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Mars surface phase function constrained by orbital observations

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The bidirectional photometric properties of the surface of Mars describe how remote measurements of surface reflectance can be linked to hemispherical albedo used for energy balance calculations. A simple Lambert's law is frequently assumed for global data processing, even though several local studies have revealed the complexity of Mars surface phase functions. In this paper, we derive a mean Bidirectional Reflectance Distribution Function (BRDF) representative of widespread typical Martian terrains. OMEGA and CRISM orbital observations are used to provide observational constraints at solar wavelengths over a wide range of viewing conditions all over the planet. Atmospheric contribution is quantified and removed using a radiative transfer model. We observe a common phase behavior consisting of a 5%–10% backscattering peak and, outside the backscattering region, a 10%–20% reflectance increase with emergence angles. Consequently, nadir measurements of surface reflectance typically underestimate hemispherical reflectance, or albedo, by 10%. We provide a parameterization of our mean Mars surface phase function based on Hapke formalism ($\omega=0.85$, $\theta=17$, $c=0.6$, $b=0.12$, $B_0=1$ and $h=0.05$), and quantify the impact of the diffuse illumination conditions which change surface albedo as a function of local time and season. Our average phase function can be used as a refinement compared to the Lambertian surface model in global data processing and climate modeling.

1. Introduction

The surface phase function characterizes the distribution of scattered radiation intensity with incidence and emergence directions. It is a function of surface texture (grain size, roughness, topography, depending on spatial scale), surface composition (complex refractive index), and illumination conditions (incidence angle, or distribution of incidence angles for a diffuse source). The surface phase function links single-direction reflectance to hemispherical reflectance integrated over all emergence directions. While most remote measurements of Mars surface reflectance are performed in a single viewing geometry (usually nadir), hemispherical reflectance is the physical quantity that measures the balance between incoming solar flux and scattered power in all directions, a critical value for climate modeling. For a perfectly Lambertian surface, the reflectance factor measured for any viewing geometry is equal to the hemispherical reflectance ("albedo"), a simplifying assumptions frequently used on Mars.

Estimating the surface phase function at Mars is a thorny issue. On the one hand, remote multi-angle measurements are sensitive to both surface and atmosphere, the latter being frequently dominant (Clancy and Lee, 1991; Clancy et al., 2003; Vincendon et al., 2008; Wolff et al., 2009; Fernando et al., 2012; Shaw et al., 2012). Hence, complex modeling strategies are required to disentangle atmosphere and surface (Ceamanos et al., 2012) as estimations performed without removing the atmospheric contribution (Thorpe, 1977; Pleskot and Kieffer, 1977; de Grenier and Pinet, 1995; Soderblom et al., 2006; Jehl et al., 2008) can result in ambiguous functions. On the other hand, surface measurements performed by Landers (Guinness et al., 1997; Johnson et al., 1999; Johnson et al., 2006a, b) are restricted to a limited number of sites and are not necessarily representative of remote measurements of km-sized pixels which average various surface materials, textures and local topographies.

In this paper, we use observations obtained for various viewing geometries by the visible and near-IR imaging spectrometers OMEGA and CRISM to constrain over solar wavelengths the average phase function representative of typical Martian terrains observed at low spatial resolution (pixels $>$ km). We account for the contribution of the atmosphere to both derive surface-only phase functions and study the impact of the changing diffuse illumination conditions through the spread of incidence directions over which the BRDF is integrated. Using Hapke formalism, we parameterize a mean Mars surface phase function consistent with these new data and the range of previously published constraints. This function provides a second order, better than the first order Lambertian surface model, surface phase function that can be used to integrate global data and compute albedo for surface energy balance calculation.

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2. Method

2.1. Characterization of the surface phase function

We briefly define in this paragraph the physical quantities subsequently used, following conventions of Hapke (1993). The surface phase function refers to how a given surface scatters light as a function of emergence and incidence directions. The incidence direction is defined by the incidence angle *i*, or solar zenith angle (equal to 0° when the Sun is at zenith and 90° at the terminator). The emergence direction is defined by the emergence angle *e*, ranging from 0° toward zenith (i.e., for "nadir viewing") to 90°, and the azimuth angle. The phase angle *g* is the angle measured from the surface between emergence and incidence directions, ranging from 0° to 180°; it can be calculated from the three previous angles (see equation 8.4 of Hapke (1993)). The phase function is described by the Bidirectional Reflectance Distribution Function, *BRDF* (*i*, *e*, *g*) (see e.g. paragraph 10.B of Hapke (1993)). The BRDF is the ratio of the radiance scattered by a surface into a given direction to the collimated power incident on a unit area of the surface. Integrating the BRDF over all emergence directions provides the hemispherical reflectance (see e.g. paragraph 10.D.2 of Hapke (1993)), which corresponds to the total power scattered into the upper hemisphere by a unit area over the collimated power incident on this unit area. The hemispherical reflectance thus corresponds to the fraction of incoming energy not absorbed by the surface ("albedo"); it depends on solar zenith angle. For a Lambertian surface, the BRDF is constant, and the hemispherical reflectance is simply equal to $\pi \times BRDF$ and does not depend on incidence angle. By analogy, the reflectance factor $\mathrm{REFF}(i,e,g)=\pi \times \mathrm{BRDF}\ (i,e,g)$ is frequently used to characterize the reflectance in one direction (see e.g. equation 10.3 of Hapke (1993)).

We will use the same Hapke formalism as used in recent studies (Johnson et al., 2006a, b; Wolff et al., 2009; Fernando et al., 2012) to provide a parameterization of the phase function: the BRDF corresponds to the reflectance of equation 12.55 of Hapke (1993) divided by cos (*i*). Parameters are: opposition effect magnitude (B_0) and width (h), macroscopic roughness (θ), single scattering albedo (ω), and the asymmetry parameter (b) and backward fraction (c) of the 2-terms Henyey–Greenstein (HG) function. We use the same formalism as Johnson et al. (2006a) for c, i.e. $c=(1+c_{\mathrm{hapke}})/2$ with c_{hapke} corresponding to the "c" of equation 6.18a of (Hapke, 1993).

2.2. OMEGA and CRISM data

The OMEGA (Observatoire pour la Minéralogie, l'Eau, les Glaces, et l'Activité) onboard Mars Express and CRISM (Compact Reconnaissance Imaging Spectrometers for Mars) onboard Mars Reconnaissance Orbiter instruments are imaging spectrometers observing the sunlight reflected by the surface and atmosphere of Mars at visible and near-IR wavelengths for various viewing geometries (Bibring et al., 2005; Murchie et al., 2007). Neither instrument performs complete measurements of the BRDF of the surface; nevertheless, their specificities make it possible to probe complementary portions of the surface phase function.

OMEGA mostly observes the surface of Mars with a near-nadir pointing direction and various incidence angles ranging from zenith to terminator depending on local time, season and latitude. Most places on Mars have been observed several times with various incidence angles since the beginning of OMEGA operations in early 2004. We can thus probe the BRDF for $e=0°$ and i between 0° and 90° by constructing time series of OMEGA observations. The spatial resolution of OMEGA ranges from 0.3 to 5 km depending on spacecraft altitude along its elliptical orbit. Time series of overlapping observations are constructed by looking at all observations obtained within homogeneous areas of a few tens to a few hundreds of km. Off-nadir (±20° emergence) observations occasionally obtained by OMEGA were not used in our study. A dozen of "spot pointing" observations of the surface with varying emergences have also been acquired by OMEGA; however, preliminary modeling results (Vincendon et al., 2007b) indicate that these observations are dominated by aerosols effects, which makes them poorly suited for our surface analysis.

CRISM targeted observations are obtained by pointing to a target area on the ground with emergence angles ranging from 70° to 0° to 70° as the spacecraft flies over the target. The local time of observations is 15.00. These "Emission Phase Function" (EPF) observations thus probe the BRDF for a constant mid-afternoon solar zenith angle, an emergence angle varying from 0° to 70° for two opposite azimuth angles. CRISM targeted observations cover an area about $10 \times 10\ \mathrm{km}^2$ wide on the ground with a spatial resolution decreasing with emergence from 20 m at nadir to approximately 450 m at 70° (Ceamanos et al., 2012); we sum all pixels within the covered area and thus derive CRISM EPF with spatial extent comparable to OMEGA time series.

2.3. Atmospheric contribution

Observations of the surface of Mars by remote sensors are troubled by the scattering and absorption of light within atmospheric aerosols and gas. Gas influence can be easily bypassed by selecting wavelengths over which gas is transparent, which is the case for a major fraction of the visible and near-IR range. Both dust and ice particles compose Mars atmospheric aerosols. Ice forms localized clouds which can largely be isolated and removed in the dataset using climatology database (Smith, 2004) and spectroscopic evidence contained in near-IR OMEGA and CRISM data itself (Langevin et al., 2007). On the contrary, dust aerosols are ubiquitous: even under "clear" atmospheric conditions and favorable illumination conditions, at least 30% of solar photons interact with dust aerosols, with substantial effect on observed surface reflectance (Lee and Clancy, 1990).

We use the multiple scattering Monte-Carlo radiative transfer code, aerosols optical properties, and methodology of Vincendon et al. (2007a, 2009) to model the contribution of dust aerosols to OMEGA and CRISM data. Look-up tables of apparent reflectance as a function of surface reflectance, and conversely, are produced as a function of viewing geometries and aerosols optical depths. The resulting atmospheric correction makes it possible to relate reflectance seen through the aerosols layer in a given direction to surface reflectance. The model assumes a Lambertian surface at the bottom boundary: the impact of this simplifying hypothesis will be discussed with other aerosols assumptions in Section 3.3.

We also need to account for the non-collimated nature of incoming radiations due to aerosols scattering: as the BRDF depends on incidence angle, the diffuse Martian sky modifies the distribution of light scattered by the surface compared to a single incidence angle. The distribution of incoming illumination angles, as results from the dispersal of a single incoming solar zenith angle, is simulated using the same atmospheric radiative transfer code (see e.g. Figure 5 of Vincendon et al. (2009)). Optical depths at time of observations are derived from Mars Exploration Rover (MER) measurements (Lemmon et al., 2004) performed during the Mars Express and Mars Reconnaissance Orbiter missions. The corresponding BRDF is then built by averaging the BRDF according to the modeled distribution of incidence angles.