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Origin and Evolution of Saturn's Mid-Sized Moons

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1 Introduction

The ages of Saturn's inner mid-sized moons (Mimas, Enceladus, Tethys, Dione and Rhea) are debated. Their crater distributions suggest surfaces billions of years (Gyr) old [1], but their fast expanding orbits [2] indicate that this compact system is <1 Gyr old. Additionally, the moons have vastly different levels of geological activity, uncorrelated with the level of tidal dissipation expected from their orbital properties or their size. Mimas, despite being on a closer-in, more eccentric orbit than geysering Enceladus, is utterly inactive. Rhea, the largest moon most prone to retaining endogenic heat, seems less differentiated [3] than its smaller siblings.

We present recently published numerical simulations [4] coupling thermal, geophysical and simplified orbital evolution for 4.5 billion years that reproduce the observed characteristics of the mid-sized moons' 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 (or forms together with) 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. We discuss the limitations and next steps for these simulations, as well as what the computed lifetime for Enceladus' ocean might imply for its habitability.

2. Simulations

In order to model tidal effects on the moons' evolution, both geophysical (Gyr) and orbital (daily) timescales must be considered, which is currently unachievable. For this reason, previous work prescribed either interior or orbital properties [e.g. 5,6]. We have simulated the concurrent evolution of all five moons from formation to the present day. Our 1D simulations compute internal structures, heat transfer, and simplified orbital evolution [5,7] due to moon-Saturn, moon-ring, and moon-moon interactions.

2.1. Old Enceladus, Young Mimas

In the simulation that best matches constraints from the Cassini mission, the rings and four outer moons are assumed primordial. 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. Tethys' shrinking orbit converges into a 4:3 mean-motion resonance with Enceladus, raising Enceladus' eccentricity to > 0.1. The resulting tidal dissipation triggers runaway heating. Meltwater circulates throughout its porous core, distributing tidal heat throughout the interior to a homogeneous 300–400 K. Enceladus thus develops an ocean that persists for 1 Gyr. It refreezes as Enceladus' eccentricity plummets below the present-day value at 4 Gyr. Freezing could be stalled by resonant ocean tidal heating [8], neglected in our model. Mimas forms < 1 Gyr ago from Saturn's rings [5] and never heats up. Its orbit expands quickly due to interactions with the rings. New measurements suggest the rings too formed around that time [9], maybe together with Mimas [10], a situation close to the case simulated since the orbital evolution of the other moons seldom depends on the rings' age.

2.2. A Close Match to Cassini Constraints

Moon radii, bulk densities, and core sizes are matched within 5% or within reported ranges. A snapshot taken between 3 and 4 Gyr reproduces an ocean on Enceladus, circulating through its warm core (≥ 323 K [11]). Computed global heat fluxes across the ice shell are bracketed by direct measurements [12] and estimates from crustal relaxation [13]. Despite simplifications, the model reasonably reproduces the present-day orbits of all moons, although Enceladus and Dione are not quite in a 2:1 resonance. The range of eccentricities experienced by each moon includes its current value.

3. Discussion and implications

These results are sensitive to unknown initial conditions, such as the initial orbits and time of formation of the moons. They cover a small fraction of an immense parameter space, especially regarding the time and frequency dependence of tidal dissipation inside Saturn, the rings' mass through time, and the number of moons through time (a balance between accretion/capture and collisions/ejections). The simplifications in the orbital modeling remain to be checked with N-body simulations. Despite these limitations, coupled modeling of interior and orbital evolution holds the key to unlocking questions such as the age of Enceladus' ocean, the properties of Saturn's interior, and the age of its rings.

Detecting signs of a subsurface biosphere in Enceladus' plume hinges on the unknown age of its ocean. Too young, and life may not have had time to emerge. Too old, and the ocean may approach chemical equilibrium with the rocky core, limiting the extent or activity of any biosphere below detection. Our results suggest that Enceladus is likely billions of years old; otherwise stored radiogenic heat is too low for interior melting induced by orbital excitation. They also suggest that (1) the ocean is not a fluke triggered by recent orbital upset, and (2) once emplaced, the ocean can last up to 1 Gyr due to the stabilizing feedbacks of convective heat distribution and high tidal dissipation in warm ice. On Earth, by 1 Gyr, a global biosphere had emerged. 1 Gyr also seems short enough for chemical energy to still be available from ocean-core interaction, as measurements also suggest [14]. If the ocean's age is just right, seeking to detect a biosphere on Enceladus would be transformative no matter the outcome: another instance of life with a likely independent origin, or a habitable but lifeless world.

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