LETTERS
PUBLISHED ONLINE: 24 JANUARY 2010 | DOI: 10.1038/NGEO746

nature geoscience

Origin of the Ganymede–Callisto dichotomy by impacts during the late heavy bombardment

Amy C. Barr* and Robin M. Canup

Jupiter's large moons Ganymede[1,2] and Callisto[2,3] are similar in size and composition. However, Ganymede has a tectonically evolved surface[1] and a large rock/metal core[2], whereas Callisto's surface shows no sign of resurfacing[3] and the separation of ice and rock in its interior seems incomplete[2]. These differences have been difficult to explain[4–11]. Here we present geophysical models of impact-induced core formation to show that the Ganymede–Callisto dichotomy can be explained through differences in the energy received during a brief period of frequent planetary impacts about 700 million years after planet formation, termed the late heavy bombardment[12–15]. We propose that during the late heavy bombardment, impacts would have been sufficiently energetic on Ganymede to lead to a complete separation of rock and ice, but not on Callisto. In our model, a dichotomy between Ganymede and Callisto that is consistent with observations is created if the planetesimal disk that supplied the cometary impactors during the late heavy bombardment is about 5–30 times the mass of the Earth. Our findings are consistent with estimates of a disk about 20 times the mass of the Earth as used in dynamical models that recreate the present-day architecture of the outer solar system and the lunar late heavy bombardment[15,16].

The origin of the 'Ganymede–Callisto dichotomy' has puzzled scientists since the Voyager era[4–7,9–11]. Ganymede (radius $R = 2{,}631$ km) and Callisto ($R = 2{,}410$ km) have mean densities $\rho = 1.942\ \mathrm{g\,cm^{-3}}$ and $1.834\ \mathrm{g\,cm^{-3}}$, respectively, indicating half-rock/half-ice compositions[2]. Ganymede's grooved terrain suggests extensive interior evolution[1], and its moment of inertia indicates that all of its rock has consolidated into a central core[2]. Callisto's ancient surface shows no signs of endogenic resurfacing[3]. Its moment of inertia suggests that rock core formation has been incomplete[17]. The moons are thought to form in similar environments[5,7,10,11], and so creating the dichotomy during their accretion is possible only if small differences in formation conditions are amplified[11]. It is also difficult to explain the dichotomy by appealing to differences in the satellites' later thermal evolution because divergent outcomes are achieved only for a small range of material properties[6]. Melting of Ganymede by tidal heating[18] is a possible explanation; however, strong tidal heating in Ganymede occurs in a narrow window of possible orbital evolution histories[8,9,18].

We propose that the dichotomy is created by impacts onto the satellites during the late heavy bombardment (LHB). The LHB is a period of enhanced impact rates by asteroids[12,13] and/or comets[14,15], during which the large lunar impact basins were formed[12,13]. It has recently been proposed that the LHB was triggered by dynamical interactions between the outer planets and a disk of icy planetesimals that created a brief shower of cometary and asteroidal material onto the terrestrial planets[14,15], and predominantly cometary material onto the outer planet satellites[14]. The LHB would have been a much more energetic event at Ganymede than Callisto. Ganymede, which is closer to Jupiter, experiences twice as many impacts as Callisto with higher characteristic impact velocities ($v_i \approx 20\ \mathrm{km\,s^{-1}}$ for Ganymede and $15\ \mathrm{km\,s^{-1}}$ for Callisto[19], see Table 1). Dynamical simulations of the outer solar system in the 'Nice model'[15,16] show that scattering of a planetesimal disk that initially contains ≈35 Earth masses ($M_\oplus$), whittled down to $M_D \sim 20M_\oplus$ at the time of the LHB, delivers $\approx 8 \times 10^{21}$ g of cometary material to Earth's moon during the LHB, and a similar mass in asteroids[15]. This is comparable to the total mass of lunar LHB impactors[14,15] estimated from crater counts[14]. During an outer solar system LHB, Ganymede receives 80 times the mass of cometary objects hitting Earth's moon owing to strong gravitational focusing by Jupiter[14,19]. Scattering of an $M_D = 20M_\oplus$ planetesimal disk will deliver a total mass $M^G_{LHB} \sim 6 \times 10^{23}$ g of cometary impactors during the LHB to Ganymede and half this amount, $M^C_{LHB} \sim 3 \times 10^{23}$ g, to Callisto. The associated impact energy at Ganymede, $E_{LHB} \sim (1/2)M^G_{LHB}v_i^2 \sim 10^{36}$ erg, is five times higher than the energy required to melt all of Ganymede's ice, $E_{melt} \sim (1 - m_r)ML = 2 \times 10^{35}$ erg, where $M = 1.48 \times 10^{26}$ g is Ganymede's mass, $m_r = 0.52$ is its rock mass fraction[20] and $L = 3 \times 10^9\ \mathrm{erg\,g^{-1}}$ is the latent heat of water ice[21]. Callisto ($M = 1.07 \times 10^{26}$ g, $m_r = 0.44$) receives $E_{LHB} \sim 2 \times E_{melt}$. At face value, this suggests that both satellites melt during the LHB. However, the calculation assumes that 100% of the impact energy is used to melt the satellites' ice, which is unrealistic[22].

Here, we develop a detailed model of impact-induced melting and core formation[23,24] (W. B. Tonks, *et al.*, unpublished) to address the effect of an LHB on Ganymede and Callisto. A hypervelocity impact creates a shock wave that compresses and does irreversible work on a roughly spherical region beneath the impact point (see Supplementary Methods S1.2). At locations where the peak shock pressure exceeds the pressure required to induce melting of ice on release from the shock state, a buried pool of liquid water and ice crystals is created. In the region where the volume fraction of melt is >50% post-impact[25], the water/crystal/rock particle mixture has a low viscosity, comparable to that of liquid water, so that concomitant rock rapidly sinks and accumulates at the base of the melt pool (W. B. Tonks, *et al.*, unpublished). The denser rock ultimately descends through the ice/rock mantle, liberating gravitational potential energy as heat inside the satellite as it sinks to the satellite's centre in a few thousand years[6] (see Supplementary Methods S3.3.3, Fig. 1b,d, and Supplementary Movies). If the energy released by the impact-induced ice/rock separation is sufficient to melt the remainder of the satellite's ice, the process becomes energetically self-sustaining and will drive itself to completion (so-called 'runaway differentiation'[6]).

Department of Space Studies; Center for Lunar Origin and Evolution, Southwest Research Institute, 1050 Walnut St, Suite 300, Boulder, Colorado 80302, USA. *e-mail: amy@boulder.swri.edu.

Table 1 | Key model parameters and their values.

Property	Symbol	Ganymede	Callisto
Satellite density	ρ	$1.942\ \mathrm{g\,cm^{-3}}$	$1.834\ \mathrm{g\,cm^{-3}}$
Satellite radius	R	2,631 km	2,410 km
Latent heat of water ice	L	$3\times10^{9}\ \mathrm{erg\,g^{-1}}$	$3\times10^{9}\ \mathrm{erg\,g^{-1}}$
Rock mass fraction[20]	m_r	0.52	0.44
Initial volume fraction of rock	ϕ_o		
Nominal		0.34	0.27
High density		0.19	0.15
Low density		0.46	0.40
Characteristic impact velocity[19]	v_i	$20\ \mathrm{km\,s^{-1}}$	$15\ \mathrm{km\,s^{-1}}$
Characteristic projectile radius	$\langle r_p \rangle$	30 km	30 km
Melt region, radius	χ	$5.06 r_p (v_i/15\ \mathrm{km\,s^{-1}})^{0.6}$	$5.06 r_p (v_i/15\ \mathrm{km\,s^{-1}})^{0.6}$
Melt region, burial depth	ξ	$2.85 r_p (v_i/15\ \mathrm{km\,s^{-1}})^{0.47}$	$2.85 r_p (v_i/15\ \mathrm{km\,s^{-1}})^{0.47}$
Impact probability relative to Moon[19]		80	40
Mass of impactors during LHB	M_{LHB}	M^{C}_{LHB}	M^{G}_{LHB}
LHB disk mass	M_D	$(M^{C}_{LHB}/1.68\times10^{22}\ \mathrm{g})M_{\oplus}$	$(M^{C}_{LHB}/1.68\times10^{22}\ \mathrm{g})M_{\oplus}$

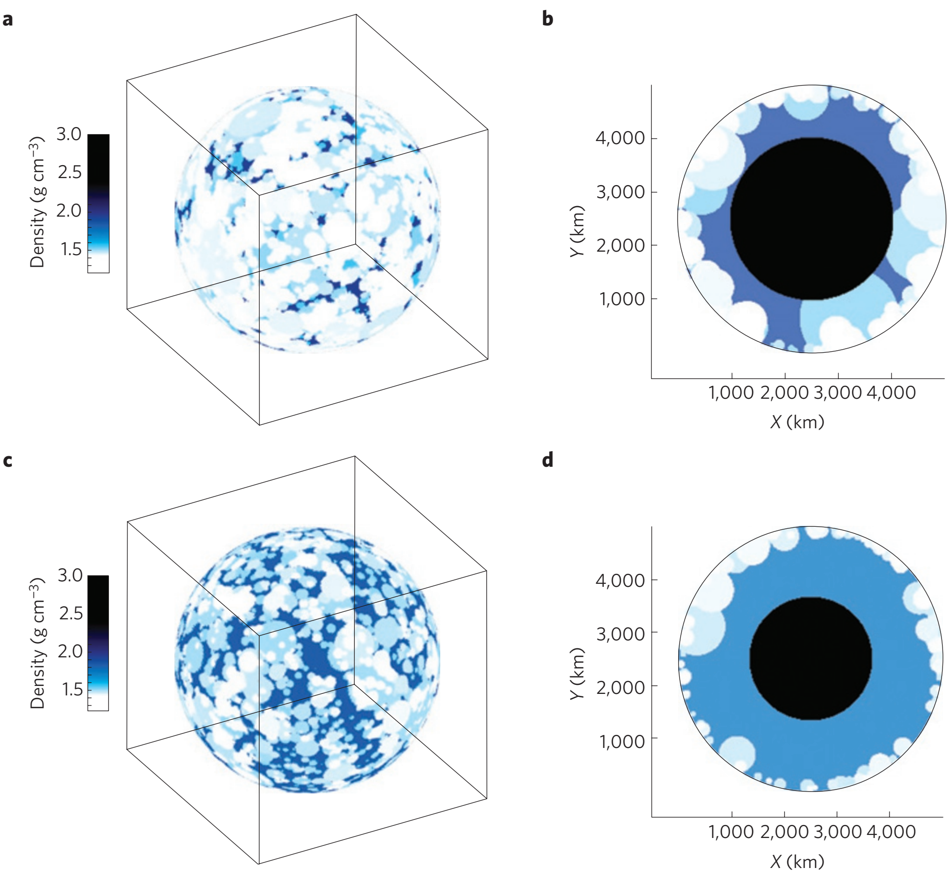

Figure 1 | Interior structures of Ganymede and Callisto after the LHB. Heterogeneous interior structures created by an outer solar system LHB with $M_D = 14M_{\oplus}$, $\langle r_p \rangle = 30$ km, and our nominal ice/rock composition model. **a**–**d**, Satellite density at the surface as a function of latitude and longitude (**a**,**c**) and longitudinal slice through the ice/rock (blue) and ice (white) globes in the y–z plane, illustrating the rocky core (black) (**b**,**d**), for Ganymede (**a**,**b**) and Callisto (**c**,**d**).

A simple estimate is that runaway differentiation of the entire satellite will occur if

$$f_m = \frac{\Delta E_{gr}}{(1-m_r)(1-\frac{x^3}{\phi_o})ML} > 1 \qquad (1)$$

where ΔE_{gr} is the difference in gravitational potential energy between the initial uniform-density and final differentiated states[6], ϕ_o is the bulk volume fraction of rock in the satellite's interior and x is the fractional radius of the rocky core ($x \equiv R_{core}/R$).

First, we use analytical estimates of the gravitational potential energy released by impact-induced ice/rock separation to show that the Ganymede–Callisto dichotomy can be produced during an outer solar system LHB. For the dichotomy to form, Callisto must avoid runaway differentiation. This gives an upper limit on LHB mass (M_{LHB}), and by extension, an upper limit on the planetesimal disk mass (M_D) consistent with dichotomy creation. Requiring Ganymede to experience runaway differentiation gives a lower limit on M_{LHB} and M_D. We consider an initially uniform-density satellite containing a volume fraction $\phi_o = m_r(\rho/\rho_r)$ of rock (density ρ_r) hit by a total mass M_{LHB} of objects with a characteristic projectile radius r_p, velocity v_i, and vertical impact angle. The bombardment has $N = M_{LHB}/[(4/3)\pi r_p^3 \rho] = (M_{LHB}/M)(R/r_p)^3$ objects, where impactor and satellite densities are assumed to be equal and constant.

If impactors are large and melt pools from successive impacts do not overlap, the satellite evolves to a two-layered structure: a rock core of radius xR produced by the rock liberated from impact-produced melt pools, and a rock-depleted mantle. Our numerical impact simulations (see Supplementary Methods S1) show that the region shocked to >50% melt is well described by a sphere of radius χr_p, buried at a depth ξr_p (ref. 22), where $\chi = 5.06(v_i/15\,\mathrm{km\,s^{-1}})^{0.6}$ and $\xi = 2.85(v_i/15\,\mathrm{km\,s^{-1}})^{0.47}$. Each impact melts a volume $V_i \sim (4/3)\pi(\chi r_p)^3$. The volume of rock removed by N impacts, $V_{core} = NV_i\phi_o$, forms a core $x \sim [(M_{LHB}/M)\chi^3\phi_o]^{1/3}$ (see Supplementary Methods S2.1). For non-overlapping large impacts, x is independent of r_p, so core formation outcomes in this regime are insensitive to the size-frequency distribution of LHB impactors, and the final core size depends primarily on the total mass of LHB impactors.

For Callisto to avoid runaway differentiation, $x < 0.52$ (see Supplementary Methods S2.2), requiring that the mass of LHB impactors hitting Callisto, M^C_{LHB}, is $M^C_{LHB} < 4 \times 10^{23}$ g (assuming a nominal $\rho_r = 3.0\,\mathrm{g\,cm^{-3}}$, $\rho_i = 1.4\,\mathrm{g\,cm^{-3}}$). For Ganymede to fully differentiate, $x > 0.52$, which occurs for $M^C_{LHB} > 10^{23}$ g. The dichotomy is then created for $10^{23}\,\mathrm{g} < M^C_{LHB} < 4 \times 10^{23}$ g, equivalent to $6M_\oplus < M_D < 23M_\oplus$. Per arguments above, simulations of an outer solar system LHB that reproduce the present-day orbital architecture of the outer solar system[16] predict $M_D \sim 20M_\oplus$ at the time of the LHB, within the range required for dichotomy creation in the large impactor limit. If the impactors are small and melt pools overlap, the resulting core size does depend on r_p (see Supplementary Methods S2.1). Outcomes of our numerical core formation model are generally consistent with the large impactor case, although some dependence on r_p is observed.

Next, we construct a numerical model to simulate impact-induced core formation for a realistic distribution of impactors, impact velocities and angles (see Supplementary Methods S3 and the Methods section). Consistent with our analytical estimates, we find a >50% chance that the LHB creates the Ganymede–Callisto dichotomy if $8.8 \times 10^{22}\,\mathrm{g} < M^C_{LHB} < 3.6 \times 10^{23}$ g, corresponding to $5M_\oplus < M_D < 21M_\oplus$ (Fig. 2a,b) for a most likely impactor radius $\langle r_p \rangle = 30$ km. For $\langle r_p \rangle = 20$ km, there is >50% probability of creating the dichotomy for $10^{23}\,\mathrm{g} < M^C_{LHB} < 5 \times 10^{23}$ g, corresponding to $6M_\oplus < M_D < 29M_\oplus$. Broadly similar estimates of M_D result if the density of the satellites' ice and rock components are changed (see the Methods section and Fig. 2c). For $M_D = 20M_\oplus$ predicted for the time of the LHB (refs 15, 16), there is a ~70% (~95%) chance of creating the dichotomy for $\langle r_p \rangle = 30$ km ($\langle r_p \rangle = 20$ km).

We have compared our model results to predictions from a particular outer solar system evolution model for the origin of the LHB (refs 15, 16), but our results are relevant to any scenario that invokes an outer solar system LHB (ref. 14). A key strength of our hypothesis is that creating the dichotomy is relatively insensitive to variations in uncertain parameters. The dichotomy arises primarily because of differences in gravitational focusing by Jupiter, giving a larger total impact energy at Ganymede compared with Callisto.

If the LHB triggers runaway differentiation in Ganymede, melting by tides[18] is not required and a simple story for Ganymede and Callisto's early evolution emerges. Both satellites form undifferentiated[10,11]. Ganymede evolves into its current orbital state through interactions with the circumjovian disk[26] or later

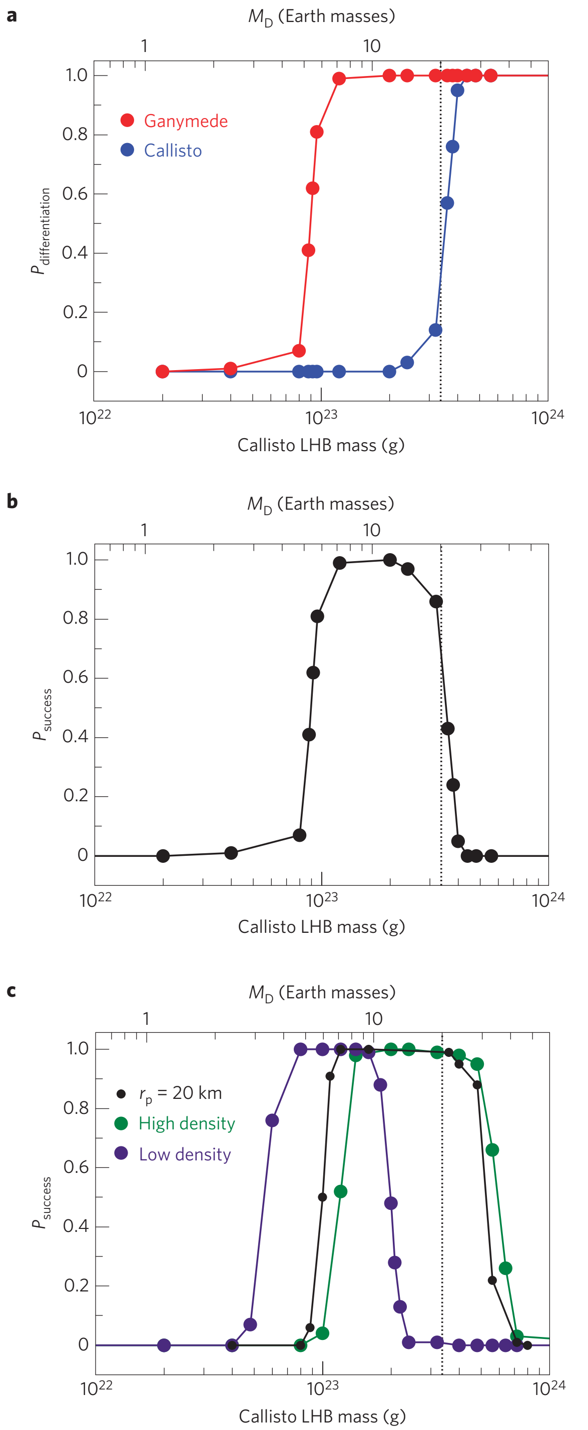

Figure 2 | Results of Monte Carlo modelling constraining the probability of forming the Ganymede–Callisto dichotomy as a function of LHB mass. The vertical line shows M^C_{LHB} predicted by the Nice model. **a**, Probability of runaway differentiation for Ganymede (red) and Callisto (blue) for our nominal compositional case. **b**, Probability of creating the dichotomy during the LHB. **c**, Probability of creating the dichotomy considering variation in the impactor size distribution (black) and rock density (colours; see the Methods section).

tidal evolution[8,18]. Ganymede differentiates during the LHB; the burst of energy from runaway differentiation could drive melting and provide a natural explanation for the formation of its grooved terrain. Callisto is partially differentiated during the LHB and remains geologically inactive.

Impacts occurring in the 700 Myr before the LHB also drive differentiation. Our calculated limits on impacting mass assume that all of the energy of differentiation is retained. Unlike during the LHB (which lasts only ∼10–100 Myr, see Supplementary Methods S3.3.4), some fraction of the energy of differentiation may be removed by vigorous convection during the earlier, more prolonged impact period. In the limit that no energy of differentiation is retained, the total mass of objects striking Callisto can be constrained by its moment of inertia. Requiring that Callisto's moment of inertia is greater than the value implied by Galileo data constrains the total mass of hypervelocity impactors onto Callisto over its entire lifetime to be less than $\sim 10^{24}$ g. In the context of simulations of a disk scattering event[15], Callisto's interior state limits the initial mass of the planetesimal disk to $M_{\mathrm{D,initial}} < 65$–$130 M_{\oplus}$ (see Supplementary Methods S2.3).

Methods

Model satellites are represented by a three-dimensional Cartesian sphere that contains an initially uniform volume fraction ϕ_o of rock. Such a state is probable if the satellites formed in a cold, 'gas-starved' disk around Jupiter produced during the final stages of slow gas accretion by the planet[10,11,27]. Latitude, longitude, v_{i}, r_{p} and impact angle for each of several thousand impacts are selected using a Monte Carlo approach. Radii are drawn from a population similar to the jovian Trojan asteroids[28], with a double-power-law size distribution for small ($\mathrm{d}N_{\mathrm{sm}}/\mathrm{d}r_{\mathrm{p}} \propto r_{\mathrm{p}}^{-3}$) and large objects ($\mathrm{d}N_{\mathrm{bg}}/\mathrm{d}r_{\mathrm{p}} \propto r_{\mathrm{p}}^{-6.5}$). For a size distribution of impactors that changes slope at magnitude $V = 9$, the average radius of LHB impactors is $\langle r_{\mathrm{p}} \rangle = 30$ km. The LHB impact energy is delivered on a timescale that is short compared with solid-state heat transport, so these processes do not affect model outcomes and are not included (see Supplementary Methods S3.3.4). The core formation model sums the volume fraction of rock, ϕ, from impact-melted elements to determine the amount of rock added to the core during each impact. That amount of rock is removed from impact-melted elements in the icy mantle. New core elements are added to the core's outer edge in a radially symmetric fashion (see Fig. 1, Supplementary Movies S1, S2, and Supplementary Methods S3.3.3). Values of f_m (equation (1)) are calculated using $E_{\mathrm{gr},f} = \int (Gm/r(m))\mathrm{d}m$ based on the model satellite's final heterogeneous density structure, and $E_{\mathrm{gr},i} = -(3/5)GM^2/R$. One hundred bombardment histories are calculated for each LHB mass to determine the probability of runaway differentiation.

The density and extent of hydration of Callisto's rock is unknown[2,17,20], so we explore how outcomes vary for three compositional models. In our nominal model, we assume that Callisto is composed of rock (density $\rho_{\mathrm{r}} = 3.0$ g cm^{-3}, mid-way between densities for CI chondrite and Prinn–Fegley rock, two models for the composition of the satellites' rock[29]) and ice (with density $\rho_{\mathrm{i}} = 1.4$ g cm^{-3} chosen to give $m_{\mathrm{r}} = 0.44$ for Callisto and $m_{\mathrm{r}} = 0.52$ for Ganymede, consistent with detailed interior modelling[20]). This gives a rock volume fraction $\phi_o = 0.34$ for Ganymede and $\phi_o = 0.27$ for Callisto. We explore two alternative models for rock composition. In our 'high density' model, a plausible upper limit on rock density, $\rho_{\mathrm{r}} = 3.8$ g cm^{-3}, is paired with $\rho_{\mathrm{i}} = 1.5$ g cm^{-3} to give a lower limit on Callisto's $\phi_o = 0.15$ and Ganymede's $\phi_o = 0.19$. In our 'low density' model, a plausible lower limit on rock density, $\rho_{\mathrm{r}} = 2.8$ g cm^{-3}(ref. 29), is paired with $\rho_{\mathrm{i}} = 1.2$ g cm^{-3} to give an upper limit on $\phi_o = 0.40$ for Callisto and $\phi_o = 0.46$ for Ganymede. We also consider the effects of an impactor size distribution that changes slope at $V = 10$, which gives an average impactor size $\langle r_{\mathrm{p}} \rangle = 20$ km (see Fig. 2c).

Received 3 August 2009; accepted 4 December 2009; published online 24 January 2010

References

1. Pappalardo, R. T. *et al. Jupiter: The Planet, Satellites & Magnetosphere* 363–396 (Cambridge Univ. Press, 2004).
2. Schubert, G., Anderson, J. D., Spohn, T. & McKinnon, W. B. *Jupiter: The Planet, Satellites & Magnetosphere* 281–306 (Cambridge Univ. Press, 2004).
3. Moore, J. M. *et al. Jupiter: The Planet, Satellites & Magnetosphere* 397–426 (Cambridge Univ. Press, 2004).
4. Schubert, G., Stevenson, D. J. & Ellsworth, K. Internal structures of the Galilean satellites. *Icarus* **47,** 46–59 (1981).
5. Lunine, J. I. & Stevenson, D. J. Formation of the Galilean satellites in a gaseous nebula. *Icarus* **52,** 14–39 (1982).
6. Friedson, A. J. & Stevenson, D. J. Viscosity of rock–ice mixtures and applications to the evolution of icy satellites. *Icarus* **56,** 1–14 (1983).
7. Stevenson, D. J., Harris, A. W. & Lunine, J. L. *Satellites* 39–88 (Univ. Arizona Press, 1986).
8. Tittemore, W. C. Chaotic motion of Europa and Ganymede and the Ganymede–Callisto dichotomy. *Science* **250,** 263–267 (1990).
9. Peale, S. J. Origin and evolution of the natural satellites. *Ann. Rev. Astron. Astrophys.* **37,** 533–602 (1999).
10. Canup, R. M. & Ward, W. R. Formation of the Galilean satellites: Conditions of accretion. *Astron. J.* **124,** 3404–3423 (2002).
11. Barr, A. C. & Canup, R. M. Constraints on gas giant satellite formation from the interior states of partially differentiated satellites. *Icarus* **198,** 163–177 (2008).
12. Kring, D. A. & Cohen, B. A. Cataclysmic bombardment throughout the inner solar system 3.9–4.0 Ga. *J. Geophys. Res.* **107,** 5009 (2002).
13. Strom, R. G., Malhotra, R., Ito, T., Yoshida, F. & Kring, D. A. The origin of planetary impactors in the inner solar system. *Science* **309,** 1847–1850 (2005).
14. Levison, H. F. *et al.* Could the lunar 'Late Heavy Bombardment' have been triggered by the formation of Uranus and Neptune? *Icarus* **151,** 286–306 (2001).
15. Gomes, R., Levison, H. F., Tsiganis, K. & Morbidelli, A. Origin of the cataclysmic Late Heavy Bombardment period of the terrestrial planets. *Nature* **435,** 466–469 (2005).
16. Tsiganis, K., Gomes, R., Morbidelli, A. & Levison, H. F. Origin of the orbital architecture of the giant planets of the Solar System. *Nature* **435,** 459–461 (2005).
17. Anderson, J. D. *et al.* Shape, mean radius, gravity field, and interior structure of Callisto. *Icarus* **153,** 157–161 (2001).
18. Showman, A. P. & Malhotra, R. Tidal evolution into the Laplace resonance and the resurfacing of Ganymede. *Icarus* **127,** 93–111 (1997).
19. Zahnle, K., Schenk, P. M. & Levison, H. F. Cratering rates in the outer solar system. *Icarus* **163,** 263–289 (2003).
20. McKinnon, W. B. NOTE: Mystery of Callisto: Is it undifferentiated? *Icarus* **130,** 540–543 (1997).
21. Petrenko, V. F. & Whitworth, R. W. *Physics of Ice* (Oxford Univ. Press, 1999).
22. Pierazzo, E., Vickery, A. M. & Melosh, H. J. A reevaluation of impact melt production. *Icarus* **127,** 408–423 (1997).
23. Tonks, W. B. & Melosh, H. J. Core formation by giant impacts. *Icarus* **100,** 326–346 (1992).
24. Tonks, W. B. & Melosh, H. J. Magma ocean formation due to giant impacts. *J. Geophys. Res.* **98,** 5319–5333 (1993).
25. Reese, C. C. & Solomatov, V. S. Fluid dynamics of local martian magma oceans. *Icarus* **184,** 102–120 (2006).
26. Peale, S. J. & Lee, M. H. A primordial origin of the Laplace relation among the Galilean satellites. *Science* **298,** 593–597 (2002).
27. Canup, R. M. & Ward, W. R. A common mass scaling for satellite systems of gaseous planets. *Nature* **441,** 834–839 (2006).
28. Morbidelli, A., Levison, H. F., Tsiganis, K. & Gomes, R. Chaotic capture of Jupiter's Trojan asteroids in the early Solar System. *Nature* **435,** 462–465 (2005).
29. Mueller, S. & McKinnon, W. B. Three-layered models of Ganymede and Callisto—Compositions, structures and aspects of evolution. *Icarus* **76,** 437–464 (1988).

Acknowledgements

A.C.B. and R.M.C. are grateful to NASA's Planetary Geology and Geophysics programme. We thank H. Levison, D. Nesvorný, O. Barnouin-Jha and E. Pierazzo for useful discussions, V. Mlinar and R. Citron for comments on draft manuscripts and W. B. Tonks for helpful comments.

Author contributions

A.C.B. and R.M.C. formulated the model; A.C.B. carried out the calculations, and A.C.B. and R.M.C. jointly interpreted the results.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/naturegeoscience. Reprints and permissions information is available online at http://npg.nature.com/reprintsandpermissions. Correspondence and requests for materials should be addressed to A.C.B.