Origin of a partially differentiated Titan

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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 (Toibie 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 subnebula (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, 2006). Canup and Ward (2002) instead proposed satellite growth in a "gas-starved" disk supplied by the slow inflow of gas and with <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 10^7-10^8 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).

Note

Keywords:
Titan
Saturn

References


2.1. Methods

We calculate accretion temperature profiles for Titan (final mass $M_T = 1.345 \times 10^{26}$ g and radius $R_T = 2575 $ km) by balancing radiation from its surface, heating of accreted material from its initial temperature (assumed to be the disk temperature, $T_d$) to the satellite surface temperature $T$ and accretional heating (Squyres et al., 1988; Barr and Canup, 2008),

$$ \dot{\rho} = \dot{\rho}_{esc} + \dot{\rho}_{acc} + \dot{\rho}_{runaway} \text{, with } \dot{\rho}_{acc} = \dot{\rho}_{q} + \dot{\rho}_{s} \text{,} $$

where $\dot{\rho}_{q} = \dot{\rho}_{tot} \int (T - T_d) \, dV$, $\dot{\rho}_{s}$ is the accretional heating rate, and $\dot{\rho}_{esc}$ is the escape rate.

After accretion, material at radius $r$ is heated by $\Delta T_r$,

$$ \Delta T_r(t) = \int_{t}^{\infty} m_q(t) \, dt = \int \frac{m_q(0)}{C_s(q)} \exp(-\frac{r}{C_s(q)}) \, dt, $$

due to radiogenic heating, where $m_q(0) = 1.8 \times 10^{-1} \text{ erg/g}$ is the $26$Al heating rate at the time of CAI formation (Barr and Canup, 2008) assuming initial $26$Al/$^{27}$Al = $5.85 \times 10^{-5}$ (Thranie et al., 2006), $C_s(q) = 9.68 \times 10^{-7} \text{ yr}^{-1}$, and $t(t)$ is the time at which a layer at radius $r$ forms, $t(t) = t_{acc} + t_{esc}(R_T)$ (Barr and Canup, 2008), where $t_{acc}$ is the time at which the satellite starts accreting relative to CAI formation. By integrating to $t = \infty$, we assume that all $26$Al heating is retained in the satellite (Barr and Canup, 2008). The rock mass fraction is $m_r = \rho_r / (\rho_r + \rho_i)$, where $\rho_r = 3.0 \text{ g/cm}^3$.}

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doi:10.1016/j.icarus.2010.05.028
mid-way between the density of Prinn–Fegley rock and CI 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 \text{ 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, \( C_p \approx m_r \), \( C_{p,i} \approx (1 - m_r) C_p \approx 1.429 \times 10^7 \text{ erg/g K} \), where the specific heat of rock \( C_p = 7 \times 10^7 \text{ erg/g K} \) and the specific heat of ice \( C_{p,i} \approx 2.1 \times 10^7 \text{ erg/g K} \).

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, \( T_m \). Data from Hobbs (1974) are used to construct \( T_m(P) \) 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, \( \rho(r, t) = 2(1/3)Gm(2/r - r') \), where \( r \) is the radius of the growing satellite at time \( t \) during accretion. The temperature at which an ice/ammonia mixture becomes completely melted is determined using \( T_m(P, X) = T_m + A P + B P^2 - C X - DX^2 \), where \( T_m = 273.2 \text{ K}, A = -7.95 \times 10^{-5} \text{ K/Poise}, B = 9.6 \times 10^{-19} \text{ K/Poise}^2, C = 53.8, D = 650, \) and \( 0 < X < 1 \) is the ammonia concentration by mass in the liquid phase (Lelwica-Kopystynski et al., 2002). During accretion when 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 I–III phase boundary at a depth of \( \sim 100 \) 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 \( T(r) + \Delta T \) 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).

\[
\tau_{\text{acc, min}} = \frac{1}{4} \frac{m_r}{\rho_i} \rho_i \frac{A P + B P^2 - C X - DX^2}{3P \left(T_m - T_d \right)}
\]

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} \sim 100 \text{ km when it reaches its final radius} R_i = 2575 \text{ km (i.e.,} r > 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}} \text{ varies as a function of} T_d \text{ and ammonia concentration in the absence of radiogenic heating. If the ammonia concentration for Titan} \sim 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 \( T_d \), \( T_{\text{end}} \), and \( X \). Considering accretional and radiogenic heating, a Titan without ammonia \((X = 0)\) must finish forming no earlier than \( \tau_{\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,} \tau_{\text{end}} > 4.1 \text{ Myr to avoid melting. The corresponding accretion time scale for Titan must be} \geq 0.8 \text{ Myr for} T_d > 70 \text{ K. If Titan contains} 5\% \text{ 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\% \text{ 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, \( \sim 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).}

![Fig. 1](image-url) Critical accretion time scales and endpoints of accretion (\( \tau_{\text{end}} \)) for formation of an undifferentiated Titan. (a) Minimum accretion time scale in the absence of radiogenic heating as a function of disk mid-plane temperature \( (T_d) \) and mass fraction of ammonia. (b) Earliest endpoint of accretion of an undifferentiated Titan as a function of \( T_d \) and \( \tau_{\text{end}} \). (c) Same as (b), but for 5% ammonia, which decreases the minimum melting temperature to 248 K at a depth of 100 km. (d) Same as (b), for 15% ammonia, which gives \( T_m \approx 230 \text{ K at} 100 \text{ km depth. As ammonia concentration is increased, accretion must occur more slowly and end later in Solar System history for Titan to remain undifferentiated during formation.}
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 planet formation, Jupiter and Saturn cross a mutual mean-motion resonance, destabilizing the planetesimal disk (which has been depleted to \( M_0 \approx 20M_\oplus \)) at the time of the LHB), and causing \( 8 \times 10^{17} \) 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 \( M_{\text{LHB}} \sim 3 \times 10^{17} \) g due to gravitational focusing by Saturn. The cometary impacts originate in heliocentric orbit and impact Titan with \((v_\text{impact}) \approx 10.5 \text{ km/s} \) (Zahnle et al., 2003) and deposit their impact energy at depth in the satellite, in contrast to smaller and low-velocity impacters during its accretion. Such large LHB im-

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 impacters. We assume an initially uniform-density ice/rock Titan with rock density \( \rho_\text{rock} = 3.0 \text{ g/cm}^3 \), \( \rho_i = 1.4 \text{ g/cm}^3 \), and rock fraction \( \phi_\text{rock} = 0.30 \).

Before the LHB, Titan's interior must cool to avoid melting from long-lived radioactive species (cf. Friedson and Stevenson, 1981). The time period during the time of the end 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 \( ^{40}\text{K} \rightarrow ^{40}\text{Ca} \) is the dominant contributor to radiogenic heating, providing \( q(\phi) = 1.43 \times 10^{-9} \text{ erg/g per gram of CI chondrite, decaying with a half-life of 1.39 \text{ yr}} \). The onset of convection in the outer ice shell of Titan may take (Zarneck and Parmentier, 2004) \( t_i = \left( \frac{500}{k_i} \right) \left[ \frac{(r_p \Delta T)/g}{(r_i \Delta T)/g} \right]^{2/3} \), with satellite density \( \rho_i = 1.88 \text{ g/cm}^3 \), coefficient of thermal expansion \( \alpha = 1 \times 10^{-4} \text{ K}^{-1} \), temperature difference driving convection \( \Delta T \sim 20 \text{ K} \) (Barr and Canup, 2008), gravity \( g \sim 130 \text{ cm/s}^2 \), ice viscosity \( \eta_i \), and thermal diffusivity \( \kappa_i \sim 10^{-6} \text{ cm}^2/\text{s} \). In the outer ice 1 shell, \( \eta_i \sim 10^{13} \text{ Pa} \cdot \text{s} \), implying \( \tau_i \sim 2 \times 10^5 \text{ yr} \). In the first 2 Myr after accretion, we estimate that Titan's interior warms by less than 1 K due to \( ^{40}\text{K} \) decay. In the deep interior, where the dominant ice phases have higher viscosities, and the local gravity is lower, it can take \( t_i \sim 100 \text{ Myr} \) to start convection (Barr and Canup, 2008). During this period, the temperature rise from \( ^{40}\text{K} \) is \(-10 \text{ K} \).

A Monte Carlo approach is used to select random impact angle, position, \( \theta \) and impactor radius \( r_i \). We set \((v_{\text{impact}}) = 10.5 \text{ km/s} \) (Zahnle et al., 2003). Because an outer Solar System LHB is thought to populate Jupiter’s trojan asteroids (Morbidelli et al., 2005), impactor radii are drawn from a double-power-law size distribution distribution 

strained by that population: for small impacters, \( dN/dR \propto R^{-2.5} \), and for large impacters, \( dN/dR \propto R^{-0.5} \) (Jewitt et al., 2000; Morbidelli et al., 2005). The division between large and small impacters occurs at an absolute visual magnitude \( V \approx 9 \).

Using an albedo \( C_{\text{rock}} = 0.056 \) (Morbidelli et al., 2005), this corresponds to a transition radius \( r_{\text{trans}} = 47 \text{ km} \). The most likely impactor size in the distribution is \( r_{\text{imp}} = 30 \text{ km} \).

Titan's interior is represented by \(-10^{15} \) cubic elements with sides of 15 km that initially contain a uniform rock volume fraction \( \phi_\text{rock} \). Each impact induces melting in a roughly spherical region beneath the impact site. We use the scaling relations from Barr and Canup (2010) to determine the radius of the region where the volume fraction of the melt is \( \geq 50\% \) post-impact. This degree of melting allows the rock particles in this region to sink to the bottom of the melt pool, where they coalesce and rapidly sink to the core of the satellite (e.g., Tonks et al., 1997) within a few thousand years (much less than the duration of the LHB Barr and Canup, 2010). The melted region is described by a sphere of radius \( r_{\text{melt}} = 4.09 \left( \eta_i/10^5 \text{ cm/s} \right)^{0.69} \) buried at depth \( z_{\text{melt}}(r_t) = 2.40 \left( \eta_i/105 \text{ km/s} \right)^{0.69} \) (Barr and Canup, 2010).

The core formation monolith sums the volume fraction of rock, \( \phi \), from impact-melted elements to determine the amount of rock added to the core from each impact. That amount of rock is removed from impact-melted elements in the icy mantle and new rock core elements are added to the core's outer edge, replacing ice/rock elements at the core's outer edge in a radially symmetric fashion. 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; Friedson and Stevenson, 1983). A simple estimate is that runaway differentiation of the entire satellite will occur if \( \Delta E_{\text{tot}} = 1 - M_\text{imp} \left( 1 - x \right) / M_\oplus \Delta E_\text{LHB} \), where \( \Delta E_\text{LHB} = E_\text{imp} - E_\text{sat} \) is the difference in gravitational potential energy between the initial uniform-density and final differentiated states (Friedson and Stevenson, 1983), \( L \sim 10^\text{3} \text{ erg/g} \) is a representative latent heat for the various water ice phases (Kirk and Stevenson, 1987), and \( x \) is the fractional radius of the rocky core \( (x = R_{\text{rock}}/R_\text{sat}) \). We calculate \( E_\text{imp} = (\gamma/3)(\rho_i/m)(d m/dt) \) based on the model satellite's final heterogeneous density structure, and \( E_\text{sat} = (4/3)\pi R_\text{sat}^3 \rho_\text{sat} \). The LHB impactors are delivered on a time scale short compared to solid-state heat transport, so these processes do not affect model outcomes and are not included (Barr and Canup, 2010). For each LHB mass we calculate 100 bombardment histories to determine the probability of runaway differentiation.

3.2. Results

Fig. 1 illustrates that an initially undifferentiated Titan has a 99.5% probability of avoiding runaway differentiation for \( M_{\text{LHB}} < 4 \times 10^6 \text{ g} \). This corresponds to an icy planetesimal disk mass at the time of the LHB, \( M_\text{LHB} < 32M_\oplus \), where \( M_\text{LHB} \approx \left( M_\text{sat}/10.5 \right)^2 \times 10^6 \text{ g} \). Our prior work shows that Callisto avoids complete differentiation if \( M_\text{LHB} < 21M_\oplus \). (Barr and Canup, 2010). Titan avoids runaway differ-

4. Discussion

We find that the timing and duration of formation required for an undifferen-
tiated 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 it did at Jupiter, and over comparable or slower timescales, an undifferen-

\[ A_{\text{rock}} = \frac{\pi}{6} \left( \frac{r_{\text{imp}}}{2} \right)^3 \]
tiliated 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 \( v_i / C_{24} = 10 \text{ km/s} \) (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-ice-rich phases from the primordial core, \( \sim 700 \text{ Myr} \) 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; Gomez 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 \( CJ/MR^2 \leq 0.38 \) 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 \( CJ/MR^2 \) by 5% (McKinnon, 1997), we estimate that compression may plausibly decrease the upper limit on Titan’s \( CJ/MR^2 \) to 0.36. Our estimates of Titan’s \( CJ/MR^2 \) 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, \( CJ/MR^2 = 0.3419 \pm 0.0005 \) (Iess et al., 2010).

**Acknowledgments**

Barr acknowledges NASA OPR NNX09AP30G. Citron acknowledges NASA GSRP NNX09AM18H and the NASA Lunar Science Institute. Canup acknowledges NASA OPR NNX08AQ06G. We thank G. Tobie and an anonymous reviewer for helpful comments.

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