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# Orbital evolution and tidal heating of Saturn's mid-sized moons

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## Abstract

The formation and orbital evolution of Saturn's inner mid-sized moons (Rhea, Dione, Tethys, Enceladus, and Mimas) are still in debate. The most puzzling points are how the moons passed through some strong mean motion resonances during their tidal orbital evolution toward the current orbital configuration, and strong heat flux from Enceladus observed by Cassini CIRS instrument. Here we performed N-body simulations of the moons' orbital evolution with various initial conditions assuming that the moons were formed from Saturn's hypothetical massive ring. In most cases of our simulation, the moons cannot avoid trapping at mean motion resonances during their orbital evolution. However, we find the only way to avoid these resonance captures and explain the current heating of Enceladus is by taking into account both the eccentricity excitation and the orbital expansion caused by the ring torque.

## 1. Introduction

Saturn's mid-sized moons – Mimas, Enceladus, Tethys, Dione, and Rhea – are located outside the Saturn's ring, but closer than Saturn's massive moon Titan. These moons have two unique aspects: 1) the current orbital configuration – how the Tethys-Dione pair and the Mimas-Enceladus pair passed through their strong 3:2 mean motion resonances during the tidal orbital evolution, and 2) the current intensive heat flow from Enceladus – a few orders of magnitude higher than the tidal energy dissipation caused by the present orbital eccentricity of Enceladus.

If we ignore mutual gravitational interactions and orbital eccentricity, tidal orbital expansion rate of the moons depends on their semi-major axis ($a$), mass ($M_\mathrm{m}$) and Saturn's dissipation factor ($k_{2,\mathrm{p}}/Q_\mathrm{p}$ where $k_{2,\mathrm{p}}$ and $Q_\mathrm{p}$ are the Love number and quality factor of Saturn). Recently, the detailed analysis of astrometric observational data were suggested $Q_\mathrm{p} = 1,700$ [2]. Based on this value of $Q_\mathrm{p}$, one theory for the formation, these mid-sized moons were formed from the spreading of a previous massive ring [3, 4], was proposed. When the migration is convergent, two or more moons can be captured in a mean motion resonance. Currently, Tethys is just inside of the 3:2 resonance with Dione and their migration is convergent, and the Tethys-Dione pair should have passed a strong 3:2 resonance and also their 2:1 resonance during their tidal evolution. To avoid these resonance capture, we consider the additional orbital expansion and eccentricity excitation caused by ring torque. Figure 1 shows the orbital evolution including the tide and ring torque without mutual gravitational interaction. If the eccentricity is excited over a threshold value, the capture probability at a resonance is significantly reduced [5] and a pair of moons can avoid becoming trapped.

Tidal heating is also affected by eccentricity evolution (proportional to $e^2$). Here we consider the possibility that the intense heat production during the past orbital evolution of Enceladus is the result of eccentricity excitation due to the ring torque, and that this heat is still stored in Enceladus' interior and is slowly being released.

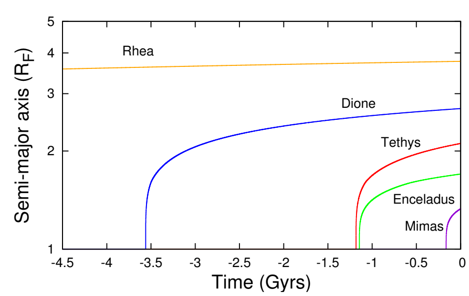


Figure 1: Evolution of semi-major axis of Mimas, Enceladus, Tethys, Dione, and Rhea, backwardly integrating from the current semi-major axes without mutual interactions between the moons. Taking into account the torque and $Q_\mathrm{p} = 4,000$.

## 2. Methods

We simulate the orbital evolution of Saturn, Enceladus, Tethys and Dione using SyMBA [6]. We have incorporated the tidal interaction and ring torque, which affect the semi-major axis expansion, eccentricity dumping or excitation, into this simulation. The ring mass is assumed to be constant. On the other hand, we mainly change the initial orbital configuration of these moons and tidal quality factor of Saturn $Q_{\rm p}$ between 1,700-4,000.

## 3. Summary and Conclusions

We found that, if eccentricity excitation by the ring torque is effective, it has the potential to solve the problem of the orbital configuration of the mid-sized moons and heat flux from Enceladus. Figure 2 shows the result of the orbital evolution of the moons with gravitational interaction between the moons. With the relatively high eccentricity pumped up by the torque, Enceladus passes through all the mean motion resonances with Tethys due to the excited eccentricity, and the Tethys-Dione pair passes through their 2:1 resonance. In this case, Tethys and Enceladus collide with each other at $\sim$ 0.18 Gyr. However, when the eccentricity of Enceladus becomes smaller, they never collide and it can reproduce the orbital configuration. At the end of this simulation ($\sim$ 1.1 Gyr), Enceladus and Dione get trapped in 2:1 resonance, which is the current state. The heat that was tidally dissipated due to the eccentricity excitation by the ring torque in the past is stored in the moons and slowly radiated away through conductive transfer. The stored heat in Enceladus may account for the current anomalously high heat flow.

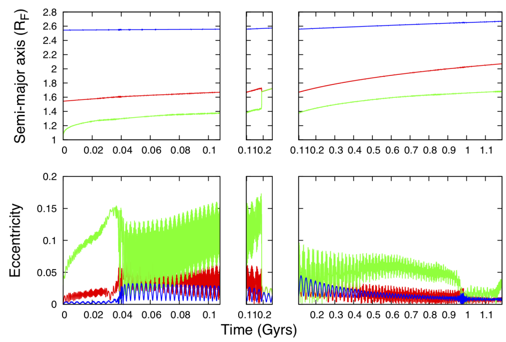


Figure 2: The evolution of semi-major axis (upper) and eccentricity (lower) of Enceladus (green), Tethys (red), and Dione (blue). The middle panels start from the end state of the evolution in the left panels and the eccentricity becomes smaller in the right panels.

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