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An ongoing satellite–ring cycle of Mars and the origins of Phobos and Deimos

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SI 1: Validating the Model

Here we use our RING-MOONS code to reproduce published results on the dynamics of the Saturnian system as a validation test. As described in the Methods, we use the work of Salmon et al. (2010) to describe the physics of how the ring viscously spreads. In order to test our solution of Equation 3, we replicated their results for the spreading of a variably viscous ring orbiting Saturn. We chose initial conditions that were nearly identical to those of Salmon et al. (2010). The initial surface mass density of the ring is a steeply peaked Gaussian function, centered at a semi-major axis of 110,000 km. The mass of the ring is equal to a Mimas mass, and the particles in the ring have a radius of 1 m and a density of 1000 kg/m^3. In Figure SI2 we display these results at various points in time for 10^5 years of evolution, achieving good agreement with the results of Salmon et al. (2010).

In addition to validating our description of the spreading of the ring, we also compare our RING-MOONS code to HYDRORINGS, a code used in Charnoz et al. (2011) to model the accretion of satellites out of Saturn's rings. The viscous spreading of Saturn's rings and the accretion of small satellites is directly analogous to our model for the evolution of the martian ring/satellite system. In Fig. 3, Charnoz et al. (2011) display results for a viscously spreading ring accreting material into satellites over 4 Gy, assuming various tidal parameters between the satellites and Saturn. HYDRORINGS results for a system in which satellites undergo tidal interactions with the planet, but not other satellites are presented in Fig. 3 panel d. This scenario is very similar to our desired analysis of Mars. Because of the observational evidence for small satellite accretion from the saturnian rings and the observed mass-distance relationship of the accreted satellites, the results of Charnoz et al. (2011) are an ideal test case to check the validity of our model against reality and other models established in the literature.

The HYDRORINGS code is not publically available, however the results displayed in Charnoz et al. (2011) are well described, and should be reproduced by our model. In Fig. 3, panel d of that work are displayed the results of satellites accreting out of a ring after ~ 4 Gy, given no tidal dissipation between the satellites. In these results the mass of the initial ring is set at 4 Rhea masses (~ 9.2 x 10^{21} kg) and the density of particles within the ring is set at 900 kg/m^3. The tidal dissipation factors for Saturn are set to be k_2 = 0.341 and Q = 1680. We use these same conditions to test whether the output of our model matches the results of HYDRORINGS, 4.1308 Gy after the simulation has progressed, and the current satellite mass-distance relationship of Saturn's satellites.

The results of Charnoz et al. (2011) do not include a description of the initial profile of the surface mass density of the ring, the size of the ring particles, nor the radial extent of the ring. In comparing our model to this work, we model the surface mass density profile of the ring as $\Sigma(r) \propto r^{-3}$, and the ring extends from the surface of Saturn to 90% of Saturn's FRL. For computational efficiency we set the particles in the ring to have a radius of 1 km. In Figure SI3 we compare the results of our model, "RING-MOONS" against the results of HYDRORINGS[31], and the current Saturn system. In the described scenario, after 4 Gy HYDRORINGS produces at least 16 satellites, while RING-MOONS produces 7. As displayed in Charnoz et al. (2011), the current Saturn system contains 10 satellites that may have accreted from Saturn's rings. Additionally, we find the general trend of Saturn satellites to have greater masses at greater semi-major axis which was reproduced by HYDRORINGS is also reproduced with our model. The initial conditions selected here may differ than those selected in Charnoz et al. (2011), and may explain discrepancies between the results of the two models. However, dependent upon further work, both models may be able to reproduce the actual Saturn system.

SI 2: The Dichotomy-Forming Impact

The dichotomy-forming impact event sets two constraints: the upper limit to the mass of the initial ring created by the impact, and the starting time for the ring/satellite cycle. From a study of the formation of the martian hemispherical dichotomy from an impact using a large suite of smoothed particle hydrodynamics (SPH) simulations, the maximum mass of a ring created by the best case scenario is $\sim 3 \times 10^{23}$ g[14]. Our preliminary results indicate that a satellite that is disrupted at the RRL will eventually accrete a new satellite with a mass ~ 20% of the primordial satellite's mass (see Equation 15). Based upon this result, we calculate the mass of the ring that must have formed Phobos and call this "Cycle 1." Assuming this ring formed as a result of the tidal breakup of a primordial satellite that also evolved to the RRL, we calculate the mass in the previous cycle and call this "Cycle 2". Assuming tidal breakup of satellites occurs at the RRL, we find that if the dichotomy-forming impact produced a satellite with a mass of $\sim 2.6 \times 10^{22}$ g, this system would eventually evolve over 5 cycles to produce a single satellite with the mass of Phobos.

As the impact event that formed the dichotomy likely occurred 4.3-4.5 Gy ago, the entire process, from the initial impact debris ring which cycles to produce a Phobos sized satellite that evolves into the orbit we observe today, *must* take at least ~ 4.3 Gy. There are several factors that affect the timescale of an individual cycle including: the mass of the ring, the tidal parameters chosen for Mars and the satellites, and the size of the particles within the ring. The mass of the ring is determined via Equation 15, and we find it unlikely that the tidal parameters of the satellites are much different than previously found[7,16].

Because the ring particle size is unconstrained, we use this as a free parameter in the model and choose a value that allows the complete evolution to occur over the time since the dichotomy-forming impact 4.3 Gy ago. Between our results for different size ring particles we compare four timescales: the time for the ring to evolve from the RRL to the FRL, the time for satellites to accrete from the ring and evolve outwards due to ring torques, the time for the ring to deplete such that Lindblad torques no longer dominate the orbital evolution of the satellites, and the time for satellites to evolve inwards to the RRL due to planetary tides.

The time for the ring to evolve from the RRL to the FRL scales directly with particle radius, and is confirmed by our results for all cycles and all particle sizes. The time for the particles to accrete and evolve outwards has some dependency on particle size. This is confirmed by our results for rings composed of particles with a radius of 1 km and 100 m for all cycles, and for our results for rings composed of particles with a radius of 10 m for cycles 6, 5, and 4. The time for the ring to deplete has a strong dependence on particle size being largely set by the spreading timescale of the ring, similar to the evolution of ring material from the RRL to the FRL. The time for the satellites to evolve to the RRL after the ring has depleted is largely independent from the radius of the ring particles, as it is mainly driven by the orbital evolution of the satellite due to planetary tides.

To determine the necessary ring particle size needed to fit the giant impact age constraint we compare the timescales in our results for rings composed of different sized particles. For the early cycles, the time required for the ring to spread to the FRL is short compared to the time required to eventually evolve accreted satellites to the RRL. Thus, the mass of the ring, and not the particle size, is the primary factor determining the time it takes for the early cycles to complete. However, in the later cycles the mass of the ring is never sufficient for Lindblad torques to greatly perturb the satellites' orbits[7], and the satellites orbit near the edge of the ring. In these later cycles the time it takes for the ring to spread to the FRL, where it may begin to accrete into satellites, is much longer than the satellites' orbital evolution. Therefore, the time it takes for later cycles to complete is driven by the dynamics of the ring and shows a much greater dependency on particle size.

Because the evolution of the ring scales with the size of the ring particles, for cycles 3, 2, and 1 we assume that the ratio between these timescales for rings composed of particles which differ by an order of magnitude in radius remains constant. We are then able to extrapolate the amount of time a ring composed of any size particle will take to complete a given cycle. With this methodology, we estimate that modeling the ring particles as 0.18 m bodies would take the system roughly ~ 4.3 Gy to form Phobos and place it in its current orbit. This result is in agreement with Saturn's rings today, which are estimated to be composed of particles with a radius between few centimeters to several meters[22].

SI 3: Uncertainty in the Location of Tidal Breakup:

The greatest uncertainty in our estimation of the total number of cycles is the location where tidal breakup of each satellite occurs. Severe tidal deformation of a satellite may occur when the satellite is only a few Mars radii away, yet Phobos orbits Mars at ~ 2.76 R_M as a coherent body and is not believed to be losing material due to tidal torques. Therefore, we know tidal breakup should only occur when the satellite's semi-major axis is less than that of Phobos, which is currently orbiting inside the FRL. The Rigid Roche Limit (RRL) is defined as the orbital location where a particle on the equator of a spherical satellite is no longer bound to the surface of the satellite. Assuming the satellite is a gravitational aggregate with no cohesion forces between particles, this occurs when the outward centrifugal forces of the satellite's rotation and tidal shear are stronger than the attractive gravitational forces of the satellite[15]. Therefore, for our nominal case we select the RRL as the location where satellite breakup occurs.

However, real satellites may have some internal cohesive strength, and it has been found that for a satellites with a plausible range of internal strength tidal breakup should occur somewhere within 1.2 – 1.7 R_M[16]. This range sets the greatest uncertainty in our measurements. In Figure SI4 we ran simulations for a ring composed of particles with a 1 km radius and with a total ring mass of ~ 1.2 x 10^{23}g until the cycle mechanism resulted in a satellite with a mass less than or equal to Phobos. However, in these simulations we varied the location where tidal breakup of the satellite occurred. We then compared the mass of the ring at the beginning of a cycle to the final satellite mass produced by the cycle.

These results show that if tidal breakup of the satellites occurs at 1.2 R_M, each cycle will produce a satellite with ~ 6% the mass of the ring at the beginning of the cycle. Beginning with a Phobos mass satellite and working backwards, we find that if the initial ring formed by the dichotomy-forming impact produced either a ring or a satellite with a mass of ~ 5 x 10^{22}g, Phobos would form after only 3 cycles. Furthermore, to place Phobos in orbit in ~ 4.3 Gy after the dichotomy forming impact, we find that our model would require the radius of ring particles to be 0.15 m. On the other hand, if satellite breakup were to occur at 1.7 R_M, we find that if the dichotomy forming impact produced either a ring or a satellite with a mass of ~ 1.7 x 10^{23}g, Phobos would form after 7 cycles. In order to place Phobos in orbit in ~ 4.3 Gy after the giant impact, we find that our model would require the radius of the ring particles to be 0.32 m.

The uncertainty in the location of tidal breakup therefore constrains the uncertainty in our results. In our "nominal case" we find a ring with an initial mass of 1.2 x 10^{23} g that is composed of particles with a radius of 0.18 m will evolve over 6 cycles to produce Phobos. As described above, if satellite breakup occurs at 1.2 R_M the initial ring is less massive, fewer cycles occur, and the required particle radius is smaller. If satellite breakup occurs at 1.7 R_M, the initial ring is more massive, more cycles occur, and the required particle radius is larger. Therefore, we find that an initial ring with a mass of $1.2^{+0.5}_{-0.7}\times10^{23}$ g that is composed of particles with a radius of $0.18^{+0.14}_{-0.03}$ m would complete 6^{+1}_{-3} cycles to place Phobos in its current orbit after ~ 4.3 Gy.

SI 4: Existence of a Ring Today

At the completion of Cycle 1, our simulation results in a Phobos-mass satellite orbiting Mars at its current semi-major axis. However, our simulations also result in the existence of a low-mass ring orbiting Mars. As there is no evidence that a ring exists today, this remains as a caveat to our work. The surface mass density of our remnant ring is on the order of ~ 1 g/cm^2 (see Figure SI5). We estimate that the radius of the ring particles would be $0.18^{+0.14}_{-0.03}$ m and therefore this ring would have an optical depth $\tau \ll 1$ (see Methods). Although we have modeled our ring to have particles of identical size, a more realistic ring may have a distribution of particle sizes. For an optically thin ring, the effects of solar radiation may work to deplete the material, with the smallest particles experiencing Poynting-Robertson drag and the larger particles affected by the Yarkovsky Effect. Both these processes may work to remove material from the low mass remnant ring, explaining why we do not see it in the present day. Modeling of the effects of solar radiation on the remnant ring is beyond the scope of the present work.

SI 5: Astro-Sediments in the Geologic Record:

As the mass of the ring decreases, so does the rate of its evolution. Thus, initially the ring deposits material onto Mars at a very rapid rate which then decreases over time. Using our estimates of the timescales for a ring composed of 0.18 m particles (our "best case" scenario), we estimate the amount of time it would take for the ring to deposit 80% of the total cycle's deposit, as well as at what time the deposit would have occurred in Mars geologic history.

We do not hypothesize how these "astro-sediment" deposits would appear in the geologic record. In addition to not knowing the interior and bulk composition of Phobos, there are a multitude of factors affecting the composition of the astrosediments including their interaction as they enter the atmosphere, the Martian geologic period at which the deposit occurs, and any weathering that would occur on the planet after the deposit, among others.

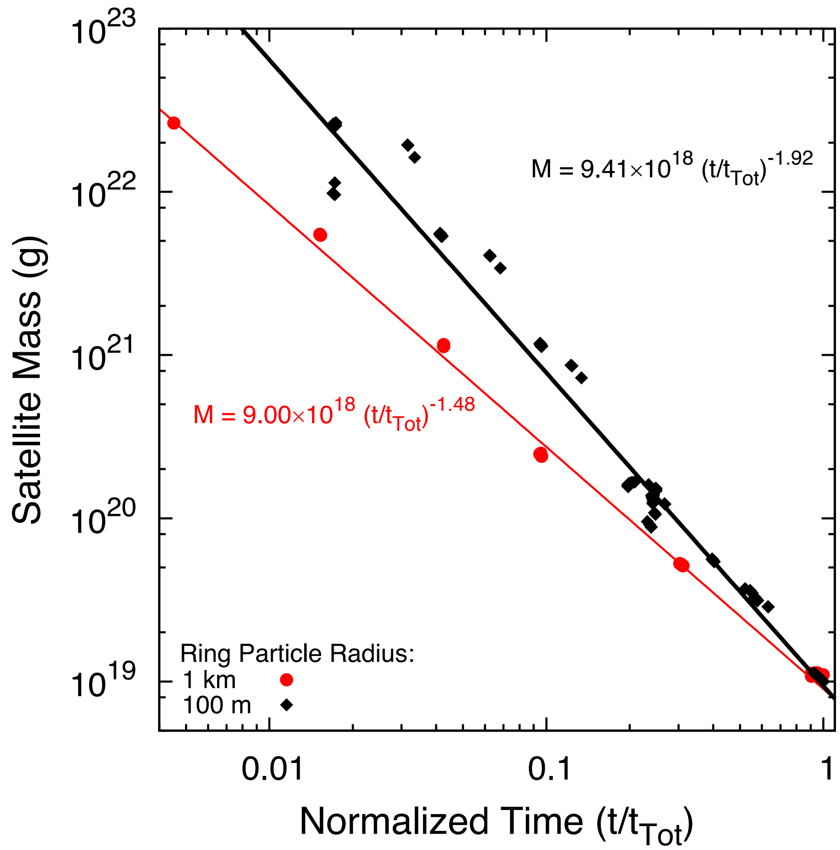

Figure SI1: Massive Early Cycles May Produce Multiple Massive Satellites

Results for the mass evolution for Martian satellites over time, assuming all particles in the ring have a radius of 1 km (red circles), or a radius of 100 m (black diamonds). The y-axis represents the mass of the satellites. The x-axis displays the time each satellite crossed the Rigid Roche Limit, save for the final Phobos analogs (bottom right). Time is represented as a fraction of the total time (t_{Tot}) from our initial conditions to placing a Phobos analog in the current orbit of Phobos. In rings with 1 km radius particles, each cycle produces one massive satellite. In rings with 100 m radius particles, early cycles may create several satellites which reach the RRL at different times.

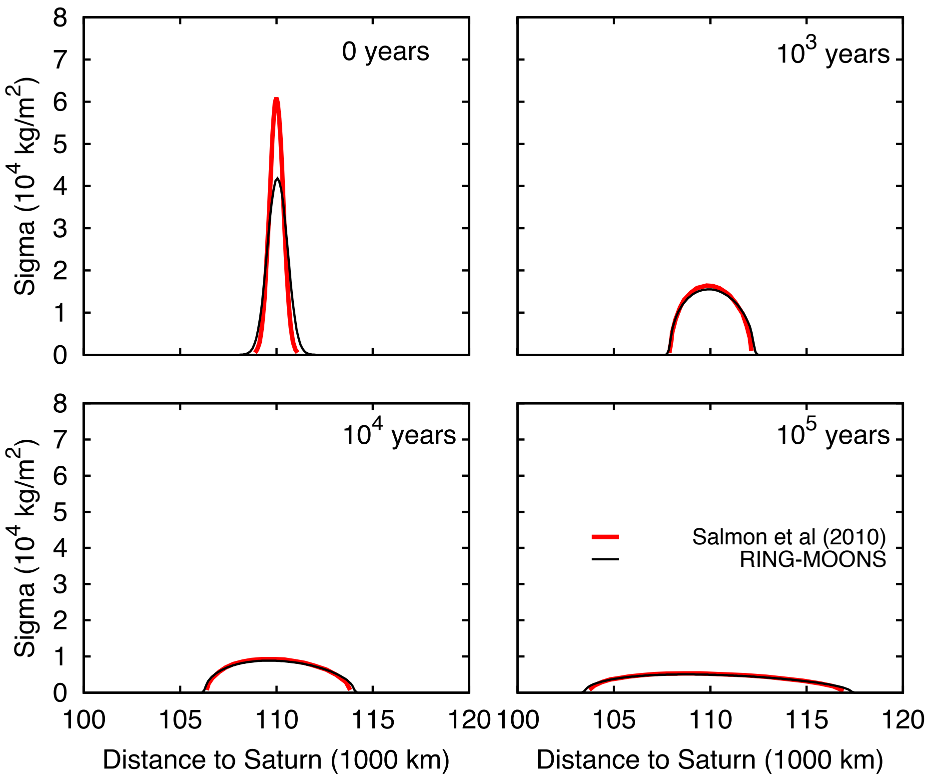

Figure SI2: Modeling Saturn's Rings Using RING-MOONS.

Here we compare the results from our model, "RING-MOONS (black line) for a sharply peaked ring viscously spreading in the Saturn system to others in the literature. To solve the viscous spreading of the rings, we follow the viscous spreading model described in Salmon et al. (2010). Despite our implementation of a different integration scheme, our results convincingly match the results displayed in Figure 3 of Salmon et al. (2010) (red line).

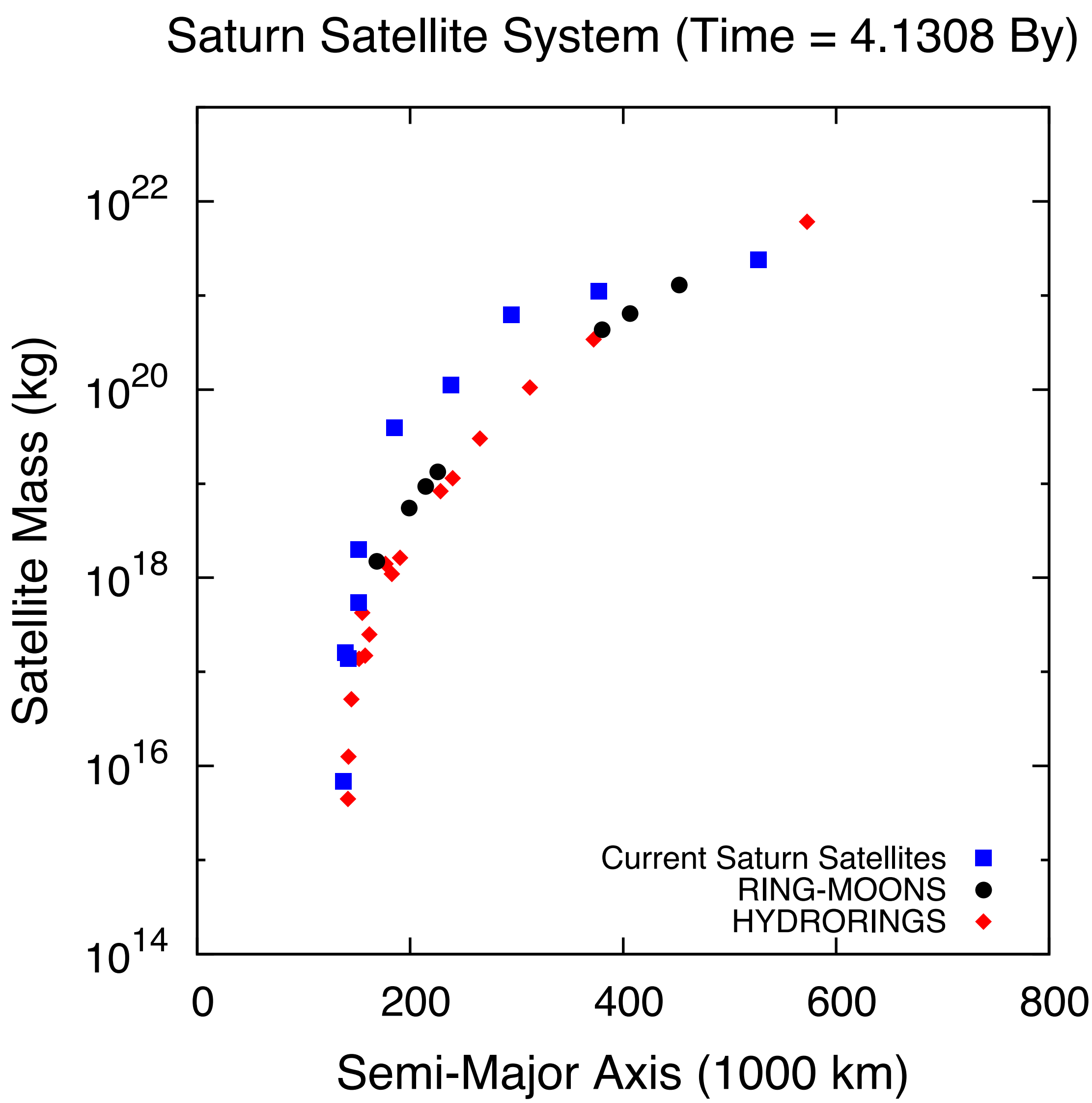

Figure SI3: Modeling Saturn Satellite Accretion Using RING-MOONS.

Here we display the results of our model, "RING-MOONS" (black dots) for the accretion of satellites from Saturn's rings, and their orbital evolution over ~ 4 Gy, assuming no tidal dissipation in the satellites and the tidal quality factor of Saturn $Q = 1680$. We perform this simulation to benchmark our model against the actual Saturn system (blue squares) and other models in the literature (red diamonds). Our model is similar in many ways to the HYDRORINGS model described in Charnoz et al. (2011), and presents similar results.

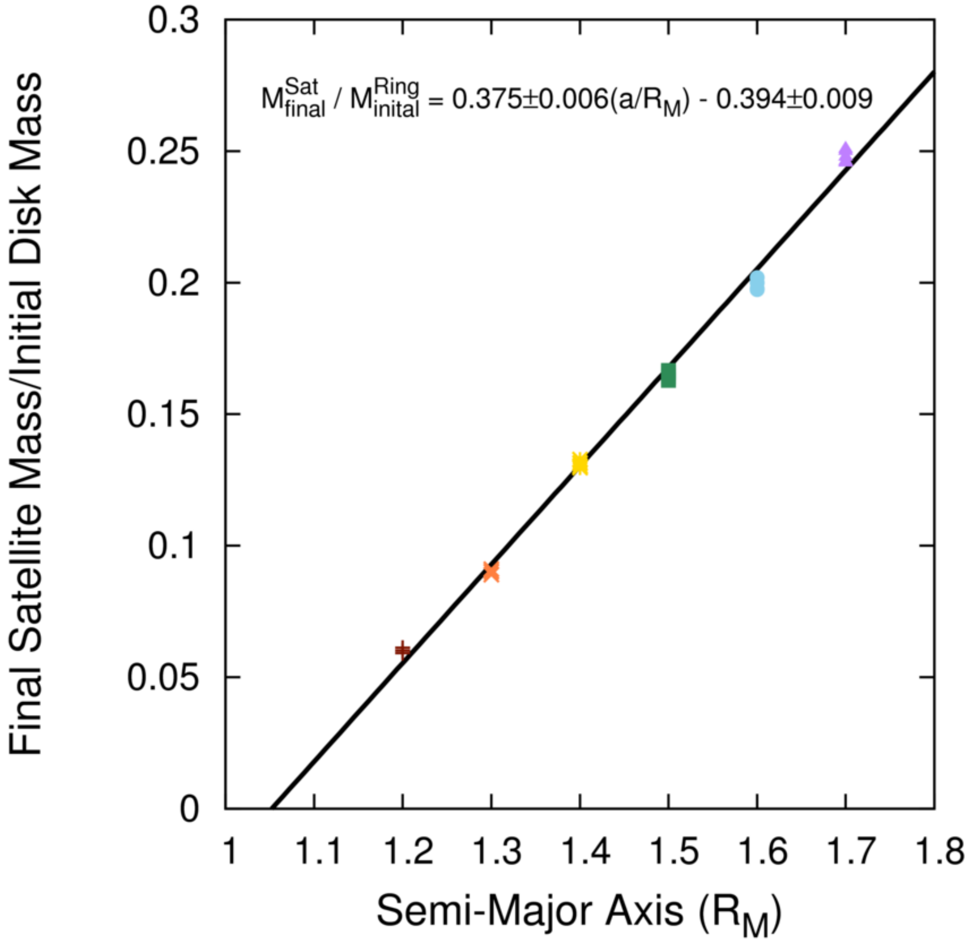

Figure SI4: Location of Tidal Breakup Affects Cycle Mass

Here we display the ratio of the final satellite mass to the initial ring mass for each cycle while varying the location of total satellite breakup. Satellite breakup may occur anywhere within 1.12 – 1.7 R_M. We find that if a satellite disrupts at a location closer to Mars, the resulting ring will produce a final satellite with a mass smaller than if the breakup was to occur farther away from the planet.

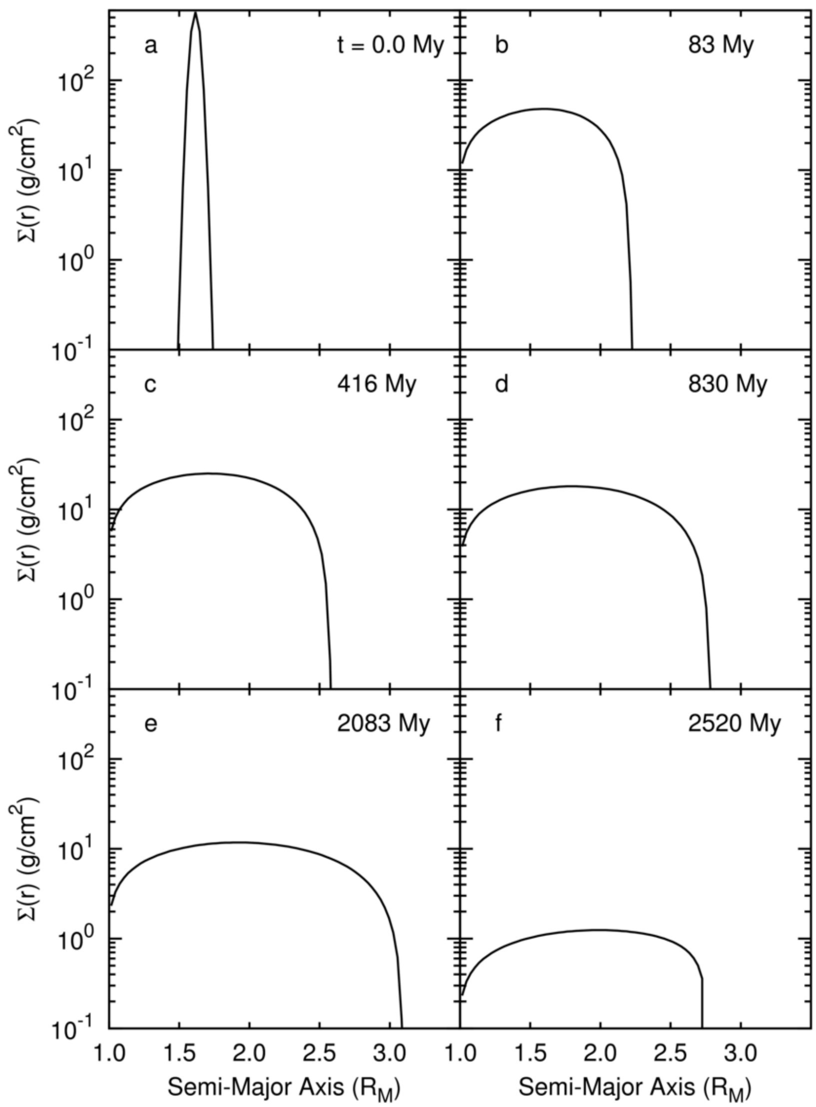

Figure SI5: Surface-Mass Density of Ring During Cycle 1.

Here we display the surface mass density (Σ) of the ring during Cycle 1, the ring that produces Phobos, for our "nominal case" at different times during the cycle. Although a ring still exists at the completion of our simulation, there is likely not a ring visible today. Our results indicate the ring at the completion of Cycle 1 is optically thin, with $\tau \lesssim 0.03$. We hypothesize that this low mass remnant ring may be depleted due to solar radiation effects, which we do not model currently.

Cycle #	Maximum Satellite Orbit (R_M)
6	4.9
5	3.9
4	3.5
3	3.3
2	3.1
1	3.1

Table SI1. **Maximum Semi-Major Axis of Satellites**

Here we report the maximum semi-major axis for our "nominal" case (where satellite breakup occurs at the RRL) that Lindblad torques could possibly evolve any accreted satellites for each cycle. In cycles 6 and 5 the mass of the ring is massive enough for Lindblad torques to overcome tidal torques and drive the satellites far away from the ring. However, by cycle 4 the mass of the ring has been depleted enough that satellites are not driven far from the ring. In the most recent cycles the Lindblad torques are not sufficient to drive the satellite away from the ring, with their maximum semi-major axis existing near the ring edge.