THREE-MICRON SPECTROSCOPY OF PHOBOS AND DEIMOS.

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Introduction: The origin of the Martian moons Phobos and Deimos is still not well understood; two scenarios have been proposed for their formation: in-situ and captured asteroid [1]. The in-situ scenario suggested that Phobos and Deimos were formed from Martian materials by co-accretion with Mars [2] or re-accretion of Mars (e.g., [3, 4, 5]). The captured asteroid scenario proposed that Phobos and Deimos were formed from captured primitive materials originating from the outer solar system [6, 7].

Previous telescopic data have revealed significant information about Phobos' and Deimos' spectral properties [8, 9, 10, 11]. Additionally, spacecraft and spectrometers such as Observatoire pour la Mineralogie, L'Eau, Les Glaces et l'Activité (OMEGA) on board Mars Express and the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) on board Mars Reconnaissance Orbiter (MRO) collected visible to near-infrared imaging spectroscopic data of both Phobos and Deimos [12, 13, 14 ,15]. Spacecraft spectra show that the two moons are moderately low albedo objects with no significant diagnostic absorptions of common ferrous minerals such as olivine and pyroxene. Both ground- and space-based spectroscopic studies of Phobos and Deimos covered a spectral range that did not go beyond ~3.5 µm. Here, we present spectra of Phobos and Deimos that included more comprehensive spectral range (~0.7-4 µm) to search for signatures of hydrated minerals, organics, and carbonates. With this extended spectral range, we are able to better constrain the thermal models and absorption features (e.g., OH/H_2O) for Phobos and Deimos.

Methodology:

Observations and data reduction. We collected spectra of Phobos and Deimos using the Prism (0.7-2.52 µm) and long-wavelength cross dispersed (LXD: 1.9-4.2 µm) modes of the SpeX spectrograph/imager at the NASA Infrared Telescope Facility (IRTF) [16] on the nights of 14, 15, 16, and 29 September 2020. During those nights the two moons were visible and bright with a V-magnitude ranging from 10 to 11. We divided the spectral image frames of Phobos and Deimos by a flat field measured using an internal integrating sphere. Two solar analog standard stars HD 11061 and HD 9595 (G-type stars close to Phobos and Deimos on the sky at similar airmass) were used to correct for the contributions of OH line emission and thermal emission from the sky (longward of ~2.3 µm). We also measured the sky proximal to Phobos and Deimos by placing the SpeX slit exterior to their orbits to remove any residual Mars' scattered light (**Figure 1**). The Phobos and Deimos spectra were taken when their angular separations with Mars were ~20-29 arcsec and 50-69 arcsec, respectively. Therefore, the two moons were negligibly affected by Mars' scattered light (**Figure 1**). We processed and reduced Phobos' and Deimos' Prism and LXD spectra using the Interactive Data Language (IDL)-based spectral reduction tool Spextool (v4.0) provided by the NASA IRTF [18] in addition to some IDL custom routines.

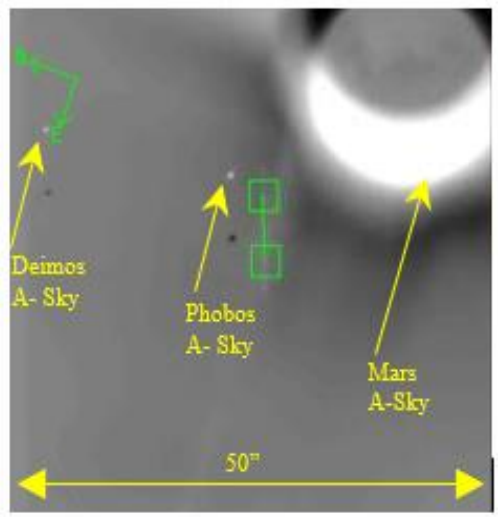

Figure 1. IRTF SpeX's Guidedog buffer image showing Deimos, Phobos, and Mars (difference of AB image pair). The green boxes are SpeX's guide box. This image shows that Phobos and Deimos were negligibly affected by Mars' scattered light.

Thermal modeling and correction. We used the Near-Earth Asteroid Thermal Model (NEATM) [19] to constrain Phobos' and Deimos' model thermal flux longward of 2.5 µm. The measured thermal excess was fitted with a model excess that was then subtracted from the measured thermal flux relative spectra of the two moons. We used visible geometric albedos of p_v = 0.069, 0.070 and slope parameter of G = 0.30 [19], 0.49 [20] for Phobos and Deimos, respectively. The beaming parameter (η) is used in the thermal model to adjust the surface temperature to match the measured thermal flux [21]. The values of the beaming parameters were varied from η = 1.1 to 1.3 until we got the best thermal model while keeping the geometric albedo constant (e.g., **Figure 2**). We assumed both bolometric and spectral emissivities to be 0.9 for Phobos and Deimos.

Results: Figure 3 shows the final Prism and LXD spectra of Phobos and Deimos, which extend to the 0.7- 4 µm spectral range. With these spectra we were able to characterize the 3-µm band, unlike previous ground- and space-based studies that include a spectral range that did not go beyond 3-3.5 µm [11, 12].

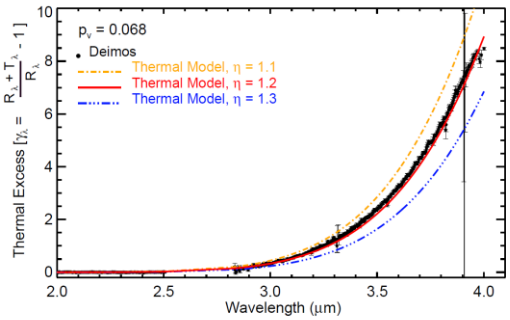

Figure 2. Uncorrected spectrum of Deimos with thermal models, using different values of the beaming parameter (η).

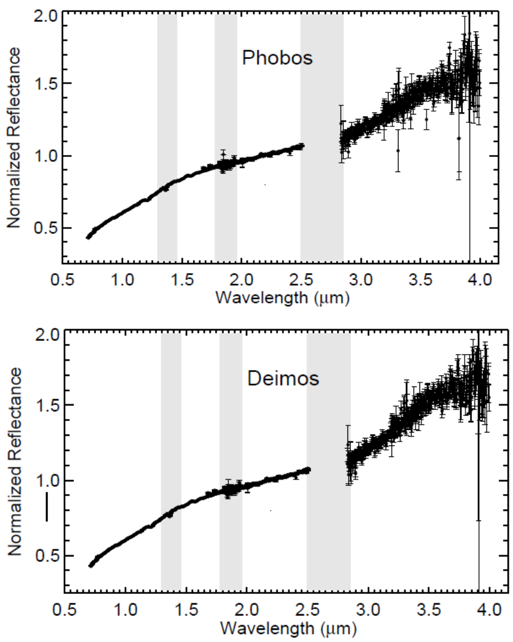

Figure 3. Final thermally-corrected spectra of Phobos (upper) and Deimos (lower), using best thermal model fits. The gray bars on each plot mark wavelengths of strong absorptions by water vapor in Earth's atmosphere. All spectra have been normalized to unity at 2.2 µm.

Discussion: Absorption features at ~3.0 µm are particularly indicative of aqueous alteration (e.g., [22]). These absorptions are likely due to hydroxyl- and/or water- bearing materials (e.g., [22]), but could also be due to surficial OH implanted from solar wind [23] or exogenic sources like those seen on Vesta [24]. The Prism portions of both Phobos' and Deimos' spectra are consistent with D-type asteroids with a low-albedo, featureless, and steep slope (longward of 0.55 µm) characteristics. Additionally, Tagish Lake, a C2-ung carbonaceous chondrite, which has been used as a spectral analog for D-asteroids, also exhibits a 3-µm band that is generally consitent with the band found in Phobos and Deimos [24]. Since our ground-based spectra were affected by strong absorptions by water vapor in Earth's atmosphere, we are not able to assess the ~2.5-2.7 µm spectral range. JAXA's Martian Moons eXploration (MMX) mission is planned to be launched in 2024 and will make NIR spectral measurements of the two moons, which will include the 2.5-2.7 µm spectral range, providing more comprehensive and complete mineralogical interpretation of their surfaces [25].

References: [1] Pieters C.M. et al. (2014) *Planetary & Space Sci.*, 102, 144-151. [2] Safronov V.S. (1986) *in Satellites*, Burns, J.A. and Matthews, M.S., Eds. , Tucson: Univ. Arizona Press, 89–116. [3] Rosenblatt P. (2011). *Astron. Astrophys. Rev.* 19, 1-26. [4] Hesselbrock A. J. and Minton D. A. (2017) *Nat. Geosci.*, 10, 266, 537-538. [5] Hyodo R. et al. (2017) *ApJ*, 845, 125. [6] Hartmann W. K. (1990) *Icarus*, 87, 236-240. [7] Higuchi A. et al. (2017) *ApJ*, 153, 155. [8] Murchie S.L. et al. (1991) *Journal of Geophysical Research.* Volume 96, issue B4. [9] Grundy W.M. and Fink U. (1992). *In Asteroids, Comets, Meteors*, 215-218. Lunar and Planetary Institute. [10] Murchie S. and Erard S. *Icarus* 123, 63-86. [11] Rivkin A. et al. (2018) *Icarus*,Volume 304, 74-82. [12] Fraeman A.A. et al. (2012). *J. Geophys. Res.* 117, E00J15. [13] Fraeman A.A. et al. (2014) *Icarus* 229C, 196-205. [14] Gondet B. et al. (2010) *EPSC*, abstracts vol. 5, EPSC2010-548. [15] Murchie S.L. et al. (2008). *Lunar Planet. Sci.* XXIX, #1434. [16] Rayner, J.T. et al. (2003) *Publ. Astron. Soc. Pacific* 155, 362–382. [17] Cushing M.C. (2004) *ASP*. 116:362-376. [18] Harris et A.W. (1998) *Icarus* 131, 291-301. [19] Simonelli D. P. et al. (1998) *Icarus*, 131, 52. [20] Thomas P. C. et al. (1996) *Icarus*, 123, 536. [21] Harris A.W. and Lagerros J.S.V. (2002). In: Bottke, W.F., Jr., Cellino, P., Paolicchi, P., Binzel, R.P. (Eds.), Asteroids III. Univ. of Arizona, pp. 205–218. [22] Takir D. et al. (2013) *Meteorit. Planet. Sci.* 48, 1618-1637.[23] Sunshine J. et al. (2009) vol. 326, Issue 5952, 565-568. [24] Reddy V. et al. (2012) *Icarus*, 221, 544-559. [24] Takir et al. (2019) *Icarus*, Volume 333, 15 Pages 243-251. [25] Usui T. et al. (2020) Space Science Reviews 216, 49.