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A semi-analytical approach to the long-term evolution of implanted satellitesimals in the inner Jovian system

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Abstract

Long-term satellite evolution over gigayear timescales is often unfeasible with direct N -body methods because timesteps must resolve orbital periods of only hours to days. Here, we present **LAPA**, a Python code that approximates the orbital evolution of satellites using averaged equations for the orbital elements. The model includes secular perturbations, classical and dynamical tides, internal dissipation, and eccentricity excitation during first-order mean-motion resonance crossings. As an application, we explore the model of [Ribeiro de Sousa et al. \(2026\)](#), which shows that, during the formation of the Galilean satellites, in some particular conditions of the gaseous circumjovian disk, satellitesimals can be implanted inside Io's orbit. Starting from the implanted population at gas dispersal, we follow its evolution for **4.5** Gyr. Mean-motion and secular resonance sweeping, together with tides, strongly sculpts the population, removing material through crossings with Io and Jupiter's rigid Roche limit. The resulting survival and depletion boundaries lie close to the present Amalthea-group orbits. In particular, 100 km satellitesimals survive across Amalthea's region, while smaller bodies develop a sharp depletion boundary immediately interior to it. These results show that implanted satellitesimals can survive over Solar-System timescales and suggest that Jupiter's inner satellites may retain dynamical signatures of an early satellitesimal population.

Keywords: satellite formation, Jovian system, tidal evolution

1 Introduction

The architecture of a satellite system around a giant planet is shaped both during the gaseous circumplanetary-disk phase, when the major satellites are expected to form (Canup and Ward 2006; Estrada and Mosqueira 2006; Moraes et al. 2018; Szulágyi et al. 2018), and by the subsequent evolution of the surviving bodies over gigayear timescales. After gas dispersal, planetary tides and mutual gravitational interactions modify their orbits, potentially driving mean-motion resonance (MMR) crossings, collisions, and scattering events. Understanding the origin of a satellite system therefore requires following its evolution from formation to the present age of the Solar System.

The Jovian system of regular satellites illustrates this problem particularly well, comprising the Galilean satellites, Io, Europa, Ganymede, and Callisto, and the inner Amalthea group: Metis, Adrastea, Amalthea, and Thebe (Anderson et al. 2005). Madeira et al. (2021) investigated Galilean satellite formation in a gas-starved circumplanetary disk using N -body simulations with embryos growing through pebble accretion and mutual collisions. Systems with three to five massive satellites in first-order resonant chains predominantly form, including four-satellite analogues in an 8:4:2:1 configuration. This might imply that Callisto was initially trapped in a 2:1 MMR with Ganymede and later reached its current orbit through divergent tidal migration (see Lari et al. 2020).

As a continuation of this investigation, Ribeiro de Sousa et al. (2026) studied whether the Amalthea group could have originated from fragments or residual satellitesimals left over from one of the Galilean satellite formation simulations of Madeira et al. (2021). They showed that gravitational scattering by the forming Galilean satellites can implant satellitesimals interior to Io. However, efficient implantation requires the inner cavity to retain a significant amount of gas, so that aerodynamic drag remains effective close to Jupiter, in contrast to the gas-free cavity adopted in Madeira et al. (2021).

Inward implantation, however, is a necessary but not sufficient condition for connecting these satellitesimals to Jupiter’s present inner moons and rings, since Ribeiro de Sousa et al. (2026) followed the system only during its approximately 2 Myr gas-disk phase. Here, we investigate whether the implanted population can survive the subsequent evolution of the Jovian system and produce an orbital distribution compatible with the Amalthea group and the inner rings.

Direct N -body integrations over the age of the Solar System are computationally prohibitive because the orbital periods of the inner Jovian satellites are only a few hours or days. To overcome this limitation, we present in Section 2 the LAPA code, which follows, to first approximation, the long-term evolution of satellites and satellitesimals through averaged equations for their orbital elements. In Section 3, we apply LAPA to the implanted population and follow its evolution over 4.5 Gyr, before discussing the implications in Section 4.

2 Methods

Our numerical simulations are performed using the custom-built LAPA code (Long-term Averaged Perturbation Algorithm), a Python-based code that tracks the orbital

44 evolution of objects through orbit-averaged equations for their orbital elements. The
 45 code distinguishes between active bodies (satellites), which mutually interact, and
 46 passive bodies (satellitesimals), which are perturbed by the active bodies but do not
 47 affect them or interact with one another. A system containing N_a active bodies and
 48 N_p passive bodies is decomposed into N_p independent simulations, each containing
 49 the N_a active bodies and one passive body. These simulations can be integrated in
 50 parallel on different computational nodes, substantially improving the computational
 51 performance.

52 The integrations are performed with a fixed timestep defined as

$$t_{\text{step}} = 0.001 \min \left(\min_j \tau_{e,j}, \min_{k,l} t_{\text{syn},kl} \right), \quad (1)$$

53 where $\tau_{e,j}$ is the tidal eccentricity-damping timescale of body j , and $t_{\text{syn},kl}$ is the
 54 synodic period between a pair of bodies k and l .

55 At each timestep, the orbital elements of body j are computed as

$$a_j = a_{\text{tid},j}^{\text{pla}} + a_{\text{tid},j}^{\text{dis}}, \quad (2)$$

$$e_j = e_{\text{sec},j} + e_{\text{res},j} + e_{\text{tid},j}^{\text{pla}} + e_{\text{tid},j}^{\text{dis}}, \quad (3)$$

$$I_j = I_{\text{sec},j} + I_{\text{tid},j}^{\text{pla}}, \quad (4)$$

$$\varpi_j = \varpi_{\text{sec},j}, \quad (5)$$

59 and

$$\Omega_j = \Omega_{\text{sec},j}. \quad (6)$$

60 Here, X_{sec} , $X_{\text{tid}}^{\text{pla}}$, and $X_{\text{tid}}^{\text{dis}}$ denote the contributions from secular perturbations
 61 (Section 2.1), planetary tides, and internal dissipation (Section 2.2), respectively. The
 62 term e_{res} is the eccentricity increment associated with an MMR crossing (Section 2.3).
 63 These contributions are described below.

64 2.1 Secular perturbations

65 A useful approach to systems with more than two bodies, which are generally non-
 66 integrable, is to describe their mutual perturbations through the disturbing function
 67 (see [Ellis and Murray 2000](#)). Its terms can be classified as short-period, resonant, or
 68 secular. In our simulations, we retain only the secular terms, which describe the long-
 69 term, non-resonant interactions between the bodies. The leading secular contribution
 70 to the disturbing function is ([Brouwer and Clemence 1961](#); [Dermott and Nicholson](#)
 71 [1986](#)):

$$\mathcal{R} = n_j a_j \left[\frac{A_{jj}}{2} e_j^2 + \sum_{l=1, l \neq j}^N A_{jl} e_j e_l \cos(\varpi_j - \varpi_l) + \frac{B_{jj}}{2} I_j^2 + \sum_{l=1, l \neq j}^N B_{jl} I_j I_l \cos(\Omega_j - \Omega_l) \right] \quad (7)$$

72 where the coefficients of the matrices $\mathbf{A}$ and $\mathbf{B}$ are (Brouwer and Clemence 1961;
73 Dermott and Nicholson 1986):

$$A_{jj} = n_j \left[\frac{3}{2} J_2 \left(\frac{R_J}{a_j} \right)^2 - \frac{9}{8} J_2^2 \left(\frac{R_J}{a_j} \right)^4 - \frac{15}{4} J_4 \left(\frac{R_J}{a_j} \right)^4 + \frac{1}{4} \sum_{l=1, l \neq j}^N \frac{m_l}{M_J + m_j} \alpha_{jl} \bar{\alpha}_{jl} b_{3/2}^{(1)}(\alpha_{jl}) \right], \quad (8)$$

$$A_{jl} = -\frac{1}{4} \frac{m_l}{M_J + m_j} n_j \alpha_{jl} \bar{\alpha}_{jl} b_{3/2}^{(2)}(\alpha_{jl}), \quad (9)$$

$$B_{jj} = -n_j \left[\frac{3}{2} J_2 \left(\frac{R_J}{a_j} \right)^2 - \frac{27}{8} J_2^2 \left(\frac{R_J}{a_j} \right)^4 - \frac{15}{4} J_4 \left(\frac{R_J}{a_j} \right)^4 + \frac{1}{4} \sum_{l=1, l \neq j}^N \frac{m_l}{M_J + m_j} \alpha_{jl} \bar{\alpha}_{jl} b_{3/2}^{(1)}(\alpha_{jl}) \right], \quad (10)$$

76 and

$$B_{jl} = \frac{1}{4} \frac{m_l}{M_J + m_j} n_j \alpha_{jl} \bar{\alpha}_{jl} b_{3/2}^{(1)}(\alpha_{jl}) \quad (11)$$

77 Here, m_j is the mass of body j , J_2 and J_4 are Jupiter's gravitational coefficients
78 (Iess et al. 2018), and $b_s^{(i)}(\alpha)$ is the Laplace coefficient (Murray and Dermott 1999).
79 The quantities α_{jl} and $\bar{\alpha}_{jl}$ are defined as (Brouwer and Clemence 1961; Dermott and
80 Nicholson 1986)

$$\alpha_{jl} = \begin{cases} a_l/a_j & \text{if } a_j > a_l \\ a_j/a_l & \text{if } a_j < a_l \end{cases} \quad \text{and} \quad \bar{\alpha}_{jl} = \begin{cases} 1 & \text{if } a_j > a_l \\ a_j/a_l & \text{if } a_j < a_l \end{cases} \quad (12)$$

81 The secular eigenfrequencies g_i and f_i are obtained from

$$\det(\mathbf{A} - g_i \mathbf{I}) = 0, \quad \det(\mathbf{B} - f_i \mathbf{I}) = 0, \quad (13)$$

82 where $\mathbf{I}$ is the identity matrix. The corresponding eigenvectors are determined from
83 (Brouwer and Clemence 1961; Dermott and Nicholson 1986)

$$\sum_{l=1}^N A_{jl} e_{li} = g_i e_{ji}, \quad \sum_{l=1}^N B_{jl} I_{li} = f_i I_{ji}. \quad (14)$$

84 At each integration timestep, the matrices are updated using the orbital elements from
85 the previous step, and the eigenfrequencies and eigenvectors are recalculated. The
86 secular eccentricity, inclination, longitude of pericentre, and longitude of the ascending

node are then obtained from (Murray and Dermott 1999)

$$e_{\text{sec},j}^2 = \left[\sum_{l=1}^N e_{jl} \sin(g_l t + \beta_l) \right]^2 + \left[\sum_{l=1}^N e_{jl} \cos(g_l t + \beta_l) \right]^2, \quad (15)$$

$$I_{\text{sec},j}^2 = \left[\sum_{l=1}^N I_{jl} \sin(f_l t + \gamma_l) \right]^2 + \left[\sum_{l=1}^N I_{jl} \cos(f_l t + \gamma_l) \right]^2, \quad (16)$$

$$\tan \varpi_{\text{sec},j} = \frac{\sum_{l=1}^N e_{jl} \sin(g_l t + \beta_l)}{\sum_{l=1}^N e_{jl} \cos(g_l t + \beta_l)}, \quad \tan \Omega_{\text{sec},j} = \frac{\sum_{l=1}^N I_{jl} \sin(f_l t + \gamma_l)}{\sum_{l=1}^N I_{jl} \cos(f_l t + \gamma_l)}, \quad (17)$$

where β_l and γ_l are phases determined from the initial conditions (see Murray and Dermott 1999).

2.2 Tidal effect

The tidal evolution is decomposed into two contributions: the tide raised on the primary by body j and the internal dissipation within body j due to the tide raised by the primary. We follow Boué and Efroimsky (2019), who expressed the tidal evolution of the orbital elements as series in eccentricity and inclination. This formulation is suitable for the initially eccentric and inclined satellites considered here. We adopt a constant-phase-lag model (Kaula 1964) and describe Jupiter's tidal response by its degree-2 Love number k_{2J} and quality factor Q_J , assuming a constant ratio $k_{2J}/Q_J = 1.102 \times 10^{-5}$ (Lainey et al. 2009). The variations of semimajor axis, eccentricity, and inclination due to the primary tides are (Boué and Efroimsky 2019):

$$\begin{aligned} \dot{a}_{\text{tid},j}^{\text{pla}} = & -2a_j n_j \left(\frac{R_J}{a_j} \right)^5 \frac{m_j}{M_J} \frac{k_{2J}}{Q_J} \sum_{p,m=0}^2 \sum_{q=-\infty}^{\infty} (2-2p+q) \\ & \frac{(2-m)!}{(2+m)!} (2-\delta_{0m}) G_{2qp}^2(e_j) F_{2mp}^2(I_j), \end{aligned} \quad (18)$$

$$\begin{aligned} \dot{e}_{\text{tid},j}^{\text{pla}} = & -\frac{1-e_j^2}{e_j} n_j \left(\frac{R_J}{a_j} \right)^5 \frac{m_j}{M_J} \frac{k_{2J}}{Q_J} \sum_{p,m=0}^2 \sum_{q=-\infty}^{\infty} (2-2p+q) \\ & \frac{(2-m)!}{(2+m)!} (2-\delta_{0m}) G_{2qp}^2(e_j) F_{2mp}^2(I_j) + \\ & + \frac{\sqrt{1-e_j^2}}{e_j} n_j \left(\frac{R_J}{a_j} \right)^5 \frac{m_j}{M_J} \frac{k_{2J}}{Q_J} \sum_{p,m=0}^2 \sum_{q=-\infty}^{\infty} (2-2p) \\ & \frac{(2-m)!}{(2+m)!} (2-\delta_{0m}) G_{2qp}^2(e_j) F_{2mp}^2(I_j), \end{aligned} \quad (19)$$

103 and

$$\begin{aligned} \dot{I}_{\text{tid},j}^{\text{pla}} = & -\frac{n_j}{\sqrt{1-e_j^2}} \left(\frac{R_j}{a_j}\right)^5 \frac{m_j}{M_J} \frac{k_{2J}}{Q_J} \sum_{p,m=0}^2 \sum_{q=-\infty}^{\infty} \frac{(2-m)!}{(2+m)!} \\ & (2-\delta_{0m}) \frac{(2-2p)\cos I_j - m}{\sin I_j} G_{2qp}^2(e_j) F_{2mp}^2(I_j) \end{aligned} \quad (20)$$

104 where $G_{2qp}^2(e_j)$ and $F_{2mp}^2(I_j)$ are eccentricity and inclination functions, respectively,
 105 given by [Boué and Efroimsky \(2019\)](#).

106 Internal dissipation is computed assuming synchronous rotation of body j . Its tidal
 107 response is described by the constants k_{2j} and Q_j , and the physical radius R_j . The
 108 corresponding variations in semimajor axis and eccentricity are ([Boué and Efroimsky](#)
 109 [2019](#))

$$\dot{a}_{\text{tid},j}^{\text{dis}} = -2a_j n_j \left(\frac{R_j}{a_j}\right)^5 \frac{M_J}{m_j} \frac{k_{2j}}{Q_j} \sum_{p,m=0}^2 \sum_{q=-\infty}^{\infty} (2-2p+q) \frac{(2-m)!}{(2+m)!} (2-\delta_{0m}) G_{2qp}^2(e_j) \quad (21)$$

110 and

$$\begin{aligned} \dot{e}_{\text{tid},j}^{\text{dis}} = & -\frac{1-e_j^2}{e_j} n_j \left(\frac{R_j}{a_j}\right)^5 \frac{M_J}{m_j} \frac{k_{2j}}{Q_j} \sum_{p,m=0}^2 \sum_{q=-\infty}^{\infty} (2-2p+q) \frac{(2-m)!}{(2+m)!} (2-\delta_{0m}) G_{2qp}^2(e_j) + \\ & + \frac{\sqrt{1-e_j^2}}{e_j} n_j \left(\frac{R_j}{a_j}\right)^5 \frac{M_J}{m_j} \frac{k_{2j}}{Q_j} \sum_{p,m=0}^2 \sum_{q=-\infty}^{\infty} (2-2p) \frac{(2-m)!}{(2+m)!} (2-\delta_{0m}) G_{2qp}^2(e_j) \end{aligned} \quad (22)$$

111 In all tidal expansions, we retain terms up to fifth order in eccentricity and second
 112 order in inclination.

113 2.3 Resonance crossing

114 During tidal migration, satellitesimals may cross MMRs with the Galilean satellites,
 115 enhancing the energy exchange between the bodies and producing an satellitesimal
 116 eccentricity kick. Depending on the masses and migration rates of the objects, resonant
 117 capture may also occur ([Deienno et al. 2020](#)). However, because no satisfactory closed-
 118 form prescription is available to determine capture, this effect is not included in **LAPA**,
 119 constituting a limitation of the model. The eccentricity kick is estimated only for
 120 first-order MMRs, which are the strongest.

121 Assuming that the back-reaction of the satellitesimal on the Galilean satellite is
 122 negligible, the disturbing function for a $\kappa:\kappa-1$ MMR is ([Murray and Dermott 1999](#))

$$\mathcal{R} = \frac{GM_G}{a_G} \left[e_j F - 2 \frac{a_j}{a_G} \delta_{\kappa 2} \right] \cos[\kappa \lambda_G + (1-\kappa) \lambda_j - \varpi_j], \quad (23)$$

where M_G , a_G , and λ_G are the mass, semimajor axis, and mean longitude of the Galilean satellite, respectively. The direct radial term is (Ellis and Murray 2000)

$$F = \frac{1}{2} \left[-2\kappa - \frac{a_j}{a_G} \frac{d}{d(a_j/a_G)} \right] b_{1/2}^{(\kappa)}(a_j/a_G). \quad (24)$$

The resulting eccentricity kick is computed as (Murray and Dermott 1999)

$$e_{\text{res},j} = \left| \frac{n_j}{\kappa n_G + (1 - \kappa)n_j} \frac{a_j}{a_G} \frac{M_G}{M_J} \left(F - 2 \frac{a_j}{a_G} \delta_{\kappa 2} \right) \right|. \quad (25)$$

3 Evolution after the gas-disk disappearance

3.1 Implanted satellitesimal population at gas dispersal

Here, we extend a particular case from the simulations of Ribeiro de Sousa et al. (2026), who interpolated one of the Galilean satellite formation scenarios of Madeira et al. (2021) (see Figure 2 of Ribeiro de Sousa et al. 2026) and followed 5000 satellitesimals initially distributed from 10 to 120 R_J , with sizes of 10 and 100 km.

Ribeiro de Sousa et al. (2026) adopted a model in which Jupiter is almost fully formed, opens a deep gap in the CSD, and is surrounded by a disk mostly composed of gas around its equatorial plane. The radial gas surface density is given by (Canup and Ward 2002, 2006, 2009; Sasaki et al. 2010; Madeira et al. 2021):

$$\Sigma_g(r) = \frac{\dot{M}_g}{3\pi\nu(r)} \begin{cases} 1 - \frac{4}{5}\sqrt{\frac{R_c}{R_d}} - \frac{1}{5}\left(\frac{r}{R_c}\right)^2 & \text{for } r \leq R_c, \\ \frac{4}{5}\sqrt{\frac{R_c}{r}} - \frac{4}{5}\sqrt{\frac{R_c}{R_d}} & \text{for } r > R_c, \end{cases} \quad (26)$$

where $R_c = 26 R_J$ and $R_d = 150 R_J$ are the centrifugal and outer disk radii, respectively, adopting the values from Canup and Ward (2002); Tanigawa et al. (2012).

In this model, the CPD is continuously supplied by material falling from the circumstellar disk, with a mass in-fall rate $\dot{M}_g$. The turbulent viscosity of the disk is denoted by ν . Note that this disk model is qualitatively consistent with the delivery of gas to the CPD through the meridional circulation of gas near the planet's gap (Tanigawa et al. 2012; Morbidelli et al. 2014; Szulágyi et al. 2014; Schulik et al. 2020; Batygin and Morbidelli 2020). The model also assumes that gas is deposited onto the CPD midplane around the centrifugal radius (R_c) and subsequently spreads viscously. The mass in-fall rate from the CSD onto the CPD is prescribed as (Sasaki et al. 2010; Ronnet et al. 2017):

$$\dot{M}_g = 10^{-7} e^{-\frac{t}{\tau_d}} M_J/\text{yr}, \quad (27)$$

where t is the time and $\tau_d = 1.0$ Myr is the disk decay timescale. For simplicity, Madeira et al. (2021) neglected Jupiter's growth through gas accretion and fixed its mass at its current value.

We selected the simulations of Ribeiro de Sousa et al. (2026) that yielded the highest implantation efficiencies interior to Io's orbit, with approximately 21% and 5%

152 implantation efficiencies for 10 and 100 km satellitesimals, respectively. These simula-
 153 tions were performed assuming a fixed inner disk edge at $R_i = 1.5 R_J$ throughout the
 154 integrations, implemented by rescaling the gas surface density according to:

$$\mathcal{R} = \tanh\left(\frac{r - R_i}{0.05 R_i}\right). \quad (28)$$

155 Following [Madeira et al. \(2021\)](#), [Ribeiro de Sousa et al. \(2026\)](#) adopted the standard
 156 α -viscosity prescription proposed by [Shakura and Sunyaev \(1973\)](#) to describe the disk
 157 viscosity:

$$\nu = \alpha_z c_s H_g, \quad (29)$$

158 where [Ribeiro de Sousa et al. \(2026\)](#) set $\alpha_z = 10^{-3}$, representing the turbulent viscosity
 159 coefficient. In this disk model, the initial location of the snowline, defined as the
 160 location in the gaseous disk where water condenses into ice, is approximately $r \sim$
 161 $14.5 R_J$. The radial temperature profile is given by ([Ronnet et al. 2017](#)):

$$T = 225 \left(\frac{r}{10 R_J}\right)^{-3/4} \text{ K}. \quad (30)$$

162 These simulations were selected because they produce a large number of particles
 163 interior to Io's orbit, providing a suitable population with which to test our numerical
 164 code. Although the adopted inner disk edge at $1.5 R_J$ does not exactly reproduce the
 165 migration history of [Madeira et al. \(2021\)](#), in which Io's precursor halts near $5 R_J$, this
 166 setup represents a useful end-member in which gas-assisted implantation is maximized.

167 Figure 1 shows the evolution of periapsis (q), semimajor axis (a), and apoapsis (Q)
 168 for the Galilean precursors (gray) and 10 and 100 km satellitesimals (black) in one
 169 simulation from [Ribeiro de Sousa et al. \(2026\)](#). As the system evolves, satellitesimals
 170 are progressively removed due to close encounters and collisions. Instead of remaining
 171 near their initial positions, they are dynamically scattered throughout the circum-
 172 planetary disk. Satellitesimal scattering becomes more prominent after approximately
 173 1.2 Myr, largely independent of the adopted gas disk profile.

174 By this time, the Galilean precursors have grown to masses close to those of the
 175 final Galilean satellites, and their gravitational perturbations become strong enough to
 176 drive substantial radial redistribution of the satellitesimal population. Many satellites-
 177 imals are scattered inward toward Jupiter. Their subsequent evolution then depends
 178 on the inner gas distribution: when gas is present at small orbital distances, aero-
 179 dynamic drag can damp their eccentricities and inclinations, allowing some bodies
 180 to settle onto nearly circular, low-inclination orbits. The final orbits of the surviving
 181 satellitesimals is showed in Figure 2 in Panel (a).

182 3.2 Long-term evolution of implanted satellitesimals

183 In our long-term simulations, the orbital elements of the surviving satellitesimals at
 184 gas dispersal (2 Myr in the simulations of [Ribeiro de Sousa et al. 2026](#)) are adopted
 185 as initial conditions. The Galilean satellites evolve under dynamical tides following
 186 [Madeira et al. \(2021, Figure 11\)](#), while satellitesimals evolve under classical tides,

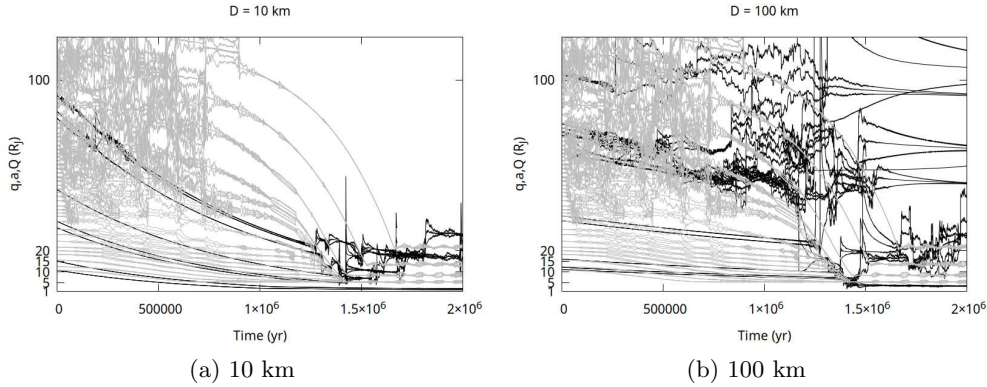


Fig. 1 Orbital evolution of the periapsis (q), semimajor axis (a), and apoapsis (Q) of the Galilean-satellite precursors, shown as gray lines, and selected satellites, shown as black lines, for a particular case from the simulations of [Ribeiro de Sousa et al. \(2026\)](#). Two satellites sizes are considered: 10 km and 100 km. This simulation is characterized by a fixed inner disk edge at $1.5R_J$. Only a small subset of satellites is plotted for readability; these curves illustrate individual dynamical pathways and are not intended to represent the full statistical distribution, which is shown in panel (a) of Fig. 2.

adopting $k_{2j}/Q_j = 10^{-3}$. Other values of k_{2j}/Q_j yield qualitatively similar results after 4.5 Gyr, differing mainly in the eccentricity-damping timescale due to internal dissipation. Satellites are removed when their orbits cross those of the Galilean satellites or Jupiter's rigid Roche limit at $\sim 1.67 R_J$.

Figure 2 shows semimajor axis versus eccentricity for 10 km satellites (blue), 100 km satellites (red), and the Galilean satellites (black) at different times after gas dispersal. As shown in panel (a), [Ribeiro de Sousa et al. \(2026\)](#) found that 98.4% of the 10 km and 99.7% of the 100 km satellites end up beyond Io's orbit. Of these, 61.6% and 15.4%, respectively, remain between Io and Callisto, mostly with $e > 10^{-2}$. Frequent crossings with the Galilean satellites therefore remove 25% and 12% of the 10 and 100 km bodies, respectively, within the first 1.0 Myr.

Satellites surviving longer in this region are strongly affected by secular perturbations from the Galilean satellites, undergoing large eccentricity oscillations that are not efficiently damped by tides. As the Galilean satellites migrate outward, their MMRs sweep across the satellites population, exciting eccentricities and driving orbital crossings that remove bodies from the system. This process clears satellites out to $\sim 40 R_J$, the current location of Callisto's 2:1 MMR and the outermost first-order resonance with a Galilean satellite.

Beyond this distance, planetary tides, internal dissipation, and secular perturbations are too weak to significantly modify satellites orbits, which remain similar to those at gas dispersal. Because gas drag drives inward migration during the gas-disk phase, this $\sim 40 R_J$ survival boundary corresponds to an initial disk extent of up to $\sim 60 R_J$. Since no regular satellites are observed beyond Callisto, the primordial satellites disk likely did not extend substantially beyond this distance; otherwise, a remnant population would be expected to survive there today.

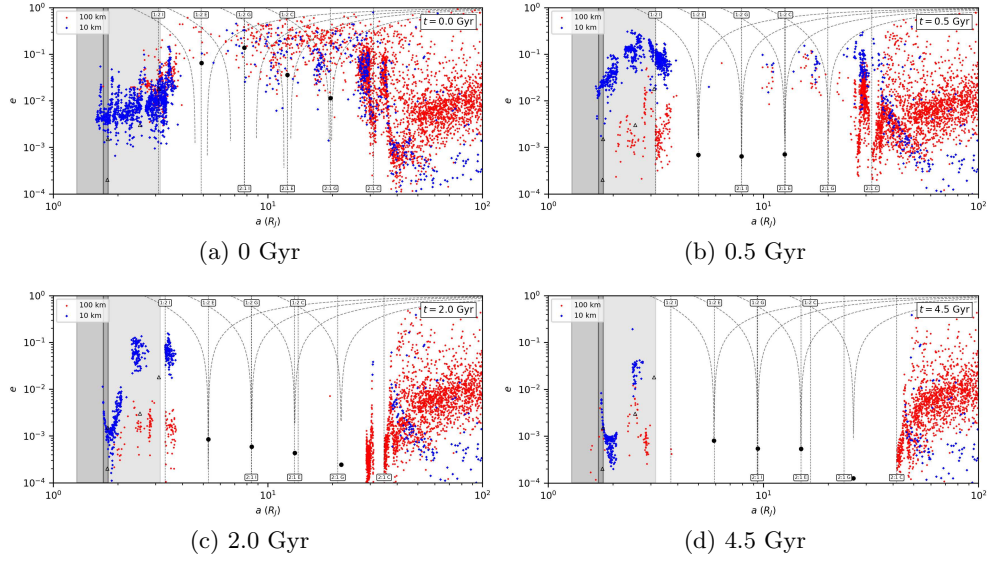


Fig. 2 Semi-major axis versus eccentricity of the satellitesimal population at different times after gas dispersal. Blue and red points represent 10 and 100 km satellitesimals, respectively, while black points show the Galilean satellites. Dashed curves indicate where the satellitesimal pericentre or apocentre crosses the orbit of a Galilean satellite, while dotted lines mark MMRs with the Galilean satellites. For reference, the present-day Amalthea-group satellites are shown as open triangles, while gray regions indicate the radial extent of the Jovian rings.

212 Focusing on the inner part of the resulting satellitesimal population, Figure 3 shows
 213 the semimajor-axis evolution of all satellitesimals initially within $5 R_J$, with colour
 214 indicating eccentricity. During the first 10 Myr, internal dissipation dominates, damp-
 215 ing eccentricities from ~ 0.1 to ~ 0.01 while reducing the semimajor axis. Afterwards,
 216 outside resonances, eccentricity is controlled by the competition between secular per-
 217 turbations from the Galilean satellites, which induce oscillations of order $\sim 10^{-2}$, and
 218 internal dissipation, which tends to damp them.

219 As the Galilean satellites migrate outward due to dynamical tides, internal MMRs
 220 with Io sweep across the satellitesimal population, exciting eccentricities and driv-
 221 ing orbital crossings with Io or Jupiter’s rigid Roche limit. Through this process, the
 222 region between Thebe’s orbit at 3.1 and $5.9 R_J$ is almost completely cleared of satel-
 223 litesimals. In addition to MMRs, secular resonances between the satellitesimals and
 224 the Galilean system, occurring when the apsidal precession frequency of a satellites-
 225 imal, $g(a)$, approaches one of the secular eigenfrequencies g_i , act through a similar
 226 mechanism, exciting eccentricities and leading to material removal.

227 For 10 km satellitesimals, the secular resonance $g = g_2$ completely depletes the
 228 region between the rigid Roche limit and $\sim 1.75 R_J$, close to the orbits of Metis
 229 and Adrastea. Since the physical radii of Metis (~ 22 km) and Adrastea (~ 8.2 km)
 230 are comparable to the 10 km bodies considered here, this suggests that the present
 231 location of the two innermost satellites may reflect a dynamical inner edge sculpted by
 232 the secular resonance. In other words, if a population of satellitesimals of comparable

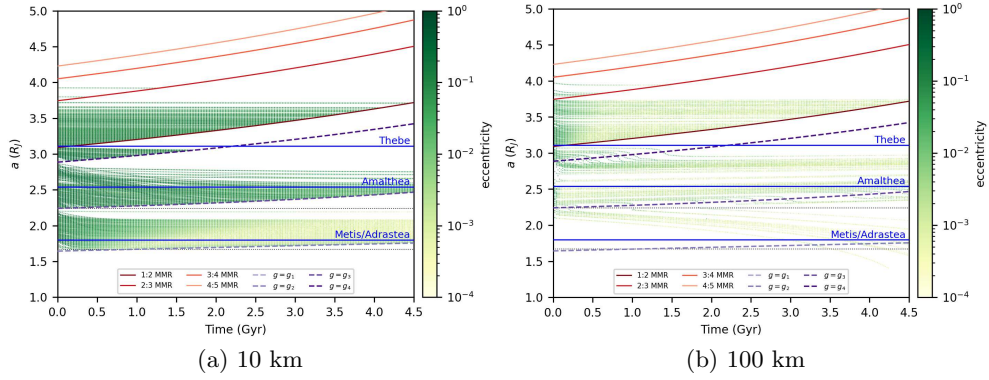


Fig. 3 Semimajor-axis evolution of the surviving satellitesimals after gas dispersal for (a) 10 km and (b) 100 km bodies. Each point is colored by the instantaneous eccentricity of the satellitesimal. Solid reddish curves show the locations of the first-order MMRs with Io, while dashed purplish curves indicate the apsidal secular resonances $g = g_i$ with the Galilean system. Horizontal blue lines mark the present orbits of Metis/Adrastea, Amalthea, and Thebe.

size existed in this region, regardless of its origin, the $g = g_2$ resonance would tend to remove material interior to the present Metis-Adrastea region, naturally establishing a survival boundary near their current orbits.

The secular resonance $g = g_3$ also completely depletes 10 km satellitesimals between 2.2 and 2.4 R_J , with its outer edge again lying close to Amalthea's semimajor axis (2.54 R_J). If Amalthea formed relatively recently through the accretion of ~ 10 km satellitesimals, its present location could therefore be linked to the current position of the $g = g_3$ secular resonance. However, given Amalthea's physical radius of ~ 84 km, the simulations with 100 km satellitesimals provide a more appropriate comparison. For these larger bodies, the eccentricity excitation produced by the secular resonance is insufficient to remove them. Instead, the excited eccentricity is damped by internal dissipation, accompanied by a decrease in semimajor axis, such that resonance passage transports satellitesimals to more internal orbits. Consequently, no fully depleted region with an outer edge coincident with Amalthea's orbit is produced in the 100 km population.

In fact, together with the reduced efficiency of secular resonances in removing 100 km satellitesimals, stronger tidal evolution allows this population to spread over a wider radial range. Bodies exterior to the synchronous orbit migrate outward by a few tenths of R_J , whereas those interior to it efficiently migrate inward, populating the inner region. In some cases, satellitesimals initially exterior to the synchronous orbit have their eccentricities excited by a secular resonance and subsequently damped by internal dissipation, accompanied by sufficient semimajor-axis decay to move them inside the synchronous orbit. Planetary tides then drive further inward migration toward the Metis region. Consequently, 100 km satellitesimals survive throughout the region between the rigid Roche limit and $\sim 2.8 R_J$. Thus, if Amalthea is a surviving satellitesimal from the Galilean satellite formation epoch, its progenitor could have formed interior or exterior to its present orbit, or even at a similar distance from Jupiter.

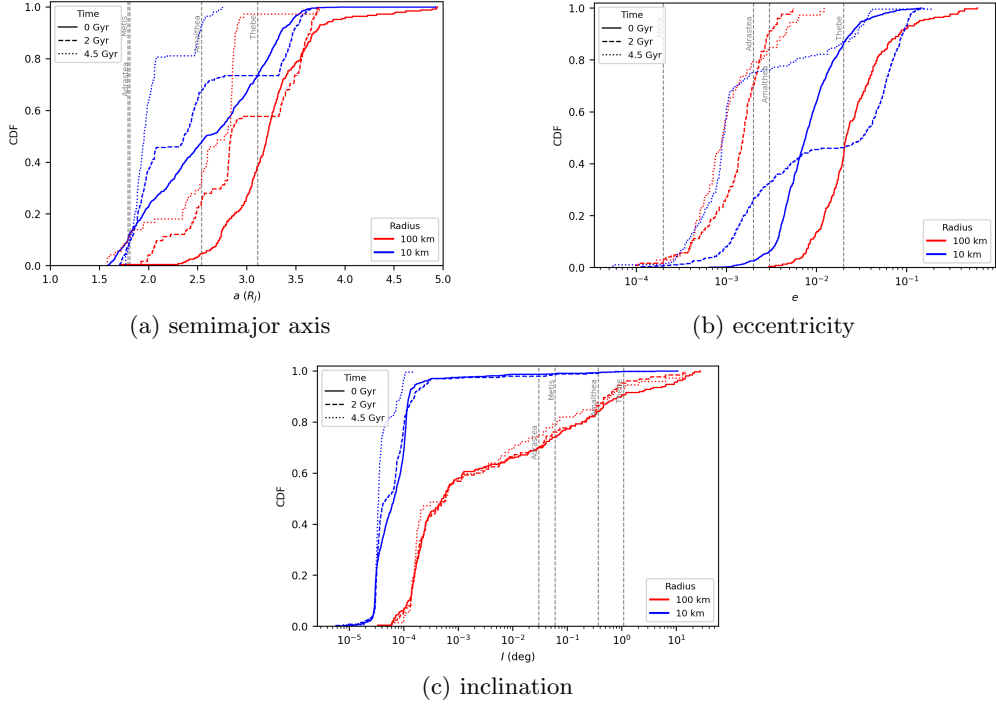


Fig. 4 Cumulative distribution functions (CDFs) of the surviving satellitesimal population in (a) semimajor axis, (b) eccentricity, and (c) inclination at 0, 2, and 4.5 Gyr after gas dispersal. Blue and red curves represent 10 and 100 km satellitesimals, respectively, while solid, dashed, and dotted lines correspond to the different evolutionary times.

Thebe, with a physical radius of 49 km, represents an intermediate case between the 10 and 100 km satellitesimals considered here. The 1:2 MMR with Io initially lies interior to Thebe's current orbit, at $\sim 3 R_J$, and for both sizes its outward sweep efficiently clears material around this region. In addition, at ~ 2.0 Gyr, the secular resonance $g = g_4$ reaches $\sim 3 R_J$, close to a plausible location for Thebe's progenitor. For 10 km satellitesimals, this excitation leads to their removal, leaving the region beyond $\sim 2.7 R_J$ almost completely depleted.

For 100 km satellitesimals, instead, passage through the secular resonance promotes inward orbital drift, producing a depleted region beyond $\sim 2.9 R_J$, again close to Thebe's present orbit. Moreover, if Io emerged from the gas-disk phase slightly beyond $5 R_J$, its 1:2 MMR would initially lie exterior to Thebe's current orbit, shifting the resulting depletion edge outward. Although these depletion edges do not necessarily determine the present locations of the inner satellites, their repeated proximity to the observed satellite orbits suggests a dynamical connection between the present architecture of the Amalthea group and the resonance-sculpted structure of the primordial satellitesimal population.

Figure 4 shows the cumulative distribution functions of the satellitesimals in semimajor axis, eccentricity, and inclination. The eccentricity distributions show continuous damping due to internal dissipation, whereas the inclination distributions evolve much less, largely preserving the values inherited from the end of the gas-disk phase. Metis and Adrastea, whose physical sizes are closest to the 10 km satellitesimals considered here, have very low eccentricities, while most surviving 10 km bodies retain eccentricities larger than $\sim 3 \times 10^{-3}$. This could indicate that additional eccentricity damping, for instance through collisions between satellitesimals, contributed to reducing their eccentricities. We note, however, that a small fraction of the simulated satellitesimals reaches values comparable to those of Metis and Adrastea.

Nearly all surviving 100 km satellitesimals, in turn, reach eccentricities below Amalthea’s present value of $e \simeq 0.003$, while Thebe’s eccentricity, $e \simeq 0.02$, is substantially larger than that of the final simulated population. Given the simplifications of our numerical model, one possible explanation for this discrepancy is eccentricity excitation by second-order e -type MMRs with Io or by mutual interactions among satellitesimals, neither of which is included here and would require dedicated N -body simulations to assess.

A similar argument applies to inclination, since i -type MMRs with Io could also excite the satellitesimals. As shown in the figure, the final inclinations generally remain below those of the present satellites. Nevertheless, a fraction of the 100 km population reaches inclinations comparable to Amalthea and, more rarely, Thebe. In contrast, the 10 km population remains well below the inclinations of Metis and Adrastea, indicating that their present orbital elements cannot be reproduced solely by the secular and tidal evolution considered here.

4 Discussion

Considering a residual satellitesimal population after Galilean satellite formation, our results show that the subsequent migration of the Galilean satellites can strongly sculpt the inner Jovian system. Mean-motion and secular resonances excite satellitesimal eccentricities, leading either to orbital crossings with Io or to passages inside Jupiter’s rigid Roche limit. The resulting combination of depleted and populated regions produces survival boundaries that repeatedly lie close to the present orbits of the Amalthea-group satellites.

We do not interpret these boundaries as uniquely determining the satellite locations, but their correspondence suggests a dynamical connection between the present architecture of the inner Jovian system and the resonance-driven evolution of an earlier satellitesimal population. Importantly, once such a population exists, this mechanism does not depend on the specific implantation process proposed by [Ribeiro de Sousa et al. \(2026\)](#); it should operate on any residual population occupying the same region.

For Metis and Adrastea, the clearest correspondence is produced by the secular resonance $g = g_2$. For 10 km satellitesimals, this resonance removes material from the rigid Roche limit out to $\sim 1.75 R_J$, establishing an inner survival boundary immediately interior to the present orbits of the two satellites. Since their physical sizes are comparable to the 10 km bodies considered here, their current locations are consistent

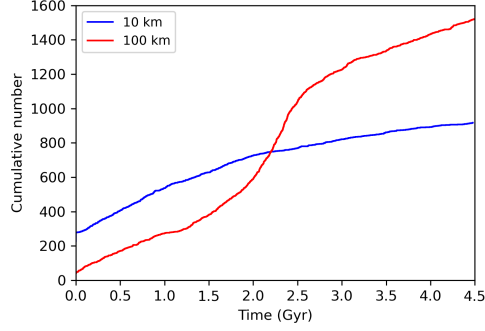


Fig. 5 Cumulative number of satellitesimals removed after crossing Jupiter’s rigid Roche limit as a function of time. Blue and red curves correspond to 10 and 100 km satellitesimals, respectively.

with the inner edge of a satellitesimal population sculpted by this resonance. In this sense, if a population of kilometre-sized bodies existed close to Jupiter, independently of its origin, the sweeping of $g = g_2$ would naturally inhibit long-term survival interior to the Metis-Adrastea region.

Amalthea occupies a dynamically different region. Its present orbit is unaffected by the main clearing resonances for 100 km bodies, which can reach the Amalthea region through inward or outward tidal migration or remain near their initial orbits. Thus, if Amalthea is a primordial remnant, its progenitor need not have formed near its present location. Nevertheless, for 10 km bodies the $g = g_3$ resonance produces another sharp depletion boundary just interior to Amalthea’s orbit. Therefore, if Amalthea instead formed through the accretion of smaller satellitesimals, its present location would again lie close to the inner edge of a region where such material can survive.

Thebe provides a complementary outer constraint. Its physical radius lies between the two sizes explored here, and its present orbit is close to a region sculpted by both the 1:2 MMR with Io and the secular resonance $g = g_4$. For 10 km satellitesimals, these resonances remove nearly all material beyond $\sim 2.7 R_J$, whereas for 100 km bodies the inward drift associated with secular-resonance passage produces a depleted region beyond $\sim 2.9 R_J$. If Io emerged from the gas-disk phase slightly beyond $5 R_J$, its 1:2 MMR would initially lie exterior to Thebe’s present orbit, shifting this depletion boundary outward. The repeated proximity between these dynamically generated edges and the present satellite orbits therefore suggests that resonance sweeping played an important role in shaping the radial architecture in which the Amalthea group survived or formed.

This interpretation, however, introduces an important caveat. The same resonances that sculpt survival boundaries near the present satellite orbits also drive a substantial number of satellitesimals across Jupiter’s rigid Roche limit. As shown in Figure 5, the cumulative number of Roche-limit crossings increases throughout the evolution, indicating a sustained delivery of solid material to the innermost Jovian system. If most of these bodies were tidally disrupted, this process would continuously feed a circum-jovian ring and could produce substantially more ring material than suggested by the tenuous, dust-dominated rings observed today. The present rings are instead generally interpreted as being maintained by dust released from the inner satellites (Thomas

et al. 1998). Thus, the same dynamical mechanism that provides the intriguing correspondence between resonance-sculpted boundaries and the present satellite locations may simultaneously overproduce ring material.

This tension could be reduced if many satellitesimals were sufficiently cohesive that their actual disruption limit lay significantly interior to the rigid Roche limit adopted here, allowing them to continue inward and potentially collide with Jupiter before disruption. Such a solution is not straightforward, however, because highly cohesive bodies would be difficult to reconcile with the porous and weakly cohesive nature expected for the Amalthea-group satellites. A more complete assessment therefore requires modelling the tidal disruption and collisional fate of satellitesimals after they enter the nominal Roche region, rather than removing them instantaneously as done here.

Taken together with Ribeiro de Sousa et al. (2026), our results suggest that the formation of the present inner Jovian system may be understood as a two-stage dynamical filtering process. During the gas-disk phase, gravitational scattering by the growing Galilean satellites, combined with aerodynamic damping, determines which satellitesimals can be implanted interior to Io. After gas dispersal, tidal evolution and resonance sweeping provide a second filter, determining which of the implanted bodies survive and where they can remain over gigayear timescales. Consequently, the orbital distribution produced at gas dispersal should not be interpreted as a direct precursor of the present-day inner satellite system.

An important consequence of combining the gas-phase and post-gas evolution is that implantation efficiency does not necessarily translate into long-term survival efficiency. In Ribeiro de Sousa et al. (2026), 10 km satellitesimals are more efficiently delivered into the inner Jovian system because of their stronger coupling to the gas, whereas 100 km bodies are less efficiently implanted. Our long-term calculations show, however, that the subsequent dynamical evolution is also size dependent. Smaller bodies are more strongly affected by some of the resonance-driven depletion mechanisms, while 100 km satellitesimals can survive throughout a broad region encompassing Amalthea’s present orbit. Thus, the present population reflects the combined action of size-dependent implantation and size-dependent long-term survival.

An important point to note is that we neglect the effects of the giant-planet instability during the long-term evolution considered here. In dynamical models of the early Solar System, Jupiter may have undergone close encounters with an ice giant, a process that can capture planetesimals from heliocentric orbits and account for the observed population of Jovian irregular satellites (Nesvorný et al. 2007, 2014; Nimmo et al. 2026). Such encounters can also perturb the Galilean satellites, potentially exciting their eccentricities and inclinations and modifying their orbital architecture (Deienno et al. 2014). Therefore, an early phase of giant-planet instability could have affected both the implanted satellitesimal population and the subsequent resonance-sweeping history considered in our simulations. Quantifying these effects would require coupling the evolution of the inner Jovian system to a specific giant-planet instability history and is beyond the scope of the present work.

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Data availability. The data underlying this article will be shared on reasonable request to the corresponding author.

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