). This implies \( \tau_{\text{acc,min}} \geq 0.8 \text{ Myr} \) for \( T_d = 100 \text{ K} \). If the impacts that assemble Titan deposit accretional energy at depth, if Titan accretes in a gas-rich environment, has ammonia in its interior, and/or experiences radiogenic heating, longer accretional time scales are required to avoid large-scale melting during formation. Fig. 1a illustrates how \( \tau_{\text{acc,min}} \) varies as a function of \( T_d \) and ammonia concentration in the absence of radiogenic heating. If the ammonia concentration for Titan is \( \approx 15\% \), \( \tau_{\text{acc,min}} \geq 1.3 \text{ Myr} \) is required to avoid complete ice/ammonia melting for \( T_d = 100 \text{ K} \).

Fig. 1b–d illustrates constraints on the timing and duration of formation of an undifferentiated Titan as a function of \( T_d \), \( \tau_{\text{acc}}, \) and \( X \). Considering accretional and radiogenic heating, a Titan without ammonia (\( X = 0 \)) must finish forming no earlier than \( t_{\text{end}} = 4.26 \text{ Myr} \) after CAI formation to avoid melting during accretion for \( T_d = 100 \text{ K} \). For \( T_d = 70 \text{ K}, t_{\text{end}} \geq 4.1 \text{ Myr} \) to avoid melting. The corresponding accretional time scale for Titan must be \( \geq 0.8 \text{ Myr} \) for \( T_d > 70 \text{ K} \). If Titan contains 5% ammonia by mass, the lowest temperature for complete melting of its outer icy layers is \( T_m = 248 \text{ K} \) at \( 209 \text{ MPa} \) (compared to \( T_m = 253 \text{ K} \) for pure water ice). In this case, to avoid melting, Titan must finish forming no earlier than \( 4.33 \text{ Myr} \) for \( T_d = 100 \text{ K} \). If Titan contains 15% ammonia by mass, it must finish forming no earlier than \( 4.8 \text{ Myr} \) after CAI's for \( T_d = 100 \text{ K} \).

In addition to accreting slowly, an undifferentiated Titan must also be assembled from objects small enough to deposit their energy in a boundary layer close to the surface where it can be removed by radiation between successive overlapping impacts (an implicit assumption of Eq. (1)). Small impactors, \( \approx 50–100 \text{ m} \) in radius, are likely in the Canup and Ward model (see Appendix B of Barr and Canup, 2008). If impactors are large, and a significant fraction of impact energy is deposited at depth, longer accretion time scales and later accretion are required (Barr and Canup, 2008).
Titan must also be assembled from objects which are themselves undifferentiated, containing small rock grains rather than large fully formed rock cores in order to form in an undifferentiated state (Barr and Canup, 2008). These conditions are implicit assumptions of Eqs. (1) and (2).

3. Titan remains partially differentiated after the late heavy bombardment

A leading theory is that the lunar late heavy bombardment (LHB) was triggered by the dynamical evolution of the outer Solar System (Levison et al., 2001; Gomes et al., 2005). In the so-called Nice model, gravitational interactions between the four outer planets and a ~35M⊕ disk of icy planetesimals drives the outer planets to migrate to their current orbits (Tsiganis et al., 2005). It has been proposed that ~70–90% of the present-day Saturn and planet formation, Jupiter and Saturn cross a mutual mean-motion resonance, destabilizing the planetesimal disk (which has been depleted to \( M_o = 20M_0 \)), at the time of the LHB, and causing 8 x 10^{21} g of cometary material, and a comparable mass of asteroids, to impact Earth’s Moon over a 10–100 Myr time span (Gomes et al., 2005).

Any model that invokes an outer Solar System source for the LHB will produce an intense bombardment of Titan. During an outer Solar System LHB, Titan would receive an impacting mass ~35 times larger than Earth’s Moon (Zahnle et al., 2003), or \( M_{mhd} = 3 \times 10^{19} g \) due to gravitational focusing by Saturn. The cometary impactors originate in heliocentric orbit and impact Titan with \( \langle v_i \rangle = 10.5 \text{ km/s} \) (Zahnle et al., 2003) and deposit their impact energy at depth in the satellite, in contrast to smaller and low-velocity impactors during its accretion. Such large LHB impacts (see below) would melt the outer layers of Titan, permitting any rock suspended in the ice to sink rapidly to its center, creating a rock core (Tonks et al., 1997; Barr and Canup, 2010). If enough potential energy is released by partial melting at the impact site, the accreted rock and ice will form a differentiated state (Barr and Canup, 2008). If satellite formation occurred at Saturn at the same time or later as at Jupiter, it is likely that the outer Solar System LHB of magnitude and distribution predicted by the Nice model would accrete Titan undifferentiated if it forms slowly and from small impactors. We assume that Titan initially contained a uniform rock volume fraction \( 0.3 \), and rock fraction \( D_{\text{Ti}} = 3.8 \text{ g/cm}^3 \). (Mueller and McKinnon, 2001), representative of the compressed densities of the high-pressure ice polymorphs, and a plausible upper limit on the density of Titan’s rock, \( D_{\text{Ti}} = 20 \text{ K} \) (Barr and Canup, 2008).

3.1. Results

Fig. 2 illustrates that an initially undifferentiated Titan has a >99% probability of avoiding runaway differentiation for \( M_{mhd} < 4.8 \times 10^{20} \text{ g} \). This corresponds to an icy planetesimal disk mass at the time of the LHB, \( M_o < 32 M_{\text{J}} \), where \( M_o \approx (M_{mhd}/1.5 \times 10^{20} g) M_{\text{J}} \). Our prior work shows that Callisto avoids complete differentiation if \( M_o < 21 M_{\text{J}} \). Barr and Canup (2010) concluded that Titan avoids differentiation during an outer Solar System LHB of magnitude and distribution predicted by the Nice model.

The likelihood of avoiding complete differentiation during a Nice-model LHB is only weakly dependent on the assumed ice/rock density and the size distribution of impactors. If the size distribution of LHB impactors changes slope at absolute magnitude \( V > 10 \), \( r_p = 20 \text{ km} \). Fig. 2 shows that \( M_{mhd} \) > predicted by the Nice model is required to trigger runaway differentiation if the impactors are this small. In our “low-density” model, a lower limit for the density of Titan’s ice, \( D_{\text{ic}} = 1.2 \text{ g/cm}^3 \), is paired with the density of CI chondrite, \( D_{\text{ci}} = 2.8 \text{ g/cm}^3 \) (Mueller and McKinnon, 1988) to give \( D_{\text{ic}} = 0.43 \). In our “high-density” model, \( D_{\text{ic}} = 1.5 \text{ g/cm}^3 \), representative of the compressed densities of the high-pressure ice polymorphs, and a plausible upper limit on the density of Titan’s rock, \( D_{\text{ic}} = 3.8 \text{ g/cm}^3 \). Fig. 2 illustrates that regardless of assumed ice/rock densities, a Nice-model LHB does not fully differentiate Titan. Fig. 2 shows a sample partially differentiated Titan interior resulting from a nominal Nice-model LHB.

4. Discussion

We find that the timing and duration of formation required for an undifferentiated Titan is similar to the timetable required to accrete an undifferentiated Callisto (Barr and Canup, 2008). If satellite formation occurred at Saturn at the same time or later as at Jupiter, and over comparable or slower timescales, an undifferentiated Titan would be accreted from impactors which are themselves undifferentiated, containing small rock grains rather than large fully formed rock cores in order to form in an undifferentiated state (Barr and Canup, 2008). These conditions are implicit assumptions of Eqs. (1) and (2). Titan is buried at depth (~10 km) (Zahnle et al., 2003), or \( M_{mhd} = 3 \times 10^{19} g \) due to gravitational focusing by Saturn. The cometary impactors originate in heliocentric orbit and impact Titan with \( \langle v_i \rangle = 10.5 \text{ km/s} \) (Zahnle et al., 2003) and deposit their impact energy at depth in the satellite, in contrast to smaller and low-velocity impactors during its accretion. Such large LHB impacts (see below) would melt the outer layers of Titan, permitting any rock suspended in the ice to sink rapidly to its center, creating a rock core (Tonks et al., 1997; Barr and Canup, 2010). If enough potential energy is released by partial melting at the impact site, the accreted rock and ice will form a differentiated state (Barr and Canup, 2008). If satellite formation occurred at Saturn at the same time or later as at Jupiter, it is likely that the outer Solar System LHB of magnitude and distribution predicted by the Nice model would accrete Titan undifferentiated if it forms slowly and from small impactors. We assume that Titan initially contained a uniform rock volume fraction \( 0.3 \), and rock fraction \( D_{\text{Ti}} = 3.8 \text{ g/cm}^3 \). (Mueller and McKinnon, 2001), representative of the compressed densities of the high-pressure ice polymorphs, and a plausible upper limit on the density of Titan’s rock, \( D_{\text{Ti}} = 20 \text{ K} \) (Barr and Canup, 2008).

3.1. Methods

We use a numerical model of impact-induced core formation in an icy satellite developed by Barr and Canup (2010) to simulate the effect of an outer Solar System LHB on Titan for a range of LHB masses. As per arguments in Section 2, Titan may accrete undifferentiated if it forms slowly and from small impactors. We assume an initially uniform-density ice/rock Titan with rock density \( \rho_i = 3.0 \text{ g/cm}^3 \), ice density \( \rho_s = 1.4 \text{ g/cm}^3 \), and rock fraction \( D_{\text{Ti}} = 0.3 \).

Before the LHB, Titan’s interior must cool to avoid melting from long-lived radionuclides (cf., Friedson and Stevenson, 1983). During the period of time between the endpoint of accretion and the onset of convection, radiogenic heating will build up in its interior, however, it is unlikely that this will cause global melting. Over the first billion years of Solar System history, the decay of \( ^{40}K \rightarrow ^{40}Ca \) is the dominant contributor to radiogenic heating, providing \( q(t) = 1.43 \times 10^{-19} \text{ ergs/g per gram of Cl chondrite, decaying with a half-life of 1.39 Myr. The onset of convection in the outer ice shell of Titan may take (Zaremsky and Parmentier, 2004) \( t_m = 500 \). In our “high-density” model, \( \rho_i = 2.8 \text{ g/cm}^3 \) (Mueller and McKinnon, 1988) to give \( \rho_i = 0.43 \). In our “high-density” model, \( \rho_i = 1.5 \text{ g/cm}^3 \), representative of the compressed densities of the high-pressure ice polymorphs, and a plausible upper limit on the density of Titan’s rock, \( \rho_i = 3.8 \text{ g/cm}^3 \). Fig. 2 illustrates that regardless of assumed ice/rock densities, a Nice-model LHB does not fully differentiate Titan. Fig. 2 shows a sample partially differentiated Titan interior resulting from a nominal Nice-model LHB.
tiated interior state for Titan post-accretion can occur, although partially differentiated states could also result. Avoiding differentiation during accretion also requires that Titan form without a thick atmosphere (e.g., Stevenson et al., 1986) and from small planetocentric impactors. The formation of a mixed ice/rock Titan with limited accretional melting and vaporization lends support to a deep interior source for atmospheric methane, which could be liberated due to the satellite’s later interior evolution (Tobie et al., 2006). Formation of an undifferentiated Titan is precluded in an MMSN because of short accretion time scales (e.g., Stevenson et al., 1986).

An outer Solar System LHB implies that Titan was subjected to an intense bombardment from heliocentric impactors at velocities $v_{i} \sim 10 \text{ km/s}$ (Zahnle et al., 2003; Barr and Canup, 2010). For the LHB mass predicted by the Nice model, Titan remains only partially differentiated. These conclusions are robust against variations in the density of Titan's rock and ice, and plausible variations in the impactor size distribution. In the context of the Tobie et al. (2006) evolution scenario, LHB-induced formation could have squeezed out clathrate-rich ices from the primordial core, ~700 Myr after its formation, jump-starting the gradual liberation of methane into the atmosphere. Vigorous convection is required to prevent Titan from melting over its long term thermal evolution and remain partially differentiated at present (Friedson and Stevenson, 1983).

If the LHB had a significant outer Solar System source (Levison et al., 2001; Gomes et al., 2005), Titan should have an outer rock-poor layer, an ice/rock mantle, and a rocky core occupying at least 40% of its radius. By calculating the moment of inertia of model titans based on their heterogeneous post-LHB density structures (and neglecting compression of ice and rock at depth), we find that Titan's $CMR^2 \leq 0.38$ if an LHB of the magnitude predicted by the Nice model triggered partial differentiation. By analogy with Callisto, where compression of ice and rock decreases its $CMR^2$ by 5% (McKinnon, 1997), we estimate that compression may plausibly decrease the upper limit on Titan's $CMR^2$ to 0.36. Our estimates of Titan's $CMR^2$ are upper limits only: melting during Titan's formation and/or later thermal evolution can decrease the moment of inertia, plausibly to the estimated value, $CMR^2 = 0.3419 \pm 0.0005$ (Iess et al., 2010).

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References


Fig. 3. (a) Post-LHB density (colors) of Titan’s surface as a function of latitude and longitude for our nominal ice/rock composition model, $\rho_{i} = 30 \text{ km}$, and $M_{p} = 20 \text{ M}_{\text{J}}$. Dark blue indicates $\rho_{0} = 0.30$ and $\rho = 1.88 \text{ g/cm}^3$, black indicates $\rho = 3.0 \text{ g/cm}^3$, and light blue/white indicates rock-free ice $\rho = 1.4 \text{ g/cm}^3$. (b) Slice through the globe in (a), illustrating Titan’s partially differentiated state after the LHB, with a rocky core (black), ice/rock mantle (blue) and ice-rich upper surface (light blue/white).