EVOLUTION OF SATURN'S MID-SIZED MOONS.

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How old are the moons? The compact yet fast-expanding orbits of Mimas, Enceladus, Tethys, Dione, and Rhea [1] suggest young dynamical ages [2] difficult to reconcile with their rich geological history [3-8]. To sustain this fast expansion, the tidal quality factor Q of Saturn (inverse of the mean angle between the actual and frictionless tidal bulges) must be 1500–5000 at the orbital frequencies of Enceladus, Tethys, and Dione and ≈300 for Rhea's [1]. If constant over time, this Q implies moons a few hundred million years old.

Why is Enceladus active whereas Mimas is not? Enceladus has a global ocean thicker at the south pole [9], interacting with the rocky core [10,11] and vented to space [12] in an area of high heat flow [5,13-15]. Mimas, in contrast, shows no geological activity [3,16]. Being closer to Saturn and on a more eccentric orbit, Mimas should experience 30 times more dissipation than Enceladus, all else being equal [17]. The two moons must differ in their propensity to deform due to tides.

Model: To tackle these questions, we simulate the coupled internal and simplified orbital evolution of all five moons from their formation to the present day. Our 1D model [17] accounts for radiogenic and tidal heat production and transfer, parameterized convection in the core, ocean, and shell, and porosity compaction. Semi-major axes a and eccentricities e change due to tidal dissipation in Saturn and in the moons. Here, the model is upgraded to also account for moon-ring interactions as in [18]. Mutual interactions between moons are modeled in a simplified way, as a full N-body simulation is beyond the reach of current computers. As [18], we assume that moons entering a mean-motion resonance can undergo a forcing in e scaled to their relative masses and orbital positions.

We vary Saturn's Q, from which approximate moon accretion positions and times are inferred. The moons start closer to Saturn, because the transfer of angular momentum from Saturn's fast spin into the moons' orbits increases a more than tidal dissipation in the moons decreases them. Moons able to migrate from the outer ring orbit to their present orbit in less than 4.5 Gyr are assumed to form from the rings [18] already layered into a rock-rich core and icy shell, as rock would coalesce first due to its higher resistance to tidal shear [18]. Moons that must form beyond the rings to reach their present orbit within 4.5 Gyr are assumed primordial; we start them as a homogeneous ice-rock mixture and explicitly compute their ice-rock differentiation [17]. In either case, the core is assumed to retain ≈25% water-filled porosity [19,20]. This yields a porosity-free bulk core density of 2421 kg m^{-3}, consistent with constraints for Enceladus [9,21-24], Dione [24], Rhea [25], and Mimas [26]. The interior of Tethys is unconstrained. The rock volume fraction is sufficient to dominate the core rheology, as ice grains are on average not adjoined.

Saturn's Q is arbitrarily decreased linearly over time to the present-day value of 2450. A constant Q leads to inner moons younger than the age of the solar system; assuming higher initial values allows us to probe scenarios in which the moons are primordial. We do not relate variations in Q to changes in Saturn's interior over time and neglect its dependence on orbital frequency.

Young Mimas, old Rhea: Moon-ring interactions greatly hasten orbital expansion out to $a =$ 222000 km, where the lowest-order inner Lindblad resonance leaves the outer ring edge [18]. Only Mimas is still affected by these interactions. Its a could have increased from 160000 km in ≈ 1.1 (10^{19} kg/$M_{\rm ring}$) Gyr. Thus, Mimas cannot be primordial if Saturn's rings predate its accretion [27].

Conversely, Rhea is likely primordial, even if Saturn's Q (300 at Rhea's orbit and 10 times higher for closer-in past orbits) was equally low in the past. A constant $Q = 1650$ out to $a > 5 \times 10^5$ km would result in Rhea forming primordially just outside the rings. Rhea-ring interactions would speed up early orbital expansion, but any high tidal dissipation inside Rhea would slow it down. Higher past values of Q would result in Rhea being primordial.

Thus, we explore scenarios in which Mimas is spawned from the rings at a time that depends on the ring mass, Rhea is primordial, and the other moons fall into either category depending on Saturn's initial Q.

The Canonical Case: With an initial $Q =$ 80000, all moons but Mimas are primordial. The ring mass is assumed to be 1×10^{19} kg, but 5×10^{19} kg yields very similar results. A starting $e = 0.016$ is assumed for all moons. The four outer moons start with e higher than today, but their cold interior ice (initiated at 100 K) is poorly dissipative: heating is mainly radiogenic in the first 0.5 Gyr. As it warms, ice compacts and becomes less viscous and more dissipative, lowering the moons' e. Heating also differentiates Dione and Rhea. Rhea even sustains a ∼100-km thick ocean for the next 1.5 Gyr until it refreezes as radioactivity decreases. Tidal heating remains much lower due to Rhea's low e. No liquid water layer overlies Dione's core, but there is pore liquid in the >273 K core.

At ≈2.8 Gyr after formation, Enceladus enters a 4:3 mean-motion resonance with Tethys. Our simplistic model computes a sudden increase in Enceladus' e from $\sim 10^{-7}$ to 0.5. This increases tidal dissipation, heating the ice, making it even more dissipative in a runaway fashion. The innermost zones of Enceladus melt, triggering differentiation. Meltwater circulates through the porous core, distributing the tidal heat from the shell so the whole interior reaches 300–400 K. Enceladus develops a ocean somewhat thicker than today, which persists for 1 Gyr but refreezes as its eccentricity decreases quickly from 0.070 at 3.90 Gyr to 0.0007 at 4.00 Gyr. Enceladus then returns to its pre-3 Gyr state of quiescence.

Tethys and Dione enter a 3:2 mean-motion resonance at 2.7 Gyr, which leads to Tethys maintaining an ocean between 3.1 Gyr and the present day, and Dione's shell melting briefly. It re-melts at 3.7 Gyr due to a 7:4 resonance with Rhea.

At 3.4 Gyr, Mimas is spawned from the rings. Its proximity to the rings generates interactions that cause fast orbital expansion at a relatively stable e. Its e is too high to be affected by moon-moon resonances. Because Mimas must form late, the lack of radionuclides keeps it cold and geologically inactive.

Discussion: Simulation outcomes are similar to the present-day Saturn system. Radii and bulk densities are matched within 5%. Core sizes are within observational constraints. A simulation snapshot at 3–4 Gyr reproduces an ocean on Enceladus, hydrothermally circulating through its core, with temperatures matching those ($\geq$ 323–363 K) inferred from plume analyses [10,28]. Computed heat fluxes across Enceladus' shell (20–80 GW total output) are bracketed by present-day values of 4.2–15.8 GW around the tiger stripes [13,14] and past fluxes estimated from surface features. This simulation also reproduces a possible ocean on Dione [24]. Corresponding computed heat flows of 70–85 mW m^{-2} through Dione's upper ice shell are comparable to past estimates [7,8]; so are Rhea's, computed to reach 12 mW m^{-2} at 2.4 Gyr [4]. The simulation produces a differentiated yet inactive Mimas, as observed [26]. Finally, it reasonably reproduces the present-day orbital configuration of all five moons.

Varying initial conditions produces similar results if Q starts high, but not if Q starts low, because Enceladus accretes few radionuclides, never heats up, and therefore cannot undergo runaway tidal heating. As a result, its evolution is like Mimas'. We find it easier to match today's system if all moons but Mimas are old. Mimas, if it postdates the ring, could have formed from the debris of the collisional disruption of one or more previous generations of moons [18,27,29-31].

Despite simplifying assumptions on moon-moon interactions, starting e, and the variation of Saturn's Q, these simulations provide a possible explanation for the Mimas-Enceladus dichotomy, reconcile the moons' dynamical youth and geological diversity, and consistently produce a recent ocean on Enceladus.

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