Gardening of the Martian Regolith by Diurnal CO_2 Frost and the Formation of Slope Streaks

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Introduction:

The seasonal transfer of CO_2 between the atmosphere and the surface at high latitudes is associated with a wide range of exotic processes shaping the surface morphology [1 and references therein]. In contrast, the existence of a diurnal CO_2 cycle at mid and low-latitudes has only recently been exposed [2,3]. [2,4] proposed that this diurnal CO_2 cycle could impact the physical state of the regolith, preventing dust induration/duricrust formation, maintaining large mobile dust reservoirs, or the formation of geophysical features known as slopes streaks [5].

[2] suggests that diurnal frost in low thermal inertia terrains (i.e., dusty surfaces) should be present in the pores of the regolith, not exclusively on top of it (Fig. 1). With this regolith/ice interaction, the recurring diurnal growth and sublimation of CO_2 crystals could indeed cryoturb the very surficial regolith. One consequence of this dirty frost model is that diurnal CO_2 frost in low thermal inertia terrains should be excessively difficult to detect in visible wavelength imagery, in contrast with diurnal or seasonal CO_2 frost present elsewhere on Mars forming on the top of the regolith grains.

In addition, one potential implication for this recurring diurnal growth and sublimation of CO_2 frost crystals within dusty terrain may include regular overnight surficial mechanical disruption of the soil, and possible fluffing by vertical sublimation-driven winds at sunrise. This process could maintain high regolith porosity, and prevent compaction or inter-grain induration/cementation that seems to be ubiquitous elsewhere on Mars [6,7] except in low thermal inertia terrains [8,9].

We proposed here to characterize the regolith/ice relationship in low thermal inertia terrains near equator through visible and infrared wavelength imagery analysis, surface features mapping, and numerical modeling.

Approach:

We use coincident visible and temperature observations acquired by THEMIS [10], a multispectral visible and thermal infrared wavelength imager. We only analyze data acquired near sunrise (i.e., 6 A.M. - 8 A.M), when adequate lighting allows the acquisition of multiband visible wavelength imagery of the ground. We only study infrared images coupled with visible wavelength images acquired simultaneously. Surface temperatures are derived from THEMIS band 9 centered at 12.57 µm as they offer the best signal on cold surfaces [10]. We eliminate image pairs clearly impacted by calibration issues (e.g., [11]) and poor observation conditions (mainly the identifiable presence of clouds in visible wavelength imagery). We identify the presence of ice on an image if the surface temperature retrieved is at the CO_2 condensation temperature T_{CO2}, within a margin of 5 K to account for instrumental noise.

Once an image is flagged for CO_2 ice, we inspect the associated visible wavelength image. The THEMIS visible camera has a resolution of 18 m/pixel and has five filters with band centers located at 425 (band 1), 540 (band 2), 654 (band 3), 749 (band 4), and 860 nm (band 5) [10]. When available, we use « R2B » or « RGB » products available with the THEMIS public viewer: viewer.mars.asu.edu/viewer/themis.

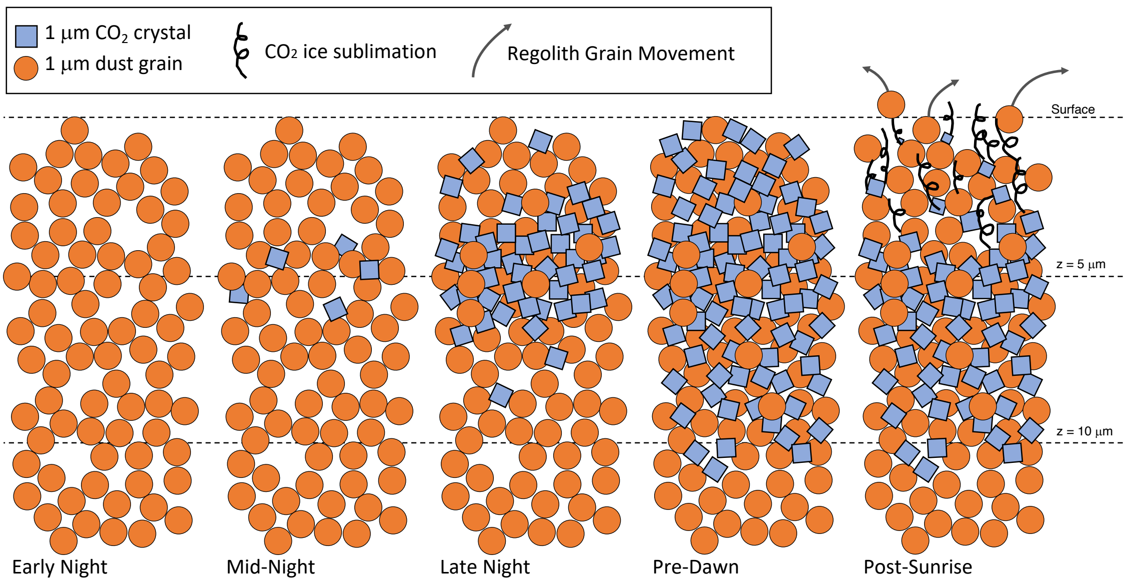

Fig 1. Schematic model of the CO_2 frost (blue squares) and regolith dust grains (orange circles) relationship in dusty low thermal inertia regions, and its evolution throughout a night and sunrise. In this model, CO_2 ice forms at depth, within the pores of the dusty surfaces. At sunrise, CO_2 ice sublimates, creating an upward sublimation-driven wind that could lead to grain displacement.

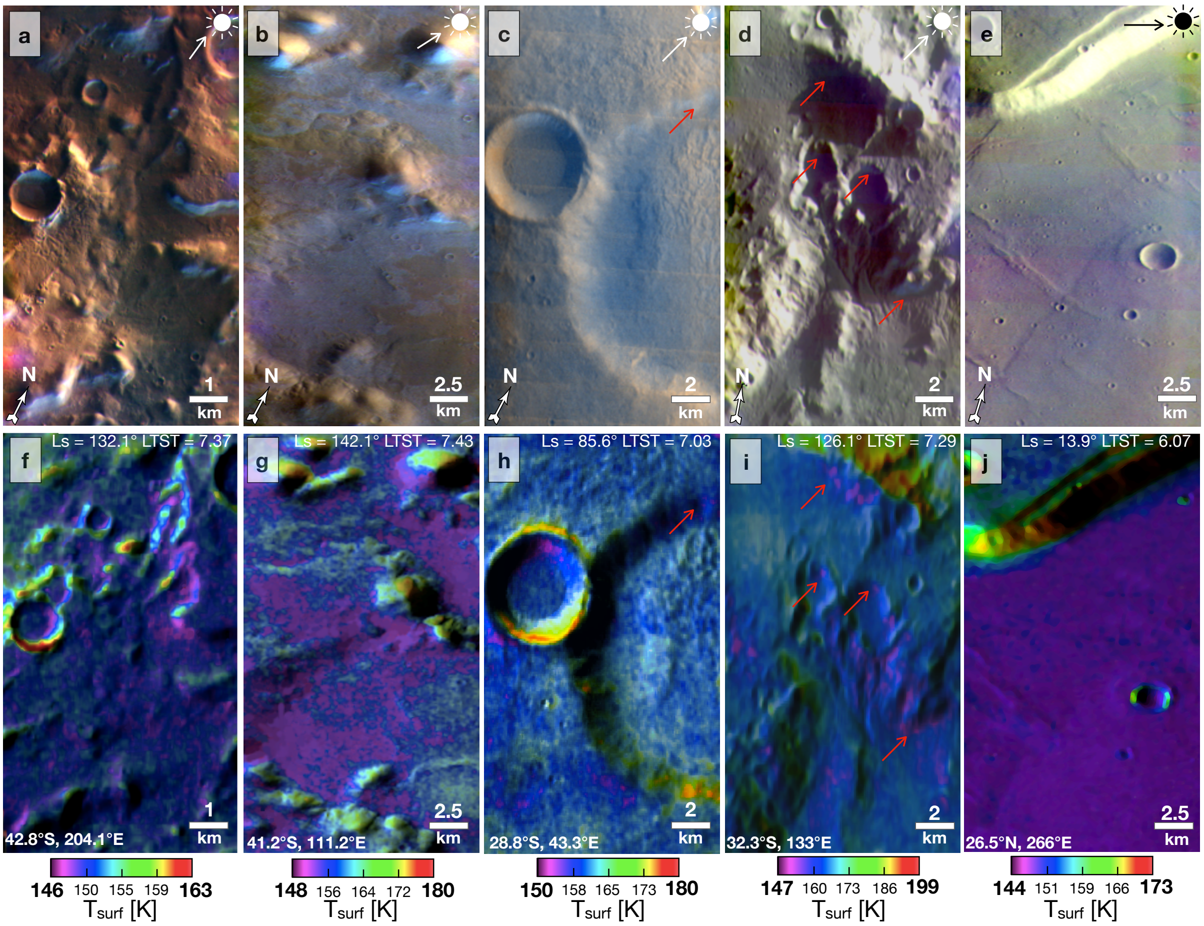

Fig. 2 Examples of THEMIS visible wavelength (a-e) and corresponding thermal infrared (f-j) images acquired simultaneously near dawn. The blue/white surface patches (a-d) and low surface temperatures within 5 K of T_{CO2} in infrared images (f-j). Coordinates, solar longitude (Ls), and local true solar time (LTST) are given in the different panels. Red arrows emphasize hard-to-distinguish blue/white patches. White arrow point to the position of the sun in the sky. a: Class 1, V71796004; b: Class 2, V63705007; c: Class 3, V78900003; d: Class 4, V63305007; e: Class 5, V76958011; f: I71796003 associated with a; g: I63705006 associated with b; h: I78900002 associated with c; i: I63305006 associated with d. j: I76958010 associated with e. f-j underlain with a THEMIS daytime IR mosaic to enhance topography [11]. Some terrains appear black in the thermal infrared images because of the background mosaic (not because of an absence of measurement)

Surface frosts are identified based on their blue/white hues, in stark contrast with the orange/brown/grey surrounding terrains (Fig. 2). The vast majority of these blue/white units are confidently attributed to the surface (as opposed to the atmosphere) based on their sharp boundaries following morphometric or color units, topography, or preferential slope orientation.

[2] demonstrated that CO_2 diurnal frost should form thin layers (i.e., a few microns to tens of microns in thickness) of micrometer size ice crystals (as opposed to translucent slab-like ice) in dusty surfaces. Micrometer size CO_2 ice crystals are associated with high albedo values at visible wavelengths [12], but dust contamination can drastically reduce it. [13] showed however that micrometer size ice crystals forming the top of dusty surfaces can be detected in these dusty surfaces. Hence, the albedo (or color) of frosted terrains provides an excellent diagnostic tool of the relationship between the ice and the regolith grains. Furthermore, the surface emissivity is highly sensitive to the presence of frost on the surface at $\lambda \sim 12.57$ µm (THEMIS band 9, [10]), even for thin frost layer. We therefore also use the surface emissivity to further constrain the frost/regolith relationship in the low thermal inertia regions of Mars.

Results:

THEMIS surface temperatures acquired at sunrise are consistent with the presence of CO_2 frost at virtually all latitudes (black and white dots in Fig. 3), confirming results presented by others with MCS [2] and THEMIS [3]. We find that 848 image pairs (out of 2,761, i.e. ,~30%, that have been flagged for CO_2 ice) that do not show a signature of frost in visible wavelength imagery, while the ground is at CO_2 ice temperature. Noticeably, no identification in visible wavelength imagery is located in the 45°N-15°S latitude band in the low thermal inertia terrains (i.e., purple in Fig.3,), where widespread diurnal CO_2 frost forms during a significant fraction of the year [2]. In contrast, at other latitudes, 87.5% of the image pairs at the CO_2 frost point temperature are associated with bright patches on the ground (whether contaminated by water ice or not). Most of the missing frost signatures in visible wavelength imagery when the surface temperatures at T_{CO2} at high latitudes are generally linked to poor image quality, with challenging illumination conditions that prevent us from clearly assessing the color of the surface. This

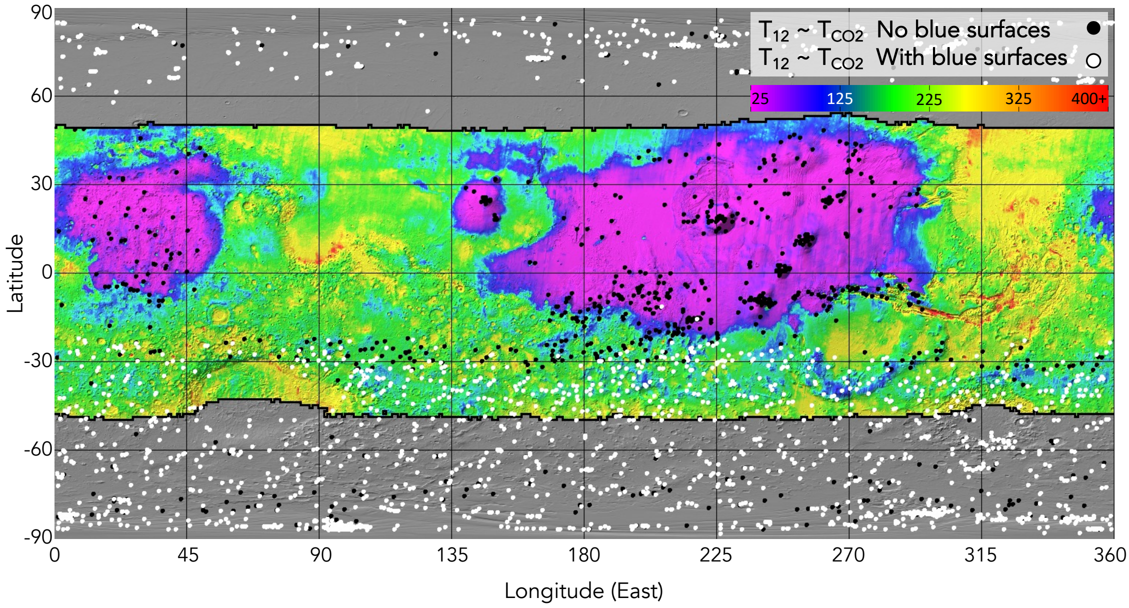

Fig. 3 Distribution of dawn THEMIS visible and infrared wavelength image pairs within 5 K of the local CO_2 frost point. Black dots indicate no signature of frost in visible wavelength images (848 images). White dots indicate the presence of image pairs where frost is identified at visible wavelengths (1,931 cases). Colorized background is a thermal inertia map overlaid on with a MOLA shaded relief only shown outside the maximum extent of the continuous seasonal caps. During the winter, the Northern high/mid latitudes are subject to much fewer observations than the Southern high/mid latitudes, partially explaining the hemispheric asymmetry

difference suggests that on low thermal inertia terrains, the visible wavelength optical properties of diurnal frost are uniquely dominated by those of the surface dust, i.e., ice forms within the pores the dusty layer.

We acknowledge that a regolith/ice relationship diagnosis solely based on terrain color can be complicated by the lowering of the ice's albedo by dust (e.g., [12]). Fig. 4 shows that most of THEMIS images in dusty grounds display a high surface emissivity, close to the emissivity of ice-free dusty grounds (0.96 [2]). We find that more than 70% of the images show a CO_2 frosted surface emissivity between 0.96 ± 0.04 (uncertainty defined as the 3-σ spread from our 5 K tolerance). Such high emissivities at 12.57 µm suggest the absence of CO_2 frost over dusty surfaces, or over micrometer size thickness (Fig. 11 in [2]). But in the latter case the ice thicknesses would be inconsistent with mass/energy balance results [2]. Thus, the high surface emissivity values are most consistent with an absence of frost on the surface.

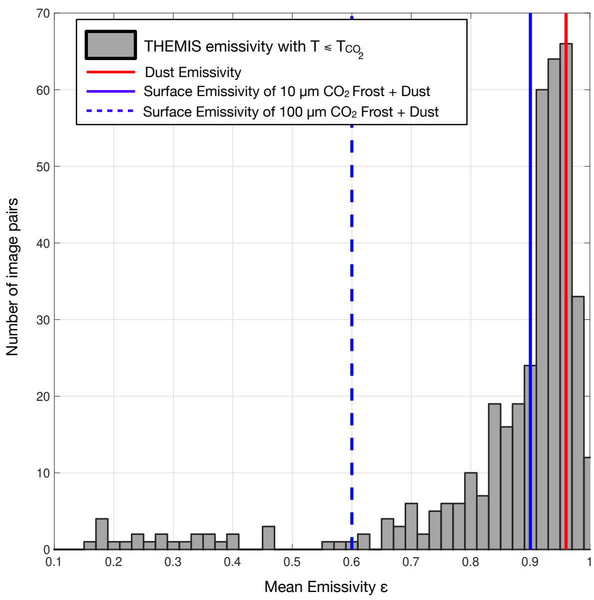

Fig. 4 CO_2 emissivity derived at λ = 12.57 µm. Dust emissivity at 12.57 µm (red line) from [2]. Modeled emissivity of the dusty surface overlaid by 10 µm (solid line) and 100 µm (dashed line) CO_2 ice layer indicated in blue [2].

The observations are thus consistent with dirty diurnal CO_2 ice in these terrains, following the hypothesis formulated by [2] , and illustrated in Fig.1.

Discussions:

Based on Earth analogies [14,15], we assume that the recurring growth and removal of ice may create a stress cycle in the regolith leading to internal grain displacement and microscopic weathering. At sunrise, the rapid sublimation of the diurnal ice creates a short-lived wind field within the regolith that exerts a drag on individual grains, that could promote the displacement of the dust grains. [13] computations show that frost sublimation-driven wind at sunrise reaches up to 3.2 cm s^{-1}, with a mean value between 1.5 and 2.0 cm s^{-1} (standard deviation of 0.8 cm s^{-1} as a function of season, latitude, and elevation. These values are upper limits and are generally larger than (but comparable to) other values reported in the literature for seasonal ice sublimation and Knudsen pumping [16,17]. Using a simple 1-D balance model, we show that [13] the vertical drag exerted on individual grains can be larger and opposite in direction to cohesion plus gravity forces, suggesting that motion can be initiated by this wind. Local slope, and more importantly grain packing angle as well as cohesion forces between grains are important factors controlling whether grain motion can occur. Winds faster than 2.5 cm s^{-1} are occasionally encountered and should be able to disrupt the ground on most sloped and poorly cohesive low thermal inertia terrains;

Consequently, this grain-displacement induced by CO_2 sublimation could promote other dynamic phenomena as slope streaks. Slopes streaks are dark wedge-shaped surface features on sloped dusty terrains, associated with mass movement downslope [18]. The formation process for slope streaks is still debated, and generally falls into two categories: wet vs. dry mechanisms, although both types can be associated with dust avalanches. [19]. These slope streaks are observed where diurnal dirty frost is expected most of the year [13]. We therefore assume that at sunrise, this diurnal frost sublimates, initiating a vertical drag on individual grains able to set those uncohesive in motion . In this model, steep dusty terrains already close to the angle of repose (i.e., 30-35° [20]) are destabilized and initiate an avalanche of dust. Our results also show that the velocities reached during sublimation can be high enough to exceed the velocity threshold computed in [21] required for fluidization of avalanching material. These fluidization of the avalanching material is necessary to explain the length and width of the slope streaks given.

We hypothesize that diurnal CO_2 ice sublimation may be triggering and sustaining the growth of slope streaks, but other factors such as local winds may be involved in this process. Our proposed model overcomes several limitations of competing dry mechanisms presented in the literature, but it is not unequivocally validated by observations constraining the seasonality or orientation of slopes highlighted by others.

Conclusions:

We have conducted an analysis of THEMIS visible and thermal infrared data acquired at dawn. This work constrains the relationship between diurnal frost and the surficial regolith on Mars. It unveils the potential geomorphological impact of the diurnal CO_2 cycle. Specifically:

- The distribution of THEMIS thermal infrared data acquired at dawn confirms the widespread nature of CO_2 frost on Mars previously reported [2,3];
- Multiband THEMIS visible wavelength images acquired at dawn frequently show blue/white hues interpreted as clean surface frost over a significant fraction of the surface. However, In the mid-to-low latitude low thermal inertia terrains (45°N-15°S), surface temperatures consistent with the presence of CO_2 frost on the ground do not show any frost signature in visible wavelength imagery, suggesting the formation of dirty frost.
- This conclusion is also supported by the high emissivity at 12.57 µm of these frosted surfaces;
- Recurring regolith grain movement on Mars instigated by overnight CO_2 crystal growth and rapid sublimation at sunrise could prevent the induration of the regolith observed elsewhere, maintaining large surface dust reservoirs available for lifting in the atmosphere;
- Within the regolith, wind generated by the sublimation of CO_2 ice could exert a drag on the dust grains, promoting the displacement of these grains;
- This displacement induced by the sublimation of diurnal frost could trigger the formation of slope streaks, especially since wind velocities required for fluidization are met. The sublimation of CO_2 frost after dawn may not be the only necessary factor required for their formation
- This potential CO_2 sublimation-driven geomorphological activity show that CO_2 is a geomorphological agent on all of the surface of Mars, not only in the polar latitudes.

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