Icarus 229 (2014) 196–205

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Spectral absorptions on Phobos and Deimos in the visible/near infrared wavelengths and their compositional constraints

A.A. Fraeman [a,*], S.L. Murchie [b], R.E. Arvidson [a], R.N. Clark [c], R.V. Morris [d], A.S. Rivkin [b], F. Vilas [e]

[a] Washington University in St. Louis, 1 Brookings Dr, Campus Box 1169, St. Louis, MO 63130, United States
[b] The Johns Hopkins University Applied Physics Laboratory, 11101 Johns Hopkins Road, Laurel, MD 20723, United States
[c] US Geological Survey, Denver Federal Center, Box 25046, Denver, CO 80225, United States
[d] ARES, NASA Johnson Space Center, 2101 NASA Parkway, Houston, TX 77058, United States
[e] Planetary Science Institute, 1700 East Fort Lowell, Suite 106, Tucson, AZ 85719, United States

ARTICLE INFO

Article history:
Received 23 September 2013
Revised 12 November 2013
Accepted 13 November 2013
Available online 21 November 2013

Keywords:
Mars, satellites
Spectroscopy
Satellites, composition

ABSTRACT

Absorption features on Phobos and Deimos in the visible/near infrared wavelength region (0.4–3.9 μm) are mapped using observations from the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM). Fe^{2+} electronic absorptions diagnostic of olivine and pyroxene are not detected. A broad absorption centered around 0.65 μm within the red spectral units of both moons is detected, and this feature is also evident in telescopic, Pathfinder, and Phobos-2 observations of Phobos. A 2.8 μm metal–OH combination absorption on both moons is also detected in the CRISM data, and this absorption is shallower in the Phobos blue unit than in the Phobos red unit and Deimos. The strength, position, and shape of both of the 0.65 μm and 2.8 μm absorptions are similar to features seen on red-sloped, low-albedo primitive asteroids. Two end-member hypotheses are presented to explain the spectral features on Phobos and Deimos. The first invokes the presence of highly desiccated Fe-phyllosilicate minerals indigenous to the bodies, and the second invokes Rayleigh scattering and absorption of small iron particles formed by exogenic space weathering processing, coupled with implantation of H from solar wind. Both end-member hypotheses may play a role, and *in situ* exploration will be needed to ultimately determine the underlying causes for the pair of spectral features observed on Phobos and Deimos.

1. Introduction

The compositions of Mars' small and irregularly shaped moons, Phobos and Deimos, have remained controversial despite multiple Earth- and space-based observations acquired during the last 40 years (Rivkin, 2007 and references therein). Phobos exhibits two spectral units that are both dark, yet distinctly different at visible to near infrared wavelengths (Figs. 1 and 2). The two units are a spectrally red-sloped (increasing reflectance with increasing wavelength) "red unit" that covers most of Phobos and a less red-sloped "blue unit" that is present in the interior and ejecta of the ~9-km diameter impact crater Stickney (Murchie and Erard, 1996; Rivkin et al., 2002). Deimos is similar spectrally to Phobos' red unit (Rivkin et al., 2002; Fraeman et al., 2012) (Fig. 2). Studies using visible to near infrared spectroscopy show that the moons' surfaces resemble D- or T-type asteroids or carbonaceous chondrite meteorites (e.g. Murchie and Erard, 1996; Rivkin et al., 2002; Fraeman et al., 2012), although their specific mineralogy is difficult to determine because they lack strong diagnostic absorption features.

The bulk compositions of Phobos and Deimos provide constraints on how the moons formed. Current hypotheses are that Phobos and Deimos formed *in situ* in Mars orbit (Burns, 1992) or by capture of asteroidal bodies originating outside the Mars system (Hunten, 1979; Sasaki, 1990). Possible compositions for the moons have been proposed based on these formation mechanisms (reviewed by Murchie et al., 2014) including (1) primitive phyllosilicate-rich carbonaceous chondrites or anhydrous, olivine- and pyroxene-dominated carbonaceous chondrites, representing capture of a body from outside the Mars system or late stage addition of primitive materials, (2) darkened ordinary chondrites, similar to a predicted bulk Mars-like composition possibly representing co-accretion, and (3) a Mars crust-like composition representing accretion of ejecta after a giant impact early in Mars' history. Surface materials on Phobos and Deimos have also been proposed as possible *in situ* sources of water or hydrogen for future human mission to Mars (Castillo-Rogez et al., 2012; Muscatello et al., 2012), and remote sensing constraints on their surface compositions aid in assessing this concept's viability.

---

* Corresponding author.
E-mail address: afraeman@wustl.edu (A.A. Fraeman).

0019-1035/$ - see front matter © 2013 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.icarus.2013.11.021

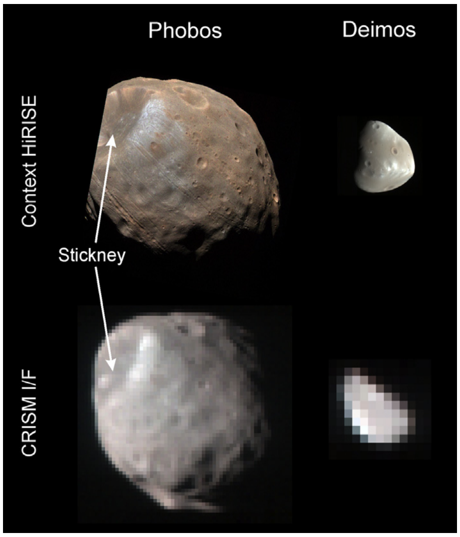

Fig. 1. (top) High spatial resolution context HiRISE observations of Phobos (PSP_007769_9010) and Deimos (ESP_012065_9000) and (bottom) CRISM observations acquired at similar illumination and viewing geometries for Phobos (FRT00002992_03) and Deimos (FRT00002983_03). The Phobos blue spectral unit is visible to the east of Stickney crater. Most of Phobos is covered by the red spectral unit which is spectrally similar to Deimos. Two additional CRISM observations of Phobos (FRT00002992_01 and FRT00002992_05) and Deimos (FRT00002983_01 and FRT00002983_05) are not shown but have similar viewing geometries. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

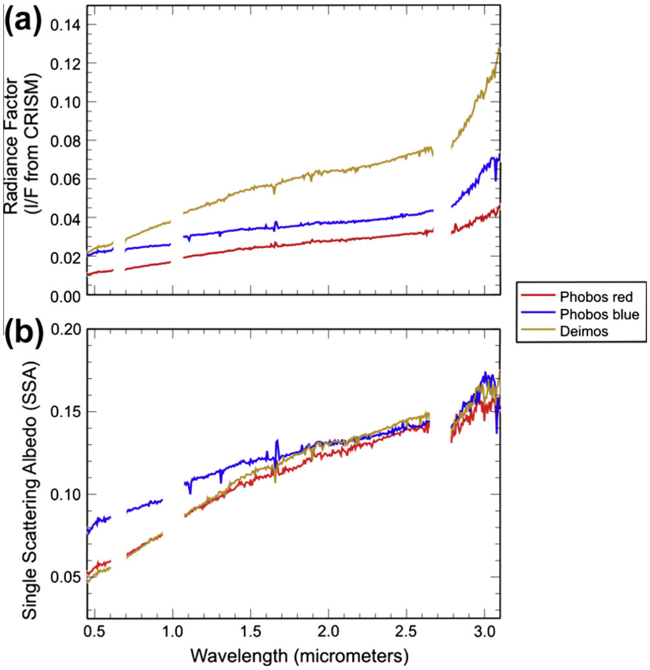

Fig. 2. (a) Representative CRISM I/F spectra from regions of interest covering the Phobos red and blue units and Deimos. The Deimos spectrum is brighter than the Phobos spectra because it was acquired at a lower phase angle and the moons have backscattering surfaces. (b) Derived single scattering albedo spectra (SSA) for the same regions, by definition independent of lighting and viewing geometries.

In this paper, results are presented that provide new insights into the compositions of Phobos and Deimos. Band-depth mapping using data from the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) shows no evidence for olivine or pyroxene. However, CRISM data do show a broad absorption feature centered at 0.65 μm for the entire surface of Deimos and for the red unit of Phobos. New telescopic data of Phobos reported here as well as a reexamination of older spacecraft observations of Phobos and Deimos support the CRISM-based detection. CRISM data also show a 2.8 μm metal–OH absorption present on both moons, although the feature is less deep in the Phobos blue unit. Two end-member models are presented for the origin of this pair of features, representing either a phase inherent to the bodies or phases formed through exogenic processes.

2. Data reductions and visible/near-infrared absorptions in CRISM observations

In June and October 2007, the CRISM instrument on the Mars Reconnaissance Orbiter (Murchie et al., 2007) acquired three disk-resolved hyperspectral images each of Deimos and Phobos (Fig. 1) using the instrument's full spectral range (0.4–3.9 μm) with a spectral sampling of ~6.55 nm/channel (Murchie et al., 2008; Fraeman et al., 2012). These data provide the highest spatial (~350 m/pixel) and spectral resolution hyperspectral coverage of Phobos to date, as well as the first disk-resolved (~1200 m/pixel) hyperspectral observations of Deimos. Both sets of observations were acquired over the night side of Mars so that scattered light and Mars-shine on the moons' surfaces are not significant (Goguen et al., 1979). Data shortward of 0.45 μm have lower reliability owing to differences in how the spectrometer's diffraction gratings perform on the two moons, which highly underfill the field of view, versus the internal calibration source, which completely fills the field of view. Measurements longwards of ~3.1 μm are known to be confounded by poorly characterized calibration artifacts and are not analyzed here (Murchie et al., 2007).

Fraeman et al. (2012) derived Hapke scattering parameters for Phobos using observations of the moon made by the Observatoire pour la Mineralogie, l'Eau, les Glaces et l'Activité (OMEGA) onboard Mars Express (Bibring et al., 2004). The OMEGA observations cover a similar wavelength range as the CRISM dataset but at lower spectral resolution, and were acquired over multiple phase angles from 38° to 99° (Fraeman et al., 2012). The OMEGA-based scattering parameters are valid for the CRISM Phobos and Deimos observations (Fraeman et al., 2012), and are used in this paper to derive single scattering albedo spectra for Phobos and Deimos at wavelengths less than 2.5 μm (Fig. 2). Single scattering albedo values are by definition independent of lighting and viewing conditions (Fig. 2b).

At wavelengths longer than ~2.5 μm, the moons' radiance factor measured by CRISM (also referred to as I/F and defined as radiance/(solar irradiance/π)) contains a component from emitted thermal radiation as temperatures on the surface of Phobos and Deimos can reach up to 300–350 K (Kuzmin and Zabalueva, 2003; Lynch et al., 2007). In this wavelength region, we therefore must solve for single scattering albedo by jointly modeling both the reflected solar and the thermal emission contributions. The Hapke equation describing contributions from bidirectional reflectance and directional emissivity is expressed as a function of incidence angle i, emission angle e, phase angle α, and kinetic temperature T for a given wavelength is (Hapke, 1993):

$$r(i,e,\alpha,T) = \frac{w}{4}\frac{\mu_0}{\mu_0+\mu}[(1+B(\alpha))p(\alpha,g_1)+H(w,\mu_0)H(w,\mu)-1]$$
$$S(i,e,\alpha,\theta)+\sqrt{1-w}\cdot H(w,\mu)\cdot\frac{\beta_0(T)}{J/\pi} \quad (1)$$

where w is the single scattering albedo we wish to solve for, r is the radiance factor measured by CRISM, μ and μ_0 are the cosines of the emergence and incidence angles, respectively, $B(\alpha)$ models