Can Large Icy Moons Accrete Undifferentiated?

J. Monteux
G. Tobie, G. Choblet, M. Le Feuvre
Laboratoire de Planétologie et de Géodynamique de Nantes, France

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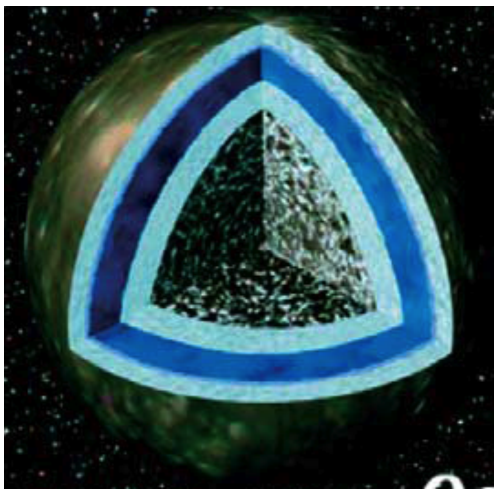
Introduction

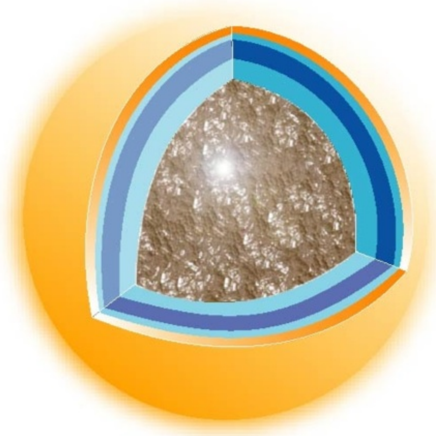
Internal structures of icy satellites
from missions Galileo and Cassini

Callisto



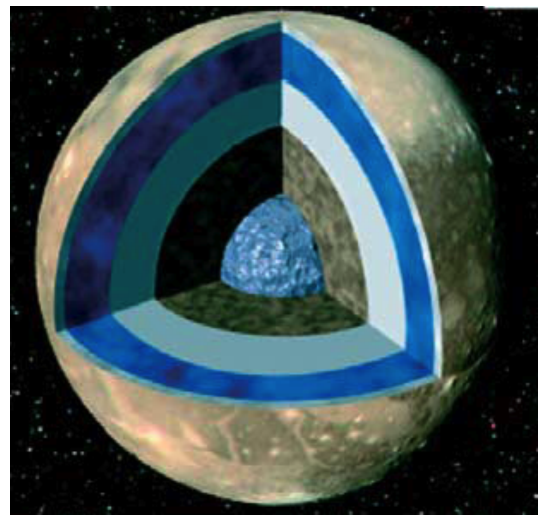
Large
undifferentiated core

Titan

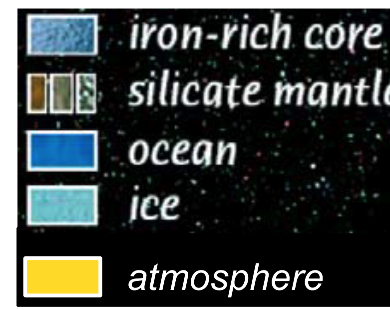


Partially differentiated
core
+ atmosphere

Ganymede



Iron-rich core
+ silicate mantle
+ ice layer
+ ocean



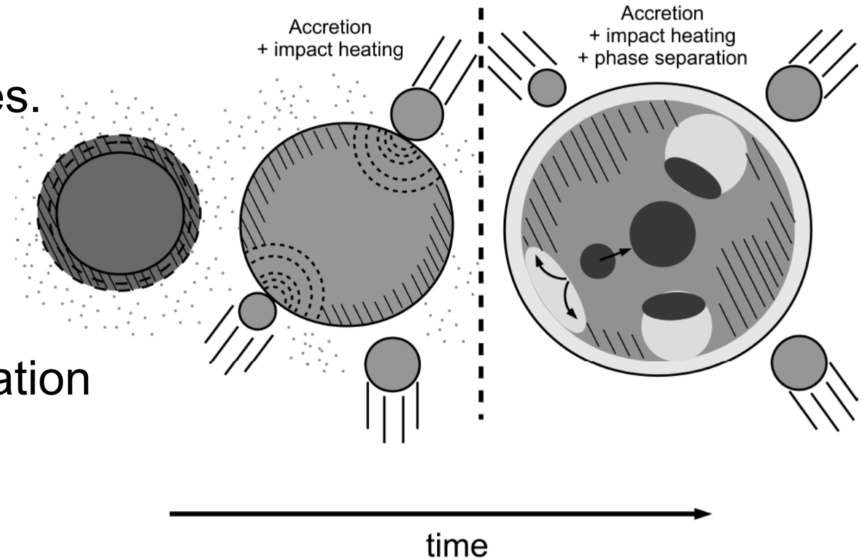
Sotin et al., 2009

Wide range in degree of differentiation among icy satellites

Introduction

Thermal evolution of growing icy satellites is a key parameter to explain internal properties.

- **radioactive heating** (^{26}Al, ^{60}Fe, K, U ...)
- **tidal heating** associated with despinning
- **accretional heating**
- **viscous heating** caused by ice-rock separation



From Tobie et al., 2012

Influence of accretionary characteristics

- **timescales** (Mueller & McKinnon 1988, Nagel et al. 2004)
  long accretion <=> energy radiated efficiently
- **impactor populations characteristics**
  high impact velocities <=> more energy available
  large impactors <=> energy buried deeper
- **late accretionary process** (Barr & Canup 2010)

Degree of differentiation might be explained by conditions of accretion

Introduction

Classical 1D approach (Kaula 1979, Schubert et al., 1981):

$$T_a(r) = \frac{hGM(r)}{c_p r}\left\{1 + ru^2 / 2GM(r)\right\} + T_e$$

r=radius
u=impact velocity
M(r)=mass
Te=Temperature of the surrounding environment
h=fraction of energy retained as heat

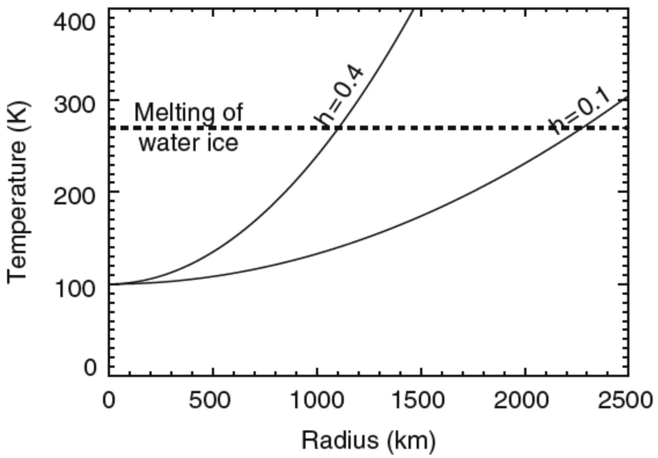


Fig. 3.2 Accretional temperature profile in Titan for different fractions h of the impact energy retained as heat *Lunine et al., 2009*

Limitation of the model

This model can not characterize properly **the influence of large impacts** that are unavoidable at the end of the accretion and that probably have strongly influenced the late thermo-chemical state of large icy satellites

The **evacuation of heat from the surface and the energy conversion of kinetic energy** are simplified within one constant parameter *h*

Introduction

New method

- We develop a model of topographical evolution of an icy satellite growing both by meteoritic impacts and layer deposits

- We consider the thermal effect after each impact

- We combine these 2 approaches in a numerical 3D to monitor the thermal evolution of a growing icy satellite

Major questions

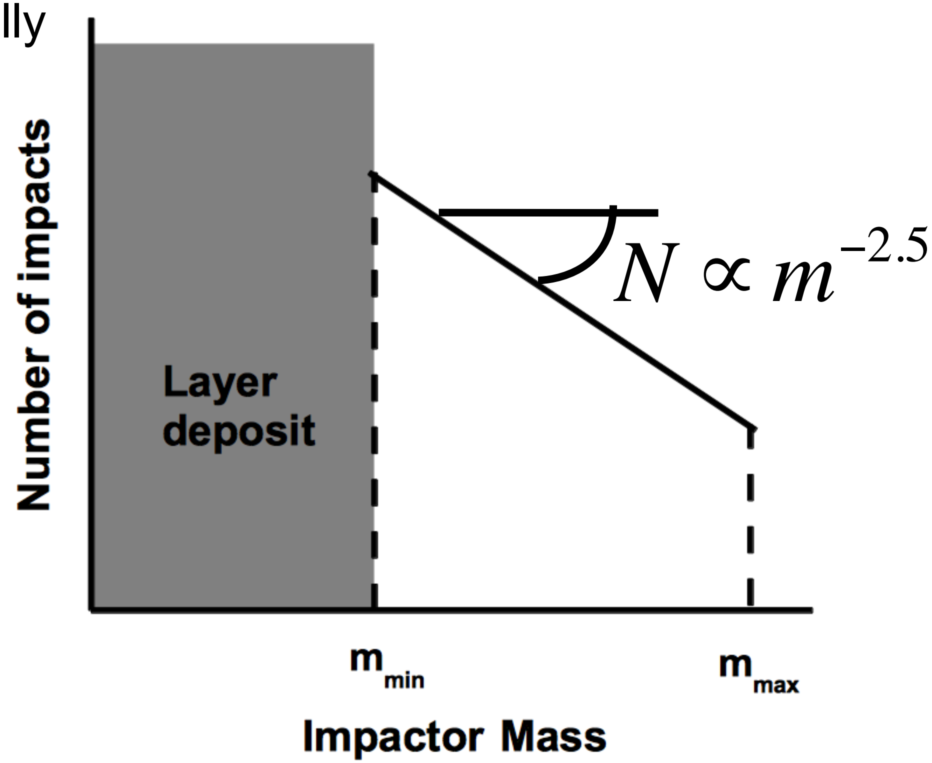
- What is the thermal evolution during the accretion of icy satellites?

- Can the accretionary parameters (impactor size, accretion time and characteristics) explain the wide range in degree of differentiation?

Topographical evolution of the growing body:

A combination of layer deposit and large impacts

- Small impactors are deposited as a layer
- Large impactors are considered individually



We define

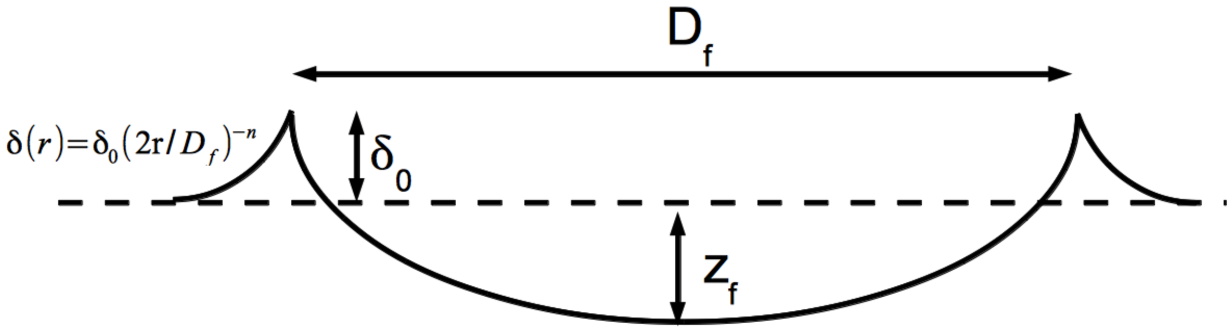
$$k_{acc} = \frac{\text{layering accretion rate}}{\text{large impact accretion rate}}.$$

Large impactors population

- Monte-Carlo sampling
- $R_{imp,min}<R_{imp}<R_{imp,max}$
- the population is (currently) assumed to be infinite
- mass distribution slope from N-body simulations (Kokubo et al., 2000)
- planetocentric/heliocentric impactors

Topographical evolution of the growing body

Large impacts: Cratering lengthscales for icy satellites:



- simple crater diameter (Zahnle et al. 1998)

$$D_s = 1.1\, R_p^{0.22}\, d_{imp}^{0.78} \left(\frac{v_{imp}^2}{v_{esc}^2}\right)^{0.22} \left(\frac{\rho_{imp}}{\rho_p}\right)^{0.33} \left(\cos(\theta_{imp})\right)^{0.44}$$

- transition simple/complex crater when $D_s>D_c$ (McKinnon et al. 1991,Zahnle et al. 2003)

$$D_f = D_s \qquad D_f = D_s (D_s/D_c)^{0.13}$$

-depth simple/complex craters (Schenk, 2002)

$$z_f = 0.75\, D_s^{0.3} \qquad z_f = 0.15\, D_s^{0.88}$$

- rim height (Schenk 1991)

$$\delta_0 = 0.017\, D_f^{0.976}$$

Topographical evolution of the growing body

Multi-Cratering model

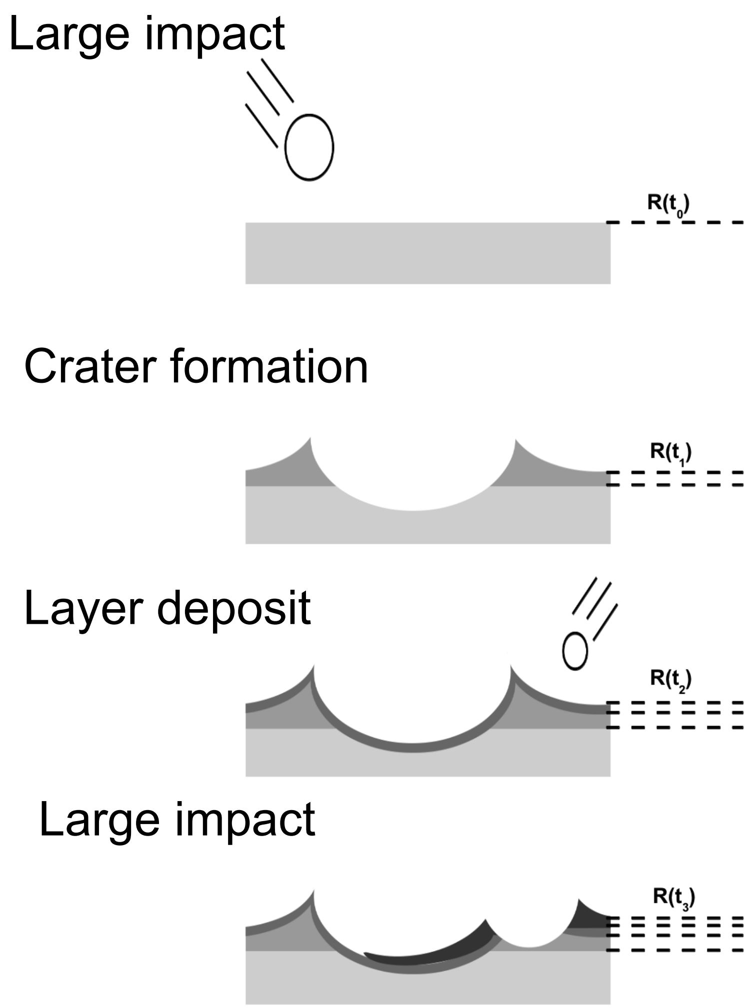
- we assume a constant accretion rate

- layer (i.e. small impactors) is deposited between 2 large impacts

- large impact craters are superimposed to preexisting topography (Howard, 2007).

- we neglect late deformation of impact craters (erosion, landslides ...)

- we consider that impacts are 100% accretive.



Accretionary heating

Large impact heating process

Kinetic energy of impacts

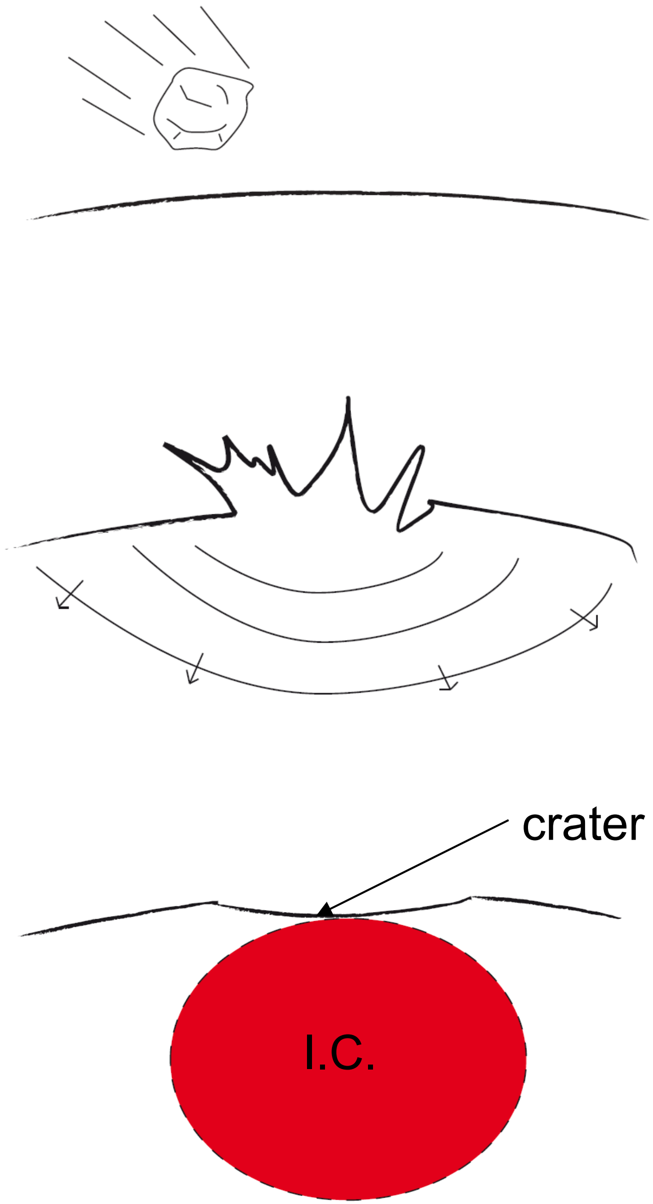
$$v_{imp}^2 = v_{esc}^2 + v_\infty^2$$

shock-wave ⇒ increase of pressure and entropy in a nearly spherical volume below the surface (Croft, 1982)

Despite the adiabatic decompression, a thermal anomaly remains
⇒ temperature increases just after impact (Senshu, 2002)

Considering $v_\infty = 0$ leads to:

$$\Delta T_0 \propto \frac{\gamma G R^2}{C_p}$$



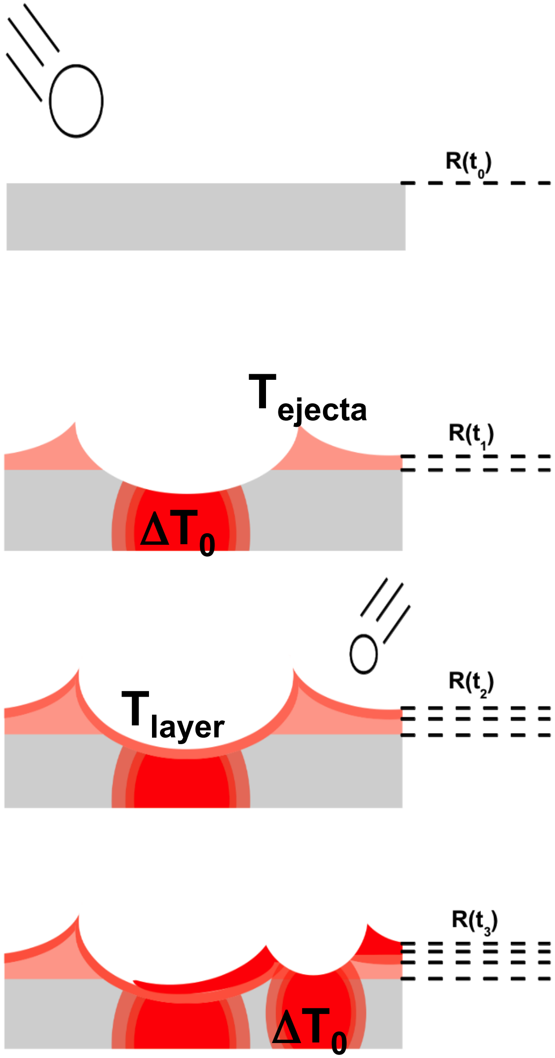
Accretionary heating

Combination between accretion and thermal evolution:
3 characteristic temperatures

- The temperature $\mathbf{T_{layer}}$ of the layer deposit is a function of the impact velocity

- The deep temperature increase $\mathbf{\Delta T_0}$ is a function of the impact velocity

- The temperature $\mathbf{T_{ejecta}}$ of the ejecta excavated after a large is a function of the preimpact temperature + impact heating



Results: Thermal evolution of a growing body

We implement our 2 models in a 3D convection code (Oedipus)

Initial setup

- Initial radius R=1000 km,
- For R<1000 km, we consider that the temperature radially increases from the center.

Experimental parameters

- planetocentric impactor population with constant impact angle

$$v_{imp}=v_{esc}$$

- large impactor radii range

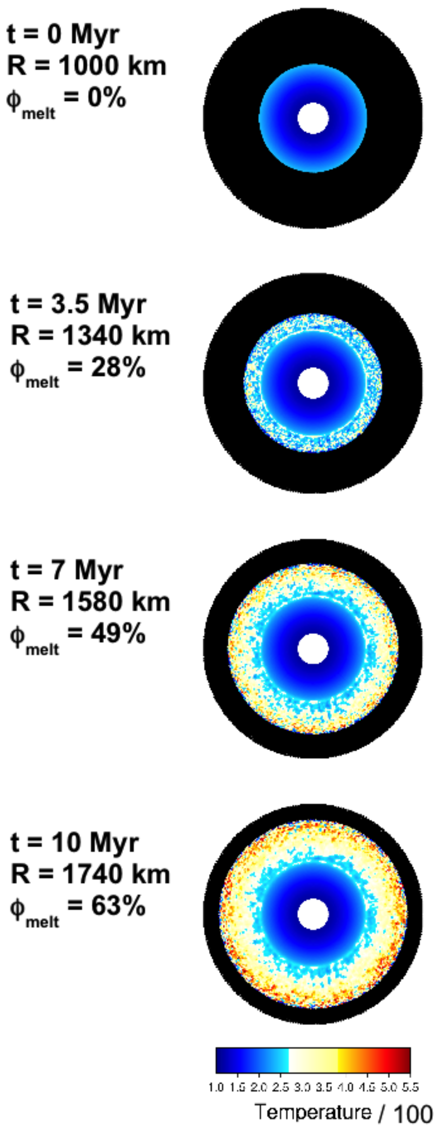
$$10 \text{ km} < r_{imp} < 100 \text{ km}$$

- $k_{acc}=1$
- time of the accretion

$$t_{acc} = 10 \text{ Myr} \quad (10^7 \text{ impacts})$$

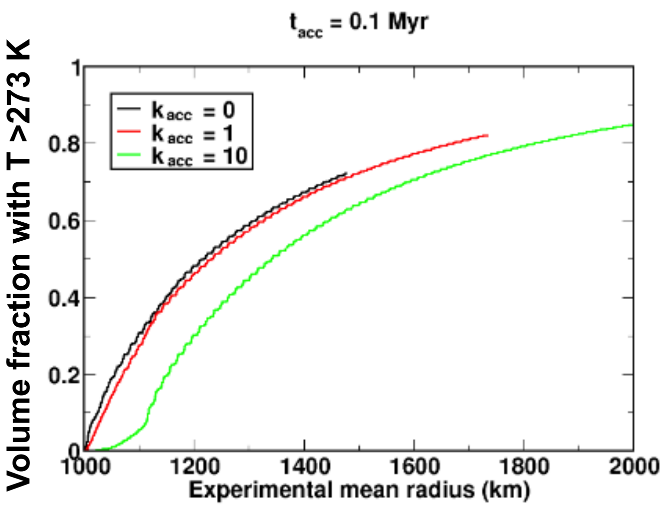
- impact energy conversion efficiency $\gamma=0.3$

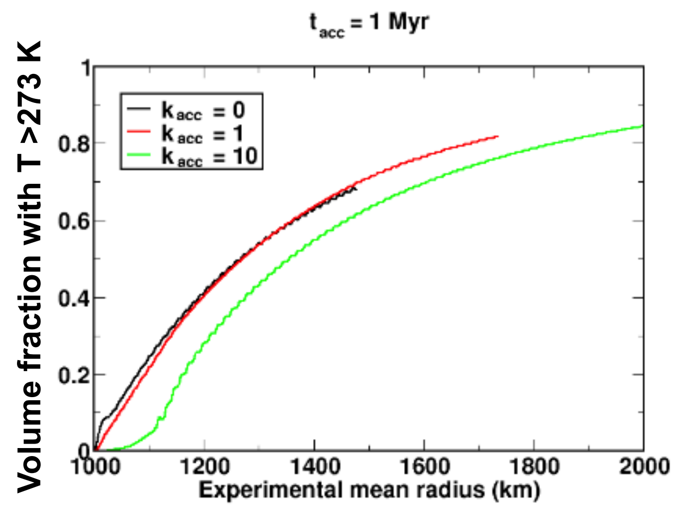
As R increases, v_{imp} and ΔT_0 increase



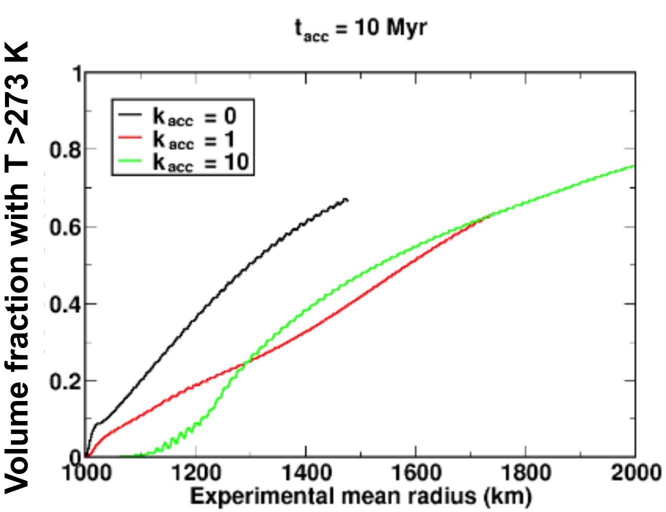
Results: Thermal evolution of a growing body

Influence of accretionary parameters





γ=0.3



Evolution as a function of

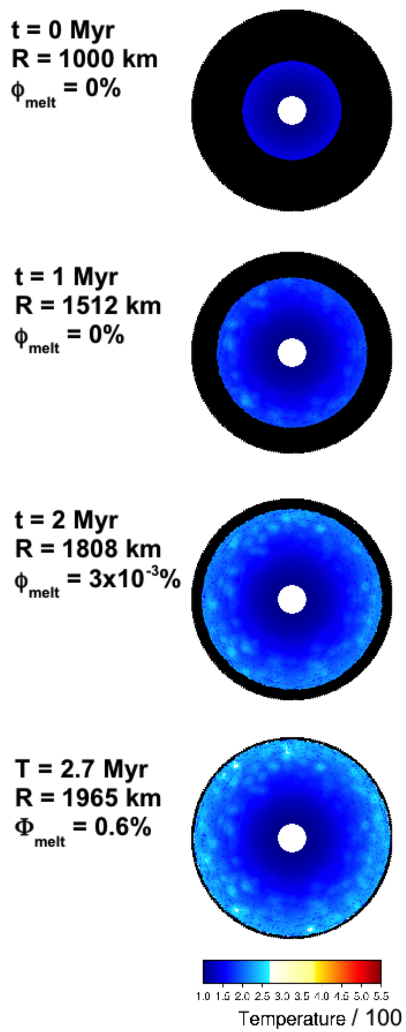
- the size of the growing body
- the accretion time
- the ratio between layer deposit .vs. large impacts

Difficult to avoid substantial melting even with large t_{acc} and k_{acc}

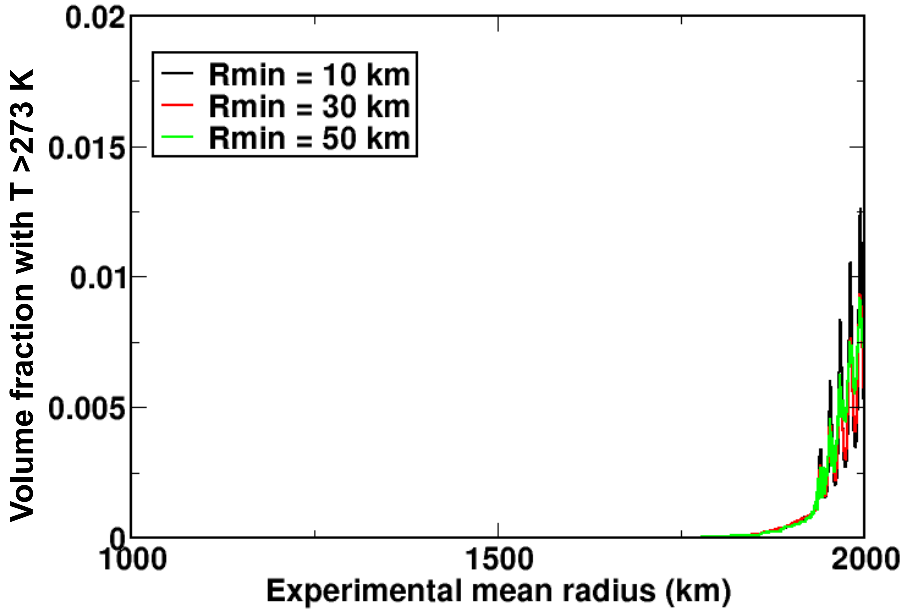
Results: Thermal evolution of a growing body

Influence of the impact energy conversion efficiency γ

γ=0.1



Experimental setup:
- 10 km<r_{imp}<100 km
- k_{acc}=10
- t_{acc}= 10 Myr



Conclusions

- We have built a numerical tool to measure the influence of the accretionary characteristics on the early thermal state of growing icy satellites

- Among the parameters studied, the energy conversion efficiency seems to be a key parameter in understanding the melting degree during icy moons growth

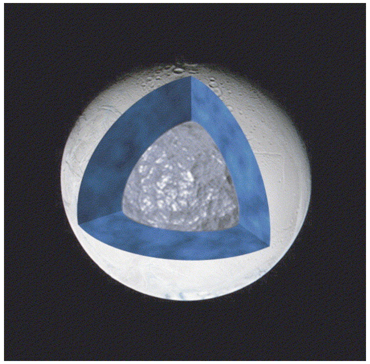
Perspectives

- Extend our study to the inner thermal state of smaller bodies

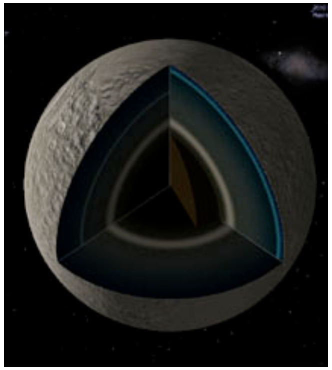
- Implement the effect of supplementary heating (tidal, radiogenic)

- Implement dynamics of differentiation (2-phases dynamics)

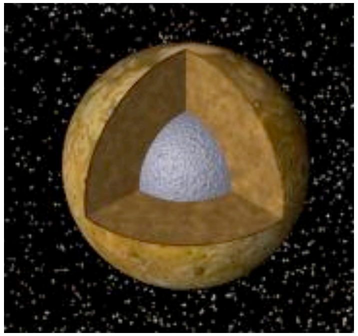
- Characterize the evolution of Titan's nitrogen atmosphere during accretion



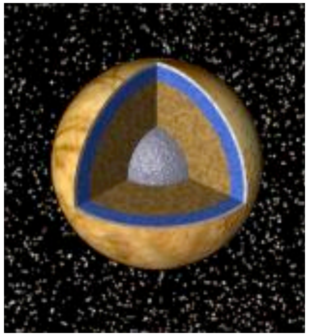
Enceladus (R=250 km)



Rhea (R=763 km)



Io (R=1820 km)



Europa (R=1560 km)