Planetary and Space Science 128 (2016) 30–51

Contents lists available at ScienceDirect

Planetary and Space Science

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

Martian surface microtexture from orbital CRISM multi-angular observations: A new perspective for the characterization of the geological processes

J. Fernando [a,b,*], F. Schmidt [a], S. Douté [c]

[a] GEOPS, Univ. Paris-Sud, CNRS, Université Paris-Saclay, Rue du Belvédère, Bât. 509, 91405 Orsay, France
[b] Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA
[c] Univ. Joseph Fourier/CNRS, IPAG, Grenoble, France

ARTICLE INFO

Article history:
Received 14 January 2016
Received in revised form
29 April 2016
Accepted 18 May 2016
Available online 21 May 2016

Keywords:
Mars surface
Photometry
Orbit determination
Geological processes

ABSTRACT

The surface of Mars has a high morphological and mineralogical diversity due to the intricacy of external, internal processes, and exchanges with the atmosphere, the hydrosphere and the cryosphere. In particular, liquid water played an important role in surface evolution. However, the origin, duration and intensity of those wet events have been highly debated, especially in the clay-bearing geological units. Similarly, questions still remain about magma crystallization and volatile quantity of the dominant basaltic crust. In this work, six sites having hydrated minerals, salts and basaltic signatures (i.e., Mawrth Vallis, Holden crater, Eberswalde crater, Capri mensa, Eridania basin, Terra Sirenum) are investigated in order to better characterize the geological processes responsible for their formation and evolution (e.g., fluvial, lacustrine, in situ weathering, evaporitic, volcanic and aeolian processes). For that purpose, we use orbital multi-angular measurements from the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) instrument on-board the Mars Reconnaissance Orbiter spacecraft to analyze the manner in which light is scattered by the surface materials (photometry) in the near-infrared range (at 750 nm). The surface bidirectional reflectance depends on the composition but also on the surface microtexture such as the grain size distribution, morphology, internal structure and surface roughness, tracers of the geological processes. The Hapke semi-analytical model of radiative transfer in granular medium is used to model the surface bidirectional reflectance estimated at 750 nm from the orbital measurements after an atmospheric correction. The model depends on different radiative properties (e.g., single scattering albedo, grain phase function and regolith roughness) related to the surface composition and microtexture. In particular previous laboratory works showed that the particle phase function parameters, which describe the characteristics of the volume scattering, are sensitive to the grain morphology and internal structure. The surface material photometric parameters estimated from the CRISM multi-angular observations at 750 nm are compared to the geological units in order to better characterize the geological processes. The photometric results show a high diversity of surface scattering behaviors (from a broad and backward scattering behavior to a narrow and forward scattering behavior) that suggests a high diversity of surface microtexture. A narrow forward scattering behavior has been detected for the first time from martian orbital data and observed in peculiar regions dominated by salt-bearing and clay-bearing materials. Hence the martian photometric results suggest that Mars experimented varied geological processes still preserved in the material microtexture. This study also demonstrates that these properties provide complementary information to mineralogy and geomorphology to better constrain the geological processes.

1. Introduction

The martian basaltic crust has been modified by endogenous (e.g., volcanism), exogenous processes (e.g., asteroid bombardment) and by interactions between the atmosphere, the cryosphere and the hydrosphere (e.g., weathering, erosion, transportation, deposition) leading to different surface materials. Even if

* Corresponding author at: GEOPS, Univ. Paris-Sud, CNRS, Université Paris-Saclay, Rue du Belvédère, Bât. 509, 91405 Orsay, France.
E-mail addresses: jennifer.fernando@u-psud.fr (J. Fernando), frederic.schmidt@u-psud.fr (F. Schmidt), sylvain.doute@obs.ujf-grenoble.fr (S. Douté).

http://dx.doi.org/10.1016/j.pss.2016.05.005
0032-0633/

the main processes responsible for Mars evolution are well-identified from orbital and in situ investigations, the mechanisms still remain poorly known. For instance, the high diversity of volcanic landforms and deposits suggests changes in volcanic style in space and time (Wilson and Head, 1994). The formation of a magmatic rock is a complex process involving many steps from magma ascent to its emplacement (e.g., crystallization, gas exsolution and segregation). Characterizing those processes will be useful to better understand the origin of this diversity. Former studies also revealed that liquid water played an important role in surface evolution but fundamental questions on the origin, duration and intensity of those wet events have been highly debated, especially in the clay-bearing units (e.g., Bibring et al., 2006; Murchie et al., 2009; Meunier et al., 2012; Carter et al., 2013; Ehlmann and Edwards, 2014).

To identify and characterize geological processes, geomorphological and geochemical clues are commonly used. However, information about the surface microtexture such as the grain size, morphology (e.g., shape, surface roughness) and internal structure can also be used as a tracer of the geological processes. For instance, in an erosion/transportation context, a coherent material is eroded into rough grains which can be transported by wind or by water polishing their surface and reducing their size. In volcanic context, the rapid quenching of liquid magmas produces amorphous glasses whereas the relatively slow cooling produces a finely crystallized microlithic texture.

Surface microtexture can be characterized from in situ high resolution imagery that gives constraints on the local geology. For example, images from the Microscopic Imager (MI) instrument onboard Mars Exploration Rover (MER)-Opportunity showed millimeter-sized spherical hematite-rich concretions and a complex texture for the sulfate-rich materials at Meridiani Planum (Herkenhoff et al., 2008) revealing a complex diagenetic history (Squyres et al., 2004). Moreover, the rounded cemented pebbles detected at the Mars Science Laboratory (MSL)-Curiosity landing site at Gale crater indicated a deposition under a fluvial environment with substantial fluvial abrasion (Williams et al., 2013).

Surface microtexture can also be indirectly characterized from remote photometric measurements by studying the manner in which light is scattered by the surface materials (photometry) in the visible and near-infrared ranges. The surface bidirectional reflectance depends on the composition but also the material microtexture (e.g., McGuire and Hapke, 1995; Johnson et al., 2006a,b, 2015; Souchon et al., 2011; Sato et al., 2014; Fernando et al., 2015). From orbit, the global average photometric behavior derived from the Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité (OMEGA) instrument and the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) instrument appears mostly backscattering (i..e., light is mainly reflected back to the light source side) (Vincendon, 2013), suggesting that complex microtextured grains dominate the martian surface. This scattering behavior may also be the result of the contribution of sub-pixel shadowing. At local scale, in situ MER measurements however showed various photometric behaviors (Johnson et al., 2006a,b, 2015) suggesting that various grain textures may exist.

Fernando et al. (2013, 2015) proposed an approach to derive maps of the surface photometric properties from CRISM multiangular observations. This approach uses a correction for the atmospheric mineral aerosols ("dust") scattering contribution in order to estimate accurate surface reflectance factors at 750 nm (Ceamanos et al., 2013). To analyze the light scattering coming from the surface materials at 750 nm, a semi-analytical radiative transfer model (Hapke, 1993) is inverted in order to estimate mean surface radiative properties (e.g., particle single scattering albedo, particle phase function and regolith roughness) related to the surface microtexture (e.g., grain size, morphology and internal structure, organization). The methodology has been validated by comparing the estimated photometric parameters to the in situ photometric and microscopic measurements from the MER rovers (Fernando et al., 2013).

In the present work, we estimated the surface material microtexture under varied geological contexts (e.g., sedimentary, volcanic) using the same methodology. The objectives of this work are: (i) to evaluate the diversity of the martian material microtexture (excluding water and carbon dioxide icy surfaces) and (ii) to determine the link between the surface scattering behavior and the surface microtexture and the geological processes (e.g. fluvial, lacustrine, evaporation, volcanism, aeolian) by correlating those results with previous geomorphological and geochemical studies.

2. Methods: determination of the surface microtexture

2.1. CRISM targeted observations

The CRISM instrument on-board the Mars Reconnaissance Orbiter (MRO) spacecraft is a visible and infrared hyperspectral imager (from 362 to 3920 nm at 6.55 nm/channel) (Murchie et al., 2007). In this work, we used the Full Resolution Targeted observations (FRT) which is composed of a set of eleven hyperspectral images of a target, acquired at different emission angles due to the rotation of the detector at $\pm 70°$. The solar incidence is quite constant (less than 2°) during the spacecraft flyby over the target. The typical FRT sequence is composed of a central image ($\sim 10 \times 10$ km) at high spatial sampling (15–20 m/pixel) and 10 off-nadir images with a $\times 10$ binning (150–200 m/pixel), taken before and after the central image, involving two azimuthal modes (Murchie et al., 2007). To have a homogeneous spatial resolution (spatial resolution of the 10 off-nadir image, 150–200 m/pixel), the central image is binned by a factor 10.

2.2. Estimation of the Hapke photometric parameters

Fernando et al. (2013, 2015) have developed a methodology to estimate and map the photometric parameters of the surface materials. The methodology has been validated by comparing to in situ images and photometric measurements acquired by the MER rovers (Fernando et al., 2013, 2015). The main steps are summarized below.

- *Selection of CRISM FRT observations*: The selected CRISM FRT observations must have favorable geometric conditions (broad phase angle range with low ($< 40°$) and high phase angles ($> 100°$) and low atmospheric aerosol contents (mineral aerosol optical thickness less than 1 and water ice aerosol optical thickness less than 0.2) to estimate accurate surface reflectances (Ceamanos et al., 2013; Fernando et al., 2013) and surface photometric parameters (Fernando et al., 2013, 2015; Schmidt and Fernando, 2015).
- *Correction for mineral aerosol contribution and estimation of the surface bidirectional reflectance*: A technique, referred to as MARS-ReCO (Ceamanos et al., 2013) was developed to correct for mineral aerosols ("dust") in order to estimate the surface bidirectional reflectance. In this work, the surface bidirectional reflectance is estimated at 750 nm where the contribution from gas is negligible. The mineral aerosol optical properties (particle size distribution and refractive index) were estimated by Wolff et al. (2009) and are reminded by Ceamanos et al. (2013). The mineral and water ice aerosol optical thicknesses ($AOT_{mineral}$ and AOT_{water}) of each studied observation are provided by Michael Wolff (personal communication, 2011, Wolff et al., 2009) and presented in Supplementary Material – Table 1. The $AOT_{mineral}$