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► **To cite this version:**

Julien Monteux, G. Tobie, Gael Choblet, M. Le Feuvre. Can large icy moons accrete undifferentiated?. Icarus, 2014, 237, pp.377-387. 10.1016/j.icarus.2014.04.041 . hal-01636068

HAL Id: hal-01636068

<https://uca.hal.science/hal-01636068v1>

Submitted on 17 Nov 2017

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1 Can Large Icy Moons Accrete Undifferentiated?

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5 Abstract

6 The apparent moments of inertia of Callisto and Titan inferred from gravity
7 data suggest incomplete differentiation of their interior, commonly attributed
8 to slow and cold accretion. To understand whether such large icy moons can
9 really avoid global melting and subsequent differentiation during their ac-
10 cretion, we have developed a 3D numerical model that characterizes the thermal
11 evolution of a satellite growing by multi-impacts, simulating the satellite growth
12 and thermal evolution for a body radius ranging from 100 to 2000 kilometers.
13 The effects of individual impacts (energy deposition, excavation) are simulated
14 and integrated for impactor sizes ranging from a few kilometers to one hundred
15 kilometers, while for smaller impactors, a simplified approach with successive
16 thin uniform layers spreading all over the satellite is considered. Our simula-
17 tions show that the accretion rate plays only a minor role and that extending
18 the duration of accretion does not significantly limit the increase of the internal
19 temperature. The mass fraction brought by large impactors plays a more crucial
20 role. Our results indicate that a satellite exceeding 2000 km in radius may ac-
21 crete without experiencing significant melting only if its accretion is dominated
22 by small impactors ($<$ a few kilometers) and that the conversion of impact
23 energy into heat is unrealistically inefficient ($<$ 10 – 15%). Based on our simu-
24 lations, if more than 10% of satellite mass was brought by satellites larger
25 than 1 km, global melting for large bodies like Titan or Callisto cannot be
26 avoided.

27 *Key words:* Thermal histories; Accretion; Satellites, formation; Impact
28 processes

29 1. Introduction

30 Differences in composition and internal structure exist between the major
31 icy satellites of Jupiter and Saturn, suggesting distinct accretion and differenti-
32 ation histories (e.g., *Kirk and Stevenson, 1987; Mueller and McKinnon, 1988;*
33 *Mosqueira and Estrada, 2003a; Barr and Canup, 2008*). The high moment of
34 inertia factor inferred from *Galileo* gravity measurements ($C/MR^2=0.346$) (*An-*
35 *derson et al., 2001*) suggests that ice-rock separation may be incomplete in the
36 interior of Jupiter’s moon Callisto. By contrast, Ganymede has a much smaller
37 moment of inertia ($C/MR^2=0.31$) (*Anderson et al., 2001*) and shows signs of
38 past endogenic activity (*Pappalardo et al., 2004*). A full separation of ice and
39 rock is suggested for Ganymede together with the formation of a metallic core,
40 which is at the origin of a relatively intense intrinsic magnetic field (*Kivelson*
41 *et al., 1998*).

42

43 With similar size and mass, Saturn’s moon Titan may be an intermediate
44 case between Callisto and Ganymede. Its moment of inertia factor, C/MR^2
45 estimated to $\sim 0.33 - 0.34$ from Cassini gravity measurements (*Jess et al., 2010,*
46 *2012*)) suggests that Titan’s interior is more differentiated than Callisto but
47 probably much less than Ganymede. Like Callisto, Titan might still possess a
48 layer of ice-rock mixture between a rocky core and a outer ice-rich mantle, un-
49 less the rocky core is mostly composed of highly hydrated minerals (*Sohl et al.,*
50 *2010; Castillo-Rogez and Lunine, 2010*). The fact that the interior of Callisto
51 and possibly Titan may still contain a layer of ice-rock mixture suggests that the
52 satellite may have avoided significant melting during accretion and subsequent
53 evolution.

54

55 The accretion of giant planet’s moons is intimately linked with the evo-

56 lution of the circumplanetary disk that formed during the transition stage of
57 the planet’s accretion, when the planet became massive enough to contract
58 and accrete gas and dust from the circumsolar disk (e.g., *Estrada et al.*, 2009).
59 The timescale of the satellite accretion is therefore mostly controlled by the
60 disk structure, the mass inflow rate, and the lifetime of the circumplanetary
61 disk. Two main categories of circumplanetary disk models have been proposed:
62 the solids-enhanced minimum mass (SEMM) model (*Mosqueira and Estrada*,
63 2003a,b; *Estrada et al.*, 2009) and the gas-starved disk model (*Canup and Ward*,
64 2002, 2006; *Ward and Canup*, 2010). In the gas-starved disk model, the disk is
65 assumed to be continuously supplied by ongoing inflow of gas and dust parti-
66 cles from the surrounding proto-planetary disk while in the SEMM model, solid
67 components of the disk are supplied by ablation and capture of planetesimal
68 fragments passing through the disk. These two approaches result in different
69 characteristic impactor sizes, ranging typically from a few meters to a few kilo-
70 metres in the gas-starved approach (*Barr and Canup*, 2008), while a significant
71 fraction of impactors with radii above 1 km size and up to 100-200 km is envi-
72 sioned in the SEMM model (*Estrada and Mosqueira*, 2011). The impactor size
73 is crucial to determine whether the impact energy is buried deep beneath the
74 surface or efficiently released to the space. Hence these two formation models
75 can potentially lead to different early thermal evolutions of growing icy moons.

76

77 Previous studies showed that it was possible to avoid melting if the accumu-
78 lation of accretion energy was inefficient, i.e. if the energy was radiated away at
79 a rate comparable to the accretion rate (e.g., *Schubert et al.*, 1981; *Squyres et al.*,
80 1988; *Kossacki and Leliwa-Kopystyński*, 1993; *Coradini et al.*, 1995; *Grasset and*
81 *Sotin*, 1996; *Barr and Canup*, 2008; *Barr et al.*, 2010). Based on these models,
82 the accretion timescales t_{acc} should be longer than 1 Myr to avoid significant

83 melting and hence differentiation of Callisto while an accretion timescale as
84 short as 10^{3-4} yr may be possible for Ganymede. However, these timescales are
85 dependent on the way heat deposition and cooling are treated. These studies
86 used an one-dimensional approach initially developed for the accretion of terres-
87 trial planets (*Safronov*, 1978; *Kaula*, 1979). In this approach, the evolution is
88 parameterized by deposition of successive material layers. The thermal effect of
89 an impact is not considered individually, but is averaged over the entire surface
90 and integrated. This approach is valid as long as the impactors remain small
91 (≤ 1 km) and are randomly distributed at the surface. This might be the case
92 during the very early stage of the accretion process, but impactors larger than
93 1 km probably became more and more abundant at the end of the accretion
94 stage (e.g., *Estrada et al.*, 2009). Impactors larger than 100 km might also be
95 expected (e.g., *Sekine and Genda*, 2012; *Dwyer et al.*, 2013). For such large
96 impacts, a detailed description of each impact including energy deposition and
97 transfer is required.

98
99 For this purpose, we have developed a three-dimensional model that char-
100 acterizes the thermal evolution of a satellite growing by multi-impacts. The
101 satellite growth and thermal evolution are simulated for a radius ranging from
102 100 kilometers to 2000 km from different populations of undifferentiated icy
103 impactors, by assuming different accretion rates and conversion rates of impact
104 energy into heat. The effects of individual impacts are simulated and integrated
105 for impactor sizes ranging from a few kilometers to one hundred kilometers. For
106 each impact event, we consider the thermal effects due to the dissipation of the
107 impactor's kinetic energy as heat as well as the topographical effect associated
108 to excavation process. For impactor sizes smaller than a few kilometers, we do
109 not treat the impact individually because the number of impacts to simulate will

110 be extremely time consuming. The small and numerous impactors are modeled
111 by successive thin uniform layers spreading all over the moon. As the icy moon
112 grows, gravitational forces increase and impacts become more and more violent.
113 Due to this, as well as the accumulation of warmed icy material, melting events
114 may occur once the icy moon reaches a critical size. As the main objective of
115 our work is to determine the maximum radius reached by a growing satellite
116 before significant melting occurs ($> 5\%$), we make some simple assumptions
117 corresponding to the least efficient scenario for initiating ice melting. The im-
118 pacts are assumed to occur with the smallest possible velocity corresponding to
119 the escape velocity determined by the mass of the growing satellite. Hence, the
120 accretion efficiency is assumed to be 100% and all impacted mass remains on the
121 growing satellite (*Asphaug, 2010*). With these assumptions, we minimize the
122 energy accumulated in the satellite during the growth, and therefore we provide
123 an upper limit for the radius that the satellite can reach without experiencing
124 significant melting. In sections 2 and 3, we present the details of our model.
125 We first describe the process associated to a single impact event and then we
126 present our multi-impact approach. The results of our simulations for different
127 accretion parameters are provided in Section 4. Finally, in section 5, we briefly
128 discuss the implications of our results for the post-accretionnal structure of large
129 icy moons and the subsequent differentiation processes.

130 **2. Single impact model**

131 Following an impact and the formation of a crater, a significant amount of
132 heat is buried deep below the impact site. In the following section we describe
133 the scaling laws used to model the thermal and topographical consequences of
134 a large single impact on a growing icy moon.

135 *2.1. Impact heating*

136 During an impact event, the initial kinetic energy of the impactor is con-
137 verted into internal energy produced by shock heating of the satellite and of
138 the impactor, internal energy produced by plastic work, and kinetic energy of
139 ejected material (e.g. *O’Keefe and Ahrens, 1977; Squyres et al., 1988*). *O’Keefe*
140 *and Ahrens* (1977) estimated that the fraction, γ_{li} , of the impactor kinetic en-
141 ergy going into shock heating of the satellite ranged from 0.2 for low-velocity
142 impacts to about 0.6 for very high velocities. As this parameter is difficult to
143 constrain, especially for large impacts, we consider here that it is a free param-
144 eter.

145
146 During the impact, a shock wave propagates from the impact site. Follow-
147 ing the adiabatic pressure release, the peak pressure being almost independent
148 of impactor size, a thermal anomaly remains below the impact site. The heat
149 deposition is nearly uniform in a hemispherical (for $v_{imp} < 1$ km/s) to spherical
150 region next to the impact (the isobaric core), and strongly decays away from it
151 (*Croft, 1982; Squyres et al., 1988; Senshu et al., 2002*) (see Fig. 1). For simplic-
152 ity, we consider in our models that the shape of the isobaric core is spherical and
153 that it does not depend on the impact velocity. Energy balance calculations and
154 shock simulations suggest that, for impact velocities lower than 10 km.s^{-1} , the
155 radius of the isobaric core r_{ic} is comparable or slightly larger than that of the
156 impactor r_{imp} (*Pierazzo et al., 1997; Senshu et al., 2002; Kraus et al., 2011*).
157 Considering the extreme case in which all of the impact energy is perfectly
158 transferred to the internal energy within the isobaric core and impactor itself
159 gives an estimation of the maximum value for $r_{ic}/r_{imp} = 3^{1/3}$ (*Senshu et al.,*
160 *2002*). Hence, after a large impact, a large amount of heat can be buried deep
161 below the impact site at a depth $\sim 2r_{imp}$ and contribute to the early thermal

162 evolution of the growing moon (*Kraus et al.*, 2011).

163

164 As already explained in the introduction, we neglect here the velocity at
165 infinity of the impactor ($v_\infty = 0$) as we want to determine the maximal size
166 a moon can reach without significant melting. For simulations presented here,
167 we do not consider any transplanetary impactor with $v_{imp} \gg v_{esc}$ (*Squyres*
168 *et al.*, 1988). The impactor velocity is only determined by the gravitational
169 acceleration of the growing target: $v_{imp} = v_{esc} = \sqrt{2gR}$ with g the gravity at the
170 surface of a moon with radius R . The impactor velocity is therefore proportional
171 to the satellite size. For isobaric core volume $V_{ic} = 3V_{imp}$, a balance between
172 the kinetic energy delivered to the growing moon and the energy used to heat
173 up the growing moon (isobaric core and the material surrounding it) without
174 melting leads to (*Monteux et al.*, 2007):

$$\Delta T_0 = \frac{4\pi \gamma_{li} \rho G \bar{R}_t^{-2}}{9 h_m C_p} \quad (1)$$

175 where ρ is the mean density of the moon, h_m represents the volume effec-
176 tively heated normalized by the volume of the isobaric core and scales with the
177 power m (see values in Tab. 1). γ_{li} is the fraction of the impactor kinetic energy
178 that is used to heat up the deep material of the impacted body. Hence, the post-
179 impact temperature increase scales with the square of the moon radius at the
180 time of impact (see Eq.1). Using parameter values from Tab. 1 and $\gamma_{li} = 30\%$,
181 for an impacted body with a radius ranging from 1000 km to 2500 km, $v_{imp} < 3$
182 km/s and ΔT_0 ranges from ~ 10 K to 100 K . Obviously, if the velocity at
183 infinity is non negligible, the delivered energy and hence temperature increase
184 would be higher. However, as we want to determine the maximum radius that
185 a growing satellite can reach without significant melting, we consider the most
186 favorable case where the velocity at infinity is zero.

187

188 Away from the isobaric core the peak pressure decays with the distance
189 from the surface of the isobaric core (*Pierazzo et al., 1997; Kraus et al., 2011*)
190 (see Fig. 1). This pressure decay can be faster for an ice/rock mixture than
191 for terrestrial material because of the ice properties (*Kraus et al., 2011*). Just
192 after the adiabatic pressure release, the thermal perturbation corresponds to an
193 isothermal sphere of radius r_{ic} and temperature $T_0 + \Delta T_0$ that decays when
194 $\bar{r} > r_{ic}$ as (see Fig. 1)

$$T(r) = T_0 + \Delta T_0 \left(\frac{r_{ic}}{\bar{r}} \right)^m \quad (2)$$

195 where \bar{r} is the distance from the centre of the isobaric core, T_0 is the pre-
196 impact temperature and m is the power characterizing the temperature decrease
197 from the isobaric core (*Pierazzo et al., 1997; Senshu et al., 2002*). The post-
198 impact temperature increase is a function of the pressure increase below the
199 impact site. For small impact velocities (i.e. $< 3 \text{ km.s}^{-1}$), the pressure P may
200 increase to peak values of 8 GPa and the post-impact temperature increase
201 scales with $P^{0.7-1}$ (*Stewart and Ahrens, 2005*). As the pressure typically de-
202 cays from the isobaric core with $\sim (r_{ic}/r)^4$ (*Kraus et al., 2011*), the post impact
203 temperature increase decays from the isobaric core following $(r_{ic}/r)^m$ with m
204 ranging from 2.8 to 4. In this study we choose a medium value of $m = 3.4$.

205

206 2.2. Topographical effect

207 An impact leads to the formation of a transient cavity of diameter D_s , reach-
208 ing its final size D_f after some modifications. The diameter of the transient
209 crater D_s can be related to the impactor diameter d_{imp} (in km) through (*Zahnle*
210 *et al., 2003*):

$$D_s = a_0 \left(\frac{v_{imp}^2}{v_{esc}^2} \right)^{a_1} \left(\frac{\rho_{imp}}{\rho} \right)^{a_2} R^{a_3} d_{imp}^{a_4} \cos(\theta)^{a_5} \quad (3)$$

211 where v_{imp} is the impactor velocity, v_{esc} is the escape velocity of the impacted
 212 moon, ρ_{imp} is the impactor density, R is the radius of the moon (in km) and
 213 θ is the impact angle. For simplicity, we assume $\rho_{imp} = \rho$ and we set $\theta = 45^\circ$
 214 (the most likely angle of impact and the average value for a uniform bombard-
 215 ment (*Shoemaker, 1962*)). a_0 , a_1 , a_2 , a_3 , a_4 and a_5 are constant values listed
 216 in Table 2. These are derived from laboratory experiments as well as numerical
 217 modelling, and are consistent with planetary surface observations.

218

219 If the transient crater diameter is smaller than a critical value D_c , no later
 220 significant modifications occur and its final diameter is $D_f = D_c$. Among the
 221 parameters listed in Table 2, D_c is the one that exhibits the largest range of
 222 values as this parameter depends on the mechanical properties and gravity of
 223 each icy moon (*McKinnon et al., 1991; Zahnle et al., 2003*). D_c typically ranges
 224 between 2-3 km for Ganymede and Callisto and up to 15 km for most of the
 225 medium-sized satellites (*Schenk et al., 2004*). Hence, D_c is expected to vary
 226 during the growth of the icy moon. Here for simplicity we consider a single
 227 value, $D_c = 15$ km (see Table 2). In our models, the majority of the impacts
 228 leads to the formation of craters that are larger than D_c . Above D_c , the post-
 229 impact strength of the target material is insufficient to prevent collapse under
 230 gravity, crater modifications occur, resulting in a complex crater with a flat
 231 floor, a central peak or peak ring, and a terraced rim. Its final diameter thus
 232 becomes:

$$D_f = D_s \left(\frac{D_s}{D_c} \right)^{b_0} \quad (4)$$

233 We express the maximal depth at the centre of the crater z_f as a function
 234 of the transient simple crater diameter (*Pike, 1977; Schenk, 1991*):

$$z_f = \begin{cases} K_1 D_s^{b_1} & \text{if } D_s < D_c \\ K_2 D_s^{b_2} & \text{if } D_s > D_c \end{cases} \quad (5)$$

235 We consider that the maximum ejecta thickness δ_0 at the crater rim is
 236 (*Schenk, 1991*):

$$\delta_0 = K_3 D_f^{b_3} \quad (6)$$

237 b_0, b_1, b_2 and b_3 are constant values listed in Tab. 2. The elevation variation
 238 depends on whether we consider a position inside or outside the crater. Within
 239 the crater, the depth increases from center to the top of the ejecta rim with a
 240 power p . Outside the crater, elevation decreases from the top of the ejecta rim
 241 to a reference elevation with a power $-n$. We define $\Delta H(\eta, \xi)$ as the elevation
 242 variation between the post-impact topography and a reference elevation (equal
 243 to 0 far from the impact site):

$$\Delta H(\eta, \xi) = \begin{cases} z_f + (z_f + \delta_0) \left(\frac{2r}{D_f}\right)^p & \text{if } r < D_f/2 \\ \delta_0 \left(\frac{2r}{D_f}\right)^{-n} & \text{if } r > D_f/2 \end{cases} \quad (7)$$

where η is the longitude and ξ the latitude. r is the distance from the crater
 center :

$$r = \overline{R_t} \arccos [\cos(\eta) \cos(\eta_{imp}) \cos(\xi - \xi_{imp}) + \sin(\eta) \sin(\eta_{imp})] \quad (8)$$

244 with $\overline{R_t}$ the mean radius of the growing moon, η_{imp} the impact longitude and
 245 ξ_{imp} the impact latitude.

246 *2.3. Ejected material and ejecta temperature*

247 The fraction of material from the impactor and from the impacted body es-
248 caping the growing moon decreases with decreasing impact velocities (*Asphaug,*
249 *2010; Korycansky and Zahnle, 2011*). For impact velocities considered in our
250 models ($v_{imp} = v_{esc} < 3 \text{ km.s}^{-1}$) and for 45° impact angle, the accretion is
251 supposed to be efficient and this fraction should remain small (less than 10% of
252 the impactor's mass) (*Asphaug, 2010; Korycansky and Zahnle, 2011*). After a
253 large impact, part of the material beneath the impact site is excavated and re-
254 deposited within the ejecta rim (see Fig. 1). We thus set n from Eq.7 to a value
255 typically ranging between 2 and 3 in order for the efficiency of mass accretion
256 to be close to 100% during the whole accretion period and we consider that the
257 whole impactor is deposited in the ejecta rim.

258

259 The temperature of this material depends on the pre-impact temperature,
260 the temperature increase from the impact and the temperature of the impactor.
261 The volume fraction of excavated material that is shock-heated increases with
262 final crater size and this hot material is redeposited in the most external part of
263 the ejecta rim (*Maxwell, 1977; Barnhart and Nimmo, 2011*). Hence, the thermal
264 repartition within the ejecta rim should also depend on the interactions between
265 the ejected material and the atmosphere during the excavation and the fallback
266 processes (*Kieffer and Simonds, 1980*). For simplicity, we will consider in our
267 models that the temperature of the ejecta rim is the average temperature below
268 the impact site over a cylindrical volume with a diameter D_f and a thickness
269 z_f .

270 **3. Multi-impact approach**

271 The accretion of an icy moon is the result of material deposited from a wide
272 range of impactor sizes (i.e. from dusts to 100 km size objects). In the following
273 sections we describe our model of accretion from multi-impacts.

274 *3.1. Impactor population*

275 For the mass distribution of the impactor, we consider a power law distribu-
276 tion with an exponent equal to -2.5: $dN_c/dm \propto m^{-2.5}$, consistent with N-body
277 simulations (*Kokubo and Ida, 2000*). We use Monte Carlo sampling to generate
278 the impactor population (*Zahnle et al., 2001; Lognonné et al., 2009*). By random
279 drawing, we determine the impactor mass (or equivalently, radius) according to
280 the above power law distribution. The time of impact is taken from a uniform
281 probability distribution, while the latitude and longitude of the crater center
282 are randomly drawn so that an isotropic impact flux is obtained. To limit the
283 computation time, a lower size limit, r_{min} , is imposed on the impactor distri-
284 bution (see Fig. 2). Below this lower limit, individual impact events are not
285 simulated and a parameterized approach using successive deposit layers is used
286 (see section 3.3 for further details). We assumed a lower limit, r_{min} , typically
287 between 1 and 10 km. We also prescribed an upper limit, r_{max} , typically 100-
288 200 km. Above these values, the validity of the scaling laws used here becomes
289 questionable. Accretion from such large bodies would require more complex im-
290 pact simulations, which is beyond the scope of the present paper. Nevertheless,
291 200 km is probably a reasonable upper limit since the growing moon is likely
292 to perturb large objects that were migrating in from the outer disk possibly
293 leading to their breakup. Hyperion, for instance, may be considered as an ex-
294 ample of such large satellitesimals (*Mosqueira and Estrada, 2003a,b; Estrada*
295 *et al., 2009*). The probability of impacts with objects exceeding 200 km is thus
296 likely low, except maybe during the very late stage of accretion (e.g., *Sekine*

297 *and Genda, 2012).*

298

299 For simplicity, the impactor population is assumed to be infinite (meaning
300 that the number of impactors of a given size does not decrease as a function of
301 time) and the accretion rates of large impactors $\tau_{acc,li}$ and layer deposit $\tau_{acc,lay}$
302 are assumed constant during one simulation. To measure the influence of large
303 impactors ($r_{min} < r < r_{max}$) relative to small impactors ($r < r_{min}$), we define
304 the ratio:

$$x_{m,li} = m_{li}/m_{acc} \quad (9)$$

305 where m_{li} is the mass accreted from large impactors and m_{acc} is the total
306 mass accreted. We define the total accretion rate τ_{acc} as

$$\tau_{acc} = \tau_{acc,li} + \tau_{acc,lay} \quad (10)$$

307 where $\tau_{acc,li}$ is the accretion rate from large impacts and $\tau_{acc,lay}$ is the ac-
308 cretion rate from small impactors modelled as thin layer deposits (see section
309 3.3). We assume that the composition of the icy moon (and of the impactor) is
310 a mixture of ice and rocks and that its density ρ is uniform with depth.

311 3.2. Multi-impact-induced topography

312 To account for the pre-impact topography, we use the multi-cratering ap-
313 proach developed by *Howard* (2007). At the i_{th} impact, the new elevation
314 variation $\Delta E_i(\eta, \xi)$ is

$$\Delta E_i(\eta, \xi) = \begin{cases} \Delta H(\eta, \xi) + (R_{i-1}(\eta, \xi) - \overline{R_{i-1}}) (1 - (2r/D_f)^2) & \text{when } r < D_f/2 \\ \Delta H(\eta, \xi) + (R_{i-1}(\eta, \xi) - \overline{R_{i-1}}) & \text{when } r > D_f/2 \end{cases} \quad (11)$$

315 $\Delta E_i(\eta, \xi)$ depends on the local pre-impact topography variation $(R_{i-1}(\eta, \xi)) - \overline{R_{i-1}}$.
 316 We consider here no late deformation of the topography before the impact (the
 317 degree of inheritance is 1 inside and outside the crater (*Howard, 2007*)). After
 318 the i_{th} impact, the local radius becomes $R_i(\eta, \xi) = R_{i-1}(\eta, \xi) + \Delta E_i(\eta, \xi)$ and
 319 the mean radius of the growing moon increases from $\overline{R_{i-1}}$ to $\overline{R_i}$.

320
 321 The growth of the satellite requires that at least part of the impactor material
 322 remains on the growing satellite. Since we consider that the volume of the
 323 impactor is retained within the ejecta rim in our models, this growth requirement
 324 provides constraints on the scaling law describing the ejecta blanket distribution.
 325 For large n values, the topography decreases rapidly from the crater rim and the
 326 volume of material accumulated in the ejecta rim decreases. On the contrary,
 327 for small n values and for the same crater rim height, the topography decreases
 328 more linearly from the crater rim and the volume of material accumulated in
 329 the ejecta rim is large. The falloff in ejecta thickness is steep. Depending on
 330 the target properties, n ranges between 2.5 and 3 (*Housen et al., 1983; Moore*
 331 *et al., 2004*). In Fig. 3, we monitor the average radius of the growing moon as
 332 a function of time for different values of n and compare it with the theoretical
 333 mean radius resulting from the 100% accretion of 1.4×10^6 impactors ranging
 334 from 10 to 100 km radii. From this figure, we see that increasing n decreases
 335 the mass accumulated and leads to a growth that is less than 100% accretive.
 336 For $n = 3$, the accretion is not fully efficient and about 30% of the impacted
 337 mass remains on the impacted body while for $n = 2.5$, 95% is accreted (see
 338 Fig. 3). For n values smaller than 2.5, the growth is unrealistic since it is more
 339 than 100% accretive. We choose a value of 2.5 which maximize the fraction of
 340 accreted material.

341 *3.3. Layer deposits from small impactors*

342 As explained previously, for numerical reasons, individual impact events for
 343 $r < r_{min}$ are not simulated. We consider that the accreted mass from small
 344 impactors is averaged and uniformly added on the surface. For a prescribed
 345 accretion rate, $\tau_{acc,lay} = \tau_{acc} \times (1 - x_{m,li})$, the thickness δ_{lay} of the uniform
 346 layer deposit between two individual large impacts is then:

$$\delta_{lay} = \left(\frac{3\tau_{acc,lay}\Delta t}{4\pi\rho} + R_i^3 \right)^{1/3} - R_i \quad (12)$$

347 At any point at the surface, this additional layer is added uniformly. We
 348 assume that the temperature of this deposit layer is homogeneous over the entire
 349 thickness δ_{lay} . The layer temperature depends on the radius of the growing
 350 moon \overline{R}_t and is calculated following an approach that is similar to the "classic"
 351 one from *Schubert et al.* (1981). In their 1D thermal evolution models, *Schubert*
 352 *et al.* (1981) considered that a fraction h of the kinetic energy accumulated
 353 during accretion progressively heats up the near surface of the growing satellite
 354 (*Kaula, 1979; Schubert et al., 1981; Lunine and Stevenson, 1987; Grasset and*
 355 *Sotin, 1996*). Hence the corresponding temperature profile is:

$$T(\overline{R}_t) = \frac{hGM(\overline{R}_t)}{C_p\overline{R}_t} \left(1 + \frac{\overline{R}_t v_\infty^2}{2GM(\overline{R}_t)} \right) + T_e \quad (13)$$

356 Considering that $v_\infty^2 = 0$ (i.e. $v_{imp} = v_{esc}$), Eq.13 becomes

$$T(\overline{R}_t) = \frac{\gamma_{lay}}{2C_p} v_{imp}^2 + T_e \quad (14)$$

357 where C_p is the heat capacity of the icy satellite material/mixture and T_e
 358 is the temperature of the surrounding environment. The coefficient γ_{lay} rep-
 359 represents the fraction of energy that is retained in the layer as heat. Note that
 360 the coefficients γ_{li} and γ_{lay} defined here differ from the coefficient h used in

361 Eq.13. h implicitly includes the post-impact surface cooling, while γ_{li} and γ_{lay}
 362 only represent the fraction of kinetic energy converted as heat from the small
 363 impacts deposited as an uniform layer (γ_{lay}) or from large impacts (γ_{li}). γ_{lay}
 364 is considered as a free parameter. It accounts for the effect of mechanical mix-
 365 ing in the shallow layers which has been described in *Squyres et al.* (1988) by
 366 a larger thermal diffusivity. Due to the heat removal by this "gardening" ef-
 367 fect of numerous small impacts (*Davies, 2009*), it is reasonable to assume that
 368 $\gamma_{lay} \leq \gamma_{li}$.

369 3.4. Numerical method

370 As the satellite grows, impactors bring material and thermal energy used to
 371 build-up and heat-up the moon. We monitor the thermal evolution of a grow-
 372 ing icy satellite using the 3D-tool OEDIPUS (*Choblet et al., 2007*) to obtain a
 373 three-dimensional solution of the energy equation in a spherical shell. We use
 374 a finite-volume formulation and a mesh based on the "cubed sphere" transfor-
 375 mation, the resulting grid consisting in six identical blocks. The computational
 376 grid in one block consists typically of $128 \times 64 \times 64$ discrete cells. Initially, the
 377 growing satellite in our models consists of a core surrounded by a shell with a
 378 thickness leading to a R_0 radius body. In the numerical domain, the overlaying
 379 shell (between R_0 and the final moon radius) is initially empty and gradually
 380 filled by impacted material during the accretion history. As the accretion time
 381 is relatively short compared to the onset time of solid-state convection (e.g.,
 382 *Robuchon et al., 2010*), we consider only the diffusion of heat with no advective
 383 term. Melt transport and water/rock separation are not considered here and
 384 simulations are stopped when a few percent of material exceeding the melting
 385 point of water ice is reached. The accreted material is assumed to be an un-
 386 differentiated mixture of ice and rocks with a thermal diffusivity that does not
 387 depend on temperature, $\kappa = 10^{-6} \text{ m}^2.\text{s}^{-1}$ (*Squyres et al., 1988; Barr et al.,*

388 2010).

389

390 To maintain an accurate spatial resolution in our models during the entire
391 accretion, we subdivide the accretion in successive stages between which the
392 mesh grid is modified. Between two stages, the temperature field from the
393 previous regime is interpolated on the mesh grid that we use in the next regime
394 (see Fig. 4). The free accretionary parameters of our models are the ratio of
395 material accreted from a large impacts $x_{m,li}$ and the accretion rate τ_{acc} . The
396 free energy conversion factors are γ_{lay} (layer heating) and γ_{li} (large impact
397 heating). γ_{lay} and γ_{li} are independent parameters.

398 3.5. Post-impact surface cooling

399 After an impact, the efficient radiative heat transfer at the surface leads to
400 a rapid cooling of the uppermost part of the heated zone (including the impact
401 site and the surrounding ejecta blanket). As such a rapid post-impact cooling
402 cannot be properly described in the framework of the relatively coarse grid mesh
403 used by the 3D OEDIPUS tool, we have implemented a more precise description
404 of heat transfer in this region. In the uppermost grid mesh of OEDIPUS, the
405 conduction of heat for uniform heat conductivity is solved in the radial direction
406 using refined sublayers with a Crank-Nicholson method (similarly to *Tobie et al.*
407 (2003)). The number of sub-layers varies between 50 and 150, depending on
408 the distance between the local surface radius $R_i(\eta, \xi)$ and the first underlying
409 OEDIPUS grid mesh. A radiative heat flux boundary condition is imposed at
410 the surface:

$$F = \sigma (T(R_i)^4 - T_{eq}^4) \quad (15)$$

411 with σ the Stefan-Boltzman constant and T_{eq} the expected equilibrium sur-
412 face temperature. In the calculations presented below, $T_{eq}=100$ K. The tem-

413 perature at the base of the refined column correspond to the temperature value
414 provided in OEDIPUS. The conductive heat flux predicted in the refined column
415 at the base of the first underlying OEDIPUS mesh interface is then imposed as
416 heat flux boundary conditions at the top of the coarse grid domain.

417 4. Numerical results

418 4.1. Early and intermediate regimes: from 100 km to 1000 km

419 We first consider the accretion of a 1000 km size ice-rock body from a 100
420 km satellite embryo. For simplicity, the initial temperature from $R = 30$ km to
421 $R = R_0 = 100$ km is set to a uniform value, here $T = T_e = 100$ K. To maintain
422 a good spatial resolution, we subdivide the accretion history of the icy satellite
423 in two stages: an early stage where the moon is growing from 100 km to 500
424 km, an intermediate stage where the moon is growing from 500 km to 1000 km.

425
426 Fig. 4 illustrates the temperature evolution during these two accretionary
427 regimes. In order to test the influence of the early and intermediate regimes on
428 the late accretive stage, we consider two accretionary different scenarios for both
429 the early and intermediate stages: a "cold accretion" where $\gamma_{li} = \gamma_{lay} = 0.1$,
430 $x_{m,li} = 10\%$ (Fig. 4, left column) and a "hot accretion" where $\gamma_{li} = \gamma_{lay} = 0.3$,
431 $x_{m,li} = 33\%$ (Fig. 4, middle column). The accretion parameters used for the
432 "Early regime" simulation are $r_{min} = 4$ km and $r_{max} = 10$ km, while for the
433 "Intermediate regime", we used $r_{min} = 8$ km and $r_{max} = 20$ km. At the end
434 of the intermediate regime, $t_{acc} = 0.5$ Myr and the impactor velocities remain
435 small (< 1 km.s⁻¹) which corresponds to small temperature increases deep be-
436 low the impact site (< 10 K).

437

438 When the moons reach a radius of 1050 km, the temperature barely exceeds

439 120 K in the cold accretive case, while it can reach values up to 250 K (near the
 440 melting point of water ice) for the hot accretive scenario. As we will show later
 441 in section 4.2, although the obtained temperature fields are very different in
 442 these two cases, this has no major influence on the evolution of the temperature
 443 field in the outer part above 1000 km. Fig. 4 (third column) also represents the
 444 3D topography at the surface of the icy moon at the end of the two stages. As
 445 we increase the r_{min} and r_{max} values between the two simulations, the impact
 446 craters become larger and the contrast in topography (the difference between
 447 the $R(\eta, \xi)$ and the mean radius \bar{R}) also increases.

448 4.2. Late accretive regime: > 1000 km

449 To simulate the evolution for $R > 1000$ km (late accretion regime), we use
 450 the thermal state reached at the end of the intermediate regime as the initial
 451 thermal state. In Fig. 4 we show results obtained for the same accretionary
 452 parameters in the late regime ($\gamma_{li} = 0.1$, $\gamma_{lay} = 0.3$, $x_{m,li} = 33\%$, $r_{min} = 10$ km
 453 and $r_{max} = 100$ km) but for different initial temperature fields: "cold accretion"
 454 scenario (left column) and "hot accretion" scenario (middle column) obtained
 455 at the end of the corresponding intermediate regime. Fig. 4 illustrates that the
 456 temperature field obtained from the intermediate regime (hot or cold accretion
 457 scenario) only plays a minor role on the critical radius from which melting be-
 458 comes significant during the late regime. Using the intermediate thermal state
 459 obtained from the cold accretion regime leads to $R_{crit} = 1609$ km while using
 460 the intermediate thermal state obtained from the hot accretion regime leads to
 461 $R_{crit} = 1608$ km (Fig. 4, last line). For this reason, in the following, the tem-
 462 perature field and topography from the "hot accretion scenario" are considered
 463 as initial conditions for all simulations of the accretion of bodies larger than
 464 1000 km.

465

466 As explained previously, we assume that the impactor velocity is only deter-
 467 mined by the gravitational acceleration, and we specifically test the influence
 468 of (1) accretion rate τ_{acc} , (2) mass fraction provided by large impactors $x_{m,li}$
 469 and (3) energy conversion factors (i.e. γ_{li} and γ_{lay}) on the thermal state of the
 470 growing moon. We monitor the temperature field evolution as well as the vol-
 471 ume fraction of satellite material that reaches the melting temperature of pure
 472 water ice (i.e. with $T > 273$ K) as a function of satellite growth (see Fig. 4). As
 473 complex physical processes associated with melting and water-rock separation
 474 are beyond the scope of the present study, we interrupt the simulations when
 475 the volume fraction of the growing moon where $T > T_{melt}$ exceeds a threshold
 476 value fixed to 5% here. We define R_{crit} as the satellite radius at which this
 477 threshold is reached. In this "late regime", the accretionary parameters can
 478 be different from the values used in the previous regimes which may lead to
 479 temperature "discontinuities" within the growing moon as emphasized in Fig.
 480 4). As indicated above, such artefacts do not influence the value of R_{crit} . As
 481 illustrated in Fig. 4, the regions where melting occurs (the regions where the
 482 temperature scale is saturated in white) are mainly confined in the most exter-
 483 nal parts of the growing moon.

484

485 *4.3. Influence of the accretion rate, τ_{acc} and of the fraction of large impactors,*

486 *$x_{m,li}$*

487 For this simulation, we assume that the conversion rate of impact energy is
 488 similar for small and large impactors: $\gamma_{li} = \gamma_{lay} = 30\%$ or 10% . and we focus
 489 only on the late accretive regime. From our models, we can measure the influ-
 490 ence of large impacts relative to layer deposition of small impactors by varying
 491 the value of $x_{m,li}$. Fig. 5 shows the evolution of R_{crit} as a function of $x_{m,li}$ and
 492 for three different accretion rates. For a better comparison with other studies,

493 we express the accretion rate, τ_{acc} , in terms of M_{Titan}/Myr where M_{Titan} is the
 494 mass of Titan ($= 1.345 \times 10^{23}$ kg) and we consider values ranging between 0.015
 495 M_{Titan}/Myr ($= 2 \times 10^{15}$ kg.yr $^{-1}$) and 1.5 M_{Titan}/Myr ($= 2 \times 10^{17}$ kg.yr $^{-1}$).
 496 $\tau_{acc} \leq 1.5 M_{Titan}/Myr$ corresponds to a relatively slow accretion, which is com-
 497 monly assumed for the accretion of Callisto (*Mosqueira and Estrada, 2003a;*
 498 *Barr and Canup, 2008*).

499
 500 Fig. 5 shows that, even for the least efficient conversion rate of impact energy
 501 ($\gamma_{li} = \gamma_{lay} = 10\%$), the satellite cannot grow above 1500 km without signifi-
 502 cant melting, if the accretion is dominated by large impactors ($x_{m,li} \sim 1$). For
 503 $\gamma_{li} = \gamma_{lay} = 30\%$, the critical radius is even below 1200 km. The critical radius
 504 can be increased only if a significant fraction of small impactors (< 10 km) is
 505 considered. However, even if small impactors dominate, the critical radius does
 506 not exceed 1400 km if $\gamma_{li} = \gamma_{lay} = 30\%$. The critical radius can exceed 2000
 507 km only if $\gamma_{lay} = 10\%$ and if at least 50% of the accreted mass is brought by
 508 small impactors ($x_{m,li} < 0.5$).

509
 510 The accretion rate has some influence on the results only if the accretion is
 511 dominated by small impactors, as the rate at which new layers are added limits
 512 the cooling of the previously accreted layers. For simulations dominated by large
 513 impactors, as most of the energy is buried a few kilometers below the surface, the
 514 cooling is very inefficient and the progressive temperature increase only weakly
 515 depends on the accretion rate. Therefore, the size distribution of impactors
 516 is more crucial than the accretion rate in controlling the thermal evolution of
 517 growing satellites. However, as illustrated by the comparison between $\gamma_{li} =$
 518 $\gamma_{lay} = 10\%$ and $\gamma_{li} = \gamma_{lay} = 30\%$ in Fig. 5, the energy conversion rate remains
 519 the most crucial parameters, and we explore in more details the sensitivity of

520 our results to γ_{lay} and γ_{li} in the next subsection.

521 4.4. Influence of the energy conversion parameters, γ_{lay} and γ_{li}

522 As shown in Fig. 6, for $x_{m,li} = 33\%$ and $\tau_{acc} = 0.15 M_{Titan}/Myr$, γ_{lay} and
523 γ_{li} must be smaller than 0.12 to allow the accretion of a body larger than 2000
524 km without significant melting. Conversion parameters as low as 0.1 correspond
525 to the lowest value usually considered in previous studies (e.g., *Squyres et al.*,
526 1988; *Coradini et al.*, 1995). Such low values could be obtained for small im-
527 pactors, but are probably a strong underestimation for large impactors. Fig. 6
528 also illustrates the relatively weak influence of the mean density on the thermal
529 evolution of the growing moon. A decrease in the average density leads to a
530 decay of the impact-induced temperature increase (see Eq.1). As a consequence,
531 decreasing ρ by 25% increases R_{crit} by $\sim 15\%$.

532

533 Fig. 7 shows the influence of increasing the energy conversion rate associated
534 to large impactors, γ_{li} for a fixed value of γ_{lay} ($= 0.1$) for small impactors and
535 for three different values of $x_{m,li}$. As expected, the critical radius strongly
536 decreases when the conversion rate and the mass fraction associated to large
537 impactors are increased. For $\gamma_{li} = 0.3$ (Fig. 8), the critical radius never exceeds
538 1600 km. Fig. 9 represents the stability domain of a growing icy moon with
539 $x_{m,li} = 33\%$ and $\tau_{acc} = 0.15 M_{Titan}/Myr$ for different values of γ_{lay} and γ_{li} .
540 From Fig. 9, we see that, for $\gamma_{li} \sim 0.3$ (*O'Keefe and Ahrens*, 1977; *Squyres*,
541 *et al.*, 1988; *Monteux et al.*, 2007) melting is more likely to occur as soon as the
542 growing moon reaches a radius of 1200-1500 km which is in good agreement with
543 *Estrada and Mosqueira* (2011). According to Fig. 9, it is difficult to envision a
544 cold accretion as soon as γ_{lay} is larger than 0.3 even with small γ_{li} . However,
545 we may envision that the icy moon grows unmelted up to a radius of 1200 km
546 even with $\gamma_{li} > 0.5$ only if γ_{lay} is smaller than 0.15.

547 **5. Conclusion**

548 We have developed a 3D numerical model that accounts for the influence of
549 large impacts on the thermal evolution of growing icy satellites and have consid-
550 ered the least efficient scenarios and parameters to initiate melting. Our results
551 show that the size distribution of impactors (i.e. ratio between large and small
552 impactors) is a key factor in determining the temperature increase during the
553 accretion stage. We show that the accretion rate as well as the thermal state
554 of the satellite embryo only play a minor role, therefore the apparent degree of
555 differentiation of a satellite’s interior cannot be used to constrain the duration
556 of its accretion.

557

558 Our simulations confirm that the most crucial parameter is the coefficient
559 of impact energy conversion into heat (γ_{lay} and γ_{li}). Our results show that it
560 is impossible to avoid significant melting during accretion, unless the fraction
561 of impact energy retained as heat is very low, in the order of 10%. Such an
562 inefficient conversion rate is difficult to explain and does not seem realistic with
563 respect to available estimates from impact experiments (e.g., *Ahrens and Okeefe,*
564 *1985*). Much lower initial temperature of the impactors as well as more efficient
565 subsurface cooling associated with impact gardening (not modelled explicitly
566 here but included in the γ_{lay} conversion efficiency) may reduce the effective
567 conversion rates (*Anderson, 1989*). Lower environment temperature (< 100 K)
568 may also increase the cooling rate of the shallow layers. Therefore, the absence
569 of extensive melting during accretion may reflect a very cold ambient subnebula
570 rather than a long accretionary timescale.

571

572 Several additional heat sources such as radiogenic heating, tidal/despinning
573 heating or heating associated with high-velocity impact, have not been consid-

574 ered in the heat budget in our model. Including these would require an even less
575 efficient energy conversion and storage to avoid melting and subsequent differen-
576 tiation. We also made the conservative assumption that the impacts are 100%
577 accretive. If some fraction of impact is not fully accretive, more impacts are
578 needed to accrete the same mass resulting in more impact energy. Hence, the
579 temperature increase would be higher and melting even more likely. Therefore,
580 the maximal radii of the accreted satellite reached without significant melting
581 in our simulations can be considered as upper limits.

582

583 Based on our simulations, when more than 10% of the accreted mass is
584 brought by impactors larger than 1 km, it seems unlikely that a satellite larger
585 than 2000 km may accrete without significant melting unless the environment
586 is extremely cold and the conversion rate of impact energy unrealistically low
587 ($< 10 - 15\%$). If the accretion is dominated by km-size impactors, impact-
588 induced melting may occur for radii as small as 1100-1500 km. Above this
589 critical radius, separation between liquid water and rock should initiate, thus
590 leading to the accumulation of dense rock blocks above the undifferentiated core
591 consisting of a mixture of rock and ice (e.g., *Kirk and Stevenson, 1987*). The
592 dense layer of accumulated rock is gravitationally unstable, and in such condi-
593 tions it is difficult to avoid subsequent full separation of rock and ice phases.
594 Depending on the size of the core and thickness of the rocky layer, the differen-
595 tiation may be catastrophic (*Kirk and Stevenson, 1987*) or more gradual (*Nagel*
596 *et al., 2004*). Recently, *O'Rourke and Stevenson (2013)* showed that although
597 rock-ice separation may be delayed by double-diffusive convection in the ice-rock
598 interior, ice melting due to progressive radiogenic heating and subsequent dif-
599 ferentiation cannot be prevented. Further modelling efforts are needed to better
600 understand the processes controlling rock-ice segregation and how the internal

601 structure inherited from the accretion process has evolved to the present-day
602 state.

603

604 A series of arguments now questions the apparent partially differentiated
605 state of Callisto and Titan, suggested by their elevated moment of inertia as
606 estimated using the Radau-Darwin Approximation (e.g., *Anderson et al.*, 2001;
607 *Iess et al.*, 2010; *Gao and Stevenson*, 2013). On Titan, the existence of a non-
608 negligible degree-three in the gravity field as well as significant topography sug-
609 gest that non-hydrostatic effects may significantly affect the estimation of the
610 Moment-of-Inertia factor (*Iess et al.*, 2010; *Gao and Stevenson*, 2013; *Baland*
611 *et al.*, in revision) and that the MoI factor may be significantly smaller than the
612 value estimated from the Radau-Darwin Approximation. On Callisto, similar
613 non hydrostatic contributions originating in the lithosphere may also affect the
614 estimation of its moment of inertia (*McKinnon*, 1997; *Gao and Stevenson*, 2013).
615 On these two moons, the hydrostatic dynamical flattening is relatively small as
616 they orbit relatively far from their planet, and therefore the non-hydrostatic
617 contributions need to be correctly estimated in order to accurately infer the
618 moment of inertia and the density profile of their interior. On Callisto, future
619 measurements performed by the ESA JUICE mission that will be launched in
620 2022 (*Grasset et al.*, 2013) will provide constraints on the non-hydrostatic con-
621 tribution by measuring independently the different quadrupole coefficients, as
622 well as by estimating the degree three and four coefficients of the gravity field.
623 On Titan, future measurements during Cassini flybys will also permit a better
624 determination of the degree-four (*Iess et al.*, 2012), which will provide pertinent
625 tests on the topography compensation process in the outer ice shell (*Heming-*
626 *way et al.*, 2013; *Lefevre et al.*, 2014), and consequently on the non-hydrostatic
627 corrections required to infer more precisely the moment of inertia.

628

629 **Acknowledgements**

630 The authors also thank the anonymous reviewers for constructive comments. J.
631 Monteux is funded by Agence Nationale de la Recherche (Accretis decision no.
632 ANR-10-PDOC-001-01). The research leading to these results has received fund-
633 ing from the European Research Council under the European Community's Sev-
634 enth Framework Programme (FP7/2007- 2013 Grant Agreement no. 259285).

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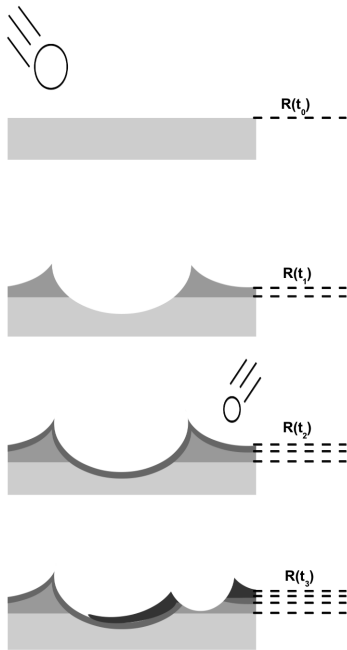
Table 1: Typical parameter values for numerical models

Moon radius	R	100-2000 km
Impactor radius	r_{imp}	4-100 km
Isobaric core radius	r_{ic}	
Average moon density	ρ	1500-2000 kg m ⁻³
Mean heat capacity	C_p	1200 J K ⁻¹ kg ⁻¹
Environment temperature	T_e	100 K
Mean heat diffusivity	κ	10 ⁻⁶ m ² s ⁻¹
Large impact energy fraction retained	γ_{li}	0.1-0.6
Temperature power decrease from the isobaric core	m	3.4
Volume effectively heated by impact	h_m	5.8
Layer deposit energy fraction retained	$\gamma_{lay} \leq \gamma_{li}$	0.1-0.3
Gravitational constant	G	$6.67 \times 10^{-11} \text{m}^3 \text{kg}^{-1} \text{s}^{-2}$

Parameter	Value	References
a_0	1.1	(<i>Zahnle et al.</i> , 1998, 2003)
a_1	0.217	"
a_2	0.333	"
a_3	0.217	"
a_4	0.783	"
a_5	0.44	"
D_c	15 km	(<i>McKinnon et al.</i> , 1991)
b_0	0.13	"
K_1	0.15	(<i>McKinnon et al.</i> , 1991; <i>Zahnle et al.</i> , 2003)
b_1	0.88	"
K_2	0.75	"
b_2	0.3	"
K_3	0.017	(<i>Schenk</i> , 1991)
b_3	0.976	(<i>Schenk</i> , 1991)
p	2 – 3	(<i>Howard</i> , 2007)
n	2 – 3.5	"

Table 2: Crater geometrical parameters used in our models.

Topographical effects



Thermal effects

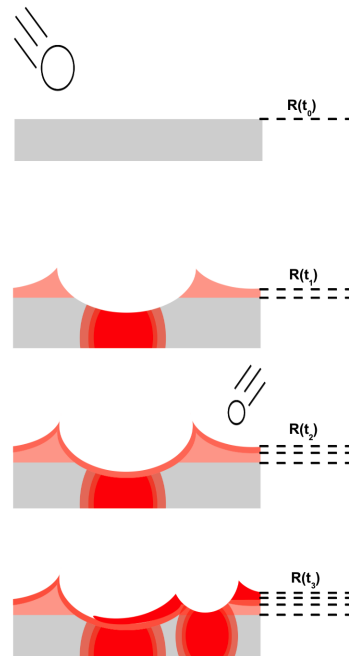


Figure 1: Schematic illustration of the topographical (left) and thermal (right) evolutions after large impacts. When the first large impact occurs (first line), a crater with diameter D_f , depth z_f and rim height δ_0 is formed (second line, left). Before the next large impact, the layer deposition occurs (third line, left). When a second impact occurs close enough to the first one (fourth line), the pre-existing topography is modified according to Eq.11. When a large impact occurs (first and second line, right), heat is buried deep below the impact site following Eq.1 while the ejecta rim temperature is the average temperature below the impact site over a volume that is D_f large and z_f thick. The temperature of the layer deposited before the next large impact (third line, right) obeys Eq.13.

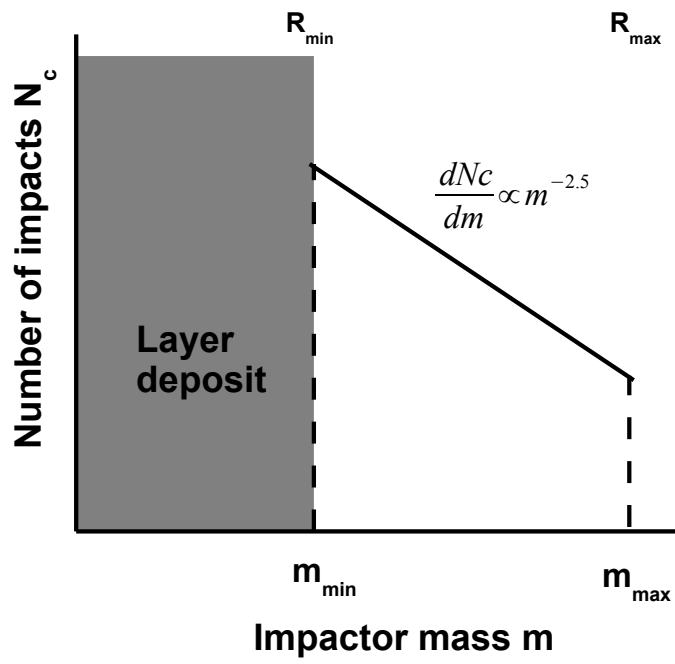


Figure 2: Schematic representation of the cumulated number of impacts as a function of the impactor mass. All the material with a mass smaller than m_{\min} (i.e. with $r < r_{\min}$) is deposited as a thin global layer over the moon surface. The impactors with a mass ranging from m_{\min} and m_{\max} are considered here as successive impact events (selected randomly) and their effects (impact cratering and heating) are treated individually.

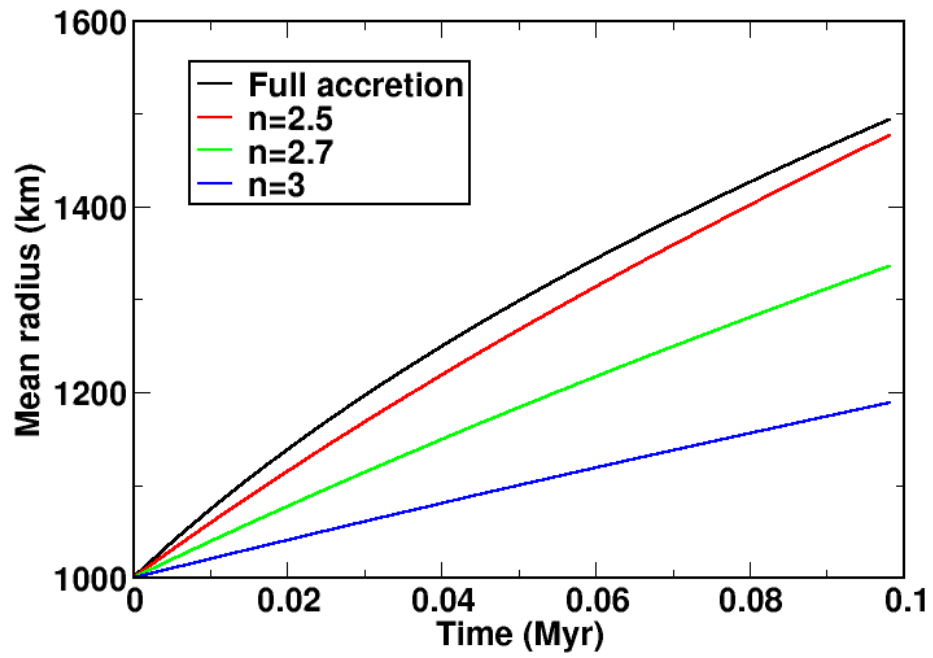


Figure 3: Time evolution of the average radius of the growing icy moon after the accretion of 1.4×10^6 impactors ranging from 10 to 100 km radii with $n = 2.5$ (red solid line), $n = 2.7$ (green solid line) and $n = 3$ (blue solid line). For comparison, we also represent the time evolution of the average radius consisting in the 100% accretive accumulation of the impactor bodies (black solid line).

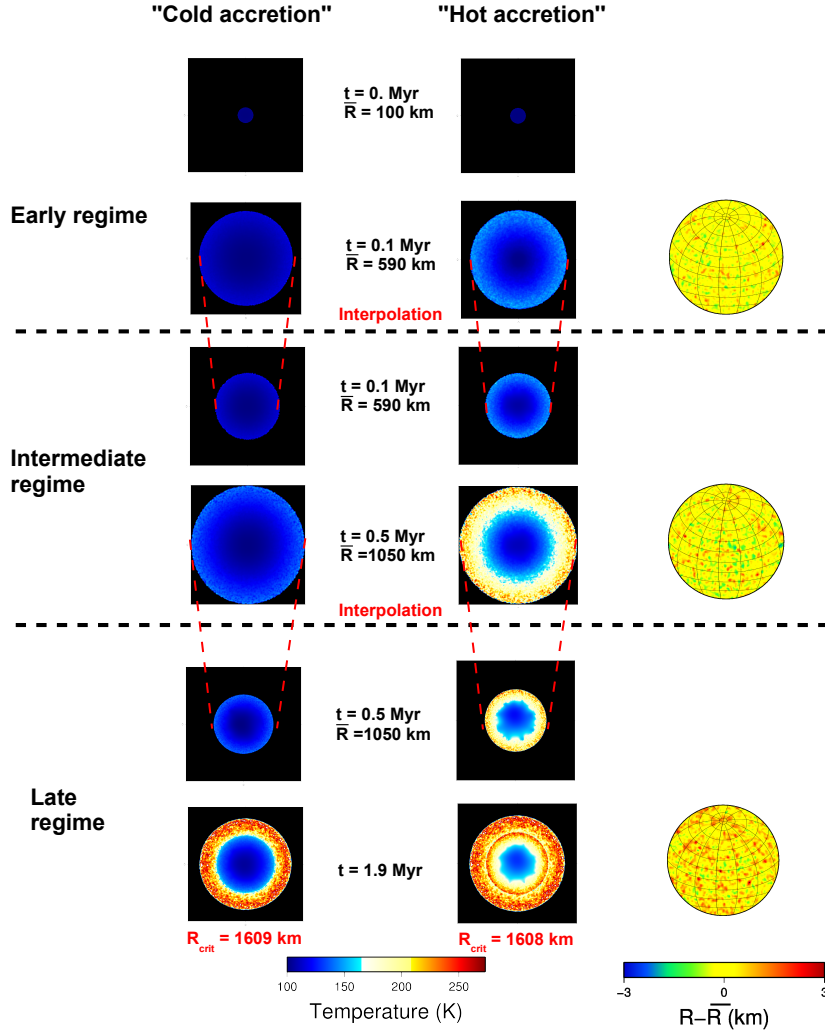


Figure 4: Equatorial cross sections of the temperature field (left and middle columns) and 3D topographical representations (right) of the growing icy moon as a function of time (from top to bottom). The left column represents the "cold accretion" evolution where, up to the end of the intermediate regime, $\gamma_{li} = \gamma_{lay} = 0.1$, $x_{m,li} = 10\%$ while the middle column represents the "hot accretion" evolution where $\gamma_{li} = \gamma_{lay} = 0.3$, $x_{m,li} = 33\%$ (Fig. 4, middle column). Temperature colour scale is saturated in white for temperature at the melting point (> 273 K). Between each regime (early, intermediate, late), the temperature field is interpolated to a larger mesh grid. In the "Late regime", $\gamma_{li} = 0.1$, $\gamma_{lay} = 0.3$, $x_{m,li} = 33\%$, $r_{min} = 10$ km and $r_{max} = 100$ km for both the left and middle columns.

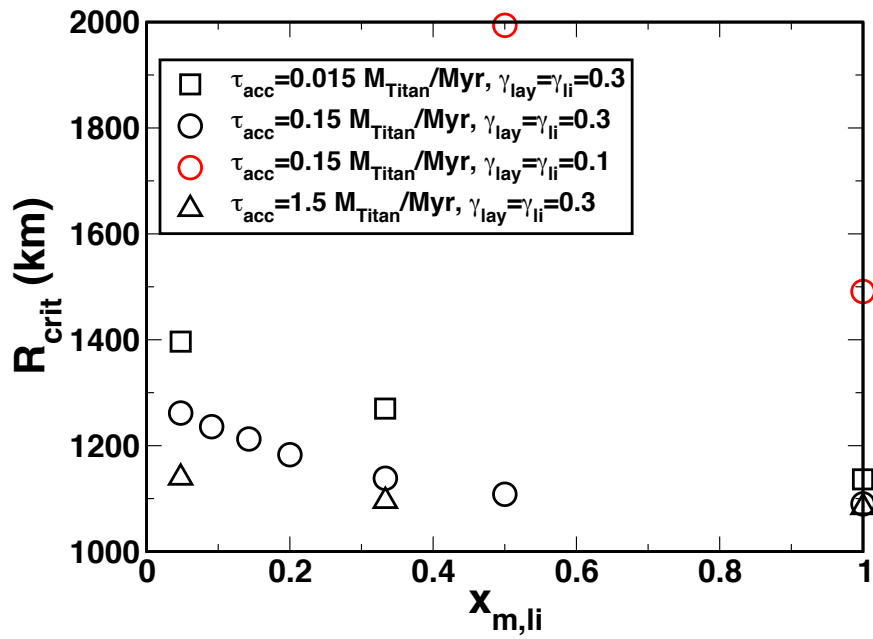


Figure 5: Critical radius R_{crit} (above which more than 5% of the volume of the icy moon has a temperature larger than the melting temperature) as a function of the fraction of material accreted from large impacts $x_{m,li}$ for different accretion rates ranging from $0.015 M_{Titan}/Myr$ to $1.55 M_{Titan}/Myr$. Black symbols represent R_{crit} for $\gamma_{lay} = \gamma_{li} = 0.3$ while red circles represent R_{crit} for $\gamma_{lay} = \gamma_{li} = 0.1$.

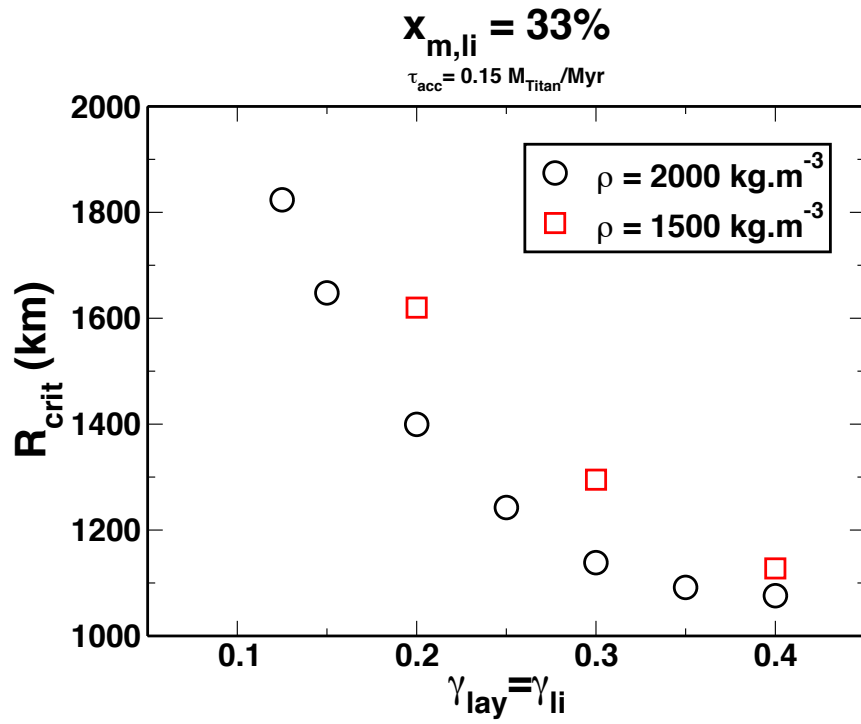


Figure 6: Critical radius R_{crit} (above which more than 5% of the volume of the icy moon has a temperature larger than the melting temperature) as a function of the energy conversion coefficients (γ_{lay} and γ_{li}) for two density values ($\rho = 1500 \text{ kg.m}^{-3}$ and $\rho = 2000 \text{ kg.m}^{-3}$). In these models, the energy conversion coefficients are set to be equal $\gamma_{lay} = \gamma_{li}$, the accretion rate is set to $0.15 M_{Titan}/Myr$ and the mass fraction of material accreted from large impacts is $x_{m,li} = 33\%$.

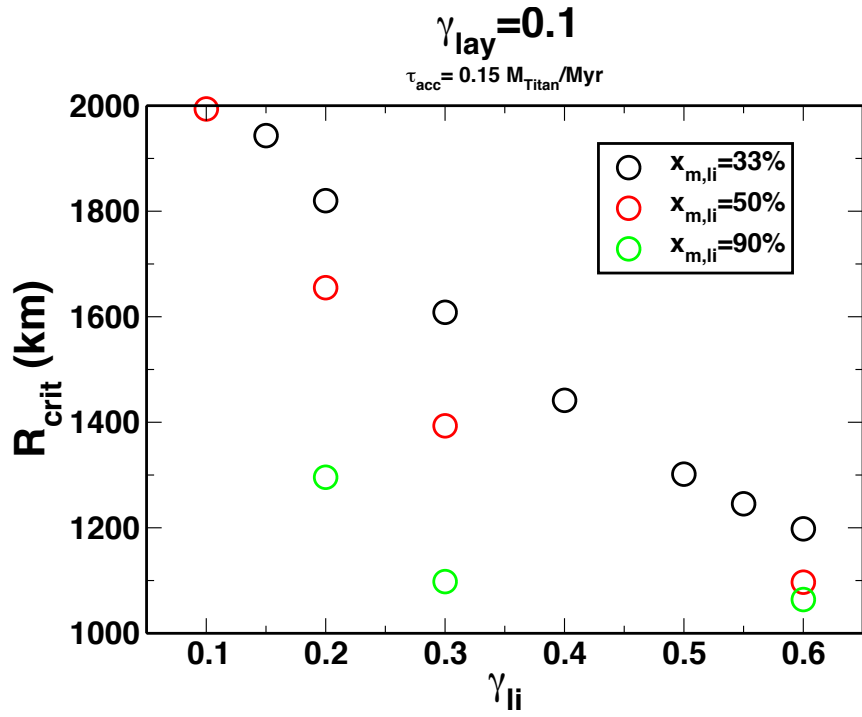


Figure 7: Critical radius R_{crit} (above which more than 5% of the volume of the icy moon has a temperature larger than the melting temperature) as a function of the energy conversion coefficient γ_{li} , for three values of $x_{m,li}$ (33, 50 and 90 %). In these simulations, the energy conversion coefficient γ_{lay} is set to $\gamma_{lay} = 0.1$ and the accretion rate is set to $0.15 M_{Titan}/Myr$.

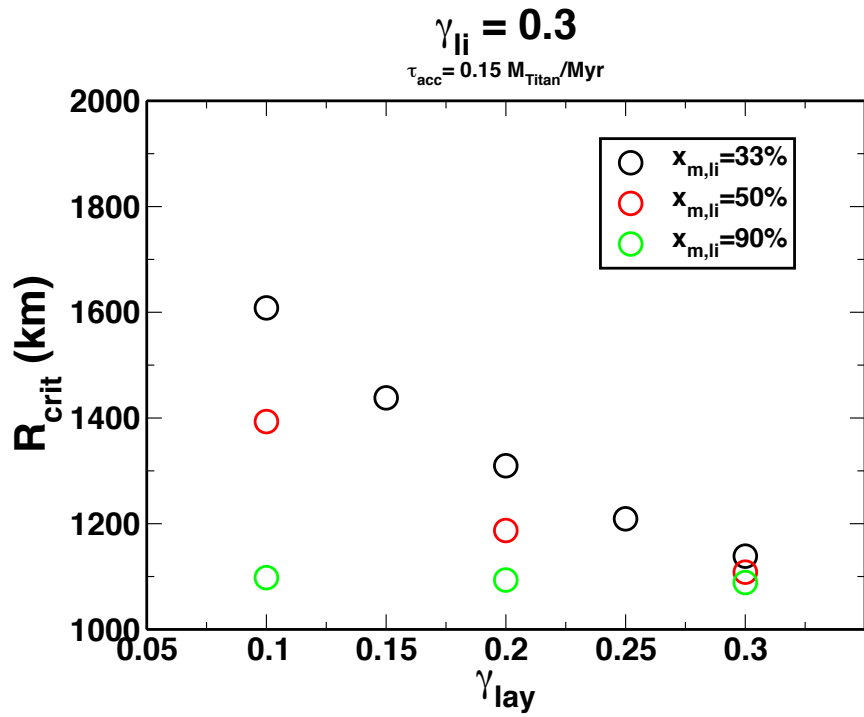


Figure 8: Critical radius R_{crit} (above which more than 5% of the volume of the icy moon has a temperature larger than the melting temperature) as a function of the energy conversion coefficient γ_{lay} for three values of $x_{m,li}$ (33, 50 and 90 %). In these simulations, the energy conversion coefficient γ_{li} is set to $\gamma_{li} = 0.3$. We only represent the results with $\gamma_{lay} \leq \gamma_{li}$. The accretion rate is set to $0.15 M_{Titan}/Myr$.

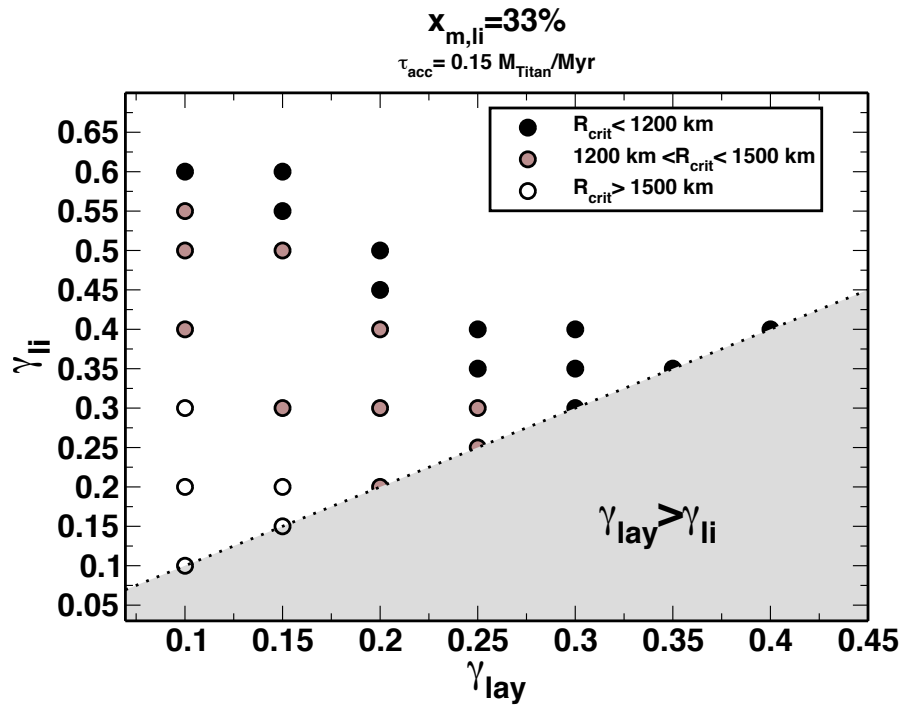


Figure 9: Melting behaviour of a growing icy moon as a function of the energy conversion coefficients γ_{lay} and γ_{li} . For black-filled symbols, $R_{crit} < 1200$ km. For brown-filled symbols, $1200 < R_{crit} < 1500$ km. For white-filled symbols, $R_{crit} > 1500$ km. In these simulations, the accretion rate is set to $0.15 M_{Titan}/Myr$ and the mass fraction of material accreted from large impacts is $x_{m,li} = 33\%$. In the grey domain, $\gamma_{lay} > \gamma_{li}$ and the corresponding cases are not considered here.