ORIGIN OF PHOBOS-DEIMOS BY THE IMPACT OF A VESTA-TO-CERES SIZED BODY WITH MARS. R. M. Canup[1] and J. Salmon[1]; [1]Southwest Research Institute, 1050 Walnut St., Ste. 300, Boulder, CO 80302; robin@boulder.swri.edu.

Abstract: It has been proposed that Mars' moons formed from a disk produced by an impact with the planet by a giant, ~2000-km diameter impactor containing ~3% of Mars' mass (M_M) [1-5]. Using a model of moon accumulation that includes an explicit treatment of moon-moon dynamical interactions, we identify new constraints on the disk properties needed to produce Phobos-Deimos. We then simulate the impact formation of disks using a novel approach that resolves the impact ejecta with order-of-magnitude finer mass resolution than existing methods. We find that the scale of giant impact advocated previously is inconsistent with the formation of Phobos-Deimos. Instead, we find that forming Phobos-Deimos requires a much smaller Vesta-to-Ceres sized impactor, with mass ~ $10^{-3}M_M$ and diameter ~ 570 to 1000-km [6].

Background: Phobos and Deimos' combined mass is only $M_{PD} = 2 \times 10^{-8}\ M_M$. Synchronous orbit is located at $a_{sync} \approx 6$ Mars radii (R_M); interior [exterior] to a_{sync} a moon's orbit spirals inward [outward] due to martian tides. Integrating back in time suggests that both moons originated in the region between ~5 and $7R_M$, with orbits near but on opposite sides of a_{sync}.

The moons' spectra resemble primitive asteroids, inspiring the idea that they are captured asteroids [7]. However intact capture is difficult to reconcile with the moons' regular orbits, which instead suggest accretion from a disk [7-8]. A large impact with Mars could produce a disk. Mars' 25-hr day implies an oblique collision by an impactor of mass M_{imp} ~ few × $10^{-2}M_M$ [9]. Recent works propose this type of impact produced Phobos-Deimos [1-5]. Successful scenarios require *i*) an initial disk that extends to ~ 6 to $7R_M$ in order to account for Deimos' position and the lack of more distant martian moons, and *ii*) that tiny Phobos and Deimos are the only survivors of a disk whose initial mass is orders-of-magnitude larger than M_{PD}. The latter is a key constraint, because although massive inner moons may eventually be lost to tidal decay [4-5], they may first dynamically destabilize and accrete Phobos-Deimos analogs forming near a_{sync}.

Disk evolution: We simulate moon accretion using a hybrid numerical model [10-11] Exterior to the Roche limit ($a_R \approx 2.7R_M$), we treat moon accretion and interactions using an *N*-body simulation. Interior to a_R, material is modeled as a continuous disk of uniform surface density, whose mass and outer edge evolve due to gravitational interactions with outer moons and a collisional viscosity that causes the disk to spread. Inner disk material that spreads past a_R is added to the *N*-body code in the form of new moonlets. Resonant interactions between moons and the inner disk cause moon orbits to expand. We include inward [outward] tidal evolution due to Mars tides for moons interior [exterior] to a_{sync}.

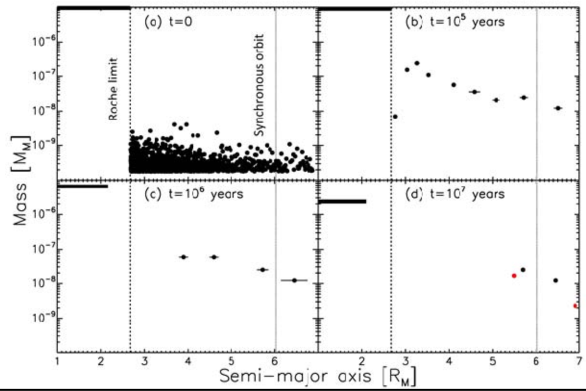

Fig. 1: Accretion of a Phobos-Deimos type system from an impact-generated disk with initial mass $M_d = 10^{-5}M_M$. Roche interior disk's mass and radial extent indicated by thick bar; black circles show masses and semi-major axes of simulated moons, with lines indicating eccentricity. (a-b) Moons with up to ~ 10 times the mass of Phobos-Deimos accrete in the mid-region of the outer disk, but strong tidal interaction with Mars causes them to spiral inward and be lost (c). (d) After 10^7 yr, two small moons with similar properties to those inferred for Phobos and Deimos (red circles) remain on orbits straddling a_{sync}.

Fig. 1 shows the evolution of a disk with initial mass $M_d = 10^{-5}M_M$. Strong tidal interaction, equivalent to Mars tidal parameters $(Q/k_2) \approx 30$ at a distance of $5R_M$, is assumed. The most massive inner moons remain interior to ~ $5R_M$ and spiral inward due to tides in ~10^5 to 10^6 yr. After 10^7 years, the system has two Phobos-Deimos class objects on opposite sides of a_{sync}.

Across a broad range of disk conditions we find that survival of small satellite(s) near a_{sync} requires $M_d < 3 \times 10^{-5}M_M$ and $(Q/k_2) < 75$. The latter is plausible for early Mars with estimated k_2 ~ unity [12]. For disk masses > $3 \times 10^{-5}M_M$, we find no cases that leave small moons near a_{sync}. The latter contradicts results in [4], whose models underestimated the number of large moons forming between a_R and a_{sync}, as well as their outward orbital excursions.

Impact simulations: We simulate impacts into Mars using SPH [13-14] including particle splitting [15]. We first use a standard 10^6-particle simulation to

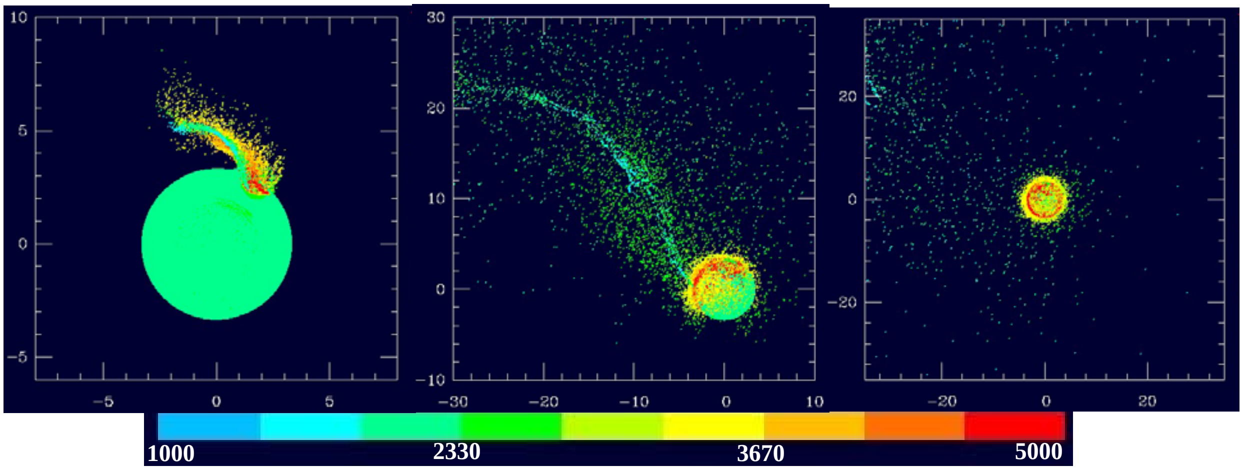

Fig. 2: Simulation of the impact of a Vesta-mass body with Mars, with $M_{imp} = 0.5 \times 10^{-3} M_M$, $v_{imp} = 1.5 v_{esc}$ (7 km s^{-1}), and a 45° impact angle. Color scales with temperature in K (color bar); distances shown in units of 10^3 km. The impact is modeled with SPH + particle splitting and an order-of-magnitude higher resolution of the ejected material. After 10 hr, the disk mass is $8.5 \times 10^{-6} M_M$, with ~ $2M_{PD}$ having equivalent circular orbits at and beyond ~$5R_M$, consistent with subsequent accumulation of Phobos and Deimos in the 5 to $7R_M$ region. Outer disk material is 85% martian in origin and 12% vapor by

identify the regions on the colliding bodies from which the ejected material is derived. We then split each "parent" particle within and neighboring these regions into 13 lower-mass "child" particles. We then repeat the simulation including the split particles. The final simulation resolves the ejecta with order-of-magnitude finer mass resolution, so that the disk material is described by particles whose masses are comparable to M_{PD} (e.g., Fig. 2), a factor of ~ 10 to 10^2 higher resolution than in prior works [2-4].

To produce favorable disk conditions ($M_d < 3 \times 10^{-5} M_M$ and an outer disk edge near 6 to $7R_M$), we find an upper limit of $M_{imp} \sim 3 \times 10^{-3} M_M$ (larger impactors produce overly massive disks), and a lower limit of $M_{imp} \sim 0.5 \times 10^{-3} M_M$, because for this impactor mass many disks appear too compact to yield Deimos. This constrains the mass of a Phobos-Deimos forming impactor to between that of Vesta and twice that of Ceres, a much smaller body than previously suggested.

The impacts we identify have energies between 5×10^{34} to 2×10^{36} erg, with the higher end falling within the lower range estimated for Mars' Borealis basin (3×10^{35} to 6×10^{36} erg) [16-17]. Our smallest impactor has a 570-km diameter, within the range of projectile diameters estimated for the Utopia (~ 400 to 800 km) and Hellas (~ 300 to 700 km) basins based on two different crater scaling relationships [18].

Phobos and Deimos' compositions remain uncertain. Reflectance spectra for both moons are similar to those of primitive, D-type asteroids, or alternatively to space-weathered, iron-bearing silicates [19]. Phobos' thermal emission spectra most closely resemble silicates rather than chondritic materials [20]. Recent work argues that the moons' spectra are consistent with surfaces composed of submicron-sized grains that condensed from vapor at temperatures < 2200 K in the outer portions of an impact-generated disk [21], potentially in agreement with conditions found here. JAXA's MMX mission will assess the moon compositions through remote characterization of their subsurfaces and the eventual return of samples. Such data will be crucial to determining whether the moons formed by impact or through an alternative process.

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