SF2A 2024
M. Béthermin, K. Baillié, N. Lagarde, J. Malzac, R.-M. Ouazzani, J. Richard, O. Venot, A. Siebert (eds)

THERMAL EVOLUTION OF PROTO-GALILEAN MOONS DURING THE ACCRETION PHASE

Y. Bennacer[1], O. Mousis[1, 2], M. Monnereau[3], V. Hue[1] and A. Schneeberger[1]

Abstract. The analysis of Callisto's moments of inertia, derived from Galileo's gravity data, indicates that the moon remains only partially differentiated, contrasting sharply with the fully differentiated Ganymede. This structural dichotomy challenges existing models of Galilean moon formation and evolution. Both moons likely experienced several heating mechanisms during their formation, including tidal forces, radiogenic heating from short-lived radionuclides, accretional heating from impacts, and heat transfer from the circumplanetary disk. Our study examines how variations in accretion parameters, such as the timing, duration, and size distribution of impactors, could explain Callisto's incomplete differentiation compared to Ganymede's fully molten state. We propose that this difference likely arose during the early stages of accretion, despite both moons forming under similar conditions. Notably, the size distribution of impactors played a critical role in Callisto's heat budget, with our findings suggesting it accreted less than 30% of its mass from kilometer-sized impactors to avoid global melting. Additionally, the accretion of both Callisto and Ganymede is estimated to have occurred over a timescale exceeding 2 million years, concluding no earlier than 5.5 million years after the formation of calcium-aluminum-rich inclusions in the protosolar nebula.

1 Introduction

The moons of giant planets in our Solar System offer insights into the origins and evolution of ocean worlds, both locally and in exoplanetary systems. In the Jovian system, the internal structures of the moons vary significantly. Callisto, the outermost moon, shows no evidence of global melting, contrasting with the fully differentiated Io, Europa, and Ganymede. This undifferentiated state of Callisto (Anderson et al. 2001) compared to Ganymede's molten past imposes important constraints on formation models for the Galilean moons.

Radiogenic heating, primarily from short-lived radionuclides like ^{26}Al, is believed to drive ice-rock separation and thermal runaway in early giant planetary satellites. Accretional heating has also been suggested as a key mechanism (Schubert et al. 1981), with impact heat influenced by factors such as impactor size, velocity, and protosatellite growth timescales. Callisto's state is often linked to late formation, slow accretion, and small impactors (under 100 m) (Barr & Canup 2008). However, the role of larger impactors, as indicated by kilometer-sized satellitesimals near Io and beyond Callisto, remains unclear (Ronnet & Johansen 2020).

In this study, we develop a thermal evolution model to explore the accretion conditions that could result in an unmelted Callisto and a differentiated Ganymede. The model simulates the growth of a satellite embryo through impacts from various populations of disk-derived particles (cisplanetary impactors), accounting for radiogenic heating, thermal energy from the Jovian CPD, and tidal dissipation. Key variables include the timing, duration of accretion, and impactor size distribution.

2 Model

We use the one-dimensional heat diffusion equation in spherical geometry with a time-dependent radius elaborated by Monnereau et al. (2013) to simulate the thermal evolution of a growing moon, incorporating radiogenic heating as a heat source. This heating is crucial during the early history of satellites and can potentially drive

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[1] Aix- Marseille Université, CNRS, CNES, Institut Origines, LAM, Marseille, France
38 Rue Frédéric Joliot Curie, 13013 Marseille, France

[2] Institut Universitaire de France (IUF), France

[3] IRAP, University of Toulouse, CNRS, Toulouse, France

global melting within their interiors. Specifically, short-lived radionuclides ^{26}Al provides nearly all the energy during accretion, while long-lived radionuclides are negligible during this phase. The time-dependent heating rate $Q(t)_{\mathrm{rad}}$ of ^{26}Al is given by:

$$Q(t)_{\mathrm{rad}} = m_r \rho X_{26} q_0 \exp[-\lambda_{26}(t + t_{\mathrm{start}})] \tag{2.1}$$

where m_r is the rock mass fraction in the body, $\lambda_{26} = 9.68 \times 10^{-7}\,\mathrm{yr}^{-1}$ is the decay constant of ^{26}Al, $X_{26} = 11.3 \times 10^{-3}$ is the mass fraction of Al in chondrites (Wasson et al. 1988), and $q_0 = 1.77 \times 10^{-5}\,\mathrm{W/kg}$ is the initial heating rate of pure ^{26}Al (Monnereau et al. 2023). The newly accreted material layers produce heating associated with their formation time $t + t_{\mathrm{start}}$, where t_{start} is the time when satellite accretion begins, following a chosen timespan after the formation of calcium-aluminium inclusions (CAI's) in the protosolar nebula (PSN).

Table 1. Impactor populations

Population	Size range	Energy deposit
Small	1 cm–100 m	Surface
Medium	100 m–1 km	Surface and subsurface
Large	1–100 km	Deep inside

The accretion conditions of the Galilean moons are primarily determined by three factors: the lifetime of the circumjovian disk, the mass inflow rate, and the size of the bodies orbiting around the gas giant. The growth of the satellites occurs as they accrete particles from the CPD surrounding Jupiter, with a mass inflow rate depicted by the following relation:

$$\dot{M}_{\mathrm{Sat}} = \frac{M_{\mathrm{Sat}}}{\tau_{\mathrm{acc}}}, \tag{2.2}$$

where M_{Sat} is the mass of the satellite and τ_{acc} is the length of accretion phase. Since the timescale of accretion depends on the assumed disk model, we consider various accretion rates by treating τ_{acc} as a free parameter.

We assume Ganymede and Callisto accreted from the same pristine material in the Jovian CPD. The impactors, with a mean density of $\rho \sim 1850$ kg/m^3, followed a size distribution:

$$\frac{dN}{dr_{\mathrm{imp}}} \propto r_{\mathrm{imp}}^{-\alpha}, \tag{2.3}$$

where α ranges from 1 to 6 (Squyres et al. 1988). Impactor radii r_{imp} vary from centimeters to hundreds of kilometers, depending on disk models and formation mechanisms (Ronnet et al. 2017; Estrada et al. 2009; Batygin & Morbidelli 2020). We consider three particle populations contributing to the growth of the moon's radius $R_s(t)$ (Table 1). Small impactors deposit energy on the surface, medium impactors affect the subsurface beyond the cooling layer (Barr & Canup 2008), and large impactors generate deep shock waves (Monteux et al. 2014). The mass fraction of the ith population x_m^i is obtained by the ratio between the mass of ith population M^i and the total mass, where M^i is derived by integrating the number of particles (Eq. 2.3) times volume and density.

3 Results

Figure 1 illustrates the melting behavior of satellites as influenced by the critical accretion parameters: τ_{acc}, t_{start}, and α, respectively the onset time of accretion, the length of the accretion phase, and the slope of the impactor size distribution. To determine if melting occurs during accretion, we compare the temperature profiles within the newly formed satellite to the pressure-dependent melting temperature of water ice. The total melt fraction in radius, at the end of the accretion, is represented by ϕ_{fus}. Based on the random nature of impact frequency, we assume that a melt fraction ϕ_{fus} less than 5% prevents the satellite from differentiating.

The top two panels highlight the fact that both Ganymede and Callisto experience global ice melting when large impactors dominate the size distribution, and neither prolonged accretion times nor delayed formation would be sufficient to prevent melting. Callisto can only remain undifferentiated if it accreted from a limited

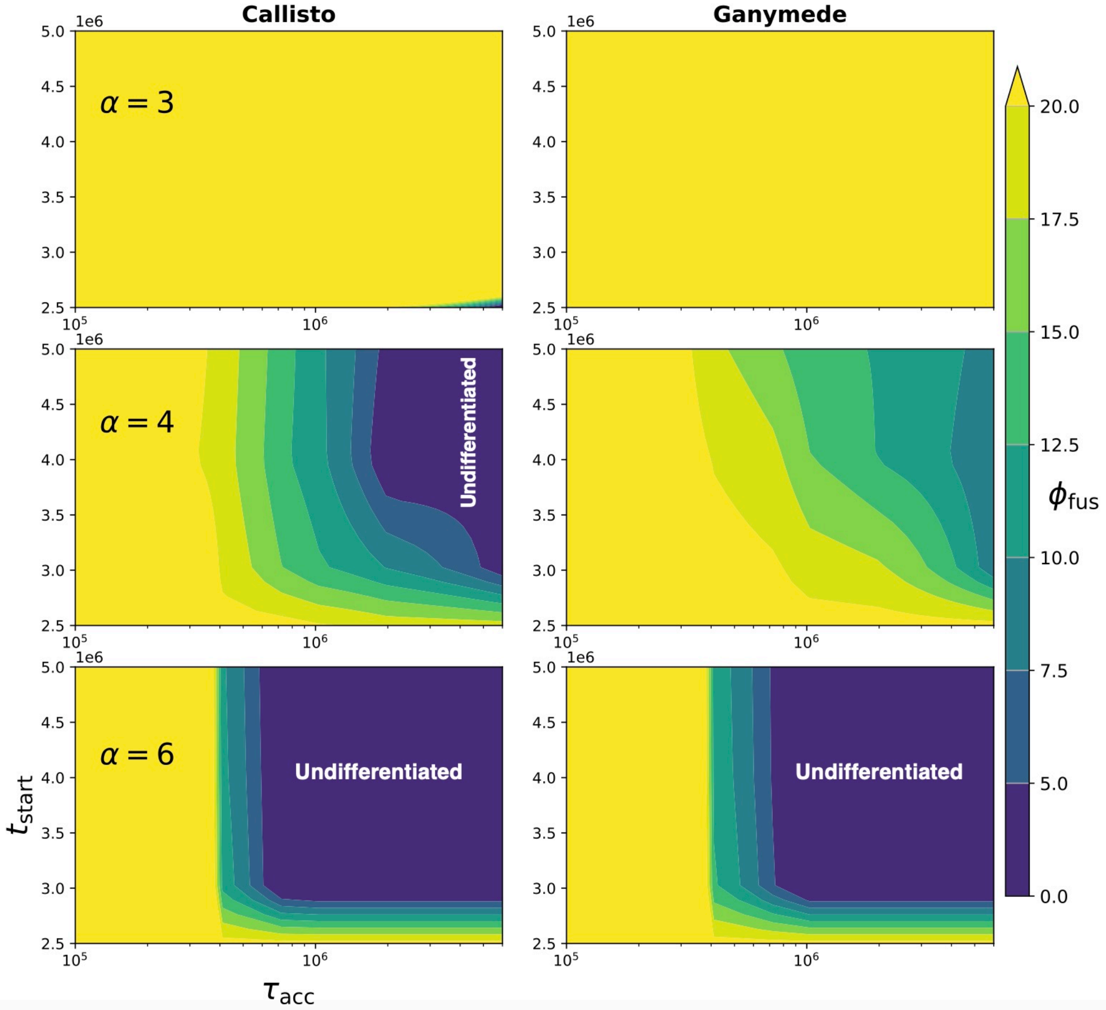

Fig. 1. Final value of the total melt fraction ϕ_{fus} for Callisto and Ganymede as a function of t_{start} and τ_{acc}. From top to bottom, the panels display increasing values of α, ranging from 3.5 to 6. Values equal to 5 are not shown, as the mass fraction distribution remains unchanged between $\alpha = 5$ and $\alpha = 6$, with $x_m^{\mathrm{small}} \sim 100$ % in both cases. To prevent melting during formation, Callisto must accrete a minimum amount of large impactors ($\alpha \gtrsim 4$), namely less than 30% of its final mass. For $\alpha = 4$ (or $\alpha = 5$) Callisto's accretion likely occurred slowly, with $\tau_{\mathrm{acc}} \gtrsim 2$ Myr (or $\tau_{\mathrm{acc}} \gtrsim 0.6$ Myr) and started no earlier than $t_{\mathrm{start}} = 3.5$ (or $t_{\mathrm{start}} = 3$ Myr) after CAI's. Using the same parameters that prevented Callisto from melting, Ganymede could have differentiated early if $\alpha = 4$, suggesting that the observed dichotomy may be primordial.

fraction of large particles, contributing less than one-third of its current mass. This result challenges the conventional view that collisions between satellitesimals dominate the formation process ($x_m^{\mathrm{large}} \sim 100\%$), suggesting that Callisto would require longer accretion periods or delayed formation to avoid melting caused by large impactors, as discussed in Barr & Canup (2008) and Batygin & Morbidelli (2020).

With the same parameters (τ_{acc}, t_{start}, α) that prevent Callisto from melting, we find that Ganymede could achieve early differentiation if both satellites accreted a significant number of medium and large-sized bodies ($\alpha \sim 4$), over a timescale $\tau_{\mathrm{acc}} \gtrsim 2$ Myr, and before $t_{\mathrm{start}} \gtrsim 3.5$ Myr after CAI's. The dichotomy between Ganymede and Callisto can naturally emerge during the accretion phase, with both moons forming under identical conditions governed by the same set of parameters (τ_{acc}, t_{start}, α). Furthermore, this result holds even if both moons accrete the same mass flux, $\dot{M}_{\mathrm{Sat}}$.

4 Discussion

It is also possible to envision a scenario where Ganymede and Callisto formed exclusively from small bodies with radii of $r_{\rm imp} \lesssim 100$ meters and had an accretion timescale of $\tau_{\rm acc} \gtrsim 800$ kyr, which aligns well with the Canup and Ward model (Canup & Ward 2002; Barr & Canup 2008). In this case, the dichotomy between the two moons would likely result from divergent evolutionary pathways (Barr & Canup 2010). However, a recent study by Bottke et al. (2024) questions this scenario, as their estimated mass flux is five times lower than that assumed by Barr & Canup (2010), reducing the likelihood of Ganymede melting due to impacts. Additionally, the possibility of Ganymede and Callisto accreting only from small particles is low, given the presence of large impactors in the CPD. Ronnet & Johansen (2020) demonstrated that about 10% of planetesimals captured from the solar nebula avoided complete mass loss during ablation, retaining significant sizes of several kilometers. Further research is needed to better constrain the time-dependent size distribution of impactors during the accretion process.

O.M. acknowledges support from CNES. This research holds as part of the project FACOM (ANR-22-CE49-0005-01 ACT) and has benefited from a funding provided by l'Agence Nationale de la Recherche (ANR) under the Generic Call for Proposals 2022.

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