ON AN ORIGIN OF PHOBOS-DEIMOS BY GIANT IMPACT. R. M. Canup[1] and J. Salmon[1], [1]Southwest Research Insitutte, 1050 Walnut St., Ste. 300, Boulder, CO 80302; robin@boulder.swri.edu

Introduction: Remarkably little is known about how Phobos and Deimos formed. A frequently cited idea is that the moons were carbonaceous asteroids captured into Mars orbit. However, intact capture appears inconsistent with their nearly circular orbits, which instead imply formation from a disk [1-2]. A natural way to form a disk is through a large, oblique impact. Mars' 25-hr day implies that it experienced at least one large impact by an object containing a few percent of its mass [3], which could have produced a disk and perhaps the Borealis basin as well [4-6].

A large impact would produce a disk—and largest moons—orders of magnitude more massive than Phobos-Deimos [6-7]. However Mars' synchronous orbit is at $a_{sync} \approx 6$ Mars radii (R_M), and large moons interior to this distance would have been lost due to inward tidal evolution. What remains unclear is whether even tiny Phobos and Deimos could survive. Rosenblatt & Charnoz [8] considered a disk that was initially entirely within the Roche limit ($a_R \approx 3R_M$), and found that all moons formed as the disk spread outward were eventually lost to collision with Mars.

We here consider the alternative proposed in [7], in which an impact produces a radially extended disk whose outer edge is comparable to Deimos' position at $\approx 7R_M$. In this case, Phobos and Deimos might perhaps accrete from the outer disk and survive, while more massive inner companions evolve inward and are lost.

Impact simulations: We simulate large impacts into Mars using SPH. Our code [9] implements the equation of state ANEOS [10]. The energy budget is determined by shock dissipation, and work done by compressional heating and expansional cooling. Smoothing lengths increase as local density decreases.

Figs. 1-2 show results from 26 simulations involving an impactor with 3% the mass of Mars ($M_{imp} = 0.03M_M$), shown at 10 to 12 hr after the initial impact. Each simulation had 500,000 SPH particles, and considered the limiting case of a non-rotating Mars prior to the impact. Resulting disks contain ~10^{-4} to $10^{-3}M_M$.

A broad range of impact angles and impact velocities produce a Martian day near 25 hr for $M_{imp} = 0.03M_M$ (Fig. 1). Disk material is initially on eccentric orbits, but collisions among the material represented by each SPH particle would rapidly damp eccentricities while approximately conserving angular momentum. Thus debris will relax to a characteristic distance $a_{eq} \equiv a(1-e^2)$, where a and e are the post-impact semimajor axis and eccentricity of the SPH particle. We estimate the disk's outer edge by computing the maximum value of a_{eq} in each simulation. While resulting disks are centrally condensed, they all have 10 to 20% of their mass initially orbiting beyond the Roche limit, contrary to the assumption in [8]. Cases producing appropriate length days have outer edges between 6 and $10R_M$ (Fig. 2), broadly similar to Deimos' orbital radius (~$7R_M$).

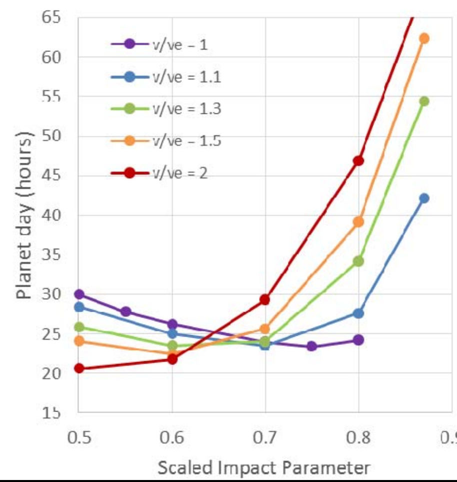

Fig. 1: Results of SPH simulations of impacts into Mars with $M_{imp} = 0.03M_M$. Resulting planet day shown vs. scaled impact parameter (1 = grazing impact). Colors indicate impact velocity scaled to the escape velocity.

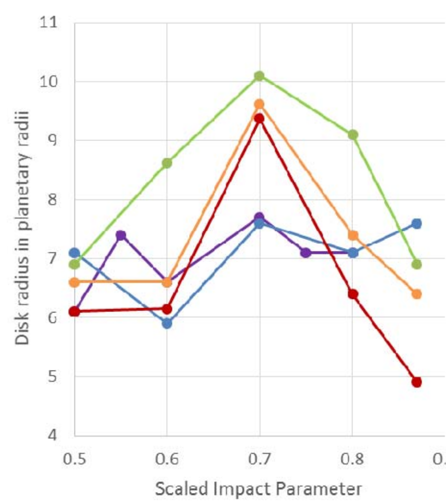

Fig. 2: Outer disk edge produced by each impact vs. impact parameter, for the Fig. 1 simulations.

Satellite accretion simulations: We model the disk's evolution using a code developed to describe lunar accretion [11]. The code represents material within the Roche limit as a uniform surface density disk whose mass and outer edge position (r_d) evolve with time due to viscosity (ν) and interactions with outer moons. Material beyond a_R is described by an *N*-body accretion simulation. The viscous spreading timescale for the inner disk is [12] $\tau_\nu \sim r^2/\nu \sim a_R^2\Omega^3/(\pi G\sigma)^2 \sim 10^5$ yr $(10^4$ g cm$^{-2}/\sigma)^2$, where σ is the inner disk surface density and Ω is orbital frequency. As inner disk material spreads beyond the Roche limit, it is removed from the inner disk and added to the *N*-body code in the form of new moonlets near a_R.

We include the strongest resonant interactions between growing moons and the inner disk (the 2:1, 3:2, etc.) when these resonances fall in the disk, i.e., for moons interior to $1.6r_d$. Resonant interactions produce a positive torque on moon orbits that causes them to expand on a timescale [13] $\tau_{res} \sim M_M^2[(a-r_d)/a]^3 [1.7a^2\sigma\Omega m]^{-1}$, where m and a are the moon mass and semi-major axis. We include [14] the inward (outward) tidal evolution of moons interior (exterior) to a_{sync}. For a moon within a_{sync}, disk torques are then positive while the tidal torque is negative.

We have performed a series of accretion simulations, with initial disks inspired by results of our SPH simulations. Outer disks are described by 10^3 to 10^4 initial particles, with a size distribution including many objects smaller than Deimos. We consider the limiting case of no satellite tides and a Mars tidal dissipation rate comparable to its current value [15].

The most massive moon initially forms just outside the Roche limit, and because τ_{res} is shorter than τ_ν, it first recoils away from the disk and confines the disk's edge to within a_R. This is followed by the slower viscous expansion of the disk and spawning of new moonlets once r_d reaches a_R. The outer disk accretes into 5 to 10 substantial satellites within ≤ 10^6 yr.

As an inner moon recoils outward due to disk torques, it can be captured into a Mean Motion Resonance (MMR) with an exterior moon. The resonant configuration then drives the exterior moon outward as well, even though it is not directly interacting with the disk. The challenge is that orbitally expanding moons may sweep up all of the small material in the ~ 5 to $7R_M$ region, leaving no analogs to Phobos or Deimos.

Fig. 3 shows a sample simulation. Several resonant configurations excite eccentricities, which ultimately lead to instability and mutual collision, removing the small outer Deimos analog. By 10^7 yr, two large moons (with ~10^2 times the mass of Phobos) remain; these are interior to a_{sync} and would tidally evolve inward and be lost. We find that with no satellite tides, similarly unsuccessful outcomes typically result.

Two effects might increase the stability of Deimos-Phobos analogs. First, stronger planetary tides could decrease the extent of orbital expansion driven by disk torques for moons interior to a_{sync}, perhaps increasing the likelihood that small moons formed from outer disk debris could survive. Second, the inclusion of satellite tides would reduce eccentricity growth, increasing stability. We are currently investigating such cases.

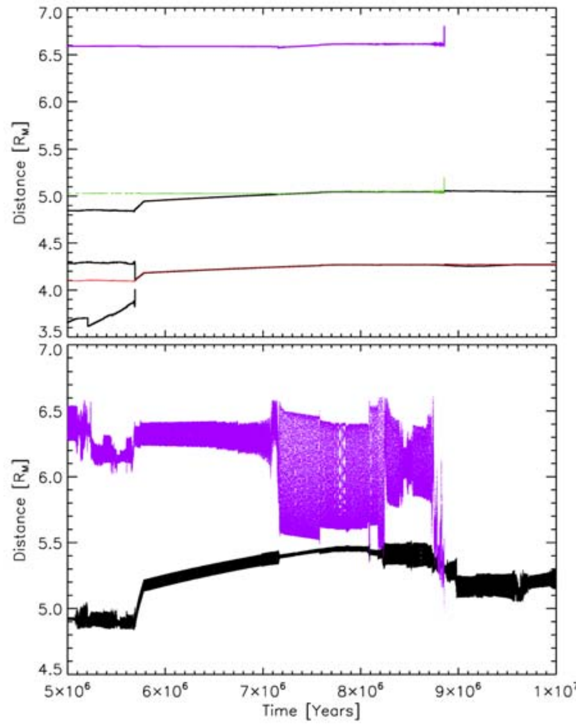

Fig. 3: Top: a vs. time for largest growing moons in a sample run. The green line is the 3:2 MMR with the outer moon; the red line is the 9:7 MMR with the middle moon. Inner moon orbits expand due to disk torques. At 5.7×10^6 yr, the inner moon is captured into the 9:7 MMR with the middle moon, causing it to migrate outward as well, leading to its later capture into the 3:2 MMR. Bottom: pericenter of the outer moon (purple) and apocenter of the middle moon (black). Resonant interactions excite the eccentricity of the outermost object, eventually resulting in a collision at ~ 8.8 Myr.

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