PHOBOS AND DEIMOS: A POTENTIAL COMET CONNECTION

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Introduction: The origin of Mars' moons, Phobos (L~27 km) and Deimos (L~15 km), remains an enigma. There are three main hypotheses: H1) they are captured small bodies from the outer main belt or beyond; H2) they are remnants of Mars' formation; H3) they are reaccreted Mars impact ejecta [1.2]. There are dynamical difficulties associated with each one of these hypotheses. It is also not clear if Phobos and Deimos share the same origin. The two martian moons present similarities, but are also distinct. While both have low densities and dominantly D-type spectra, there are differences between the two on both counts. Deimos' density (1.471±0.166 g/cm^3) is lower than Phobos's (1.876 g/cm^3). And while Deimos is uniformly dark red, Phobos presents two spectral units: a "Redder Unit" (similar to Deimos) dominating most of Phobos (> 65%), and a "Bluer Unit" (red also, but less so than Deimos) of more limited surface extent (< 35%). It has been suggested that the "Redder Unit" on Phobos might be an exogenous veneer of D-type-like material imported from Deimos, with the "true" Phobos being better characterized by its "Bluer Unit". Morphologically, Phobos is more visibly craterered and rugged than Deimos, and presents con-networks of "grooves" which Deimos lacks entirely. Deimos has more subdued topography and a smoother surface.

Remarkable Characteristics: Aside from these bodies being the moons of Mars, the following characteristics of Phobos and Deimos make them remarkable small bodies when considering their current heliocentric location:

Large "Small Bodies". Phobos and Deimos are relatively *large* small bodies compared to most objects in the Near-Earth Object (NEO) population (Fig. 1). If counted among NEOs, Phobos would rank #3 in size, and Deimos #5. NEAs 1036 Ganymed (D~33 km) and 433 Eros (L~34 km) rank #1 and #2, while NEA 3552 Don Quixote (D~ 18 km) would rank #4. Thus, only one NEA is intermediate in size between Phobos and Deimos: 3552 Don Quixote.

Rare, D-Type Spectrum. Deimos has a D-type spectrum, and most of Phobos as well. That both these two inner solar system small bodies have D-type spectra is remarkable, because most D-type asteroids are found in the outer main belt and beyond, and among Jupiter Trojans. Only ~1.5 % of NEAs are D-type. Given this scarcity, Phobos and Deimos would be in a spectral minority among NEOs. 3552 Don Quixote stands out again: it is a D-type object.

Volatile-Rich Bodies & D-Type Spectrum. While it remains unclear if D-type asteroids are generally rich in volatiles, the visible and near-IR spectra of Phobos and Deimos, and those of all D-type asteroids, are best matched by the Tagish Lake meteorite, an unusual carbonaceous chondrite rich in water and organics.

Figure 1: Compared to the largest NEOs, Phobos (center), Deimos (far right), and Don Quixote are in a remarkable group of large, D-type small bodies, an otherwise rare (<1.5%) spectral type among NEOs.

3552 Don Quixote: NEA 3552 Don Quixote is a Jupiter and Mars orbit crosser, with an orbital inclination of 31.210^o. These orbital characteristics suggested early that it might be an (extinct) comet. The cometary nature of Don Quixote was confirmed when it was observed to be actively outgassing CO_2 and had a coma and a tail [3]. Given the above considerations, might 3552 Don Quixote represent an earlier stage of Phobos and/or Deimos, or of the objects that Phobos and Deimos' materials were once part of, prior to capture in Mars orbit?

Discussion: Although the possibility that Phobos and/or Deimos are cometary remnants may seem unlikely, that possibility remains part of the current trade space and cannot be excluded with available data. Phobos and Deimos are morphologically very different from active cometary nuclei imaged to date, but the evolutions that comet nuclei and their materials would experience in Mars orbit following capture might be expected to produce significantly evolved morphologies. Assuming a CM chondrite-like composition for their rock fraction, the current densities of Phobos and Deimos suggest that they might contain up to 37% and 55% water by volume, respectively [4]. If true, this would represent a significant resource for ISRU in Mars orbit and have considerable implications for shaping future human Mars exploration architectures. The main caveats to the comet connection hypothesis presented here are that i) capture remains dynamically difficult (be it of a comet or a passing asteroid), and ii) Phobos might not be a "true" D-type object as its "Redder Unit" might have been imported form Deimos. It is also unclear if volatiles would actually survive ~4.5 GY in Mars orbit even if initially buried deep inside Phobos and Deimos.

References: [1] Rosenblatt, P. et al. (2016) *Nature Geos*. [2] Craddock, R. (2011) *Icarus* 211,1150. [3] Mommert et al. (2014) Ap. J.,781:25. [4] Tagaki Y. & P. Lee (2016) NASA ESF. [5] Lee, P. (2016) NASA ESF.