ACCRETION OF MID-SIZED ICE-RICH MOONS FROM EXPANSION OF A PRIMORDIAL MASSIVE SATURNIAN RING.

J. Salmon[1] and R. M. Canup[1], [1]Southwest Research Institute, Planetary Science Directorate, 1050 Walnut Street - Suite 300, Boulder, CO, 80302, USA (julien@boulder.swri.edu)

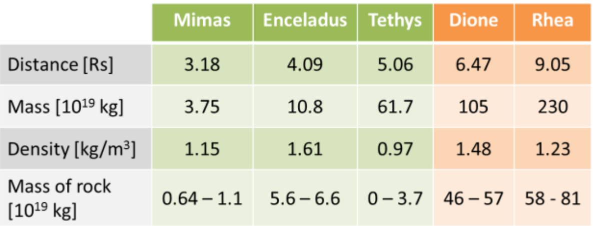
Introduction: Saturn's satellites display a diversity of compositions and masses that is challenging to explain. Massive Titan likely formed in Saturn's primordial subnebula [1]. The small moons orbiting close to the rings, from Atlas to Janus, formed recently as ring material collisionally spread outward [2]. However the origin of the mid-sized moons exterior to Janus and interior to Titan is debated.

A model for the origin of Saturn's rings via tidal stripping from a primordial Titan-sized satellite implies that the rings were initially orders-of-magnitude more massive than today [3]. Ring models show that as an initially massive ring viscously spreads, its mass asymptotically approaches that of the current rings over 4.5 Gyr [4]. It is thus natural to consider whether the mid-sized moons could have originated from material spreading outward from a massive early ring.

Initial estimates suggested that such a ring would spawn moons with masses and distances similar to those of Mimas, Enceladus and Tethys, assuming a tidal parameter for Saturn $Q \sim 10^4$ to 10^5 [3]. Subsequent simulations by [5] consider much stronger tidal dissipation with $Q \sim 10^3$, and in this case, the masses and positions of all of the mid-sized moons including Rhea and Dione could be explained as byproducts of the ring's expansion [5]. While $Q \sim 10^3$ for current Saturn has been proposed [6] based on astrometry, whether such a small value would apply to primordial Saturn is unclear, and some models suggest that early effective Q values would have been larger [7,8]. The code in [5] also did not explicitly treat interactions between growing satellites, including scattering and capture into resonances, which can affect the resulting system architecture and stability.

We here explore whether Mimas, Enceladus and Tethys (or their progenitors) could have been spawned from a massive ice-rich ring, assuming weak tidal dissipation in Saturn and using an *N*-body model to treat satellite growth [9]. Dione and Rhea would then have formed separately from the Saturn subnebula, as in [1].

Compositional constraints: Although the mid-sized moons show a diversity of densities, two groupings can be made based on the total mass of rock in each object (Table 1). The inner three moons (hereafter MET) each contain $\leq 5 \times 10^{19}$ kg in rock, while the outer two each have $\geq 50 \times 10^{19}$ kg in rock. We here consider that the inner three moons were initially primarily ice, with their rock delivered subsequently by external bombardment [10].



	Mimas	Enceladus	Tethys	Dione	Rhea
Distance [Rs]	3.18	4.09	5.06	6.47	9.05
Mass [10^{19} kg]	3.75	10.8	61.7	105	230
Density [kg/m^3]	1.15	1.61	0.97	1.48	1.23
Mass of rock [10^{19} kg]	0.64 – 1.1	5.6 – 6.6	0 – 3.7	46 – 57	58 - 81

Table 1. Properties of Saturn's mid-sized inner satellites.

Simulation: Our model [9] couples an analytic ring model to the *N*-body code SyMBA [11], and includes ring spreading (with a viscosity including the effects of the rings' self-gravity), tidal accretion criteria, ring-satellite interactions at the strongest Lindblad resonances, and satellite tidal evolution. As the ring spreads beyond the Roche limit ($a_R \sim 2.2R_S$, where R_s is Saturn's current mean radius), mass and angular momentum are removed from the ring and added to the *N*-body code as new small moonlets. We use [12] to compute the torque on satellite orbits due to Saturn tides, with a time delay equivalent to $Q \sim 10^4$. We set Saturn's radius to 1.3 to $1.5R_S$ to represent its primordial state [13], and use conservation of its spin angular momentum to compute its corresponding rotation rate. Our initial ring masses are 0.5 to 3×10^{-5} Saturn masses (M_S). Saturn's current rings contain $\sim 10^{-7}M_S$. We perform 4 sets of 12 simulations, with/without tidal dissipation in the satellites, and with/without Dione and Rhea.

Results: Figure 1 shows a sample simulation. For the runs here for $\leq$ few $\times 10^7$ yr, tidal expansion of the satellite orbits is minimal. Each satellite recoils from the ring due to direct ring torques until it reaches a distance $\sim 1.6a_R \sim 3.6R_S$, at which point its strongest resonances fall outside the ring. However the outer satellite typically evolves beyond this distance due to interactions with inner bodies. When an outer satellites scatters an inner one toward the planet, the outer can gain angular momentum and increase its semi-major axis. Also if an outer satellite becomes trapped in a mean motion resonance with an inner moonlet whose strong resonances fall in the ring, resonant expansion of the inner moon drives the outer moon outward as well to distances beyond $3.6R_S$. Figure 2 shows the mean and standard deviation of our MET equivalents, at 10^9 years, for the 4 sets of simulations. Our mass vs. orbital radius distribution of satellites generally agrees well with the current system, although Enceladus analogs tend to be more massive than the current moon, consistent with later mass loss from this body [14].

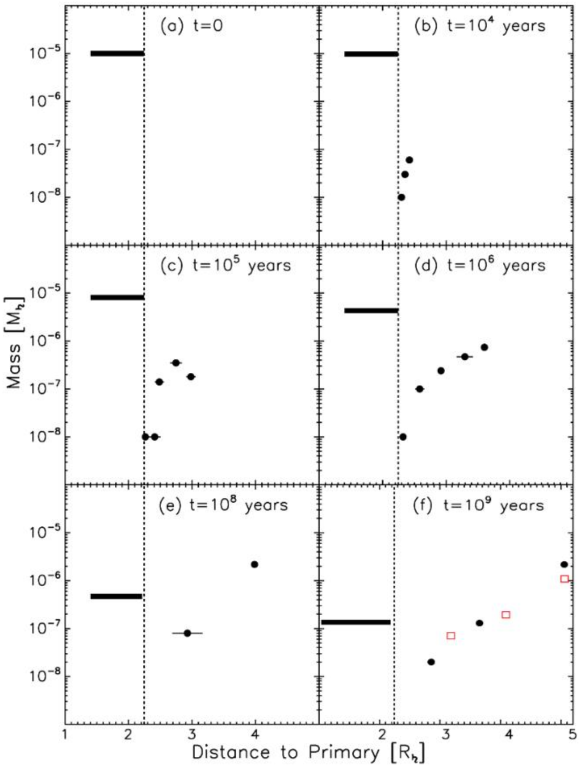


Figure 1: Snapshot of an accretion simulation. The thick horizontal line is the roche-interior ring. As the ring viscously spreads, material is delivered through the Roche limit (vertical dashed line) and forms new moonlets that recoil due to interactions with the ring and tidal torques. Vertical lines show eccentricities. Moonlets grow through mutual collisions. Red squares are the current MET.

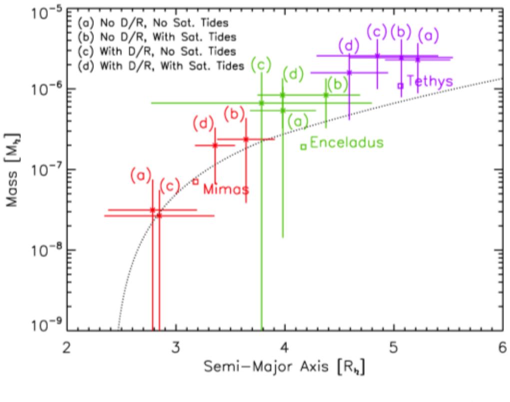


Figure 2: Mean and standard deviation of our Mimas, Enceladus and Tethys equivalents for our 4 sets of runs, at 10^9 years. The dotted line is the analytical prediction from [15].

In our study we assume the primordial ring, and thus the spawned satellites, are predominantly ice. We next estimate the amount of rock that would be delivered to the system during a Late Heavy Bombardment. Following the “Nice” model [16] we calculate the amount of rock potentially delivered by impactors originating from a primordial Kuiper belt. We use the impact probabilities from [17] to estimate the total mass hitting Saturn for a given disk mass, and follow up by estimating the impact probability p for each satellite: $p/P_S = r^2/(R_S a)$, where P_S is the impact probability on Saturn, and r and a are the physical radius and semi-major axis of the satellite. We find that the total mass of rock in MET as a group can be delivered by an LHB-type event if the mass of the primordial transneptunian disk was larger than about $20M_\oplus$ (Figure 3). We find that Dione and Rhea would receive an order-of-magnitude too little rock, suggesting their rock has a different origin.

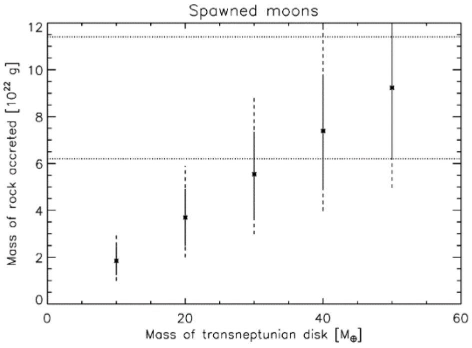


Figure 3: Average mass of rock accreted by our spawned moons. Horizontal dahed lines show the estimated range of rock in M+E+T. Vertical lines and dashes show variation for impactors containting 40 to 60% rock by mass.

Using our simulated MET-analogs (Figure 2) and their corresponding impact probabilities, we find that the mass delivered to “Mimas” and “Tethys” is similar to their actual rock content, but that our “Enceladus” analogs typically receive about a factor of 2 too little rock compared to the actual Enceladus. However if most of the mass was delivered by large LHB impactors (e.g. [18]), we estimate stochasticity could reproduce the current distribution of rock in MET with a probability of a few to 10%.

References: [1] Canup, R. M. & Ward, W. R. (2006) *Nature, 441*, 834-839. [2] Charnoz, S. et al. (2010) *Nature*, 465, 752-754. [3] Canup (2010) *Nature*, 468, 943-946. [4] Salmon, J. et al. (2010) *Icarus*, 209, 771-785. [5] Charnoz, S. et al. (2011) *Icarus*, 216, 535-550. [6] Lainey et al. (2012), *ApJ*, 752:14. [7] Ogilvie, G. (2014) *Ann Rev Astron Astrophys*, 52, 171-210. [8] Fuller, K. et al. (2016) *MNRAS* 458,3867. [9] Salmon, J. & Canup, R. (2012) *ApJ*, 760:83. [10] Canup, R. (2013) *LPSC XLIV*, 1719. [11] Duncan, M. et al. (1998) *AJ, 116*, 2067-2077. [12] Mignard, F. (1981) *Moon and Planets*, 24, 189. [13] Fortney, J. et al. (2007) *ApJ*, 659, 1661-1672. [14] Hansen, C. J. (2011) *GRL* 38, L11202. [15] Crida, A & Charnoz, S (2012) *Science*, 338, 1196. [16] Tsiganis, K. et al. (2005) *Nature*, 435,459. [17] Zahnle, K. et al. (2003) *Icarus*, 163, 263. [18] Charnoz, S. et al. (2009) *Icarus*, 199, 413.