Evolution of Saturn’s mid-sized moons

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The orbits of Saturn’s inner mid-sized moons (Mimas, Enceladus, Tethys, Dione and Rhea) have been notably difficult to reconcile with their geology. Here we present numerical simulations coupling thermal, geophysical and simplified orbital evolution for 4.5 billion years that reproduce the observed characteristics of their orbits and interiors, provided that the outer four moons are old. Tidal dissipation within Saturn expands the moons’ orbits over time. Dissipation within the moons decreases their eccentricities, which are episodically increased by moon—moon interactions, causing past or present oceans to exist in the interiors of Enceladus, Dione and Tethys. In contrast, Mimas’s proximity to Saturn’s rings generates interactions that cause such rapid orbital expansion that Mimas must have formed only 0.1–1 billion years ago if it postdates the rings. The resulting lack of radionuclides keeps it geologically inactive. These simulations explain the Mimas—Enceladus dichotomy, reconcile the moons’ orbital properties and geological diversity, and self-consistently produce a recent ocean on Enceladus.

The moons’ ages are debated. Their crater distributions, assuming Sun-orbiting impactors extrapolated from present-day observed small-body populations, suggest surfaces billions of years old. Conversely, the measured fast expansion of their orbits, probably due to tides raised by the moons on Saturn, indicates—assuming dissipation levels that are constant over both time and frequency of tidal excitation—that this relatively compact moon system is less than a billion years old. This could explain why some moons may not have encountered predicted orbital resonances, and supports scenarios of non-primordial formation from debris of moons may not have encountered predicted orbital resonances, and supports scenarios of non-primordial formation from debris of the tidal or collisional disruption of progenitor moons. The moons’ widely different bulk densities (that is, rock contents or bulk porosities) and internal structures are surprisingly uncorrelated with mass or distance to Saturn (Table 1). Formation from a debris ring could first result in stochastic accretion of rock seeds more resistant than ice to tidal disruption, then coated by ice shells as the moons raise tides on Saturn, move outward and experience lower tidal stresses. Enceladus and Dione have low-density (about 2,400 kg m⁻³) rocky cores and ice shells. Mimas too is differentiated, whereas Rhea, the largest moon and thus the most prone to retaining endogenic heat, seems to be homogeneous. Tethys’ interior is unconstrained.

The contrast in tidally driven geological activity between Mimas and Enceladus is also exceptional. Enceladus harbours a global ocean interacting with the rocky core and venting to space in an area of high heat flow. On Mimas’s closer-in, more eccentric orbit, Saturnian tides should be 30 times stronger. Yet Mimas shows no geological activity. This dichotomy must arise from the moons’ differing propensity to deform due to tides, as previously postulated but not elucidated.

To model the effect of tidal coupling on the properties of the moons, both geophysical (billion years) and orbital (daily) timescales need to be considered, which is currently unachievable. For this reason, previous approaches have assumed either orbital or interior properties.

Here we present simulations of the moons’ orbits, degree of differentiation and internal activity over time. The coupled thermal, geophysical and orbital evolution of all five moons is concurrently simulated from formation to the present day. Our one-dimensional simulations (see Methods) compute rock–ice differentiation, heat transfer, parameterized convection in the core, the ocean and the shell, and porosity compaction. Semi-major axes and eccentricities change due to tidal dissipation in Saturn and in the moons, due to moon–ring interactions, and due to mutual gravitational interactions between moons. The latter are approximated as repeated conjunctions to address the timescale issues. We validate this approach against an averaged-Hamiltonian model of resonant interactions between moon pairs. We assume that some moons form from Saturn’s rings, and that the rings predate at least these moons. Measurements of the rings’ masses, silicate contents and infall micrometeoroid fluxes suggest that the rings are young, contradicting this assumption, but proposed origin scenarios favour either much older rings or a common origin for the rings and the moon (Mimas) that accretes from the rings.

Saturn’s tidal quality factor Q (inverse of the mean angle between the actual and frictionless tidal bulges) is arbitrarily decreased linearly over time to 2,452.8, the geometric midpoint of the present-day range. A constant Q in this range leads to non-primordial inner moons. Assuming higher past values allows us to probe scenarios with older moons. We neglect any dependence on excitation frequency, as Q seems currently to be uniform within an order of magnitude at the moons’ orbital frequencies and cannot yet be quantitatively predicted from evolutionary models of Saturn’s interior. Qualitatively, a linearly decreasing Q may emulate an effective decrease linked to the evolution of Saturn’s internal structure, if dissipation inside Saturn takes place by fluid waves with velocities commensurate with the moons’ orbital velocities.

The moons start closer to Saturn than today, because the angular momentum transferred from Saturn’s relatively faster spin into their orbits tends to increase the orbital semi-major axes a more than tidal dissipation inside the moons decreases them (equation (4) in Methods). Plausible starting positions are computed by integrating the second term of equation (4) backward in time to produce the a(t) curves shown in Fig. 1. Moons beyond the outer ring radius R_out at t = 0 are assumed to be primordial. Otherwise, they are spawned from the rings when their orbit is slightly beyond R_out.

Initial conditions (Tables 1 and 2), model upgrades, and simplifying assumptions are further discussed in the Methods and the Supplementary Information.

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**Table 1 | Measured interior and orbital characteristics of Saturn’s mid-sized moons and moon-specific physical input parameters**

| Parameter                          | Mimas                | Enceladus            | Tethys               | Dione                | Rhea                  | Condition for match |
|------------------------------------|----------------------|----------------------|----------------------|----------------------|-----------------------|----------------------|
| **Observed characteristics**       |                      |                      |                      |                      |                       |                      |
| Mean radius, R (km)                 | 198.2                | 252.0                | 531.0                | 561.4                | 763.5                 | Within 5%             |
| Mass, M (kg)                        | 3.75 × 10^{19}       | 1.08 × 10^{20}       | 6.17 × 10^{20}       | 1.10 × 10^{21}       | 2.30 × 10^{21}        | NA (model input)      |
| Bulk density, ρ (kg m^{-3})         | 1.149                | 1.611                | 985                  | 1.478                | 1.237                 | Within 5%             |
| Core density, ρ_{c} (kg m^{-3})     | 1.200–3,300          | -2,400               | Unknown              | 1,940–3,120          | 1,240–2,100           | Within range          |
| Corresponding core radius, R_{c} (km) | 82–181              | 190–192              | Unknown              | 344–450              | 463–758               | Within range          |
| Present-day ocean?                  |                      |                      |                      |                      |                       |                      |
| Past near-surface heat flux (mW m^{-2}) | Not estimated       | -150–300             | 60–80                | 20–60                | 15                    | Within 20%            |
| Semi-major axis (km)                | 185,539              | 237,948              | 294,660              | 377,400              | 527,040               | Within 20%            |
| (Saturn radii)                      | 3.19                 | 4.09                 | 5.06                 | 6.48                 | 9.05                  |                      |
| Eccentricity                        | 0.0196               | 0.0047               | 0.0001               | 0.0022               | 0.0010                | Range overlaps        |
| **Assumed quantities**              |                      |                      |                      |                      |                       |                      |
| Porosity-free radius (km)           | 186.5                | 252.0                | 507.7                | 556.5                | 762.2                 |                      |
| Initial radius with 20% bulk porosity (km) | 200.9               | 271.5                | 546.9                | 599.5                | 8211                  |                      |
| Porosity-free bulk density (kg m^{-3}) | 1,378              | 1,611                | 1,127                | 1,517                | 1,267                 |                      |
| Surface temperature (K)             | 76                   | 68                   | 68                   | 70                   | 72                    |                      |
| Case with initial Q = 80,000, initial e = 0.016 |                      |                      |                      |                      |                       |                      |
| Time of formation (Myr after CAIs)  | 3,450                | Primordial           | Primordial           | Primordial           | Primordial           |                      |
| Initial semi-major axis (km)        | 160,000              | 160,000              | 27,000               | 363,000              | 523,000               |                      |
| Case with constant Q = 2,452.8, initial e = 0.016 |                      |                      |                      |                      |                       |                      |
| Time of formation (Myr after CAIs)  | 4,470                | 4,140                | 3,760                | 2,280                |                      |                      |
| Initial semi-major axis (km)        | 160,000              | 160,000              | 160,000              | 160,000              | 478,000               |                      |

**Observed characteristics are for the present day, except where noted. In the last column the conditions under which simulations are deemed to match measurements are listed.**

A young Mimas and an old Rhea

To constrain some parameters of the initial satellite system, we determine age limits on Mimas and Rhea from examination of their tidal relationships with the rings and Saturn, respectively. Moon–ring interactions hasten orbital expansion out to a = 222,000 km, where the lowest-order inner Lindblad resonance leaves the rings' outer edge. Today, these interactions affect only Mimas’s orbit (Table 1), expanded from a = 160,000 km in approximately 1.1 (10^{19} kg/M_{moon}) billion years (Gyr), that is, about 0.14 Gyr to 1 Gyr for M_{moon} = 1.1–8 × 10^{24} kg (refs. 35,36). Preliminary Cassini gravity measurements suggest M_{moon} ≈ 1.8 × 10^{24} kg (ref. 36), within this range. Expansion from a = 140,000 km, the current outer edge of the dense rings, to 160,000 km is even faster because of additional higher-order Lindblad resonances (equation(2)). Thus, Mimas must be younger than about 1 Gyr if predated by Saturn’s rings, otherwise Mimas–ring interactions would have widened its orbit beyond today’s. Alternatively, a primordial Mimas would require younger rings and a poorly dissipative Saturn.

Conversely, Rhea is probably primordial, even for a low Saturn Q. Although we neglect this dependence in our simulations, Q varies with time and orbital frequency (semi-major axis). Since today Q(a,t) = 1,500–5,000 for Enceladus, Tethys and Dione and Q(a,t) = 300 for Rhea, we assume for this argument that Q(a) > 1,650 out to 500,000 km (between Dione and Rhea) and Q(a) > 300 beyond. Provided this frequency-dependent Q was constant through time, it took >4.6 Gyr for Rhea's orbit to expand from the rings' outer radius by tides raised on Saturn. Rhea–ring interactions hasten early expansion, but dissipation inside Rhea moderates it. For higher, likelier past values of Q, Rhea is primordial. Early migration is even slower if Rhea progressively accreted from less massive moons raising weaker tides, but previous work has shown that for a low Saturn Q, a Rhea-sized moon forming from the rings accretes most of its mass within just a few million years (Myr).

Consequently, in our explored scenarios, Mimas is spawned from the rings at a time that depends on M_{moon}, Rhea is primordial, and the other moons fall into either category depending on Saturn’s initial value of Q. Primordial moons are assumed to accrete homogeneously and differentiate if heated enough. Moons spawned from rings are assumed to form in layers into a rocky core with an ice shell on the grounds that a more cohesive rock-rich seed accretes first. In either case the core, assumed to retain about 25% water-filled porosity (ref. 27) has density ρ_{c} = X_{hi}ρ_{hi} + (1 − X_{hi})ρ_{i} = 2421 kg m^{-3} (Table 2), consistent with constraints for Enceladus and Dione.
The core water volume fraction is too low to dominate the rheology of the (assumed well-mixed) rock–ice mixture, as ice grains are on average not adjoining.

The canonical case

We first assume an initial Saturn $Q=80,000$, the lowest value for which all moons except Mimas are primordial. We set $M_{\text{ring}} = 1 \times 10^{19}$ kg, 4.5–8 times lower than estimated\(^5\) to reflect the lower surface density of the A ring with which moons solely interact for $a \geq 190,000 \text{ km}$. Setting $M_{\text{ring}} = 5 \times 10^{19}$ kg yields similar results (Supplementary Fig. 1). A starting eccentricity $e = 0.016$ is assumed for all moons (see Methods). The resulting orbital $a$ and $e$; internal temperatures; and the core, ocean and shell radii are shown, respectively, in Fig. 2a,c,d. The four outer moons start with eccentricities higher than today. At initial uniform temperatures set to 100 K, their interior ice is poorly dissipative. Therefore, early heating is predominantly radiogenic and depends on each moon’s rock content, especially since hydrated rock is more insulating than cold crystalline ice. As the moons warm up in the first 500 Myr (Fig. 2c), increased dissipation in compacted, less viscous ice circularizes their orbits (Fig. 2a). Dione and Rhea differentiate (Fig. 2d). Rhea sustains a ~100-km-thick ocean for the next 1.5 Gyr until it refreezes as radiogenic heating decreases. Tidal heating remains comparatively negligible owing to Rhea’s low eccentricity. Dione has no ocean (liquid water outside its core), but harbours pore liquid water in the core (Fig. 2d).

About 2.8 Gyr after formation, Tethys and Dione enter a 3:2 mean-motion resonance that excites their orbital eccentricities, generating enough dissipation that their orbits contract. Enceladus’ expanding orbit and Tethys’ contracting orbit converge into a 4:3 mean-motion resonance (Fig. 2b), raising Enceladus’ eccentricity (but not that of Tethys, which is already high; see equation (6) in the Methods). Our simplistic model computes a sudden increase from $e \approx 10^{-3}$ to 0.5 (Fig. 2a). Using a more sophisticated treatment of moon–moon interactions similarly leads to fast excitation to $e > 0.1$ (Supplementary Information sections 2 and 3), suggesting that this behaviour is robust. The resulting tidal dissipation, equivalent to that produced for an eccentricity of about 0.1 (see Methods), results in runaway heating. As the ice viscosity decreases, Enceladus becomes more dissipative and gets warmed further. Ice melts in

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**Table 2 | Other model input parameters**

| Parameter                  | Symbol | Value or range | Units | Notes or references |
|----------------------------|--------|----------------|-------|---------------------|
| Mass of Saturn             | $M$    | $5.68 \times 10^{26}$ | kg    |                     |
| Radius of Saturn           | $R_s$  | 58,232         | km    |                     |
| Final ring mass            | $M_{\text{ring}}$ | $10^{19}$–$10^{20}$ | kg    | Robbins et al.\(^5\) |
| Ring inner edge            | $R_{\text{i}}$ | 92,000         | km    | Inner edge of B ring |
| Ring outer edge            | $R_{\text{out}}$ | 140,000        | km    | Radius of F ring    |
| Saturn’s initial tidal quality factor | $Q$ | 2,452.8–200,000 | kg    | Lainey et al.\(^2\) |
| Initial eccentricity       | $e$    | 0.016          |       | Canup\(^1\)        |
| Initial rock grain density | $\rho_r$ | 2,900          | kg m\(^{-1}\) | Hydrated rock       |
| Initial ice grain density  | $\rho_i$ | 985            | kg m\(^{-3}\) |                     |
| Water volume fraction in the core | $X_{\text{w}}$ | 0.25          |       |                     |
| Initial bulk porosity      | $\phi$ | 0.2            |       |                     |
| Initial temperature        | $T_{\text{ini}}$ | 100            |       |                     |
**Fig. 2 | The simulated orbital, structural and thermal evolution of Saturn’s mid-sized moons for an initial Saturn \( Q \) of 80,000 decreasing linearly to today’s value of about 2,450 provides a close match to observational constraints.** The final ring mass is set to \( 1 \times 10^{19} \) kg. In this case all moons but Mimas are primordial (Table 1). a, Coloured lines show orbital semi-major axes and eccentricities over time (blue, Mimas; green, Enceladus; orange, Tethys; purple, Dione; and pink, Rhea). Circles show observed present-day positions; the size scales with moon size (Table 1). b, Ratios of mean motions of the moon named at the top of each plot to the other moons, colour-coded as above. Decreasing ratios above 1 or increasing ratios below 1 indicate convergent migration, during which resonances can occur. Our rough model computes a few spurious instances of eccentricity excitation during divergent migration; these are indicated (‘DV’) and seldom affect the moons’ evolutions (Supplementary Information section 3). c, Corresponding internal temperatures (see colour scale in the Mimas plot; a switch from green to orange indicates that ice melts). d, Internal structures as a function of time (grey, undifferentiated; sky blue, ice; blue, ocean or liquid water if the moon is undifferentiated; brown, core with pore ice; teal, core with pore liquid water). Bars to the right of each plot indicate observational constraints (Table 1) on the outer radii of the core (brown), ocean (blue) and moon (black). In each panel, resonances that significantly affect orbital, thermal and/or structural evolution are marked by vertical lines.
the innermost zones, triggering global differentiation. Meltwater circulates throughout the porous core, distributing the tidal heat from the shell throughout the interior to a homogeneous 300–400 K (Fig. 2c). Core porosity arises from the thermal pressurization of pore water (see Methods) that is assumed to be trapped in rock during differentiation. Some porosity could also remain from the sedimentation of rock grains. Thus, Enceladus develops an ocean (Fig. 2d) that persists for 1 Gyr but refreezes as Enceladus’ eccentricity decreases quickly from 0.07 at 3.9 Gyr to 0.0007 at 4.0 Gyr. Freezing could be stalled by resonant ocean tidal heating, neglected in our model. Enceladus then returns to its pre-3-Gyr state of quiescence. Its eccentricity stabilizes to a few 10^{-4}, then increases slightly owing to dissipation inside Saturn.

The 3:2 Tethys:Dione resonance leads to Tethys maintaining an ocean from 3.1 Gyr to the present. Dione’s ice shell also melts briefly then, and again at 3.7 Gyr when in 7:4 resonance with Rhea (where its eccentricity is already high enough to avoid excitation).

At 3.4 Gyr, Mimas is spawned from the rings and, gravitationally interacting with them, quickly recedes to its current orbit. Its eccentricity is too low for its poorly dissipative interior to experience much tidal heating, and too high to be affected by moon–moon resonances.

The simulation outcomes have striking similarities to the present-day Saturn system (Table 3). The radii and bulk densities are matched within 5%. The computed core sizes are within the ranges reported in Table 1. A simulation snapshot taken between 3 Gyr and 4 Gyr reproduces an ocean on Enceladus, hydrothermally circulating through its rocky core, with temperatures of 300–400 K that match those (≥323–363 K) inferred from analyses of plume material\(^{14,15}\). Computed mean global heat fluxes across Enceladus’ ice shell, 25–100 mW m\(^{-2}\) (20–80 GW total heat output rate), are bracketed by present-day measurements of 4.2–15.8 GW just around the tiger stripes\(^{18,19}\) and past fluxes estimated from relaxation of surface features (Table 1). A possible ocean on Dione\(^{19}\) is also reproduced, with corresponding computed heat flows of 70–85 mW m\(^{-2}\) through its upper ice shell that are comparable to reported estimates (Table 1). So are Rhea’s, computed to reach 12 mW m\(^{-2}\) at 2.4 Gyr. The simulation results in a compositionally layered yet geologically inactive Mimas, as observed\(^{11}\). Despite approximated disk torques and N-body interactions, the model reasonably reproduces the present-day orbits of all mid-sized moons. At 4 Gyr, the semi-major axes of Mimas and Rhea are within 0.5% of today’s, although Enceladus, Tethys and Dione are slightly too close in by 12%, 20% and 7%, respectively. Therefore, Enceladus and Dione are not in a 2:1 mean-motion resonance. The match is better at 4.5 Gyr: within 3%, 9% and 5%, respectively, owing to our choice of initial semi-major axes (Table 1). The range of eccentricities experienced by each moon includes its present-day value. Mimas’s eccentricity, whose computation ends up depending only on interactions with Saturn, matches its observed value within a few per cent.

### Varying initial conditions

Some outcomes change when varying initial values for Saturn’s Q and initial orbits accordingly (Supplementary Table 1). If initially Q = 200,000 (simulation not shown), neither Enceladus nor Dione have oceans: both undergo only a weaker resonance with Mimas (5:3 at 3.4 Gyr and 3:1 at 3.9 Gyr, respectively), which does not raise their eccentricity enough to trigger melting, owing to Mimas’s relatively low mass. Dione excites Tethys’ eccentricity at 3.8 Gyr, but Tethys’ interior is too cold then for even high-eccentricity dissipation to cause melting or differentiation.

An initial Q = 50,000 requires that both Mimas and Enceladus form after 3 Gyr, in layers, from the rings (Supplementary Fig. 2). Enceladus never has an ocean: although its eccentricity is significant, its cold interior, in part due to the lack of live radionuclides accreted, is not sufficiently dissipative to elicit positive tidal feedbacks. In the first 2 Gyr, Tethys, locked in a 2:1 resonance with Dione, undergoes repeated eccentricity excitation roughly every 400 Myr, causing a repeating pattern of increased temperatures and melt (Supplementary Fig. 2e,f). High dissipation in both moons maintains their orbits at relatively constant semi-major axes. Furthermore, Tethys’ semi-major axis is kept at a minimum of 222,000 km owing to its interactions with rings about four times as massive as today, which incorporates the material that later spawns Enceladus, then Mimas. The system’s evolution is otherwise similar to the above cases and to the Q = 20,000 scenario (Supplementary Fig. 3), in which Tethys too forms late at about 3 Gyr.

With Q = 2,452.8 constant over time (Fig. 3), all moons except Rhea form late. Orbits expand promptly, especially when close to the rings. For this simulation, the final ring mass is arbitrarily higher (7×10^{19} kg, within the estimated range\(^{10}\); a lower mass would make the late-forming moons older. As in the other Q ≤ 50,000 cases, Mimas and Enceladus never have an ocean, but Rhea, Dione and even a young Tethys do.

Simulations (not shown) with starting eccentricities 10 and 100 times lower than 0.016 for primordial moons and Q = 10\(^{10}\) produce less dynamical and geological activity in the system. Enceladus’ eccentricity is only excited once (5:3 resonance with Mimas), and not sufficiently to provoke melting and differentiation. This could be due to a fortuitous lack of mean-motion resonances, compounded with less opportunity for crossing mean-motion resonances because of slow early migration at high Saturn Q and less orbital contraction in the absence of strong tidal dissipation in the moons.

Thus, varying starting Q, orbital positions and eccentricities results in simulations not matching observational constraints quite as well (Table 3), even though salient features are retained: Mimas forms late and remains cold, Rhea is primordial and radiogenically heated, and the other moons can undergo moon–moon interactions that raise their eccentricities, triggering episodes of high tidal dissipation so long as the moons’ interiors are sufficiently warm and therefore dissipative.

### Discussion

Matching the present-day Saturn system requires a high initial Saturn Q such that Enceladus, Tethys, Dione and Rhea form early on. Late-forming moons seem less prone to have interacted with other moons because their initial outward migration is dominated by interactions with the ring\(^1\). This ring-dominated regime seems a robust result, but should be confirmed with more faithful models of moon–moon interactions. In late-forming moons, radiogenic heating is negligible, further preventing the onset of significant dissipation in frigid interiors.

This provides an interpretation for the Mimas–Enceladus dichotomy, as follows. Mimas formed less than 1 Gyr ago from Saturn’s

### Table 3 | Match between simulation outcomes and observations with the conditions of Table 1 for the results depicted in Fig. 2 (initial Saturn Q = 80,000) and Fig. 3 (constant Saturn Q ≈ 2,450)

| Moon      | Initial Saturn Q = 80,000 | Constant Saturn Q ≈ 2,450 |
|-----------|---------------------------|-----------------------------|
|           | Orbit                      | Interior                     | Orbit                      | Interior                     |
| Mimas     | Match                      | Match                        | Match                      | Match                        |
| Enceladus | Match at 3–4 Gyr           | Match                        | Too cold, no ocean         | Match                        |
|           | e too large                |                              |                            |                              |
| Tethys    | Too close in               | Match                        | Match                      | Match                        |
| Dione     | Match at 3–4 Gyr           | Match                        | Past ocean only            | Match                        |
| Rhea      | Match                      | Match                        | Match                      | Match                        |
rings, whereas Enceladus formed earlier (possibly in the Saturn subnebula), underwent dynamical excitation by interacting with other moons (primarily Tethys and Dione), consequently experienced high levels of tidal dissipation, and its orbit is currently circularizing such that it is out of tidal equilibrium. This explanation for Enceladus’ extraordinary internal activity has been proposed, but not modelled consistently with the long-term evolution of the whole inner Saturn system. Observations are best
matched at about 4 Gyr into the simulation, close to today’s 4.57 Gyr. Mimas’s time of formation from the rings hinges on their mass, but is too late for radiogenic or even tidal heating to be significant. This could yield a possibly unrelaxed core\(^{12,26}\), although our computed lack of pore compaction in the shell is at odds with Mimas’s relatively relaxed shape\(^{41}\). Since Mimas is heavily cratered, a formation less than 1 Gyr ago would strongly constrain impact source populations, including secondaries, sesquinaries and planetocentric debris\(^{1}\).

Our results suggest that Saturn’s rings predate Mimas at least (or that the rings are young, but Mimas is not), but because the evolution of the other moons (if primordial) is insensitive to the presence or mass of the rings, these moons do not further constrain their origin. Thus, both primordial or more recent rings remain viable scenarios\(^{31}\). In particular, the canonical scenario is fully compatible with an origin for Mimas and the rings <1 Gyr ago from the disruption of a common parent moon\(^{31}\). More generally, it implies rings orders of magnitude less massive than rings resulting from the tidal disruption of a Titan companion\(^{7}\), but compatible with the collisional disruption of a primordial small moon\(^{31}\).

In this scenario, Enceladus’ early orbital expansion is also sped up by interactions with the rings, but equivalently Enceladus could have formed before the rings and about 220,000 km from Saturn (Fig. 2a, extrapolating a value of \(a(t)\) of 0.5–2.8 Gyr back in time to 0 Gyr). This may justify our prescribed and otherwise puzzling lack of moon formation by ring viscous spreading in the long interval between the formations of Enceladus and Mimas.

Our simulations, including the canonical case, result in eccentricities above 0.1. These would produce orbit crossing and, perhaps, collisions\(^{31}\). Re-accreted moons would probably have lost any stored radiogenic heat, which could be compensated by accretional heating. Their orbits would probably differ from those of their progenitors.

Results that consider resonance capture (Supplementary Fig. 9) suggest that Enceladus and Dione could remain at or near the 2:1 resonance for several billion years, as was previously found when assuming a constant \(Q\) for Saturn and the moons\(^{31}\). With slightly different initial orbits, the resonance can be broken after 20 Myr due to eccentricity pumping of both moons (Supplementary Fig. 8) or capture can be avoided altogether (Supplementary Fig. 7) because Dione’s eccentricity is excited by prior passage through a 3:2 resonance with Tethys. In our simulations, this 3:2 resonance is much more easily broken (after 14 Myr, Supplementary Figs. 7–9) than in a previous study\(^{27}\) for \(k_2/Q\) values similar within an order of magnitude, perhaps because \(k_2/Q\) is varied with tidal dissipation in our model. This resonance could also be broken due to inclination excitation\(^{1}\), which we did not model.

The lack of resonance capture in the repeated encounter model could strongly affect the simulated moon dynamics and thermal states. Resonances induce relative changes in semi-major axes \(\Delta a/a e_c\) (ref. \(^{4}\)), that is, about 1% for excitation of \(e < 1\) to \(e > 0.1\). This translates to differences in tidal dissipation (proportional to \(a^{-2}\)) of about 10%. More importantly, because of slow secular expansion, the timing of subsequent orbital resonances is sensitive to the relative \(a\) values of the moons, differing by >1 Gyr if the \(a\) of one moon is changed by only <1.5% (compare Enceladus and Dione in Supplementary Table 1 and Supplementary Figs. 7–9). Moreover, the duration of orbital resonances and corresponding tidal dissipation force depend sensitively on pre-resonance conditions\(^{11}\). With only slight variations of the age and initial positions of Enceladus and Dione, their 2:1 resonance can last billions of years, millions of years or not occur at all (Supplementary Information section 2). The repeated-encounter model best approximates brief (millions of years) resonance durations that punctually excite eccentricities, but fully accounting for resonance capture (for example with \(N\)-body simulations) could result in much more prolonged or much less heating. The results of this work must be interpreted with these caveats in mind: our simplified model can reproduce much of the inner Saturn system, but other families of solutions also compatible with observations may be identified as the space of initial conditions is more systematically explored with higher-fidelity models of orbital evolution.

We have assumed that moons spawned from rings were fully formed upon reaching \(a = 160,000\) km. More continuous accretion\(^{1}\) from less massive proto-moons that raise weaker tides on Saturn would imply slower orbital expansion, and further lessen the role of radioactive heating (which is dissipated faster in smaller bodies), but imply a role for impacts in affecting both interiors and orbits.

Beyond reproducing the best available constraints on the moons’ internal structures, our models suggest that a primordial Tethys must have differentiated, and probably experienced past episodes of high heat flow (up to 50 mW m\(^{-2}\)) consistent with surface evidence (Table 1). The cores of Enceladus, Dione and Rhea are much larger than expected from the full differentiation between silicates and ice. Such low-density cores, consistent with observations, can be maintained over geologic time if the rock maintains about 25% water-filled porosity\(^{12,20}\). Deep pore water in the core, better insulated from the surface, is melted more easily than in the shell, promoting water–rock interaction in the moons’ interiors.

Methods

Initial-orbital evolution code. We model the thermal evolution of each icy moon using a routine created by Desch et al.\(^{31}\), which performs time-dependent calculations of the internal temperature profile and structure of bodies made of rock and ice, including the effects of differentiation\(^{11}\). This code was modified to include a detailed model of the effects of core fracturing, hydrothermal circulation, rock hydration and dehydration\(^{11}\), as well as tidal heating (as a function of depth, temperature and composition) and porosity\(^{31}\). Self-compression is neglected.

Mass is distributed assuming spherical symmetry on a fixed-volume one-dimensional grid, with a specified number of zones (here, 200) evenly distributed in radius. The internal energy in each grid zone is computed from the initial temperature using equations of state for rock and ice (here assumed to be pure water). Accretional heating is assumed dissipated before the simulation starts. Rock and radionuclides are assumed to be solely in the core (no mud in oceans or ice shells and no leaching of \("\)K). A thermal structure is determined by balancing conductive heat transfer with radiogenic (long-lived radionuclides only; abundance\(^{11}\); ref. \(^{3}\)), gravitational\(^{11}\), thermal\(^{11}\) and tidal\(^{11}\) forces.

Using a finite-difference method and a 50-year time step. Thermal conductivities depend on composition, temperature and porosity\(^{11}\). Tidal dissipation due to orbital eccentricity is computed by solving the equations of Tobie et al.\(^{44}\) with a propagator matrix technique\(^{29}\), assuming an Andrade model for the response of non-Newtonian rock, ice and rock–ice mixtures to tidal forcing\(^{11}\). Fluid tides are ignored, even though they could induce major heating in moons with an ocean\(^{11}\). Porosity can compact at rates set by material viscosities. Volume changes due to ice melting or freezing are neglected. Enhanced heat transfer is computed in the ice shell and/or fractured core (hydrothermal circulation) if the Rayleigh number appropriate for convection between two plates or for porous media, respectively, exceeds a critical value\(^{11}\). In such grid zones, an effective thermal conductivity is computed through multiplication by the Nusselt number (ratio of convective to conductive heat fluxes, a function of the Rayleigh number\(^{29}\)). In liquid grid zones, an effective thermal conductivity is set to 400 W m\(^{-1}\) K\(^{-1}\), high enough to yield a nearly isothermal liquid layer, yet sufficiently low to satisfy the Conductant criterion.

The evolution of a moon’s orbit is computed only in terms of its semi-major axis \(a\) and eccentricity \(e\); spin and orbital planes are assumed to be coplanar with Saturn’s equator and rings. The lack of consideration of orbital inclinations prevents us from using these as an additional, useful constraint on the history of the system. In our previous models\(^{31}\), a moon’s orbit changed solely due to tidal dissipation inside this moon (which decreases \(a\) and \(e\)) and inside Saturn (which increases \(a\) and \(e\), since Saturn spins faster than the moon orbits). For the present study, we have added the effects of moon–ring and moon–moon interactions as follows.

Moon–ring interactions. We model moon–ring interactions arising from Lindblad resonances\(^{3}\). These occur when ring particles and a moon exterior to the rings have mean motions in the ratio \(k(k - 1)\), where \(k\) is a positive integer\(^{31}\). Lindblad resonances also occur for moons interior to rings, but are not relevant.
here. Such interactions result in a torque $\Gamma$ between the moon and the rings, of magnitude (equation (16) of Meyer-Vernet & Sicardy
cylinder): 
\[ \Gamma = \sum_k \sum_i \frac{4}{3} \frac{\mu_k}{\Omega_{0m}} \left( \frac{a_i}{R_m} \right)^2 \left( \frac{a_i}{R_m} \right) \]
where $\Gamma_k$ are individual torques arising from Lindblad resonances of order $k$; $\Omega_0 = \sqrt{GM/a}$ is the orbital frequency of the moon, with $G$ the gravitational
constant and $M$ the mass of Saturn; $\Omega_k = \omega/k(1-k)$ is the orbital frequency of
ring particles; and $\Sigma$ is the ring surface density, which we approximate as $\Sigma = M_{\text{ring}} \pi (R_{\text{in}} - R_{\text{out}})^2$ with $M_{\text{ring}}$, $R_{\text{in}}$, and $R_{\text{out}}$ the ring mass, outer radius and
inner radius, respectively. $A_i$ is the product of $\Omega_m/2\pi$ with the moon's mass,
and a term of order $k$ (equations (9) and (17) of Meyer-Vernet & Sicardy
cylinder); we approximate it as $A_i \approx GMk/2a_i$. Thus:
\[ \Gamma \approx \sum_k \sum_i \frac{4}{3} \frac{\mu_k}{\Omega_{0m}} \left( \frac{a_i}{R_m} \right)^2 \left( \frac{a_i}{R_m} \right) \]

The exerts a torque $\Gamma$ on the moon, whereas the moon exerts a torque $-\Gamma$ on the rings; that is, the moon and the rings repel each other. In practice, the calculation of $\Gamma$ involves summation over only a few $k$ terms, unless the moon is very close to the outer edge of the rings: $a < (R_j^3/\omega)(k/k-1)^2$, which corresponds to 150,000 km for $k = 10$, assuming $R_{\text{in}} = 140,000$ km. Beyond 222,000 km, the lowest-order ($k = 2$) resonance leaves the rings and ring torques no longer affect the moon's orbital evolution. Because Saturn's A and B rings are the densest and
most massive, we neglect the C and D rings and assume a constant surface density between $R_m = 392,000$ km (inner edge of the B ring) and $R_m = 140,000$ km (radius of the narrow F ring, just outside the A ring).

This torque is assumed to affect only the orbital semi-major axes, although it has been argued that eccentricities may be affected too. Its effect on orbital expansion is:
\[ \frac{da}{dt} = -2a^{1/2}/\Gamma \left( \frac{1}{GM} \right) \]

We add this term to equation (14) of Nereu & Rhodes
cylinder to compute the net change in a moon's semi-major axis due to tidal dissipation inside this moon (first term below), tidal dissipation inside Saturn (second term), and moon–ring interactions (third term):
\[ \Delta a = \Delta_{\text{sat}} - 2 \frac{\sum Q_{\text{tide}} a_i^2}{GMm} + \left( \frac{k_2}{\sqrt{GMm}} \right)^{1/2} \frac{m}{a_i^{1/2}} + \frac{2}{3} \frac{M_{\text{ring}}}{R_{\text{out}}^2} \left( \frac{a_i}{R_{\text{out}}} \right)^{1/2} \]

Here $R_{\text{sat}}$, $k_2$, and $Q$ refer to Saturn's radius, the degree-2 tidal potential Love number and the bulk tidal quality factor (for solid tides, this is the inverse of the mean
angle between the actual and frictionless tidal bulges), respectively. $Q_{\text{sat}}$ is the tidal heating rate inside each of the moon's grid zones. The $k_2$ of Saturn is set to its best estimate of 0.39 (ref. 1). The evolution of a moon's orbital eccentricity is governed by:
\[ \Delta e = \Delta t \times \left( -\sum Q_{\text{tide}} a_i^2 + \frac{57 k_2}{8} \frac{\sqrt{GMm} \left( R_{\text{out}}^3 \right) m}{Q a_i^{1/2}} + \frac{\Delta e}{\tau_{\text{res}}} \right) \]

in the absence of moon–moon interactions.

Moon–moon interactions. We have upgraded our code to simulate the internal evolution of $N$ objects simultaneously. The code reads the input file, sets parameters common to the entire system, such as the mass of Saturn; and then calls $N$ parallel instances of the thermal evolution subroutine (here, $N = 5$). This subroutine is run for one time step; it returns the updated orbital parameters ($a$ and $e$) of its corresponding moon to the main program, which feeds orbital parameters for all moons into each thermal evolution subroutine instance at the next time step. Thus, each moon 'sees' where all other moons are in real time, so that mutual gravitational effects can be computed. The parallelization of the code results in simulation times for five moons that are about double those for a single object. Each simulation spanning 4.5 Gyr, with 50-year time steps, takes about 300 central processing unit (CPU) hours, or 4 days with a dual 2.4-GHz Intel Xeon 8-core processor (Mac Pro).

Accurately computing mutual gravitational effects between moons would require computing the moons' orbital elements many times along an orbit. The moons' current orbit has periods of 1 day to 4.5 days; requiring time steps of 1 hour. With such small time steps, a simulation spanning 4.5 Gyr would take 10 CPU hours, an impractical amount of time (20 years per simulation on a 1,000-core supercomputer). Therefore, we compute moon–moon interactions using a simplistic but much faster approximation, which neglects any effects other than mean-motion resonances such as trapping and secular effects. We assume that resonances occur only if the mean motions of two moons $n_j = \sqrt{GM/a_j}$, (neglecting the moons' masses relative to Saturn's) remain commensurate to within less than 1% over one time step $\Delta t$: that is, $|j n_j - (k+1) n_j| < 0.01 n_j N_{\text{res}}$, if $n_j > n_i$ or $(j + k) n_j - j n_i < 0.01 n_i N_{\text{res}}$, otherwise, with $j$ and $k$ positive integers, and $N_{\text{res}} = 2(\pi n_j/\Omega_{0m})$ the number of orbits travelled over one time step. Thus, the right-hand side of each condition is implemented as $0.01 \times 2\pi/\Delta t$. We consider only low-order resonances: $j \leq 5$ and $k \leq 5$, that is, from 2:1 to 8:5. Furthermore, we assume that these interactions only act to increase eccentricities, as described by equations (4) and (5) of Charmuz et al.:
\[ \Delta e = \max \left( 0, \frac{\Delta v}{\tau_{\text{res}}} \right) \]

where $\tau_{\text{res}}$ is the period between two conjunctions between moons, equated to $2\pi/(v_j n_j)$ if $n_j > n_i$ or $2\pi/(v_i n_i)$ otherwise; $v_i$ is the Keplerian velocity of the moon experiencing the perturbation, approximated as $\pi a_i/\Delta t$; and $\Delta v$ is the velocity perpendicular to orbital motion imparted by repeated encounters between two moons:
\[ \Delta v = \frac{m_i}{m_j + m_i} \sin \alpha \sqrt{1 - \sin^2 \beta} \]

where $m_i$ is the mass of the moon and $m_j$ that of the moon it interacts with, $v_i = |n_i a_i - n_j a_j|$ the relative orbital velocity between the two interacting moons, and
\[ \sin \alpha = \left( 1 + \frac{P^2}{G^2 (m_i + m_j)^2} \right)^{-1/2} \]

with $P$ the impact parameter or distance of closest approach between the moons, approximated as $|a_i - a_j|$. The above two equations are equations (1) and (2) of Greenberg et al.\n
Thus, the evolution of a moons orbital eccentricity is governed by:
\[ \Delta e = \Delta t \times \left( -\sum Q_{\text{tide}} a_i^2 + \frac{57 k_2}{8} \frac{\sqrt{GMm} \left( R_{\text{out}}^3 \right) m}{Q a_i^{1/2}} + \frac{\Delta e}{\tau_{\text{res}}} \right) \]

These terms describe tidal dissipation inside the moon (as a function of the tidal heating rate), tidal dissipation inside Saturn, and gravitational interactions with other moons, respectively. For the mid-sized moons, $\Delta e/\tau_{\text{res}}$ has values of about $10^{-4}$ to a few $10^{-5}$, so only moons with $e < 10^{-4}$ to $10^{-5}$ are affected by interactions with other moons.

A drawback of this model is that the overall scaling of eccentricity increases, which is a physical quantity, depends on the chosen time step, which is a numerical construct. To achieve results that are physically realistic at the order-of-magnitude level, we adjusted the time step so that the maximum eccentricities excited by mutual interactions are often at least $10^3$, can be higher than 0.1, and rarely exceed 1 (ejection from the system). Such outcomes are suggested by our simulations with a more accurate averaged Hamiltonian dynamical model (Supplementary Information section 1) validated against previous computations of the orbital evolution of Saturn's mid-sized moons (Supplementary Fig. 6), and by previous studies using $N$-body simulations of the Saturn\n systems, and planetary systems in general. The resonance period $\tau_{\text{res}}$ being about $10^5$ s, the third term in equation (9) is of the order of $10^4$ to a few $10^5$, so a realistic behaviour is reproduced by choosing a time step of $\Delta t = 50$ years or $1.6 \times 10^4$ s.

Eccentricity increases due to moon–moon interactions are assumed to be instantaneous, that is, they reach maximum eccentricity within one time step owing to repeated conjunctions during that time step. This assumption is validated by a posteriori by comparison with averaged Hamiltonian model simulations, in which eccentricity increases are also fast. In simulations with either model (compared Figs. 2 to Supplementary Figs. 7–9, 3 to Supplementary Figs. 5–10, and Supplementary Fig. 3 to Supplementary Fig. 11, respectively), moon–moon interactions are more likely to occur if the moons' eccentricities (a) are low before resonance, (b) can increase to above 0.1, inducing melting in the moons' shells, and (c) tend to perturb orbits more for a moon in closer conjunction with a relatively more massive moon. Although no simulation with the averaged Hamiltonian model resulted in sufficient excitation of Enceladus' eccentricity to induce melting in its shell, the few simulations carried out sampled only a tiny fraction of an immense orbital parameter space (for example, the behaviour of Saturn's $Q$ and starting moon longitudes of peri centre and mean anomaly), which cannot be explored by a systematic or Monte Carlo approach with our computational capabilities.

In both models, even though computed eccentricities can reach values above 0.5, we truncate tidal equations to their lowest-order terms, assuming $e < 1$. At
dependence on frequency seems small at the present day at the orbital frequencies of the moons during accretion. Accretion is assumed to be complete before a simulation starts, or before a late-forming moon is spawned. This limitation could matter most for late-forming moons such as Mimas. Even then, the effect on the results is small, as quantified by control simulations carried out without Mimas (that is, a moon with zero mass at the onset of accretion; compare Supplementary Figs. 1 and 5). This assumption also prevents us from seeking explanations to the puzzling lack of trend between the moons’ bulk densities (accreted rock content) and their masses or semi-major axes.

Other assumptions and initial conditions. The moons are assumed to accrete hydrated rock (possibly hydrated in satellitesimals, in which ice may have been melted by the decay of short-lived radionuclides or accretional heat). Moon cores are assumed to retain residual volatiles of pore water. This assumption was previously made to assess whether the resulting increased tidal dissipation in Enceladus’ core could explain its level of geological activity. Interestingly, this model yields differentiated internal structures compatible with observational constraints for all five moons, in particular, the low density of Enceladus’ core and Rhea’s low degree of differentiation.

We do not attempt to realistically relate variations in Q to changes in Saturn’s interior over time, and neglect any variation of Q with excitation frequency. The dependence on frequency seems small at the present day at the orbital frequencies of Enceladus, Tethys, Dione and (to a lesser extent) Rhea. Saturn’s internal structure and evolution (presence and extent of a core, contraction over time, helium separation from hydrogen) remain too poorly constrained to fully match predictions and observations of Q as a function of frequency and time. Thus, future work could more realistically simulate Saturn’s Q.

Starting orbital semi-major axes are chosen so that the moons reach their current positions at the present day. A common canonical starting eccentricity of 0.016 is assumed for all moons, chosen so that Mimas reaches its present-day eccentricity of 0.0196 without significant internal tidal dissipation or moon–moon interactions. For late-forming moons, this value is consistent with an eccentricity increase away from Saturn for small moons between the outer edge of the rings and Mimas (Supplementary Fig. 12). For primordial moons forming in Saturn’s accretion disk, a similar value of about 0.02 reflects a balance between mutual gravitational interactions and eccentricity damping by density waves in the disk, in the absence of significant early tidal dissipation inside the moons.

If a moon forms from the rings, the ring mass is decreased instantaneously by the mass of this moon. Thus, the initial ring mass is chosen to be the final ring mass, constrained to 2.5–8 × 10^{19} kg (ref. ), augmented by those of the late-forming moons. We also run simulations with final ring masses as low as 1× 10^{19} kg to approximate the surface density of the A ring, which is several times lower than that of the B ring but governs moon–ring interactions for a > 190,000 km. Moons spawned from rings are assumed to be differentiated (layered) following the rock–seed accretion scenario, although moons may get their rock content from subsequent exogenic input. Starting semi-major axes are typically around 160,000 km, which is slightly higher than the dense rings’ current outer radius (135,000–140,000 km) to account for the fact that the moon may still be accreting material after leaving the rings; we assume it is fully formed by the time its semi-major axis reaches 160,000 km. Primordial moons are assumed to be homogeneous. In either case, the moons are assumed to accrete with 20% porosity, and they are allowed to compact over time at rates that depend on the material viscosity.

For simplicity, surface temperatures are assumed to be constant over time, even though there were probably variations in mean surface albedo, the heliocentric distance of the Saturn system, and solar luminosity. We set them to the effective temperatures determined from measured albedos, but equate Enceladus’ surface temperature to Tethys’ (the next-brightest of the five moons) on the grounds that reflective snow on Enceladus’ surface may be due to recent cryovolcanic activity.

Data availability

All data generated or analysed during this study are included in this published article and Supplementary Information. The code used to generate those data is freely available at https://github.com/MarcNeveu/IcyDwarf.

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NATURE ASTRONOMY | VOL 3 | JUNE 2019 | 543–552 | www.nature.com/natureastronomy

551
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