Slope streaks on Mars: A new “wet” mechanism

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ABSTRACT

Slope streaks are one of the most intriguing modern phenomena observed on Mars. They have been mostly interpreted as some specific type of granular flow. We propose another mechanism for slope streak formation on Mars. It involves natural seasonal formation of a modest amount of highly concentrated chloride brines within a seasonal thermal skin, and runaway propagation of percolation fronts. Given the current state of knowledge of temperature regimes and the composition and structure of the surface layer in the slope streak regions, this mechanism is consistent with the observational constraints; it requires an assumption that a significant part of the observed chlorine to be in form of calcium and ferric chloride, and a small part of the observed hydrogen to be in form of water ice. This “wet” mechanism has a number of appealing advantages in comparison to the widely accepted “dry” granular flow mechanism. Potential tests for the “wet” mechanism include better modeling of the temperature regime and observations of the seasonality of streak formation.

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1. Introduction

Search for terrestrial analogs is a powerful, widely used method in planetary science. With the absence or scarcity of “field” observations in distal worlds, the morphological similarity of remotely observed planetary features to their terrestrial counterparts is a valuable hint that suggests similar formation mechanisms. However, even striking morphological similarity is only a hint, not a proof of the similarity of mechanisms. Any inference based on morphological similarity needs to be accompanied by analysis, whether or not the suggested mechanism is consistent with conditions on other planets.

Slope streaks (Fig. 1) are one of the most spectacular modern phenomena observed on Mars; simultaneously, they are poorly understood. Studies of slope streaks may provide a clue for understanding the basic properties of the martian surface layer, dust and water cycles and the most recent (hundreds of years time scale) climate change. In this paper we first briefly summarize observations on slope streaks and provide an overview of proposed mechanisms for their formation. Next we briefly describe wet slope streaks in Antarctica, features that appear strikingly similar to the slope streaks on Mars, explain briefly how their formation mechanism works in that environment, and show why this mechanism cannot be directly exported to Mars. We, do however, export some essential aspects of this mechanism to Mars, and accommodate the constraints required by known martian conditions. On the basis of these considerations we propose a new mechanism for the formation of slope streaks on Mars and discuss possible tests of this mechanism.

2. Slope streaks on Mars

2.1. Observations

Slope streaks on Mars were first seen in Viking Orbiter images (Morris, 1982; Ferguson and Lucchitta, 1984). Using images obtained by MOC onboard Mars Global Surveyor, Malin and Edgett (2001) discovered that the slope streaks are forming in the present epoch, and Sullivan et al. (2001) gave a detailed description of these features. Some additional observations with MOC images, as well as with images obtained by the HRSC camera onboard Mars Express, were presented by Schorghofer et al. (2002), Aharonson et al. (2003), Miyamoto et al. (2004), Baratoux et al. (2006), and Schorghofer et al. (2007). The higher resolution HIRISE camera onboard Mars Reconnaissance Orbiter provided new details about these features (Chuang et al., 2007; Phillips et al., 2007). Here we present a brief summary of all these observations. Each statement in the rest of this subsection contains results from one or several papers mentioned above, unless another source is explicitly stated.

Slope streaks on Mars are very specific albedo features on slopes (Fig. 1). They are elongated along the topographic gradient and have very sharp (unresolved at ~30 cm resolution) edges. They are mostly darker, but sometimes brighter than their surroundings (Fig. 1c); the albedo contrasts are not high, reaching...
Fig. 1. A representative example of slope streaks on a hill in Cerberus Tholi. Images are highly contrast stretched. Portions of HiRISE image PSP_005786_1880, 8° N 163° E, north is at the top, illumination is from the lower left. Boxes in (a) show locations of enlargements (b–e).

~10 relative percent contrast for dark and ~3 relative percent for bright streaks. With HiRISE color observations we found little color difference between the streaks and surroundings, while Mushkin et al. (2008) reported some spectral variations on the basis of multicolor HRSC images. Examination of CRISM spectra of a few streaks shows no hydration signature (Mushkin et al., 2008).

The largest slope streaks are a few kilometers long (e.g., Fig. 1a) and up to a few hectometers wide. Their length is apparently limited by the maximum length of relatively steep slopes. Smaller streaks are often observed, down to the image resolution. In a few HiRISE images, we observed the entire continuous morphological sequence from kilometer-scale to meter-scale streaks (e.g., Figs. 1a and 1b), which suggests the same formation mechanism over at least 3 orders of magnitude in size.

Repeat imaging coverage revealed a large number of newly formed streaks. Streak formation is highly inhomogeneous both in space and in time. Due to this fact, different approaches to estimation of the mean formation rate (Aharonson et al., 2003; Schorghofer et al., 2007; Sherman and Kreslavsky, 2008) gave different results, ranging from ~3% to ~10% per streak per martian year.

Newly formed streaks are always dark, and are darker than any other streaks in the same region. Where cross-cutting relationships between neighboring streaks are observed, the younger streaks are always darker (e.g., Fig. 1d). This indicates that the streaks brighten with time and sometimes (but not always) become brighter than their surroundings, and then fade away. Direct observations of changes during a 25–30 year period support this
The rate of new streak formation is much greater than the rate of disappearance, and the total number of streaks is increasing in the present epoch, with the total effective age of the population being on the order of a hundred of years.

The streaks usually have a sharp acute upslope end and lobate to branching and braided downslope end (e.g., Figs. 1a and 1e). The upslope ends are often (but not always) at boulders, scarp, etc. (e.g., Figs. 1a and 1b). These observations strongly suggest some kind of initiation at the upslope end and propagation from the upslope to the downslope end of the streak. The streaks always follow large-scale (hectometers) changes in topographic gradients; they behave in different ways with respect to smaller (meters, decameters) topographic obstacles: they often extend through them (Fig. 1), but also can go around and leave obstacles as islands.

At present, there are no adequate data sets for systematic measurements of the steepness of slopes bearing the streaks. A few measurements with individual MOLA profiles yield slopes in the range of 10–20°. Kreslavsky (2007) reported on measurements of average (beginning to end) slopes of large (km-long) streaks with manual point matching in HRSC stereo pairs; the slopes varied within the 7–25° range. In that study, special attention was paid to streaks possibly on gentler slopes, and it was shown that a noticeable number of long streaks have average slopes gentler than 15°. Proximal (upper) parts of the streaks are often steeper than the average slope.

Slope streaks occur in certain broad regions at low latitudes (Fig. 2a). Within these regions, streak occurrence patterns are very different. In some localities every slope bears streaks. In other localities streaks are only in some places, and many slopes are free of streaks. The slope streak regions have distinctive surface layer properties: high albedo, very low thermal inertia and the spectral signature of fine dust. Apparently, the presence of a thick fine dust layer on the surface (at least a few cm) is essential for streak formation. Slope streak occurrence shows no correlation with bedrock geology. This strongly suggests that the formation mechanism is related to the surface layer and not related to geologic settings. Streak occurrences show no obvious relation to elevation. The highest streak we found was on a mesa above the Olympus Mons scarps, above 6 km elevation. Slope streak regions do not occur in lowlands; the lowest streak elevations are within 2–3 km below the datum. Streaks are formed on slopes of all orientations, except the northernmost part of the occurrence regions (32–38° N), where streaks are observed on equator-facing slopes only.

2.2. Relation to triangular scars

Topographic features with minor negative relief (less than a meter) present in the slope streak regions and resembling slope streak planforms (Fig. 3, B arrows) were first discovered on MOC images, described in detail by Gerstell et al. (2004) and dubbed “avalanche scars”. To avoid this genetic term, we refer these features as “triangular scars”. Gerstell et al. (2004) argued that these features are different from slope streaks. Later, with HiRISE images, Chuang et al. (2007) and Phillips et al. (2007) clearly showed that some dark slope streaks lie within their own scars, and interpreted the scars to represent topography associated with the streaks and produced by a specific streak formation process (dry dust avalanche). In their interpretation, scars devoid of albedo features are old slope streaks, whose albedo signature has completely faded away. Phillips et al. (2007) also documented positive topographic features in the distal parts of the triangular scars in addition to the negative topography of the proximal parts.

From our analysis of a number of HiRISE images we conclude that the relationship between slope streaks and triangular scars is more complex. There is no doubt that they are related to each other. In addition to a few undeniable examples of streaks with their own scars (e.g., Fig. 3, A arrow), there is a very strong similarity of their planforms, and also a coincidence of locations. The topographic amplitude of the scars varies between localities, perhaps due to variations in the thickness of the dust layer or some other surface layer properties; in some localities the scars are absent; perhaps they are too shallow to be visible in available HiRISE images, given the illumination and observation conditions. However, in each locality, all scars tend to have the same depth (e.g., Fig. 3, B arrows). Probably, the depth of the scars is controlled by some properties of the local surface layer; regional variations of these properties lead to the existence of localities with deeper scars, shallower scars, and no observable scars. In some localities with abundant well expressed relatively deep scars, we observed clear examples of dark streaks without any associated distinguishable topography in HiRISE images (e.g., Fig. 3, C arrows). Chuang et al. (2007) interpreted the streaks without scars as the cases where scars are too shallow to be seen; this explanation, however, is not applicable to the case shown in Fig. 3C and in analogous sites, because all scars in the vicinity have similar well-distinguishable depth. This implies that, despite the obvious genetic relationship, the scar formation process is not the same process that forms dark streaks. The relationship is more complex; for example, streak formation may sometimes initiate scar formation and sometimes not.
or, alternatively, scar formation can be a longer-term process (years or decades time scale) that always follows dark streak formation.

More detailed morphological observations, as well as observations of real-time changes, are necessary to address the intriguing problem of relationship between the slope streaks and the triangular scars. For the purposes of this paper we only emphasize that this relationship is rather indirect.

2.3. Proposed mechanisms of formation

A number of mechanisms and variants on these mechanisms have been proposed to explain the slope streaks. Originally, Morris (1982) proposed dust removal by mass wasting from cliffs. Now, in high-resolution MOC, and especially HiRISE images, details of morphologies produced by mass wasting from cliffs are clearly seen. Sometimes (not always) mass wasting produces darker lanes on slopes; these lanes, however, are very different from the slope streaks: their edges are diffuse; they do not have sharp initial points, etc. Thus, mass wasted debris itself does not produce slope streaks. (There are spectacular examples, where rolling boulders dropped from cliffs triggered formation of slope streaks, see, for example, Chuang et al., 2007.)

Another initially proposed mechanism is stains from liquid flows of brines (Ferguson and Luchitta, 1984). Recently a variety of ideas about groundwater discharge (e.g., Ferris et al., 2002; Jaret and Clevy, 2007; Mushkin et al., 2008) have been considered. We do not think that such ideas are viable because the streaks clearly occur in very different geological situations. They often are observed on slopes of small isolated hills and mesas. In martian environmental conditions, where recharge of aquifers from the surface is currently absent, such groundwater discharge from isolated hills and mesas would require a very unusual coincidence of circumstances, and even if it were possible, it is highly unlikely that it occurs at very high rates (tens of thousands to a hundred thousand per martian year over the whole planet) in thousands of locations in very different geological settings.

The “wet” mechanism that we propose below is free of these major problems of groundwater discharge and subsurface aquifers: in our mechanism, the streak formation process operates in a thin surface layer and is independent of geological environment.

The most popular and well-accepted mechanism of slope streak formation is dust avalanches. This mechanism was described in detail by Sullivan et al. (2001). In its original version, the mechanism involved exposure of a darker layer underlying the bright dust. As argued by Baratoux et al. (2006), the dark layer is not necessary, and apparent albedo contrasts can be explained by alteration of the structure of the surface. We refer to different varieties of the mechanism involving dust avalanches as a “dry” mechanism. It is important that here we deal with an unknown type of granular flow, which has no direct analogs on the Earth either in nature or in the laboratory. Such well known, and relatively well-studied varieties of granular flow as sand avalanches, snow avalanches, rock avalanches, landslides of different kinds, debris flows, and density flows differ from the hypothesized dust avalanches: their principal physical parameters and resulting morphology are different. Order of magnitude estimates made by Sullivan et al. (2001) unequivocally indicate that such a type of granular flow may exist (that is, it does not contradict the basic principles of physics); however, it should be emphasized that it has never been directly observed in the laboratory, or in a terrestrial geological environment.

The major problem with the “dry” mechanism is the fact that the presumable avalanches are required to run long distances on rather gentle slopes. As discussed in detail by Miyamoto et al. (2004), the dust avalanches should have little inertia; they need to lose and regain their momentum over short distances. It is very difficult for a dry flow to regain its momentum at slopes significantly gentler than the angle of repose. The “wet” mechanism that we propose in this paper is free of this major problem, because it involves fluid rather than granular flow.

3. Slope streaks in Antarctica

Terrestrial features most similar to the martian slope streaks are wet slope streaks in the Antarctic Dry Valleys (Head et al., 2007). In particular, slope streaks were observed in the South Fork of upper Wright Valley. These streaks typically display a low brightness relative to their surroundings, show no detectable relief, are elongated downslope, are usually <60 m in width, and extend for distances ranging from ~100 to ~400 m; length/width ratios range from ~10 to 35. They occur on steep slopes (10–30°) associated with the southern wall of upper Wright Valley in colluvium derived from bedrock scarps and masses that are exposed ~400–600 m above the valley floor. Slope streaks occur preferentially on the equator-facing slopes. New streaks are typically the darkest, some relatively bright streaks are also observed. Streaks follow local topography closely and are often digitate and branching distally; their planforms show striking resemblance to the middle and
downslope parts of the martian streaks, with the same style of branching, deflection by obstacles, etc.; however, unlike the martian streaks, Antarctic slope streaks do not have distinct and often pointed upslope ends. The boundaries between dark streaks and brighter inter-streak areas are knife sharp at the cm scale. There is no evidence for differences in grain size, surface textures, or rock types, between streak and inter-streak areas at the cm to m scale. Albedo variation within streaks is related to darkening of the finer-grained soil component of the deflated surface. The main difference between the soils of the colluvium in the streak and inter-streak areas is a difference in their water content. Soils in the inter-streak areas were dry at visible scales at the surface and down toward the ice table. Soils in the streak areas are moist from the surface down to the top of the ice table in the colluvium; however, they were not saturated with water. No evidence of fluvial activity or overland flow of water was observed.

The broader region where the Antarctic slope streaks occur is a permafrost region with year-average surface temperature well below 273 K, and warm-season, day-average surface temperature near 273 K (Marchant and Head, 2007). There is continuous permafrost in the area; the depth to the ice table in the region during near 273 K (Marchant and Head, 2007). There is continuous permafrost in the area; the depth to the ice table in the region during the warm season is ~20–40 cm (Head et al., 2007). There are no manifestations of the presence and release of deep groundwater onto the nearby surface: e.g., wettings or icings of outcrops, springs, sapping, etc.

Head et al. (2007) concluded that the mode of formation of the Antarctic slope streaks is as follows. Accumulation of snow during the austral winter in specific environments (e.g., outcrop alcoves in cliff faces) results in the preservation of snowpack well into the austral summer; during austral summer, and in areas with favorable insolation geometries, melting takes place in the snowpack and the meltwater percolates into the dry substrate to the top of the ice table, where it then migrates downslope. In areas of coarser colluvium (usually at the top of the slope) porosity is higher, and water travels downslope along the top of the ice table; when it reaches the finer-grained colluvium typical of the mid-to-lower slopes, grain-boundary contact causes “wicking” of the moisture toward the surface, resulting in the wetting of the surface that produces the dark streak. Diversions in course are caused by changes in slope orientation (mirrored in the ice table). Bright streaks occur adjacent to some dark streaks and appear to represent former dark streaks that have undergone desiccation; relative brightness may be related to salts deposited by the moisture. Repeat imaging shows that the streaks change over time scales of several years, lengthening, darkening and brightening. New streaks are always darker.

This streak formation mechanism cannot be directly exported to today’s Mars. In the equatorial regions of Mars at present there are no seasonal weather variations, and no seasonal accumulation of snow or frost; night-time frost accumulation, even if it occurs, is limited to microscopic amounts by the low total water vapor content of the cold atmosphere; melting of snow and frost, even if present, is impossible at higher elevations, where the atmospheric pressure is well below the triple point pressure of water through-out the whole year. Even at low enough elevations, where the atmospheric pressure is above the triple point, the soil immediately at the surface cannot preserve its moisture; due to relatively high day-time temperatures and low water vapor content of the atmosphere, the moisture would dry at a time scale of days or quicker, while the streaks on Mars persist for decades. Martian slope streaks develop from a sharp point at the uppermost end; Antarctic streaks do not, or their starting point is obscured. On Mars, the fine dust layer seems to play a role in the streak formation; in Antarctic such a layer is absent.

Thus, the slope streak formation process on Mars is not a replica of the process observed in Wright Valley. Striking similarity of the planforms, however, made us consider if any of the characteristic features of Antarctic streaks are applicable to understanding slope streaks on Mars. The process responsible for the downslope propagation of the streak boundary in Antarctica is percolation of a liquid (water) on top of an impermeable layer (ice table). Thus, we asked the questions, given known environment of the slope streak regions: What liquid can percolate in the shallow subsurface of Mars, and what kind of impermeable layer could be naturally present?

4. Constraints on “wet” mechanism

In this section we present the logic that led us to the formulation of the “wet” mechanism outlined in the next section. The essential question in the formulation of the “wet” mechanism is the nature of a liquid phase capable of percolation in the shallow subsurface of Mars. Atmospheric pressure and surface temperature put significant constraints on this. A necessary condition for the existence of a liquid phase is that the temperature at the surface or in the shallow subsurface should be higher than the melting point and lower than the boiling point at a given atmospheric pressure; the latter is equivalent to the statement that the atmospheric pressure should be higher than the saturation vapor pressure at a given temperature. To avoid confusion, when these necessary conditions are met, we use the phrase “metastability of a liquid phase”. These conditions are different from the conditions of a liquid phase in thermodynamic equilibrium with its vapor, when the actual partial vapor pressure is equal to the saturation vapor pressure at a given temperature.

4.1. Pressure constraints

Pure water and any dilute aqueous solutions are excluded, because the streaks are observed at elevations as high as 6 km above the datum, where the atmospheric pressure is well below the triple point pressure of water, and liquid water cannot exists as a phase.

We would like to make clear that when we speak about liquid water as a phase, we do not include thin films of H2O molecules at the surfaces of solid grains. Such films do perhaps exist in martian soils (e.g., Möhlmann, 2008), and they are known to possess many microscopic properties of a liquid H2O phase, even when pressures and temperatures are well outside the domain of liquid water metastability. However, such films do not possess the essential macroscopic property of the real liquid phase: they cannot produce macroscopic flow.

Concentrated aqueous solutions of sulfuric acid H2SO4 have been discussed as possible liquid phases that may have played a significant role in martian surface evolution (e.g., Kargel and Marion, 2004; Kreslavsky and Head, 2007); volcanic gases inevitably supply sulfur species to the atmosphere, and sulfuric acid H2SO4 is the final product of atmospheric photochemistry of sulfuric species (e.g., Wong et al., 2003, 2005). Saturation vapor pressure of H2O and the melting point of the H2SO4 + H2O system can be low enough to allow for a metastable liquid phase under conditions relevant to the slope streak regions. However, under those conditions, the saturation vapor pressure of H2SO4 is not negligible: if any (liquid or solid) H2SO4 + H2O phase existed in macroscopic amounts, this would be inevitably accompanied by the presence of some H2SO4 in the atmosphere, which, in turn, due to photochemical processes, would mean the presence of the whole range of gaseous sulfur species, like SO2, at least in trace amounts. Dedicated searches for such species with advanced spectroscopic methods did not give any positive result. Thus, aqueous sulfuric acid phases do not exist on Mars today; all sulfur released by volcanism is currently bound into sulfates.
Hydrogen peroxide $H_2O_2$ is constantly produced by atmospheric photochemistry in the present epoch (e.g., Wayne, 2000). Concentrated aqueous solutions of $H_2O_2$ have low enough saturation $H_2O$ vapor pressure and freezing temperature. Hydrogen peroxide is chemically active and not stable; however, its concentrated aqueous solutions could be metastable for a long time. As in the case of $H_2SO_4$, the saturation vapor pressure of $H_2O_2$ for $H_2O_2 + H_2O$ condensed phases is negligible, and if such phases existed in macroscopic amounts anywhere in martian soils, the partial pressure of $H_2O_2$ in the atmosphere would be comparable or about an order of magnitude less than the saturation $H_2O_2$ pressure for typical average surface temperatures (as it also occurs for $H_2O$, which does exist on Mars as a condensed phase, namely, ice). The measured atmospheric abundance of $H_2O_2$ (Encrnez et al., 2004), however, is about 5 orders of magnitude less and is not consistent with the presence of $H_2O_2 + H_2O$ as a phase. Perhaps, hydrogen peroxide produced by atmospheric photochemistry decomposes and/or oxidizes the soil.

Finally, brines (concentrated aqueous solutions of salts) can have significantly lower saturated vapor pressure in comparison to pure water. Salts known to be actually present on Mars in significant amounts are sulfates and chlorides (e.g., Wänke et al., 2001; Yen et al., 2005). The solubility of sulfates at low temperature is too low; they cannot reduce the saturation $H_2O$ vapor pressure enough to provide metastability of a liquid phase at 6 km elevation. Chlorides, however, can accomplish this.

One exception is a supercooled aqueous solution of ferric sulfate $Fe_2(SO_4)_3$. A concentrated aqueous solution of ferric sulfate, if it is cooled quickly enough, does not freeze, and remains in the form of a metastable very viscous supercooled liquid. As the temperature decreases, the viscosity increases and finally a glass phase is formed. Recent measurements (Chevrier and Altheide, 2008) showed that the saturation water vapor pressure above such a deeply supercooled concentrated ferric sulfate solution is lower than the saturation water vapor pressure above ice. The potential existence of such a metastable phase is an interesting option for Mars (Chevrier and Altheide, 2008). In the present paper, however, we do not investigate this in detail and focus instead on chlorides.

We do not believe that any non-aqueous liquid phases can be responsible for the slope streaks. In principle, a number of complex organic compounds have low enough saturation vapor pressure and low enough melting temperature. However, were such "oil" present near the surface, we would anticipate some amount of its vapor in the atmosphere along with a wide range of organic species formed due to its photodissociation. No organic atmospheric species, except a tiny amount of methane, have been reliably observed, despite intensive searches. In addition, it is very difficult to propose a reasonable explanation for the origin of such "oil" on Mars.

Thus, highly concentrated chloride brines potentially can be metastable in the whole range of atmospheric pressure under which the streaks form.

4.2. Temperature constraints

The temperature regime of the surface layer in the slope streak regions plays an important role in our considerations. We assessed the surface temperature regime for the slope streak regions using the surface temperature data in the European Mars Climate Database (Forget et al., 1999; available at http://www-mars.lmd.jussieu.fr) for the "Mars year 24 scenario", which is thought to represent typical weather conditions on the planet. These data have significant accuracy limitations. The temperature in the Climate Database is obtained as a model calculation result, with the input of TES-derived thermal inertia, which, in turn, is a model-based derivative of night-time temperatures only. This rather indirect approach might cause a bias in the model-based temperature. Comparison of the surface temperature prediction in the Climate Database with actual daytime TES temperature retrievals (Millour, E., Forget, F., "Mars Climate Database Version 4.3 Validation Document" available from http://www-mars.lmd.jussieu.fr) showed discrepancies in the slope streak regions as large as 5–15 K. In addition, these data represent horizontal surfaces, while the slope streaks occur on slopes. Slopes are warmer at night due to partial shielding of the cold sky, and may be either warmer or colder during the day, depending on location, slope orientation, and season.

The low thermal inertia of the slope streak regions causes a very high diurnal amplitude of the surface temperature. The maximum temperature exceeds 275 K everywhere in the slope streak regions, as has been noted by Schorghofer et al. (2002), and routinely reaches 300–305 K. Due to such high temperatures and generally low water vapor abundance in the atmosphere, any aqueous liquid phase at the surface will rather quickly (hours to days) lose water through evaporation and dry up. The night-time frost accumulation cannot significantly exceed a typical day-time atmospheric water column (10–20 μm), which is insufficient for producing an amount of liquid able to flow. Thus, a liquid aqueous phase, if it exists, should be hidden from the surface.

A superposed layer of soil replaces direct evaporation into the dry atmosphere with slow diffusion of water vapor in the pores and extends the time-scale of water loss by many orders of magnitude. Such a layer, however, also replaces the direct radiation from the Sun with slow diffusion of heat. The diurnal thermal skin depth for these low-thermal-inertia regions is about 7 mm (this estimate uses the measured thermal inertia and assumed density and specific heat of granulated silicate material). This means that the liquid phase should be able to exist below the diurnal thermal skin, where the temperature is approximately equal to the day-average surface temperature.

With respect to the day-average surface temperature, the slope streak regions are the coldest regions in the equatorial zone of Mars (Fig. 2c). This is caused by the combination of high albedo and low thermal inertia: the former reduces the total amount of absorbed heat; the latter has an influence due to the strong nonlinearity of thermal emission on temperature. For the slope streak regions, the day-average temperature varies within 190–230 K. Seasonal variations of the day-average temperature are 15–40 K. The seasonal pattern varies with latitude: in the southern hemisphere and close to the equator the warm season is southern summer, while farther to the north, there are two warmer seasons each year, in summer and in winter (because Mars is closer to the Sun in northern winter).

Among chlorides with abundant cations, the lowest depression of the aqueous solution freezing point is provided by CaCl$_2$ and FeCl$_3$. Both binary systems of chloride and $H_2O$ have eutectic melting temperature of about 218 K for concentrations of 30 and 34 wt%, respectively. Fig. 2c presents a global map of the year-maximum day-average temperature, a proxy for the maximum temperature at a few centimeters to a decimeter depth. This temperature exceeds 218 K almost everywhere; a single data base grid cell within a slope streak region gives the temperature as low as 209 K, measurably lower than the eutectic point, but this cannot be a serious argument against the possibility of liquid brines, given limitations of the data set considered above.

The year-average temperature (Fig. 2b) has little variation over the slope streak regions and is within the range 200–220 K, that is about or lower than the eutectic point.

In summary, pressure and temperature conditions in the slope streak regions allow for the seasonal existence of highly concentrated chloride brines within the seasonal thermal skin below the diurnal thermal skin, that is at the depth from a few centimeters to
a few decimeters. In outlining a streak formation mechanism below, we consider CaCl₂ only for the sake of brevity; however FeCl₃ can also play some role.

5. “Wet” mechanism

On the basis of the constraints considered above, we envision a “wet” mechanism of slope streak formation as depicted in Fig. 4. This mechanism requires two assumptions. First, we assume that the soil contains CaCl₂. Second, we assume that there is ground ice present (Fig. 4a). The plausibility of these two will be discussed later. With these assumptions, the following processes will occur.

The partial water vapor pressure in the pore space in contact with the ground ice is equal to the saturation vapor pressure at given temperatures. The partial water vapor pressure in the ambient atmosphere is typically lower. The ground ice is therefore secularly unstable, and water vapor slowly migrates from the ground to the atmosphere by vapor diffusion in the pore space. In a layer above the ice table, the water vapor concentration in the pores is high. When the temperature is higher than the eutectic temperature of CaCl₂–H₂O system (\( T > T_e \)), the saturated vapor pressure above the eutectic brine is lower than the saturated vapor pressure above the ice. This means that in the presence of CaCl₂, a liquid phase (brine) would form, and the water will migrate from the ice to the brine droplets until thermodynamic equilibrium is reached, that is until the concentration of the brine is reduced to the level where the saturation vapor pressure above the brine is equal to the saturation vapor pressure above the ice at the given temperature. Thus, with a seasonal increase in the subsurface temperature, the liquid phase will appear in our system in the form of droplets in the pore spaces (Fig. 4b). When the droplets grow large enough, they start moving down through the pores. Migrating downward, the brine reaches layers of lower temperatures, refreezes (forming ice and antarcticite CaCl₂·6H₂O), and clogs the pores, making an impermeable layer (Fig. 4c). Next droplets of brine reach this impermeable layer, stop, and coalesce to form larger droplets. Occasionally, in favorable locations, when a droplet gets large enough, it starts flowing on top of the ice table, merges with other droplets, grows (Fig. 4d) and initiates the runaway percolation of brine. The percolation front moves downslope and gathers brine from the soil. This runaway percolation produces the observed slope streak. It is likely that individual brine parcels do not move the entire length of the streak to the distal streak end: the percolation front leaves brine behind, and the total movement of material during the streak formation is minor. Thus, the propagation of the percolation front is a type of wave-like process. The Antarctic slope-streak analogy is a good reason to believe that shapes swept by such percolation fronts will be the same as shapes of the observed streaks on Mars.

The “wet” mechanism outlined above does not specify a particular nature of surface darkening. Martian “bright” dust, which covers the slope streak regions, is a very fine powder with relatively high albedo (e.g., Christensen and Moore, 1992). This albedo, however, is moderate in absolute scale. The apparent albedo of such a powder can be easily changed by any disturbance of surface microstructure, change of porosity, etc. This fact is well known both from everyday-life experience and from dedicated studies (e.g., Adams and Filice, 1967). Thus, even minor mechanical disturbance of the surface can lead to observable albedo changes. Such disturbance may occur in many different ways.

For example, some brine in the front area may wick to the surface, reach diurnal thermal skin, lose water through evaporation, change soil structure and leave salts. Wetting, evaporation, crystallization of salts will change surface structure and apparent albedo. From everyday experience, from the Antarctic slope streak observations, and from basic physics considerations (e.g., de Gennes et al., 2004), we know that the capillary rise of water in soils is on the order of decimeters, if a fine fraction and hence, narrow pores, \( \sim 10 \mu \text{m-scale}, \) are present in some amount in the soil. On Mars, due to lower gravity, the capillary rise will be about three times higher than on the Earth, all other conditions being the same. Low temperature, high concentration of salts, and possibly unusual physical properties of solid grain surfaces may change the surface tension and hence the capillary rise, but its order of magnitude would remain the same, from a decimeter to a meter. Thus, it is quite possible that the liquid phase from the seasonal thermal skin depth can reach the diurnal thermal skin by wicking.

Even if the brine does not wick directly to the surface, the characteristic capillary rise of decimeters indicates that the pressure produced by the surface tension is only a factor of a few less than the weight load pressure of a meter of soil. This means that changes in surface tension due to subsurface percolation of brines can easily cause some shifts of soil grains at the depth of decimeters, which can cause minor grain shifting through the whole decimeters-thick upper layer, alter the small-scale structure of the surface, and change the apparent brightness. Possible com-

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![Fig. 4. Schematic illustration of the “wet” mechanism of slope streak formation. During the cold season (a) the temperature \( T \) is below the eutectic temperature \( T_e \), and CaCl₂ and H₂O reside in the form of hydrated salt and ice. During the warm season, within the seasonal thermal skin, \( T \) exceeds \( T_e \), and some amount of brine forms (b), percolates downward (black arrow), refreezes at the bottom of the seasonal thermal skin (c) producing an impermeable layer, and sometimes can form a run-away downslope (black arrow) percolation front (d).](image-url)
paction of wet soil is a variant of this mechanism of mechanical disturbance.

We assumed above that the soil contains CaCl₂. As qualitatively discussed by Knauth and Burt (2002), on Mars, where salt deposition occurred by freezing of concentrated brines, association of the Ca cation with the Cl anion should be expected, in contrast to the Earth, where salts are mostly deposited by evaporation of dilute solutions, and Cl is associated with Na and K. Soils in the slope streak regions are moderately or highly enriched in NaCl, whereas NaCl is the eutectic mixture of chlorides providing the lowest eutectic. Fig. 4 shows the uppermost dust layer and a lower coarser-grained layer, where the seasonal brine formation occurs. Such structure is not essential for the mechanism to operate; it can be very different.

6. Possible tests

It is surprisingly difficult to distinguish between the “dry” and “wet” mechanisms on the basis of morphologic and other observations. As we noted above, any version of the “dry” mechanism needs to assume a type of dry granular flow unknown in the laboratory or nature, and thus, there is no information on flow phenomena that such a hypothetical mechanism could produce. Therefore, streak planforms themselves cannot be used to distinguish between the “wet” and “dry” mechanisms.

Both dry granular flow and propagation of a percolation front are runaway processes. This fact produces a great similarity in model predictions. For example, it is known that streak formation can be triggered by tiny meteoric impacts, rolling boulders, etc. (Chuang et al., 2007). The frequent association of the streak tops with scars and boulders have been explained as due to triggering by small pieces of talus dropping from steep walls (Sullivan et al., 2001). These observations have been considered as evidence supporting a “dry” flow origin; however, they actually only indicate the runaway nature of the streak-formation process and are equally consistent with both “dry” and “wet” mechanism. Any triggering event like those considered above can cause a few brine droplets to merge, which would then initiate percolation. Association of triangular scars with the slope streaks has been considered as strong supporting evidence for dry mass movement (Chuang et al., 2007; Phillips et al., 2007). However, as we saw above, the relationship between streaks and scars is rather complex. This complexity is difficult to explain if the scars are formed by the same process as the streaks themselves. It is easier to explain if the scars are formed by some secondary process initiated by formation of the streaks. For example, formation of a dark streak (by either mechanism) can cause an increase of the average surface temperature, enhancement of water vapor flux from the ground, quicker loss of the ground ice or bound water, and compaction of the soil, which would produce a scar at a decade time scale. Alternatively, in the framework of the “wet” mechanism, the scars can also be easily explained by sliding of an upper decimeter of the soil on a lubricating wet layer made by the percolation front. The latter explanation appears consistent with the morphological observations of positive topographic forms at the distal ends of a scar reported by Phillips et al. (2007).

The absence of a hydration signature in the NIR reflectance spectra cannot be used as evidence against the “wet” mechanism, which predicts subsurface rather than surface aqueous flow. Even if wicking to the surface is responsible for the dark appearance of the streaks, the final effect is in the small-scale surface structure, not in the presence of aqueous or hydrated phases at the surface: these phases are not stable and should disappear on the time scale of a few days. Moreover, if a hydration signature were observed for a young streak, this can not exclusively be used as evidence for the “wet” mechanism: in the context of the “dry” mechanism, removal of some surface layer can expose metastable hydrated phases present in the shallow subsurface. Thus, spectral
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Fig. 5. A new impact crater (arrow) and its dark halo formed between 9 May 2004 and 17 February 2006 (Malin et al., 2006) on the Medusae Fossae Formation surface. Boxes in (a) show locations of enlargements (b–d). Far from the impact site there are infrequent small slope streaks and abundant scars of all orientation (b). Closer to the impact (c, d) numerous dark streaks are seen on the north-facing slopes. Perhaps, these streaks were triggered by the impact event (Chuang et al., 2007). Portion of HiRISE image PSP_002764_1800, 0° N 227° E, north is at the top, illumination is from the left.

The "wet" mechanism outlined above requires a strongly constrained temperature regime: the year-maximum temperature should be above the eutectic point, and the year-average temperature (more accurately, the temperature below the seasonal thermal skin depth) should be lower than the eutectic point. Given the rather narrow seasonal temperature amplitude in the equatorial regions, this is indeed a strict constraint. As we discussed at the end of Section 4 above, the current knowledge of the surface temperature regime is insufficient to determine if these constraints are met. It is clear that the temperatures are generally in the correct range, but the actual temperatures are not known accurately enough. TES measurements (Christensen et al., 2001) provide a valuable data set of temperatures measured twice a day through several martian years with a somewhat different atmospheric dust content. Significant additional specific modeling efforts are necessary to fit the seasonal variations of the night and afternoon temperatures (in a manner similar to the analysis of Bandfield, 2007) and derive averages with an accuracy of a few degrees. Furthermore, slopes introduce more complications to the problem. Since the slopes are not resolved by TES, accurate calculation of the temperature regime is one additional modeling step farther from the direct observations.

The "wet" mechanism predicts that the streaks form in the warm season, when the temperature is above the eutectic point. This is a testable prediction. The seasonal pattern of the temperature changes is primarily controlled by the seasonal insolation pattern; the latter is known much better than the absolute temperatures. Of course, the seasonal insolation pattern also depends on slope steepness and orientation. Testing the "wet" mechanism against the seasonality predictions has a number of complications. The seasonal temperature pattern in the subsurface has some lag with respect to the insolation pattern; this lag depends on the depth where percolation occurs, which is unknown. Shadowing by surrounding topography and radiative heating from visible terrains can influence the seasonal temperature pattern. For example, two slopes of the same steepness and orientation at the same latitude will have a somewhat different seasonal temperature pattern if one of them is on a mesa wall, and the other one is on an inner crater wall. Finally, inter-annual weather variability (for example, atmospheric dust load) can affect the seasonal temperature pattern in a non-repeating manner.

Recently we made the following interesting observation consistent with the predicted seasonality of streak formation (Kreslavsky and Head, 2008). Malin et al. (2006) identified several impact events that had occurred during the last decade. Chuang et al. (2007) reported that one of these recent impacts (#7 according to Malin et al., 2006) triggered a huge number of tiny slope streaks in the immediate vicinity of the impact site (Fig. 5). These abundant streaks occur mostly on the north-facing slopes (Figs. 5c and 5d), while farther away from the impact site scarce streaks and numerous scars have orientations in all directions (Fig. 5b). Thus, the impact event has triggered streaks on slopes of one orientation and did not trigger them on the opposite slopes. It is difficult to explain this observation in the framework of a "dry" mechanism: seismic shaking would trigger streaks isotropically; an atmospheric blast from the impact event may produce only radial, not directional, anisotropy. Within the framework of the "wet" mechanism, this observation has a natural explanation: at the moment of the impact the shallow subsurface of the north-facing slopes was warmer and above the eutectic point, while on the south-facing slopes the subsurface was colder and below the eutectic point. For the impact shown in Fig. 5 the actual season when the impact event occurred is unknown. We found another similar example (site #19 according to Malin et al., 2006; 5° N, 223° E; HiRISE image PSP_003674_1855); here streaks triggered by the impact are on south-facing slopes, and, unlike the previous case, the season of the impact is known: the impact occurred between 22 of January 2004 (areocentric longitude of the sun \( \lambda_s = -23° \)) and 22 of...
April 2004 (Ls = +22°), in late winter or early spring. This season is a few months after the insolation maximum on the south-facing slopes, exactly when the subsurface is warmer. This observation is in accord with the specific prediction of seasonality within the framework of “wet” mechanism.

7. Conclusions

We propose a “wet” mechanism for slope streak formation on Mars. It involves the natural seasonal formation of a modest amount of highly concentrated chloride brines at a decimeter-scale depth in the surface layer, and runaway propagation of percolation fronts. Given the current state of knowledge of temperature regimes, composition and structure of the surface layer in the slope streak regions, this mechanism is consistent with the observational constraints. The “wet” mechanism is based on two essential assumptions: the presence of (1) calcium chloride and/or ferric chloride and (2) the presence of some water ice in the soil. Both assumptions do not contradict the observational constraints and are supported by some indirect reasoning; they, however, remain just assumptions, because there are no observations able to identify directly the presence (or absence) of ice and particular chlorides in the soil.

This mechanism has a number of appealing advantages in comparison to the widely accepted “dry” mechanism. This does not mean, however, that with our current state of knowledge these advantages allow one to discard the “dry” mechanism. Some variants of the “dry” mechanism may still be a viable option for slope streak formation. Slope streaks are clearly a complex and not easily understood phenomenon. Some observations have no straightforward explanation in the context of either proposed mechanism.

Testing the two mechanisms is surprisingly difficult. Better modeling of the temperature regime and observations of the seasonality of streak formation are difficult but very strong and perhaps feasible tests for the “wet” mechanism. Further morphological observations are essential to understand the details of the streak formation process. There is a good chance that further observations with high-resolution images can provide new clues that will reveal the actual mechanism.

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