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Observations of the surface effects of the CO_2 and H_2O cycles on Mars

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Abstract

One-third of the atmospheric CO_2 on Mars participates in an annual condensation/sublimation cycle. The generation of the seasonal polar ice caps and their subsequent sublimation in spring produce a wide range of interesting phenomena not seen elsewhere in the inner solar system. There are also numerous reservoirs of water on Mars. Here, too, exposure to insolation and subsequent phase change result in a series of transient phenomena. We review some of these phenomena with particular emphasis on work conducted by the University of Bern's remote sensing group.

1 Introduction

In recent years, remarkable progress has been made in the investigation of phenomena associated with volatile processes on Mars. The presence and dominance of CO_2 in the atmosphere and the buffering of the atmospheric pressure (at around 6–10 mbar) by condensation and sublimation of the polar caps has been well established since the pioneering paper of [21]. However, while the basic concept has remained unchanged, the details of the processes involved are themselves interesting and occasionally not well understood. The latter is particularly true because there are often no obvious Earth analogues for the processes involved. Investigation not only requires detailed study of remote sensing data and numerical modelling but also requires laboratory studies of samples held at low temperature and in near-vacuum conditions.

Similarly, although water vapour is only a trace species in the atmosphere (with a column density of typically 6–10 precipitable microns; e.g. [42]), the permanent ice caps and the sub-surface over vast areas provide large reservoirs of water. These reservoirs can be exposed and can sublime leading to volatile transport. In addition, there is increasing evidence that water in the liquid phase can be present on the Martian surface, albeit on short timescales.

Both volatiles are responsible for processes which modify the appearance of the surface of Mars. High resolution imaging (in particular from the HiRISE experiment on Mars Reconnaissance Orbiter; [24]) and spectroscopy are showing that the surface evolution resulting from these interactions is more rapid than heretofore assumed and indicates that the widely accepted view of Mars as a rather "dead" world is far from reality.

In this brief review, we shall look at some of the dynamic phenomena recently described in the literature with particular emphasis on those phenomena which are related to ices. The basic scientific questions which concern us can be framed as follows:

- Do we understand the physical processes connected with the CO_2 cycle (including interactions with water ice)?
- Is liquid water present on the surface of Mars and under which conditions?

The literature associated with this field is vast and hence inevitably we need to make a selection. Here, we primarily review topics to which the HiRISE group at the University of Bern has made a contribution and use this opportunity to "showcase" this work and place it in a more general context. For more extensive discussion of related topics, readers are referred to [3].

2 The CO_2 cycle

2.1 The basic elements

The seasonal CO_2 cycle on Mars is, to first approximation, the exchange of CO_2 between the atmosphere and the seasonal polar caps in response to changes in insolation. Insolation changes arise from Mars's orbit combined with the planet's obliquity ($\alpha = 25.19°$). A significant perturbation is produced by Mars's relatively large eccentricity (e =0.0934) which increases the duration of winter in the southern hemisphere. The seasonal insolation variation is especially large at the poles which see no insolation for more than 300 earth days. The absence of a thick atmosphere acting as a blanket results in energy loss from the poles through thermal radiation. As the temperature of the cap drops, condensation of CO_2 onto the unilluminated polar cap occurs, thereby releasing latent heat and stabilizing the temperature, T. The simplest equation to assess this behaviour is

$$\epsilon\sigma T^4 = L\frac{dm}{dt} \quad (1)$$

where ϵ is the infrared emissivity, σ is Stefan-Boltzmann's constant, L is the latent heat of sublimation of CO_2 which is around 4.5 x 10^5 J kg^{-1} and dm/dt is the mass condensation rate. The measured temperature (148 K) leads to a deposition rate of $\sim$ 45 μg m^{-2} s^{-1} which, assuming a frost bulk density of around 1 g cm^{-3}, leads to a build-up of a CO_2 frost layer at a rate of around 4 mm day^{-1} or approximately a 1.3 m layer over the entire Martian winter season.

The condensation on the winter pole is balanced by sublimation from the illuminated (summer) polar cap which can be assessed by

$$\frac{S(1 - A_H)}{{R_h}^2} = -L\frac{dm}{dt} \tag{2}$$

where S is the solar flux at 1 AU, R_h is the heliocentric distance of Mars (in [AU]), and A_H is the hemispheric albedo of the surface element. The cap temperature remains close to 148 K as sublimation rapidly compensates for the increased insolation. Both caps act as cold traps and therefore the energy balance equations combine with the equilibrium vapour pressure of CO_2 at the cap temperatures (see [16]) to produce a rather stable system but with inherent variations produced by slight differences in the albedos of the caps and by Mars's orbital eccentricity. We note that atmospheric dust and the possible presence of the slightly more stable hydrate, $CO_2.6H_2O$ are complicating factors. Hubble Space Telescope images have shown that the northern seasonal polar cap is almost completely removed by this sublimation leaving behind a residual polar cap composed of water ice. Just before the end of northern summer (at areocentric longitudes, $L_S \sim 120°$), the almost complete depletion of CO_2 leads to the temperature rising well above the 148 K expected for a CO_2 cap to reach the free sublimation temperature of water ($\sim$ 200 K). At the same time, a 10-fold increase in the atmospheric water vapour content, consistent with water ice sublimation, has been regularly observed and quantified [15]. The northern permanent cap is an impressive structure being 3 km in depth at its maximum [36]. The southern cap possesses a smaller permanent cap which, in contrast to its northern counterpart, is not centred about the rotation axis.

The total atmospheric mass is about 2.2 x 10^{16} kg. Measurements using gravity field data suggest the northern and southern polar caps have a seasonal mass change of 6 x 10^{15} kg and 9 x 10^{15} kg, respectively [17], with the difference being attributable to the longer southern winters. The pressure sensors on the Viking landers showed that the surface atmospheric pressure on Mars varies by $\approx$ 30% over the Martian year and is highly reproducible from year to year which is consistent with the seasonal mass change estimates.

The southern polar cap extends northward to 55° S in latitude. Effects of cap formation can be seen extending down to 45° in latitude in both hemispheres. There are numerous processes involved in the condensation and sublimation process which produce interesting phenomena not seen on Earth.

2.2 CO_2-ice related phenomena

When the Sun appears over the horizon in southern spring on Mars, dark fans are observed on the surface (see Fig. 1). The basic mechanism for their production has been described in detail by [18]. The hypothesis requires that during or after deposition, the approximately 1 metre thick layer of CO_2 ice becomes translucent to visible radiation. In a type of solid-state greenhouse effect the ice allows light to pass through to the dark surface below where it is absorbed. This heats and sublimes the ice slab from below. The pressure under the slab builds until a weakness is found and the gas forces its way out dragging dust with it. The orientation of the fan is generated either by the local topography or by local winds. Gas dynamics models show that these geyser-like jets are quite violent, spewing material up to 100 m above the surface [40]. Vent velocities can exceed 150 m s^{-1} with several hundred g s^{-1} of gas evolving through the vent immediately after the ice is breached.

The interaction of the jet material with the ambient atmosphere is rather complex. Particles smaller than about 30 microns, although initially fast, are rapidly slowed by collisions with the atmospheric gas and are then strongly influenced by local winds. Larger particles are less influenced by the ambient gas but do not reach as high initial velocities because they have insufficient time within the vent (the acceleration region) to reach the gas velocity. The gas itself is also in a rather complex state. The build-up of pressure beneath the slab ice implies that the gas there is warmer than ambient - perhaps by as much as 5K. On expanding out of the vent, it cools quickly to temperatures below the equilibrium vapour pressure. It is here that observations and modelling show inconsistencies. Many fans, shortly after their creation, show bright haloes surrounding the dark deposit (e.g. [39]). This has been inferred to be CO_2 ice and has been confirmed by CRISM observations and is assumed to be the result of condensation as a consequence of the adiabatic expansion of the gas [43]. The difficulty is that models currently show that the gas is in a super-saturated state for a very short time and that this is insufficient to build-up particles which are large enough not to be influenced by the ambient atmosphere and thus deposited close to the dark fans. The adiabatic expansion hypothesis is undoubtedly attractive although alternatives mechanisms for the production of the haloes can be envisaged (e.g. [40]). It therefore remains possible that there are details in the modelling of the phase transition which still need to be explored.

In Fig. 1, the orientation of the fans appears to be “organized”. Note also that there appear to be multiple fans originating from a single source but going in different directions suggesting that fan orientation is controlled by wind direction. It also shows that emission is not via a single event and, indeed, growth of fans over many days is commonly observed. Re-sealing of a vent is possible but it is more likely that the sources remain permanently open and that the outgassing through the vent is in response to the diurnal cycle. Models showing the feasibility of a “steady-state” response to solar insolation have been constructed and show that gas velocities in the cavity between the surface and the underside of the ice slab can exceed 20 m s^{-1} [41]. Given the significant dust content in the flow, this has the potential for scouring and carving the surface and may be a means of producing the so-called “spiders” (araneiform structures) seen in many regions in the southern polar regions [12]. These features (Fig. 1) are roughly 1.5 m deep with extended “arms” which are often bright in spring indicating a reflective (icy) content.

The production of fans is remarkably reproducible from year-to-year (see Fig. 3). As shown by [39], topography plays an important role in determining where fans will initiate. Weaknesses in the ice layer probably arise where the layer is draped over a local topographic feature. Where no strong feature exists, the ice can crack as a result of the pressure below. This process is more random and leads to a lack of reproducibility from year-to-year (Fig. 4).

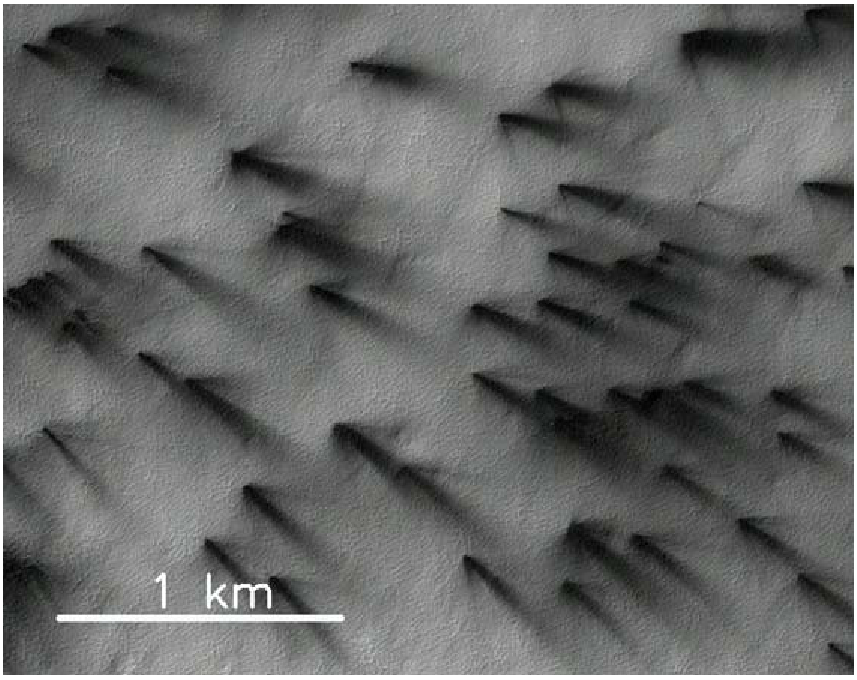

Figure 1: Sub-section of HiRISE image ESP_011671_0935 which shows multiple fans coming from the same source and many examples of fans which are aligned with each other.

The timing of these cracking events with respect to the start of southern spring has been investigated by [30] and shown to be consistent with a “Kieffer”-style model. [32] have recently extended this work.

The northern hemisphere shows some evidence of fan-like behaviour but the fans are smaller. High northern latitudes have large areas of dark dunes which exhibit dark flow-like features on their slipfaces ([13]; Fig. 5). Here again, CO_2 condensation in winter generates translucent slab ice but, in this case, geyser-like behaviour is not so profound. This may be the consequence of a thinner ice layer but is more likely to be because the dunes are composed of coarser grains [13] with the sand being more difficult to mobilize by this mechanism. Nonetheless, major mass transport is occurring in these regions with wind probably being another contributor to the overall story. Finally, it should be noted that although this might seem a fairly specific process, there are likely to be applications elsewhere in the solar system and beyond. The existence of geyser-like activity on Neptune’s moon, Triton, has been demonstrated and may result from a similar process but with a different ice (nitrogen). Possible implications for other bodies (e.g. the Jovian moons including Ganymede) should therefore be considered.

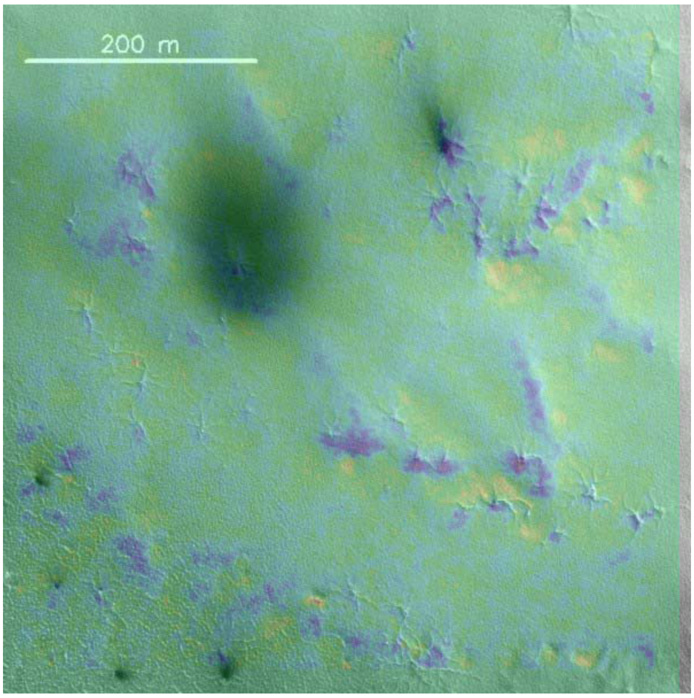

Figure 2: A region of Inca City with a colour-code topographic map superposed. Blue-violet is low (roughly 1.5 m depth). Yellow is high (roughly 1.5 m high). Note the depths of the spider-like features.

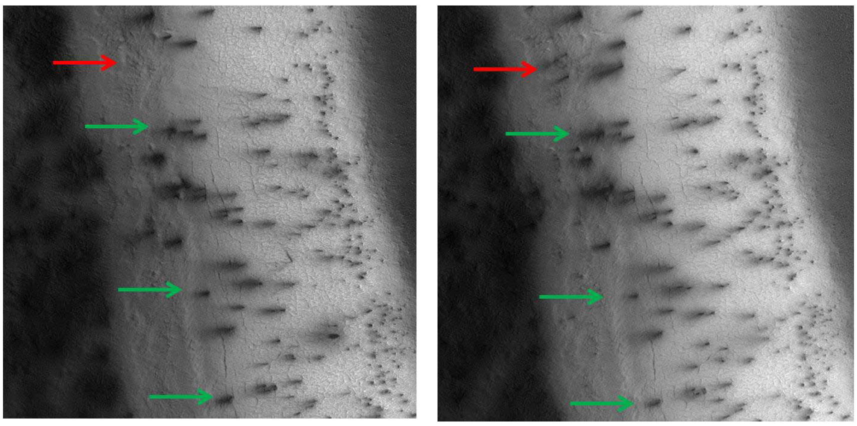

Figure 3: An inter-annual comparison showing the reproducibility of fans in Inca City. *Left*: L_s= 187.5° 7 Jan 2009 20:56:39. *Right*: L_s= 188.9° 28 Nov 2010 07:31:22. Most of the features are evident in both images. Note in particular the points indicated by the green arrows. There is one notable exception indicated by the red arrows.

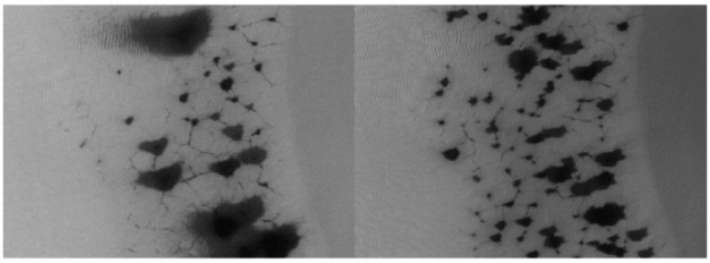

Figure 4: Area near Richardson dunes at roughly the same L_s but in two different years. HiRISE images PSP_002885_1080 and ESP_011640_1080.

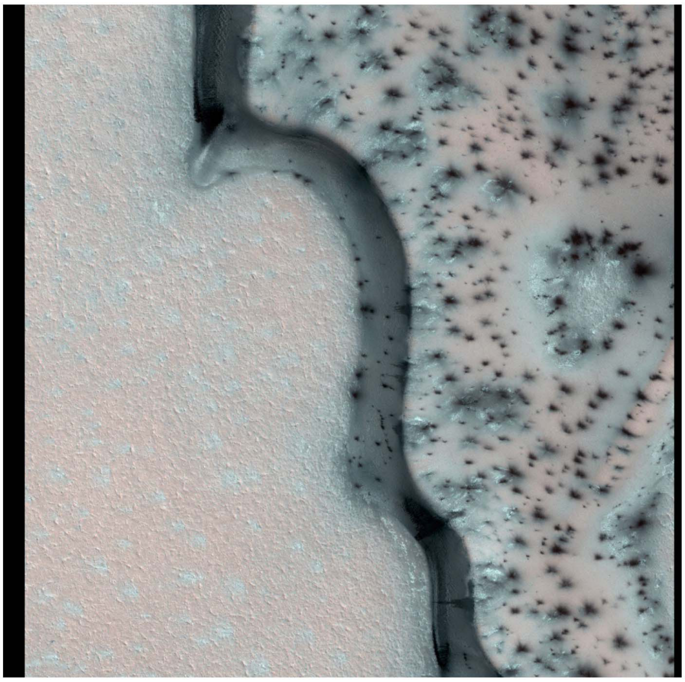

Figure 5: HiRISE image PSP_007725_2600 (122.5° E, 80° N) acquired at $L_s = 47.5°$ shows small fans on the dunes themselves. On areas where there are no dunes, there is no evidence of fan-like activity although the surface is covered with CO_2 ice. On the slopes of the dunes, there is significant mass transport evident.

2.3 Translucent CO_2 in the laboratory

The hypotheses and conclusions above rely on the natural production of CO_2 slab ice on Mars. This is actually not completely straightforward. Laboratory studies [31] show that several structurally and optically different forms of CO_2 ice can be produced - all in conditions which could easily be prevalent on Mars. Further carefully-controlled experiments are needed to establish the detailed process. On Mars, this is further complicated by the presence of dust. Dust should also be deposited in the condensation process and may even act as nucleation sites for condensation. As shown by [30] (and following ideas by [18]), dust absorbs heat and, in combination with gravity, can sink through the ice increasing the purity. On the other hand, the speed with which fan-like activity initiates on Mars after the start of southern spring remains a challenge to the model. Annealing of the ice may actually arise from the weak heating of the slab at its base as heat is returned to the surface - a consequence of thermal inertia (cf. [1]).

3 The H_2O cycle

3.1 Water reservoirs

The triple point of water (273.16 K) lies above the maximum temperature on Mars over much of the surface [11]. Hence, one expects water to be in the ice phase with relatively low atmospheric water vapour concentrations. The difficulty on Mars is to identify *where* water ice is present. The permanent polar caps have been shown to be water ice-rich. Clearly, they are large reservoirs but these structures, although interesting for their properties and as a climate record for Mars (e.g. [9]), they are, at the present, rather immobile. Elsewhere, however, optically-thick layers of dust cover much of the surface. But where water ice is exposed, it does become “active”.

For example, after the seasonal CO_2 sublimes away from an area, the surface temperature is free to rise in response to the insolation. If the temperature exceeds about 200 K, water ice begins to sublime more rapidly and the local atmospheric water vapour content can rise (as has been inferred from the seasonal behaviour observed in the northern hemisphere using the MAWD experiment on the Viking missions; [15]). Once airborne, the water vapour is free to move. As lower latitudes warm up, water vapour can be produced and this can be transported to higher latitudes where it re-condenses on the remaining CO_2 ice (which in this case is acting as a cold-trap). [29] has noted that the annual evolution of spectra at several regions on the seasonal polar caps shows interesting behaviour of the water absorption lines. Although the CO_2 slab ice must be relatively pure for the “Kieffer” mechanism to work, the surface in spring shows a build-up of water ice and dust as the CO_2 sublimes. The infrared CO_2 bands reduce in strength as the coverage increases - the water ice and dust are here almost like a lag deposit over the CO_2. Wind and more rapid sublimation as Mars moves towards summer then removes the dust and water ice and the H_2O band strength decreases.

The presence of water ice just below the surface of Mars, and in relatively pure form, has been clearly demonstrated by the Phoenix lander [6]. The presence of large quantities of water in the uppermost metre of the surface had previously been inferred from the neutron and gamma ray experiments on Mars Odyssey (e.g. [8]). HiRISE has contributed to this field by imaging fresh impact craters in the northern hemisphere (previously identified by the CTX context imager). [4] showed that shortly after the impacts, the craters contained high reflective material which was shown, via spectroscopy, to be H_2O ice. Several sites in the northern lowlands where impacts had occurred showed similar behaviour suggesting that ice just below the surface was being exposed. Monitoring revealed that the reflectivity of the surface slowly returned to its previous value over a period of several months. Sublimation of the ice, leaving behind a lag deposit, appears to be the most feasible process [7], again suggesting water transport. Numerical models, where a 30 cm layer of "damaged" dunite (simulating the dust layer) was placed over a pure water ice layer, illustrated the different effects that could occur during the impact of a 75 kg meteorite into the surface [33]. The pressures generated by the impact were found to be sufficient to liquify small quantities of water ice (although granularization is a plausible alternative).

These observations support the interpretation of various landforms in the northern lowlands as being periglacial. Polygonal terrain similar to that seen in terrestrial permafrost, shallow depressions and pingo-like structures have been observed. In terrestrial periglacial environments all these features are considered to indicate ground ice [38, 26]. [19] studied an area in Utopia Planitia which showed "scalloped" terrain and extensive polygonal cracking. Polygons initiate as a network of cracks formed by seasonal thermal contraction of ice-rich ground, often in permafrost (permafrost polygons). The depth, as well as the size and shape of the polygons, reflects thermal stress, climate conditions and ground properties [19]. Sublimation of the ground ice, in combination with dust, can lead to progressive collapse and enlargement of the troughs, forming high centre polygons. The freeze-thaw cycle can also lead to ice wedges (either through production of liquid or by decreasing the viscosity of the ice).

In the southern hemisphere, there is also ample evidence of similar periglacial features. Examples here are the scalloped terrains just outside the enormous impact feature, Hellas Basin. [20] noted that the Peneus and Amphitrites Paterae regions display large areas of smooth, geologically young, terrains overlying rougher, older topography. This type of terrain may be the remnant of a mid-latitude mantle deposit, which might be composed of ice-rich material originating from deposition during a high-obliquity period less than 5 Ma ago. Both polygonal cracks and scallop-shaped depressions are observed and have been interpreted as supporting evidence. (We note in passing that a competing thermokarst hypothesis for the production of scalloped terrain has also been proposed; e.g. [37].)

These works, in combination with many others, suggest that there is a significant sub-surface reservoir of water ice over vast areas of Mars. This water ice is occasionally exposed by numerous means and can sublime leading to transport and surface modification, including the appearance of periglacial features. The difficulty remains assessing the depth of this reservoir.

The MARSIS and SHARAD experiments are ground-penetrating radars which observe reflections from sub-surface interfaces and can be used to investigate the possible existence of sub-surface ice layers. The interpretation of the reflections is difficult (e.g. Fig. 6) be-

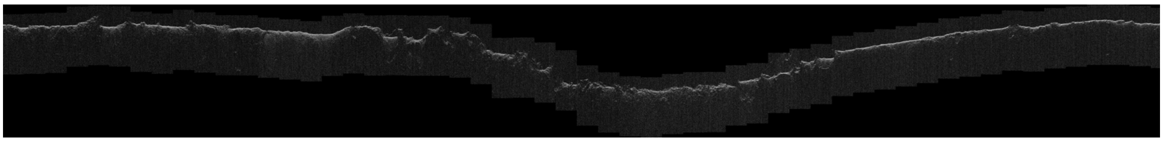

Figure 6: Example of a SHARAD track through Hellas Basin showing the complexity of the return signal. Most of the returns are reflections from the surface and the surface topography.

cause of "clutter" arising from reflections at the surface-atmosphere boundary and because of uncertainties in the form any ice layer may take (e.g. [44]). However, estimates of the global equivalent water layer comparable to that contained in the south polar residual cap have been made [27].

3.2 Sublimation as an erosional process

The sublimation/condensation cycle is also of interest as an erosional process. We have already seen how polygonal cracks can be generated as a consequence of the somewhat unusual properties of H_2O ice. The mass of condensed volatiles and the interaction of ice with scarps can also lead to mass wasting.

[34] presented remarkable observations of frost-dust avalanches from a scarp at 83.8° N, 235.5° E. An example from the following Mars year is shown in Fig. 7. The upper $\sim 500-700$ m of the scarp comprises H_2O ice-rich layers of the north polar layered deposits (NPLD) with varying dust content. The upper slopes of this structure are steep while the lower reaches are more gently sloping. The avalanches occur as the CO_2 frost coverage begins to lessen during northern spring - typically around $L_s \sim (20-50)°$. Multiple avalanches can occur along the scarp simultaneously which confirms that mass wasting may be a major driver of steep scarp retreat in this region. The process involved is probably similar to terrestrial dry, loose snow avalanches. In winter, CO_2 ice and frost accumulates on scarp ledges and crevices. As sublimation in spring occurs, parts become unstable and events can be triggered by gas expansion or wind gusts. This can lead to further erosion of the face as the material drops down the side of the slope. Hence, we have a mechanism whereby CO_2 condensation and sublimation can lead to the exposure of water ice rich layers.

3.3 The liquid phase

[11] has shown that liquid water can be stable on Mars but that the sites are limited and the durations short. However, liquid water does not have to be "stable" - it can be transient and influence the surface properties. This has clearly occurred in the past on Mars but is it occurring today?

Observations of seasonally recurring dark flow-like structures on the surface have now been seen at several sites in the HiRISE images. The identification of Recurring Slope Lineae (RSL; [25]) has prompted considerable debate and further research about the interaction of

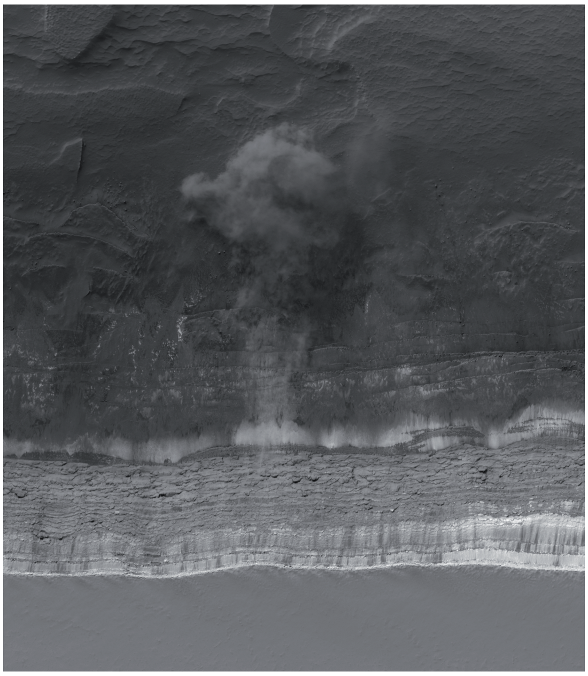

Figure 7: HiRISE image ESP_016173_2640 showing an avalanche from a scarp in the Northern Polar Layered Deposits.

liquid water with compounds which may be found on the surface of Mars. RSL is distinct from dry, slope streaks in being repetitive year-on-year. The flow features (which are small although numerous in many areas) also develop in length over time during spring. There is also an indication that, after they fade away during autumn, they leave behind a bright deposit. The sources are often equator-facing slopes which receive enhanced insolation during spring and early summer. The slopes are steep, near the angle of repose for cohesionless particles, and appear to be sites of active mass wasting ([25]).

The clear inference is that these features are related to liquid water. The temperature rises, coming close to the triple point, melting occurs and the liquid flows down the slope wetting the surface. Unfortunately, two issues complicate the problem. Firstly, the temperature is not clearly above 273 K in these regions. In particular, the surface layer is quite insulating and hence sub-surface temperatures, below one thermal skin depth, will be considerably below 273 K. This implies that liquefaction of the ice must be balanced either by mass wasting of any surface "matrix" or some form of hydraulic gradient in order to ensure reproducibility. The temperature issue might be overcome by invoking brines with eutectic temperatures below 273 K although there remain uncertainties concerning the re-charging of the source. The second issue, however, is more difficult to wave away. CRISM observations have consistently failed to detect water absorption bands from RSL. The observed darkening of the surface is extremely reminiscent of wetting of sand but this should produce strong absorption bands. The influence of brines on the properties of water and means of masking water absorption bands are currently the subjects of detailed investigations in many laboratories.

3.4 Brines and water ice in the laboratory

The influence of wetting on the photometric properties of Mars simulants was first investigated by [10]. Photometric measurements of wet samples show the strong influence of the presence of liquid water on the photometric properties of soils, both in terms of Bond albedo and shape of the reflectance distribution function. Improved experiments in this direction are now being carried out with the PHIRE 2 experiment ([28]) which including studying the photometric properties once the sample has naturally dried out. This type of work complements studies being carried out at other laboratories. Of particular interest is laboratory work on the infrared reflectance ([23]) which remains the main stumbling block in assigning RSL to a liquid water driven process.

Investigation of brines in a Martian context has been a major topic of research since the detection of perchlorates at the Phoenix landing site and the possible liquid nature of droplets on the Phoenix lander [6]. Depression of the eutectic temperature to well below 200 K is now considered feasible in the laboratory although is practically unlikely on Mars itself. The most likely brine compositions relevant to RSL are chlorides (Mg, Na, or Ca) or iron sulphates. Iron and sulphur, for example, were both detected in the Martian soil in fairly large quantities by the Viking landers and the Mars Pathfinder APXS experiment [2]. It is fairly simple to generate an iron sulphate solution which is liquid at 240 K (and lower under optimum conditions; [5]) although it needs to be stated that the viscosity of this solution is high, reducing as it warms. The pre-requisite of leaving a residue brighter than standard Mars analogues is easily achieved with such solutions.

PHIRE 2 is primarily being used to study the reflectance properties of water ice. The dependence of reflectance properties on ice structure is large with difficulties arising from ensuring reproducible results. CO_2 ice can also be studied in the facility which can allow us to characterize the unusual phenomena noted in Section 3.1.

4 Summary

Phase change processes generate remarkable dynamic phenomena on Mars. CO_2 is responsible for geyser-like activity at the poles and active mast wasting in polar areas. Although CO_2 is the main volatile, H_2O also plays a role. Indeed, some of the more subtle phenomena observed indicate that water vapour transport and condensation needs to be taken into account when the details of several processes are investigated. There is also a vast amount of water present on Mars in different reservoirs. Water ice at lower latitudes merely needs to be given a way to receive energy in order to sublime or, possibly, change into the liquid form. There are even chemical processes which can assist it such as the formation of brines.

While there is a considerable amount of hype about Mars, behind this lie a number of fascinating questions about a planet, close to the habitable zone and yet dramatically different from our own Earth.

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