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The evolution of the albedo of dark spots observed on Mars polar region

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A B S T R A C T

We present a methodology to remove atmospheric effects from High Resolution Imaging Science Experiment data in order to calculate the albedo of the martian surface in the near infrared (0.8–1 μm), red (0.55–0.85 μm), and blue green (0.4–0.6 μm) spectral bands. The application of our methodology results in corrections of up to 20% in the albedo measured by the satellite. Time evolution of the surface albedo is used to study dark spots observed in Richardson Crater, on Mars south polar region. These dark spots form in late winter and vanish in late spring. They are of high scientific interest because they appear to be caused by the flow of granular material, liquid, or a combination of both. Besides images, the following data are used as ancillary information in our study: dust optical depth derived from measurements by the Thermal Emission Imaging System, the detection of the presence of either CO_2 ice or H_2O ice by the Compact Reconnaissance Imaging Spectrometers for Mars, surface pressure and temperature values derived from measurements by the Thermal Emission Spectrometer, and finally kinetic calculations and numerical modeling.

Our results support the gas venting hypothesis previously proposed to explain the formation of dark spots. We show that the ejection of CO_2 gas and accompanying loose material through cracks in the translucent CO_2 ice layer, suggested by this hypothesis, is consistent with the time evolution of the surface albedo. Once dark spots form, surface albedo values indicate that they have three distinct areas: a dark core at their center, a brighter zone surrounding them (referred to as bright halo by various authors), and an optically distinct intermediate area separating the dark core from the bright halo. Our analysis indicates that these three areas are physically distinct and that the deposition and sublimation of CO_2 and H_2O ices are necessary to explain the time evolution of the albedo of the dark spots and the areas surrounding them. However, these conventional mechanisms cannot explain some observed features such as an unexpected decrease and subsequent increase in albedo while the surface temperature raises continuously. We hypothesize that this unexpected decrease in albedo is caused by brine formation and propose a mechanism to explain it. A new ejection of dark material or dust deposition could also explain this decrease. However, we show that these processes are unlikely to be the cause of the albedo decrease. The hypothesis that the dark spots observed in Richardson Crater contain liquid brines can be tested with laboratory experiments or in situ measurements by future landers.

1. Introduction

Albedo features on the surface of Mars have attracted the attention of the scientific community since 1965, when Mariner 4 first captured images showing white crater rims with a spatial scale of about 3 km/pixel (Leighton et al., 1965). Then in 1973, Mariner 9 imaged what appeared to be dark eolian deposits on martian polar dunes (Cutts and Smith, 1973) with a spatial scale of about 100 m/pixel. Following the Mariner missions, the Viking orbiters discovered dark slope streaks on Olympus Mons and imaged them with a spatial scale of 10 m/pixel (Ward and Doyle, 1983). After the Viking missions, the Mars Orbiter Camera (MOC) on board the Mars Global Surveyor renewed the interest in albedo features by imaging them in the late nineties with a spatial scale of up to about 1.5 m/pixel. MOC's high resolution images allowed the discovery of gullies that were postulated to have been formed by liquid water (Malin et al., 1998). Currently, the High Resolution Imaging Science Experiment (HiRISE) camera (McEwen et al., 2007) on board the Mars Reconnaissance Orbiter (MRO) has been imaging the surface of Mars with a spatial scale of about 0.25 m/pixel, allowing detailed studies of seasonal albedo features such as recurring slope lineae (RSL) (McEwen et al., 2011).

Albedo features are of utmost scientific interest because it has been hypothesized that they could be caused by aqueous processes such as the seepage of liquid brines from the shallow subsurface (Rennó et al., 2009). The idea that liquid brines are present on Mars is exciting because many microorganisms thrive in terrestrial

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brines, particularly in brines found in subglacial environments (Mikucki et al., 2009). Locating liquid brines on Mars would provide preferred landing sites for future missions, especially for sample return and the search for evidence of microbial life.

The various albedo features observed on Mars can be classified based on the latitudes in which they form. Gullies, slope streaks, and RSL form in low and mid latitudes. Fan-shaped deposits, dark spots, and the elongated features that emanate downslope from dark spots form in the polar region. These features and the mechanisms proposed to explain their formation are described below.

Gullies are complex structures that predominantly form on the southern hemisphere at latitudes $\geqslant 27^{\circ}$ (Malin et al., 2006). They encompass headward alcoves, distal aprons, and the channels which connect them. They occur mostly in craters, pits, and other depressions found on steep slopes of about $20-30^{\circ}$.

Slope streaks are low latitude features that predominantly have albedo darker than that of their surroundings, typically with a difference of about 10% (Kreslavsky and Head, 2009). They elongate along the topographic gradient on $7–25^{\circ}$ steep slopes. They typically have low thermal inertia and the spectral signature of fine dust. The formation of slope streaks is highly inhomogeneous, both in time and in space (King et al., 2010).

RSL form at low and mid latitudes between 32°S and 48°S (McEwen et al., 2011). They are predominantly found on $25-40^{\circ}$ steep equator-facing slopes and are up to 40% darker than their surroundings. They form on typically dark regions with moderate thermal inertia. They appear in late southern spring and summer, and vanish during the colder seasons.

In the polar regions, spiders are landforms that have a central depression and irregular troughs (~ 1 m wide and ~ 0.1 m deep), carved into the substrate that emerge from their center (Piqueux et al., 2003). They form mostly in the south polar region, but might also form in the north polar region (Piqueux and Christensen, 2008). In association with spiders, fan-shaped deposits are albedo features up to 40% darker than their surroundings (although they can be brighter). They are typically about 100 m long and form in both the north and south polar regions. They can also form in steep slopes without spiders (Thomas et al., 2010).

Finally, dark spots are distinctly dark albedo features that form on polar dunes (Horváth et al., 2009), both in the southern and northern hemispheres. Two types of dark spots have been observed on southern polar dunes: large dark spots, typically > 20 m in diameter, which form on flat surfaces between dunes, and smaller dark spots that form on dune ridges (Kereszturi et al., 2011). Flow-like features may emanate from the dark spots that form on dune ridges (Kereszturi et al., 2009).

Several mechanisms have been hypothesized to explain the various albedo and related flow-like features observed on Mars. In low and mid latitudes, the flow of dry granular material is widely accepted as an explanation for the formation of gullies (Hugenholtz, 2008; Treiman, 2003). The canonical explanations for the formation of slope streaks are dust avalanches (Sullivan et al., 2001) and the removal of dust by mass wasting from cliffs (Morris, 1982). However, alternative aqueous mechanisms have been proposed to explain the formation of gullies (Malin et al., 2006), slope streaks (Kreslavsky and Head, 2009), and RSL (McEwen et al., 2011).

In the polar regions, the mechanisms invoked to explain the formation of albedo features are less controversial. Albedo features are thought to be caused by the ejection of CO_2 gas and accompanying loose material escaping through cracks in a translucent layer of CO_2 ice covering the surface (Kieffer, 2007). Hereinafter we refer to this mechanism as the gas venting model. Measurements by the Thermal Emission Spectrometer (TES) indicate that a layer or slab of coarse grained CO_2 ice covers the south polar region during the cold seasons (Kieffer et al., 2000). Since Hansen (1999) shows that a slab of CO_2 ice is translucent in the solar spectral range, dust embedded in the CO_2 ice layer formed during the winter would absorb solar radiation after the end of the polar night. The warm dust would then migrate downwards through the CO_2 ice, stopping at the ice-soil interface and leaving a layer of clear CO_2 ice above. Despite the limited solar insolation available in late winter, this process can be completed in a few Sols (Portyankina et al., 2010; Aharonson et al., 2004). Then, the clean CO_2 ice layer is heated from below shortly after the polar night ends. Solar radiation efficiently transmitted through the translucent CO_2 ice layer is absorbed at the soil-ice interface, and the CO_2 ice sublimates creating high pressure gas pockets at the interface of the ice layer with the dusty soil. Eventually the pressure becomes sufficiently high to break the ice layer and eject CO_2 gas and loose material into the martian air (see Fig. 1). Plumes about 100 m tall eject granular material as far as 50 m from their center (Thomas et al., 2010). This formation process is expected to be more efficient in the south polar region because the CO_2 ice has coarser grains there, making the ice more transparent to solar radiation (Piqueux and Christensen, 2008). This explains why fewer albedo features are observed in the north polar region.

The area where dark spots form is referred to as the cryptic region of Mars because of its low albedo in the visible portion of the spectra in spite of a low brightness temperature, indicating that the temperature of the surface is below the freezing point for CO_2 ice (Piqueux et al., 2003). The reason for this apparent contradiction was first explained in connection with the gas venting hypothesis. The albedo in the visible range of the spectra is low because it is dominated by that of dark soil below a transparent CO_2 ice layer. The surface temperature is low because it corresponds to that of a CO_2 ice layer which is opaque in the thermal infrared portion of the spectra covering the dark soil.

This article focuses on a study of large dark spots that form on flat surfaces between dunes in Richardson Crater, on the south polar region of Mars. Smaller dune dark spots and the flow-like features emanating downslope from them are not studied in this article. Large dune dark spots, hereinafter simply called dark spots, are of high scientific interest because H_2O ice has recently been discovered on them (Kereszturi et al., 2011). Their temporal evolution could be driven, at least temporarily, by liquid brines

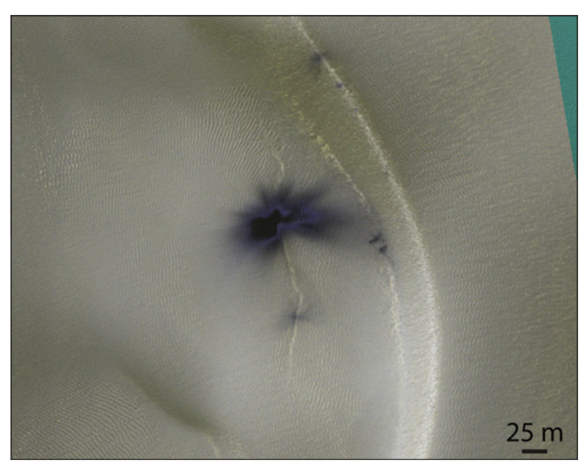

Fig. 1. HiRISE image PSP-002397-1080 of Mars south polar region (72.4°S, 179.6°E) taken at $L_s = 175.2^{\circ}$. It shows a large dune dark spot in Richardson Crater that seems to be caused by the ejection of CO_2 gas and a dark material. Dark material form a radial pattern, consistent with the ejection of granular material up to a distance of around 50 m on flat terrain (Thomas et al., 2010). At $L_s = 175.2^{\circ}$, the polar night has already ended and the Richardson Crater is covered by a layer of CO_2 ice (Kereszturi et al., 2011). This implies that this dark spot is likely caused by gas venting (Kieffer, 2007).