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Evolution of Saturn's mid-sized icy moons

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Abstract

We aim to reproduce the orbits (semi-major axes a and eccentricities e) and interiors (core radii, oceans) of the mid-sized moons of Saturn (Mimas, Enceladus, Tethys, Dione, and Rhea) as constrained by *Cassini* data. We numerically model the coupled geophysical and orbital evolution, assuming the moons formed late from Saturn's rings [1]. This closely reproduces observations, but only if Enceladus is initially warmer than its accretional heat budget. Notably, our models reconcile the moons' dynamical youth and geological diversity. We discuss next steps for these models.

1. Observational Constraints

Each moon's orbit changes due to tidal dissipation inside this moon and Saturn, and interaction with the rings and with other moons, which we model as in [1]. Beyond the zone of ring-moon interaction [1], a chiefly increases due to tides raised on Saturn: $\frac{da}{dt} \propto \frac{k_2}{Q}\ a^{-5.5}$, with k_2 and Q Saturn's surface degree-2 tidal potential Love number and bulk tidal quality factor, constrained by astrometry [2]. A constant Q yields moon ages (times at which $a <$ Saturn's Roche radius) much younger than the solar system's, but compatible with cratering from planetocentric impactors [3].

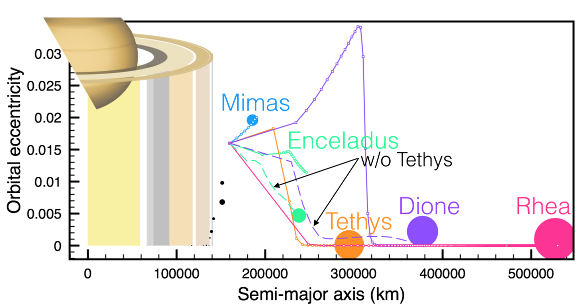

Figure 1: Orbital evolution of Saturn's mid-sized moons. Filled circles are present-day orbital a and e; curves are computed (a;e) over time, with overlapping dots showing positions every 10 million years.

Gravity and libration data suggest cores of density ≈2.4 g cm^{-3} for Enceladus [4], Dione [4], Rhea [5], and maybe even Mimas [6]. This implies high porosity over the already low density of hydrated rock (≈2.9 g cm^{-3}), likely filled with ice and/or liquid water. A density of 2.4 g cm^{-3} is obtained with 25 vol.% ice and 75 vol.% rock (assumed hydrated inside progenitor moons). This is consistent with rock seeds accreting in ice-rich rings between the Roche radii for rock and ice [1], while avoiding disruption because rock retains its cohesion (rock grains remain in contact) as long as the mixture contains ≤30-40% ice [7].

2. Model Scenarios & Results

We use the *IcyDwarf* code [8], upgraded to model all 5 moons simultaneously, with moon-moon and moon-ring interactions. We assume differentiated accretion [1] into a rocky core with 25 vol.% ice and an icy shell. Based on the a and e of Saturn's moonlets (black dots in Fig. 1), we assume that by the time the moons finish accreting, they have orbits with a≈160000 km and e≥0.01. We pick a starting e=0.016, 20 vol.% bulk porosity (which can compact over time), and uniform temperature T of 100 K, 30 K higher than current effective surface T to account for accretional heating. Starting masses and bulk densities (radii) are chosen to match today's values after compaction, if any. Moon masses and Saturn's Q are fixed. The time of formation of each moon is determined from k_2/Q; the ring mass (assumed to be 7×10^{19} kg today) is initially augmented by those of the moons, and decreases accordingly each time a moon forms.

Results show that the older and larger cores of Rhea and Dione (and to some extent Tethys) are radiogenically heated (Fig. 2). This decreases the ice viscosity, increases tidal dissipation, and thus decreases their eccentricity (Fig. 1). In contrast, younger Mimas stays cold and its e keeps increasing. Moon-moon resonances too can increase e, as shown for Tethys-Dione and Tethys-Enceladus in Fig. 1. Present-day orbits and interiors are matched (Fig. 2), assuming heating 2-3× over Andrade levels of dissipation [8], except that:

A. Radiogenic heating cannot warm Enceladus enough to damp its initial e to today's 0.0047. Damping requires a starting T=200 K (case shown in Fig. 1 & 2), i.e. heating by an impactor of radius 100 km at 810 m/s (planetocentric e=0.05), or 67 km at 1.7 km/s (e=0.1). Such energies are $>5\times$ higher than needed to make a South Polar Terrain (SPT)-sized crater [10]. Still, giant impacts, which likely conclude moon accretion [1] and may have left craters on all 5 moons (Herschel, possibly the SPT [9], Odysseus, Evander, and Tirawa/Mamaldi), would have heated Enceladus' ice the most, because Enceladus has the highest ratio of crater (SPT) size to mass of ice. Warmer interiors are also caused by higher initial e, which damp faster.

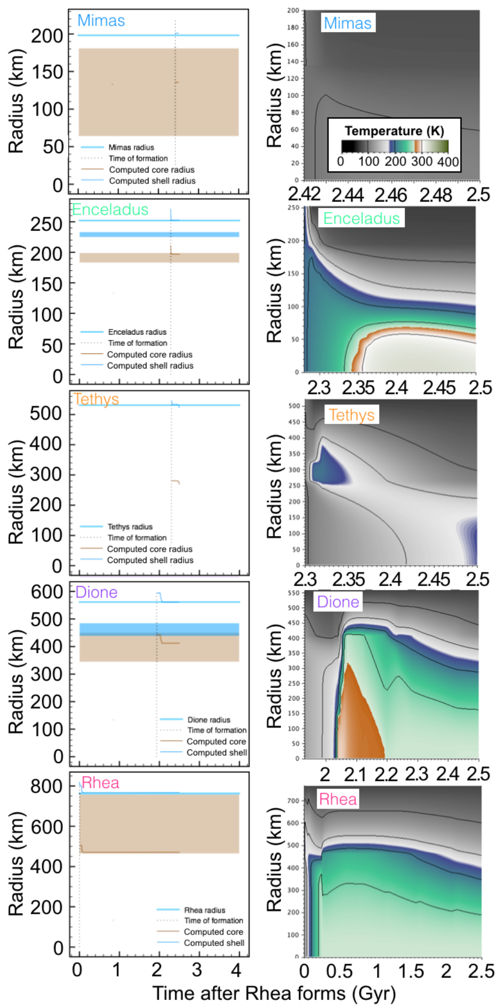

Figure 2: Left: Moon structures. Shaded are *Cassini* constraints on core (brown) and, if relevant, ocean outer radii (blue). Thick lines: moon radii. Thin lines: computed core and moon radii. Right: T over time.

B. The runs do not produce oceans on Enceladus and Dione, although they do produce liquid water in Enceladus' core today and in Dione's core in the past.

We have assumed a constant Q, and that k_2=1.5, the value for a homogeneous fluid, not 0.39 as observed [2], which yields spuriously young moons (Rhea is 2.5 Gyr old; Fig. 2). We will update runs with Q computed from models of Saturn's interior [11] that vary with frequency, i.e. a and, thus, time. We obtain similar Q to [2, 11] with a core of radius 16000 km and density 18 g cm^{-3}, and an envelope of density 0.32 g cm^{-3}, which also yield correct M and k_2 for Saturn.

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