THE ORIGIN OF PHOBOS AND DEIMOS; *Robert A. Craddock,* Center for Earth and Planetary Studies, National Air and Space Museum, Smithsonian Institution, Washington, D.C. 20560

Determining the origin of Phobos and Deimos has remained problematic. Spectral analyses suggest that the composition of Phobos closely matches black or carbonaceous chondrites [1]. This combined with other physical properties such as their low densities (~1.7 g/cm^3 [2]) and low geometric albedoes (~0.05 [3]) has led many investigators to suggest that they are captured asteroids [e.g., 4]. However, the orbits of both moons are extremely circular and their Laplace plane is very close to the martian equatorial plane. Captured objects would be expected to have elongate orbits with randomly oriented orbital planes. Phobos may have been able to attain its circular orbit because it experiences tidal perturbations from its closeness to Mars and from libration. Deimos is too far away to experience much of either. Integrate Phobos' present eccentricity into the past, and it collides with Deimos [5]. The large number of elongate craters on the martian surface attest to the possibility that Mars may at one time have had many Phobos and Deimos size objects in orbit [6,7]. In addition, recent analyses of the spins of the terrestrial planets suggest that Mars has too much prograde angular momentum to be explained by the accretion of many small bodies [8]. The spin rate of Mars can only be explained by a collision with a planetismal during accretion [8]. Could a giant collision have caused Mars to rotate at its present spin rate? Is it possible that such a collision vaporized enough material to form Phobos, Deimos, and other potential satellites as well?

The spin rate of the planet is expressed as the number of sidereal rotations per revolution around the sun, $\mathfrak{R}$. From Dones and Tremaine [8] the spin rate is written as

$$\mathfrak{R} = \frac{3\langle l_z \rangle}{2\Omega R_p^2} \tag{1}$$

where l_z is the specific angular momentum perpendicular to the orbital plane, Ω is the planet's orbital frequency (1.06 x10^{-7} rad/sec), and R_p is the planetary radius (3.39 x 10^6 m). This is assuming that the dimensionless parameter r remains constant during accretion, expressed as

$$r \equiv \frac{R_p}{R_H} \equiv \frac{R_p}{(GM_p/\Omega^2)^{1/3}} \tag{2}$$

where R_H is the Hill, or tidal, radius of the planet, G is the acceleration of gravity (3.7 m/sec^2), and M_p is the mass of the planet (6.43 x 10^{23} kg). The Hill radius is simply the distance where centrifugal force balances the gravitational attraction from the planet. For Mars, $\mathfrak{R} = 670$ and is a positive value because Mars rotates in a prograde direction and $r = 0.0022$.

If a planet is formed by ordered accretion, then a maximum prograde or retrograde spin rate is possible. Dones and Tremaine [8] show that with ordered accretion, values for $\mathfrak{R}r$ should be between -2.2 and 0.3. However, $\mathfrak{R}r = 1.5$ for Mars, which they argue is evidence that the rotation of Mars resulted from stochastic accretion. In stochastic accretion, a planet's final spin rate is determined by the imperfect cancellation of angular momentum between individual impactors. Simply, a single impactor more massive than the rest determines the final rotation rate and direction of the planet. They show that the typical rotation rate can be estimated from the equation

$$|\mathfrak{R}| \approx \frac{S_m}{r^{3/2}} \approx \frac{m_1}{M_p} r^{-3/2} \tag{3}$$

where S_m is the dimensionless effective mass of a planetismal relative to the planet, m_1 is mass of a single impactor, which is more massive than all the rest, and M_p is the mass of the planet. From this equation, it follows that

$$S_m = \frac{m_1}{M_p} \tag{4}$$

With stochastic accretion and a planet spinning prograde

$$S_m \geq 0.3r^{1/2} \tag{5}$$

For Mars, $S_m \geq 0.015$, which implies that the minimum mass of the planetismal (m_1) which induced the present spin rate of Mars, is ~9.6 x 10^{21} kg. Assuming a density of ~3.0 g/cm^3, the diameter of this impactor was ~1,800 km. Hartmann and Davis [9] calculate that the second largest object that would have formed near Mars' orbit at the end of accretion could have had a diameter of, coincidentally, 1,800 km. Assuming that this planetismal struck Mars at escape velocity, the amount of energy involved in the collision would be $\sim 10^{36}$ ergs. This is the same amount of energy estimated to have formed the 7,700-km-diameter Borealis basin [10], suggesting, perhaps, that the collision ultimately responsible for the spin rate of Mars is recorded in the crustal dichotomy.

The mass of Phobos and Deimos is very small ($\sim 1.3 \times 10^{16}$ kg). If craters with asymmetric or elongate ejecta on the martian surface are the result of satellites whose orbits slowly decayed with time (similar to present-day Phobos), then the total mass of all martian satellites would have been $\sim 1.5 \times 10^{19}$ kg [6]. Determination of how much material is placed into orbit following the formation of a giant impact is not straight-forward. A majority of material ejected ballistically from an impact that explodes below the surface of a planet either escapes into space or falls back onto the surface. Cameron and Ward [11] proposed a solution for the formation of the Earth's Moon by suggesting that large amounts of vaporized material were released during collision. Vaporization of martian geologic material following impact with a large bolide is possible because the impact velocity must be between 7 to 12 km/sec to induce shock vaporization [12]. This is slightly higher than martian escape velocity and not an unrealistic value for an approaching planetismal. Following impact, vaporized debris rising above the surface would continue to be accelerated by gas pressure effects and gravity. This mechanism allows much more material to be accelerated into orbit than by simple ballistic emplacement (~1/2 the vaporized mass [13]) because the debris is given an added "kick." Vapor from both the planet and impactor need to mix efficiently, however, otherwise vapor from the impactor will exceed escape velocity and vapor from the planet will not reach orbit [13]. Thus only a narrow set of initial conditions are possible. Using a particle-in-cell hydrodynamic code, Cameron [14] found that a "successful" accretion disk formed when the velocity of the impactor slightly exceeded escape velocity and most of the vapor came from the impactor.

Phobos, Deimos, and all the other satellites which may have orbited Mars in the past are only a tiny fraction of the mass of the Borealis impactor (~0.001). For this reason alone it seems plausible that enough material from the formation of the Borealis basin could have been placed into martian orbit as an accretion disk. There are several other proposed impact basins on Mars which may have also been capable of placing debris into martian orbit: Daedalia (4,500 km), Chryse (3,600 km) or Utopia (3,300 km) are among the largest. Once an accretion disk is formed, gravitational instabilities prevent the particles from clumping [11]. Temporary mass concentrations would, however, cause a transfer in angular momentum from Mars to the accretion disk and the disk would begin to dissipate both towards the martian surface and out towards space. Once material in the disk emerged past the Roche limit, particles in the disk would begin to accrete. Small tides raised by this body would once again cause a transfer in angular momentum, and the small satellite would begin to recede from Mars. As the accretion disk continued to dissipate another small body would form in place of the first. In the formation of the Moon, the last body to form from the accretion disk would, by necessity, be more massive than the rest [13]. Thus this large satellite would recede from the proto-Earth faster, accrete the smaller satellites, and form the Moon. However, in the martian scenario this last, large satellite does not form, and Mars is left with a number of small, Phobos and Deimos-size objects in orbit. The impact responsible for creating the accretion disk would most likely have destroyed any atmosphere Mars had at the time of collision. Formation of a thick atmosphere subsequent to this event may have been enough to induce drag on some of the satellites, causing them to spiral into the surface. Alternatively, or perhaps in conjunction, removal of the accretion disk may have caused tidal perturbations in the satellites, causing their orbits to decay.

If the impactor was chondritic in composition, the spectrally derived compositions of Phobos and Deimos could be explained. Potentially the low densities of these satellites can also be explained by this scenario: the small accretion disk particles simply coagulated (i.e., aggregated) and remained loosely packed. This suggests that they have a significant amount of pore space and uniform density, agreeing with Phobos' libration [15]. Work will continue on creating a dynamic model to illustrate this hypothesis and constrain the initial conditions which must have been present. The true test of this hypothesis will not come from such models, however. Better compositional data from both Mars and its satellites are needed before the origin of Phobos and Deimos is truly understood.

References: [1] Murchie S.L. *et al.*, *JGR*, *96*, 5925 (1991). [2] Avensov G. *et al.*, *Nature*, *341*, 585 (1989). [3] Burns J.A. in *Mars*, 1283, U of A, 1992. [4] Burns J.A., *Vista. Astron.*, *22*, 193 (1978). [5] Lambeck K., *JGR*, *84*, 5651 (1979). [6] Schultz P.H. and A.B. Lutz-Garihan, *JGR*, *87*, A84 (1982). [7] Strom R.G. et al., in *Mars*, 383, U of A, 1992. [8] Dones L. and S. Tremaine, *Science*, *259*, 350 (1993). [9] Hartmann W.K. and P.A. Davis, *Icarus*, *24*, 504 (1975). [10] Wilhelms D.E. and S.W. Squyres, *Nature*, *309*, 138 (1984). [11] Cameron A.G.W. and W. Ward, *LPSC*, *VII*, 120 (1976). [12] Ahrens T.J. and J.D. O'Keefe, *The Moon*, *4*, 214 (1972). [13] Cameron A.G.W., in *The Origin of the Moon*, 609, LPI, (1986). [14] Cameron A.G.W., *Icarus*, *62*, 319 (1985). [15] Duxbury T.C., *Icarus*, *78*, 169 (1989).