Contents lists available at ScienceDirect

Planetary and Space Science

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

Composition of Surface Materials on the Moons of Mars

Carle M. Pieters [a,*], Scott Murchie [b], Nicolas Thomas [c], Daniel Britt [d]

[a] Dept. Geological Sciences, Brown University, Providence, RI 02912, USA
[b] Applied Physics Laboratory, Johns Hopkins University, Laurel, MD 20723, USA
[c] Universitaet Bern, Bern, Switzerland
[d] University of Central Florida, Orlando, FL 32816, USA

A R T I C L E I N F O

Article history:
Received 6 November 2013
Received in revised form
1 February 2014
Accepted 18 February 2014

Keywords:
Asteroid capture
Space weathering
Regolith
Phobos
Deimos

A B S T R A C T

The two small asteroid-like bodies orbiting Mars, Phobos and Deimos, are low albedo and exhibit similar visible to near-infrared spectra. Determining the origin of these moons is closely tied to determining their composition. From available spectroscopic data Phobos exhibits two distinct types of materials across its surface, and data from both Mars Express and Mars Reconnaissance Orbiter have provided additional details about the properties of these materials and their spatial relation to one another. Although no prominent diagnostic absorptions have been detected, systematic weak features are seen in some data. An extensive regolith is observed to have developed on both moons with characteristics that may be unique due to their special environment in Mars orbit. Understanding the character and evolution of the regolith of Phobos and Deimos is central to interpreting the moons' physical and optical properties. The cumulative data available for compositional analyses across the surface of Phobos and Deimos, however, remain incomplete in scope and character and ambiguous in interpretation. Consequently the composition of the moons of Mars remains uncertain.

1. Introduction and background

The composition of Phobos and Deimos is one of the most fundamental properties of these small moons of interest to both science and exploration. Knowledge of their composition would significantly constrain their origin: Are they composed of material derived from or near Mars? Or do they represent primitive material from other parts of the solar system that has been captured in the Mars environment? Such knowledge would also resolve at least some issues about whether these bodies can provide resources in the long-term exploration of Mars.

Hypotheses for the origin of Mars' moons were relatively simple during early phases of Mars exploration in the Viking period when limited data appeared to be consistent with the view that they were captured primitive asteroids. Both were seen to be small, irregular, low-density, and dark bodies with apparently featureless spectra in the visible–UV that was comparable to low albedo asteroids (e.g., Pang et al., 1978; Thomas, 1979; see also history of telescopic data by Pascu et al., 2013). This simple hypothesis, however, was not without hurdles. Of greatest concern was the physical difficulty of Mars capturing an asteroid, either intact or even in pieces that could later accrete in Mars orbit (e.g., Burns, 1978, 1992).

With the 1989 visit of PHOBOS-2 to the Mars environment (Avanesov et al., 1989; Ksanfomality et al., 1989) it became clear that Phobos exhibits a heterogeneous surface with two spatially coherent units, one with a spectrum that is generally flat (commonly called the 'blue' unit) and the other with a spectrum that slopes more steeply into the near-infrared (commonly called the 'red' unit) (Murchie et al., 1991; Murchie and Erard, 1996). The spectrum of Deimos is comparable to the 'red' unit (Murchie et al., 1999). The "blue" unit is found in association with the large crater Stickney and a generic relation with the crater has often been presumed. The spectral diversity across the surface of Phobos was illustrated in the first color data obtained for Phobos by the multispectral cameras on PHOBOS-2 shown in Fig. 1. Although in integrated data no definitive absorptions were recognized that could be used to characterize the surface, at that time hints of a possible mafic-mineral component were suggested for the 'blue' unit.

In parallel, spectral analyses of asteroids and meteorites became increasingly more sophisticated as telescopic and laboratory data accumulated (e.g., Gaffey et al., 1993; Pieters and McFadden, 1994). No conclusive meteorite analogues for either of the two units were identified, and two quite different models for the composition of Phobos (and Deimos) were formulated and continue to be discussed (see review by Rosenblatt, 2011 and references therein). (1) The most common concept involves some

* Corresponding author. Tel.: +1 401 863 2417.
E-mail address: Carle_Pieters@brown.edu (C.M. Pieters).

http://dx.doi.org/10.1016/j.pss.2014.02.008
0032-0633

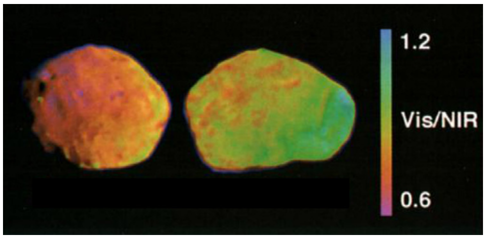

Fig. 1. PHOBOS 2 color ratio image with views of the leading side and the anti-Mars side (after Murchie et al., 1991, 1999). Stickney is on the right edge. (For references to color in this figure, the reader is referred to the web version of this article.)

form of primitive material comparable to that thought to compose low-albedo asteroids currently found in the outer portion of the main belt (e.g., asteroid type D). Such a composition would require a mechanism to capture this material into Mars orbit. (2) The alternate concept involves material related directly to Mars, formed by co-accretion with Mars or re-accretion of Mars impact debris. Such scenarios would require that the surface of the moons have been extensively processed in orbit and/or in the space environment so that the original composition is beyond recognition.

Phobos was recognized as exhibiting low density from the early analyses, and modern density values are 1.85 ± 0.07 g/cm^3 while Deimos' density is even lower at 1.48 ± 0.22 g/cm^3 (Rosenblatt, 2011; Willner et al., 2013). Phobos is thus clearly not dominated by either metal or coherent blocks of massive silicate, but is interpreted to contain high porosity (Rosenblatt, 2011). However, these physical properties could be consistent with either model for its origin and composition and could 'match' several combinations of meteorite analogue materials (see example discussion in Rosenblatt, 2011).

Since initial spacecraft measurements of Phobos, a small fleet of spacecraft with modern instruments have been orbiting Mars and have obtained a limited but valuable range of new spectroscopic data for both Phobos and Deimos. The discussion below concentrates on results from (a) multispectral imaging data that was obtained by the High Resolution Stereo Camera (HRSC) onboard Mars Express and by the High-Resolution Imaging Science Experiment (HiRISE) onboard Mars Reconnaissance Orbiter (MRO) and (b) visible to near-infrared imaging spectroscopic data that was obtained by two imaging spectrometers, Observatoire pour la Mineralogie, l'Eau, les Glaces et l'Activité (OMEGA) onboard Mars Express and the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) onboard MRO. The combination of spectroscopic data acquired at high *spectral* resolution that extend into the near-infrared along with data obtained high *spatial* resolution imaging through a few spectral channels provides a consistent characterization of the principal units on Phobos. As discussed below, these data and recent geophysical analyses also underline the importance of regolith processes on such airless bodies and the inherent ambiguity that extensively processed materials present. Although the properties of Deimos are less well documented, the similarity of its surface materials to those of Phobos is strengthened as measurements continue. The two are clearly related and any 'answer' concerning their composition and their origin must apply to both.

2. Two types of material on Phobos

Examples of recent spectral data for Phobos acquired by Mars Express and MRO are shown in Figs. 2 and 3. The orbit of MRO is within the orbit of Phobos and measurements are thus limited to the Mars-facing side of Phobos. However, since the orbit of Mars Express can extend beyond the orbit of Phobos, it has the capability to acquire data for other views. Examples of extended coverage by HRSC on Mars Express are shown in Figs. 4 and 5.

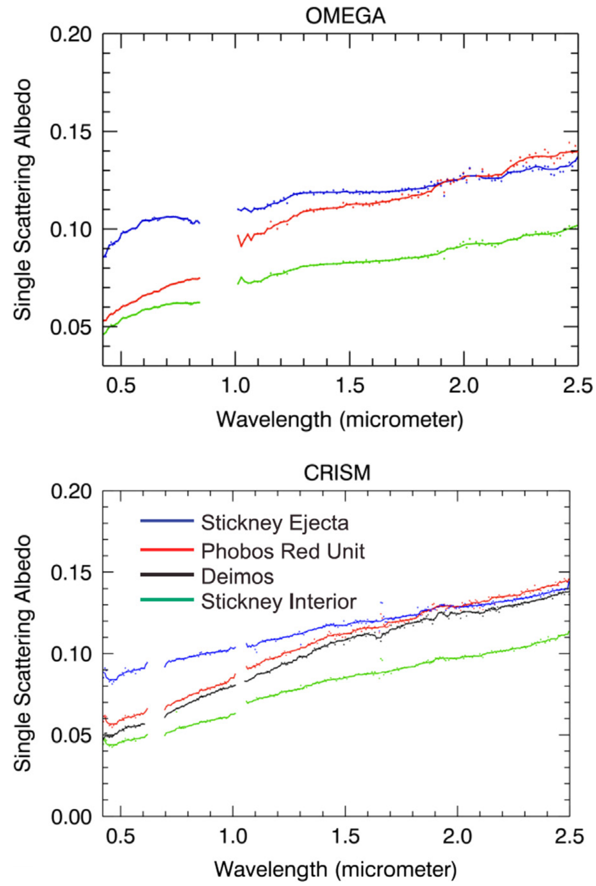

Fig. 2. Spatially resolved reflectance spectra of Phobos and Deimos acquired by OMEGA and CRISM imaging spectrometers (after Fraeman et al., 2012). Compared to Deimos and most of Phobos, Stickney is slightly brighter and exhibits a flatter (less 'red' sloped) near-infrared spectrum. OMEGA data were first presented by Gondet et al. (2010) and CRISM data were first presented by Murchie et al. (2008). (For references to color in this figure, the reader is referred to the web version of this article.)

Visible to near-infrared spectra acquired with imaging spectrometers are commonly used to identify, or at least constrain, the mineralogy of surface materials of solar system bodies through the identification of highly diagnostic mineral absorption bands (e.g., Bibring et al., 2005; Murchie et al., 2007; Pieters et al., 2009). Calibrated OMEGA and CRISM spectra of the moons of Mars are shown in Fig. 2 (presented by Fraeman et al., 2012, 2014) and illustrate several fundamental properties:

- Both Phobos and Deimos are moderately low albedo bodies. Although still quite dark, they appear to be slightly brighter than many C-type asteroids (e.g., Clark et al., 1999).
- The two units of Phobos are distinguished by differences in (1) UV–visible albedo and (2) continuum slope. Some local materials on Phobos (e.g., near Stickney) are brighter at visible wavelengths and exhibit a distinctly flatter continuum (the 'blue' unit). Although Deimos exhibits hints of a similar dual pattern at high spatial resolution (Thomas et al., 2011), spectra of Deimos and Phobos 'red' unit are almost identical.
- No significant diagnostic absorptions of common ferrous minerals (olivine, pyroxene) are detected. No other prominent spectral features appear in either Phobos or Deimos spectra. (Artifacts remain in some OMEGA spectra of Fig. 2.)

Please cite this article as: Pieters, C.M., et al., Composition of Surface Materials on the Moons of Mars. Planetary and Space Science (2014), http://dx.doi.org/10.1016/j.pss.2014.02.008