Topographic measurements of slope streaks on Mars

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\textbf{ARTICLE INFO}

\textbf{Article history:}
Received 17 February 2016
Revised 1 June 2016
Accepted 8 June 2016
Available online 14 June 2016

\textbf{Keywords:}
Mars, surface
Mars, climate
Geological processes

\textbf{ABSTRACT}

Slope streaks are enigmatic, actively forming albedo features occurring on slopes in high-albedo, low-thermal-inertia, dust-rich equatorial regions on Mars. They are a specifically martian phenomenon with no direct analogs on the Earth. Their morphology suggests that the streaks are initiated at their upslope tips and propagate down to their termini; however, the physical mechanism of their formation is uncertain. We performed a large series of measurements of slopes associated with slope streaks using stereo pairs of high-resolution orbital images obtained by HiRISE camera and generated several digital elevation models for selected streaks. We found that: (1) slopes at the upslope streak tips range widely, however, there is a strong indication that streaks can be initiated only on slopes steeper than $\sim 20^\circ$; (2) slopes of the streak termini show an even wider range, with some streaks terminating at slopes as steep as their tips, while others propagate all the way down to horizontal surfaces; (3) the streaks can propagate stably for long (many hundreds of meters) distances and can turn, following the topographic gradient on $\sim 10^\circ$–$15^\circ$ slopes; (4) no uphill propagation of streaks is detected over baselines of tens of meters; (5) the slope streaks often propagate over 1–2 m high obstacles and can climb 1–2 m uphill over short (meters) distances. We used these findings to assess the viability of two classes of hypotheses about slope streak formation mechanisms proposed earlier: 1) “dry”, some kind of run-away avalanche-like dry granular flow, and 2) “wet”, some kind of run-away propagation of a front of percolating brines in the shallow subsurface. No specific observation unambiguously proves or rejects either of the two mechanisms. Several of our findings are readily explained by the “dry” mechanism and cannot be easily explained with any kind of “wet” mechanism, while other findings are closely consistent with the “wet” mechanism and are difficult to reconcile with the “dry” mechanism. This situation might be explained by equifinality (meaning that the streaks, despite their similarity, are formed by different physical processes); alternatively, some modifications to either the “dry” or “wet” mechanisms may be able to provide a coherent explanation; it is also possible that new ideas are needed to understand the processes involved.

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\textbf{1. Introduction}

Slope streaks are very distinctive, actively forming albedo features occurring on steep slopes in high-albedo, low-thermal-inertia regions on Mars. Slope streaks are different from other active streak-like features on Mars: recurring slope lineae (RSL) (e.g., McEwen et al., 2011, 2014; Levy, 2012; Chevrier et al., 2012; Ojha et al., 2013, 2014, 2015; Grimm et al., 2014; Stillman et al., 2014; etc.), seasonal dark streaks on high-latitude dunes (e.g., Gardin et al., 2010; Mohlmann and Keresztsuri, 2010; Hansen et al., 2011; Keresztsuri et al., 2011; etc.), and different kinds of surface changes detected in a variety of gullies (e.g., Malin et al., 2006; Reiss et al., 2010; Dundas et al., 2010, 2012, 2015; Diniega et al., 2013, etc.). Although Mushkin et al. (2014a) have argued for a genetic similarity between the slope streaks and the RSL, the differences in their size, settings, and temporal occurrence are so significant that it is natural to consider them as different phenomena and analyze them separately, even if the physical processes responsible for their formation are similar.

Processes that form slope streaks remain obscure. No proposed mechanism readily accounts for all of their observed characteristics and peculiarities. In an attempt to obtain new insights on their formation mechanism, we performed observations on the interaction of streaks with topography. No systematic measurements of slopes associated with slope streaks have been performed so far.
2. Background

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 active features (they are forming now), 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 HiRISE camera onboard Mars Express, were presented by Schorghofer et al. (2002), Aharonson et al. (2003), Miyamoto et al. (2004), Gerstell et al. (2004), Baratoux et al. (2006), and Schorghofer et al. (2007). The higher resolution HiRISE camera onboard Mars Reconnaissance Orbiter (MRO) provided new data about these features (Chuang et al., 2007; Phillips et al., 2007; Bulmer et al., 2008; Kreslavsky and Head, 2009; Schorghofer and King, 2011; Bergonio et al., 2013; Chilton and Phillips, 2013). The rest of this subsection is a brief summary and synthesis of all these observations; for brevity and readability, we omit numerous repeating references to the works listed above.

Slope streaks (Fig. 1) are albedo features on slopes. They are elongated along the topographic gradient and have very sharp edges (unresolved at ~30 cm resolution of HiRISE camera). They are mostly darker, but sometimes brighter than their surroundings. Chuang et al. (2010) have argued that bright streaks are a photometric effect: they are scars with a specific meter-scale topographic texture; when this texture is unresolved, under proper illumination it appears as increased brightness. Examination of near-IR spectra (from CRISM instrument onboard MRO) of dark streaks (Mushkin et al., 2010) showed no hydration signature of any kind, and a difference from dark dust devil tracks in the same region, suggesting different darkening mechanisms.

The largest slope streaks are a few kilometers long. Their length is apparently limited by the maximum length of relatively steep slopes. Smaller streaks are often observed, down to the image resolution. A remarkable morphological similarity of longer and shorter streaks suggests the same formation mechanism over at least 3 orders of magnitude in length.

Repeat image coverage revealed a large number of newly formed streaks. Streak formation is highly inhomogeneous both in space and in time. Newly formed streaks are always dark; they brighten with time and then fade away over a time scale of decades to a century; however, Chilton and Phillips (2013) reported temporal darkening of some streaks.

Formation of slope streaks occurs as a single event. Growth, reactivation, expansion of a streak have never been observed. The duration of the formation events is unknown; it is limited from above by few-weeks-long intervals between repeat images.

The streaks usually have a sharp acute-angle upslope end (tip) and lobate to branching downslope ends (termini). The tips are often (but not always) located at boulders, scarp, etc. These observations strongly suggest some kind of initiation at the upper tips and propagation from the tips to the termini. The streaks always follow large-scale (hundreds of meters) changes in topographic gradients.

Slope streaks occur in certain broad regions at low latitudes (Fig. 2). These regions are characterized by distinctive surface layer properties: high albedo, very low thermal inertia and the spectral signature of fine dust, which suggests that the presence of a thick (at least a few cm) fine dust layer on the surface is essential for streak formation. This type of surface layer has never been
observed in-situ with landers, because dust is a landing / operation hazard.

2.2. Mechanisms of formation

A number of mechanisms and variants of 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 images, we see that mass wasting on very steep slopes (in large fresh craters, for example) in dusty regions indeed produces darker lanes; those lanes, however, are different from the slope streaks: their edges are diffuse; they often do not have sharp initial points, etc. Thus, mass-wasted debris itself does not produce slope streaks.

Another initially proposed mechanism is stains from liquid flows of brines (Ferguson and Lucchitta, 1984). Recently a variety of ideas regarding groundwater discharge (e.g., Ferris et al., 2002; Jaret and Clevy, 2007; Mushkin et al., 2010, 2014b) have been considered. We do not think, however, that such ideas are viable. First, slope streak occurrences show no correlation with bedrock geology, which strongly suggests that the formation mechanism is related to the surface layer and not related to the hydrologic setting. Second, the streaks occur on the slopes of numerous small isolated hills and mesas; since the recharge of aquifers from the surface is absent, groundwater discharge from isolated hills and mesas would require very special aquifer configurations and cannot be ubiquitous. Third, groundwater discharge is inconsistent with the observed triggering of the streaks by tiny impacts, rolling boulders, etc. (Chuang et al., 2007).

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 surface microstructure; spectral observations by Mushkin et al. (2010) support this nature of darkening. We refer to different varieties of the mechanism involving dust avalanches as a “dry” mechanism. It is important to note 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. Various well known, and relatively well-studied varieties of granular flow such as sand avalanches, snow avalanches, rock avalanches, landslides of different kinds, debris flows, and density flows differ from the hypothesized dust avalanches: they produce planforms and morphologies that differ from slope streaks. On the basis of estimations and models, Sullivan et al. (2001) argued that such a type of granular flow may exist (that is, it does not contradict the basic principles of physics); however, it has never been directly observed either in the laboratory, or in a terrestrial geological environment.

The major problem with the “dry” mechanisms is the fact that granular flows are required to propagate 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. For a dry flow, it is difficult to regain its momentum at slopes significantly gentler than the angle of repose (e.g., Jaeger et al., 1988) also known as dynamic or kinetic angle of repose, which is expected to be within 25–30° for martian gravity (Kleinmans et al., 2011). Kreslavsky (2007) reported on measurements of average (beginning to end) slopes of several selected large (km-long) streaks within the 7°–15° range, which poses a significant problem for the “dry” dust avalanche mechanism.

Kreslavsky and Head (2009) proposed a “wet” mechanism, which involves natural seasonal formation of a modest amount of highly concentrated chloride brines within a seasonal thermal skin, and run-away propagation of percolation fronts. Perchlorate brines, although not mentioned by Kreslavsky and Head (2009), may play the same role even better; perchlorates have been recently found in the surface layer of Mars (Hecht et al., 2009; Kounaves et al., 2010, 2014, Archer et al., 2014). This “wet” mechanism of the streak formation process operates in a thin (centimeters to decimeters) surface layer and is independent of bedrock geology. Percolation in a thin layer above the ice table in the Antarctic Dry Valleys (e.g. Head et al., 2007) does produce planforms of wet streaks and their termini similar to martian slope streaks. This mechanism is consistent with the observed temperature and composition constraints (Cl and H abundance) and has a few advantages explaining the observed properties of the slope streaks, for example, the fact that
they can partially overlap. Darkening of the streaks can be a photometric effect related to some mechanical changes of microscopic surface structure caused by the percolation front. Brine wicking to the surface and evaporation may cause agglomeration of dust particles cemented by salts, which also decreases surface albedo. Although ground ice is presently unstable in these tropical regions (e.g., Mellon and Jakosky, 1993; Schorghofer and Aharonson, 2005), it could have been stable in the very recent past (Jakosky et al., 2005), and the small amount of ice needed for the “wet” scenario could have remained since that time.

A testable prediction of this “wet” mechanism is streak formation seasonality. According to Kreslavsky and Head (2009), the streaks should not form when the subsurface seasonal temperature is below the year-average temperature everywhere in the seasonal thermal skin. A specific study of the seasonality of streak formation by Schorghofer and King (2011) revealed a single new streak inconsistent with this prediction, which seemingly rejects the “wet” mechanism in its specific form described by Kreslavsky and Head (2009). Yakovlev (2010, 2011) described a very similar mechanism that has the same advantages, but does not limit streak formation to the warmer season. The difference is that according to the theoretical model by Kreslavsky and Head (2009) the run-away propagation of the percolation front occurs due to mechanical coalescence of pre-existing brine droplets, while according to Yakovlev (2010, 2011) brine at the percolation front progressively melts ice crystals, gaining a sufficient amount of the liquid phase, and dissolves salt crystals, maintaining a high brine concentration. Night-time deliquescence on Mars (Martin-Torres et al., 2015) might provide a physical basis for another version of the “wet” mechanism, different from those considered by Kreslavsky and Head (2009) and Yakovlev (2010, 2011).

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 in nature; therefore, there is no information on flow planforms that such a hypothetical mechanism could produce, and the streak planforms themselves cannot be used to distinguish between the “wet” and “dry” mechanisms. Both dry granular flow and the propagation of a percolation front are runaway processes. This fact produces a significant similarity between them. For example, it is known that streak formation can be triggered by tiny impacts, rolling boulders, etc. (Chuang et al., 2007). 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 the “dry” and “wet” mechanisms. For the “wet” mechanism, any triggering event can cause a few brine droplets to merge, which can trigger a percolation wave.

Thus, we attempt to constrain the slope streak formation mechanism by detailed studies of streak interaction with topography. In particular, we examine long streaks on gentle slopes as unlikely cases for “dry” streak formation processes, and search for streak segments climbing uphill, which would mean the presence of inertia in streak propagation, and therefore would reject the “wet” kinds of scenarios.

3. Topographic measurements with HiRISE stereo pairs

We use image stereo pairs obtained by the high resolution imaging science experiment (HiRISE) camera (McEwen et al., 2007) onboard Mars Reconnaissance Orbiter (MRO) as a source of topographic information. Here we report on the analysis of full-resolution images only, those with map-projected versions sampled at 25 cm/pix. The very high resolution (~35 cm) and large size of these images greatly assist our analysis. Only a few available high-resolution digital terrain models (DTM) derived from such stereo pairs (Kirk et al., 2008) and available through the NASA Planetary Data System (PDS) contain slope streaks, while the number of stereo pairs themselves is much greater. We extracted needed topographic information directly from the stereo pairs without creation of DTM; for this we use a digital photogrammetric software complex PHOTOMOD (http://www.racurs.ru/).

“Raw” HiRISE images, also known as experimental data records (EDR) in the PDS (http://hirise-pds.lpl.arizona.edu/PDS/), were used as source data. In this data set each HiRISE image is presented as ten mosaicable image files obtained by ten red filter (550-850 nm wavelength) detectors. We used a specific computer code (Zubarev et al., 2013) to prepare the EDR to import into PHOTOMOD. This code (1) retrieves all necessary geometric information, namely, the camera model, as well as the position and orientation of the camera with respect to the surface of Mars from the relevant SPICE kernels (e.g., Acton, 1996) available from the PDS Navigation Node (http://naif.jpl.nasa.gov/), (2) creates a mosaic of individual EDR image files with fine adjustment by image matching in narrow strips of overlap, and (3) generates a set of rational polynomial coefficients that relate pixel coordinates in the mosaic to geographical coordinates on Mars. The code also applies an original heuristic radiometric correction procedure that eliminates many image imperfections, providing optimal contrast and brightness for visual analysis, and seamless mosaicking. A pair of mosaics obtained in this manner with their sets of the rational polynomial coefficients can then be imported into PHOTOMOD for photogrammetric measurements.

We manually measured slopes of short (~15–30 m) along-streak segments. PHOTOMOD facilitates such measurements, allowing an operator to move starting and ending points of straight line segments both horizontally and vertically and fit the segments to the surface using the 3D visualization. The implicit precision of manual parallax measurements by an experienced operator with high-quality HiRISE images is better than one pixel, which, depending on stereo geometry, typically yields about ~0.5 m vertical precision for full-resolution images. This precision provides slope measurement accuracy of ~2° for short ~20 m segments, and proportionally better accuracy for longer segments.

We paid special attention to streaks observed on gentle slopes and searched for examples of streak segments propagating uphill. We also measured slopes, where streaks do not form in the same area where streaks are observed. We surveyed 19 stereo pairs (Table 1, Fig. 2) with over 700 streaks and measured slopes of over 7000 streak segments.

We also created DTMs for several limited parts of HiRISE images containing individual selected slope streaks. For the DTMs, we used sites with exposure of the Medusa Fossae Formation (MFF) (e.g., Kerber and Head, 2010, and references therein) and similar materials. These terrains are heavily dissected by meter- to tens-of-meters-scale features presumably formed by Aeolian erosion of the friable MFF material. The abundance of sharp meter-scale features facilitates automated correlation between stereo images. For DTM generation, we used the iterative deformation method implemented in PHOTOMOD, which produced DTMs with 0.25 m/pix spatial sampling. Examples of DTMs obtained by this method are shown in Figs. 3 and 4.

4. Results

4.1. Slopes below streak initiation site

Fig. 5 shows a histogram of slopes of the uppermost 15–30 m long segments of ~1500 slope streaks in all the surveyed stereo pairs. It is clear that the initial slope varies over a wide range (10–40°) with a median value of 25.9°. This steepness of the initial
Table 1

<table>
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<th>#</th>
<th>1st image</th>
<th>2nd image</th>
<th>Lat. deg.</th>
<th>Lon. deg.</th>
<th>Number of segments</th>
<th>Min slope deg.</th>
<th>Max slope deg.</th>
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Fig. 3. A slope streak in Lycus Sulci (32.0ºN, 222.4ºE), on dissected terrain similar to Medusae Fossae Formation. Portion of HiRISE image ESP_03,7351_2125 and high resolution DEM (0.5 m/pixel) generated with HiRISE stereo pair ESP_03,7351_2125-ESP_03,7206_2125. Slope streak propagates in a tilted valley and stops at a ~4 m high hill. Pin indicates the streak tip (starting point), and large arrow shows general downslope direction. Streak edges are outlined in inset A. The streaks climbed a few meters at the slope of a hill marked with small arrow and stopped.
slope streak segments is noticeably gentler than a typical static angle of repose (also known as the critical angle) (e.g., Jaeger et al., 1988) of dry granular materials (∼35°). The small number of the segments steeper than ∼30° at the initiation site is at least partly caused by the paucity of such steep slopes. Variations of slopes within each surveyed stereo pair are comparable to the difference observed between stereo pairs. In other words, in the same location, streaks can originate on both steeper and gentler slopes. Some systematic differences between sites seem to be present; however, with our data set it is difficult to determine whether or not these differences are caused by differences in abundance of steep slopes.

Smooth slopes without streaks often reach 25–35°. This means that the absence of streaks in area with such slopes is not caused by slopes being too gentle, but rather is controlled by properties of the surface layer.

The majority of uppermost initial slope streak segments have slopes steeper than 17–20° (Fig. 5): the slope-frequency distribution rolls over at about 20°. There are, however, several cases where the initial segments are very gentle, down to ∼9°. We rechecked all uppermost initial segments with slopes gentler than 18° to ensure that these low values are not spurious. We noticed that the upper tips of all such streaks are located at some distinctive object, mostly small scarps or knobs; Figs. 6 and 7 show such examples. It is probable that the uppermost unresolved or poorly resolved segments ∼0.3–2 m long are significantly steeper than the measured mean slope at the 15–30 m baseline. (The image resolution is insufficient to measure slopes at ∼1 m baseline.) On the other hand, among the streaks with initial slope streak segments

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Fig. 4. Another slope streak in Lycus Sulci (32.0°N, 223.3°E) in dissected terrain similar to Medusae Fossae Formation. Portion of HiRISE image ESP_03,7562_2125 and high resolution DEM (0.5 m/px) generated with HiRISE stereo pair ESP_03,7562_2125-ESP_03,7839_2125. Slope streak propagates over isolated 2–3 m high knobs. Pin indicates the streak tip (starting point), and large arrow shows general downslope direction. Streak edges are outlined in inset A. Short arrows point to examples of a few meters tall knobs inside the streak.

Fig. 5. Slope-frequency distributions (proportions of slopes in 2-degree wide bins among all measured population) for the beginning and end segments of slope streaks. Slopes are measured at 15–30 m baselines.
with a 20–25° steepness, there are abundant examples where the upper tip is not associated with any object discernable at the full HiRISE resolution. In such typical cases the streaks appear to initiate at a slope equal to the measured slope. In summary, these observations point to the presence of a threshold of slope streak initiation: the streaks can only start at slopes (possibly, very short ones) steeper than ~18–20°.

### 4.2. Slopes of slope streak end terminations

Fig. 5 also shows a histogram of slopes of the lowermost, terminal 15–30 m long segments of streaks. This distribution is even wider than the distribution of slopes of the uppermost segments (0–40°). Many streaks terminate on a slope as steep as their beginning tip: the steeper side margin of the distribution (Fig. 5) is the same as for the uppermost segments. On the other hand, the majority of streaks terminate at slopes significantly gentler than their tips and significantly gentler than the typical slopes of their initial segments. This is partly caused by the concave profile of streak-bearing talus slopes. The median slope of the measured terminal segments is 16.0°. There are many examples where shorter streaks, that end early and at the same slope as their tips, are situated immediately adjacent to longer streaks that ran downhill until the slope flattens. Examples of this kind can be seen in Fig. 8.

The frequency distribution (Fig. 5) rolls over at ~8°, however, there are still many terminal segments on even gentler slopes. We checked to ensure that these examples are not spurious measurements. Formally, our data set contains several examples of terminal 15–20 m long segments tilted ~1° uphill, however, this is within our measurement uncertainty, and we cannot confidently claim the presence of streaks running uphill.

### 4.3. Long streaks on gentle slopes

We found a number of cases where streaks propagated long distances (many hundreds of meters) on gentle slopes, down to ~8–10°. A few examples are shown in Figs. 6–9 where slopes are noted for individual ~100 m long segments. Not only do streaks propagate on such gentle slopes, but they also turn (change direction) on them following the topographic gradient direction (e.g., Fig. 8). Slopes gentler than ~8–10° are sometimes observed for ~100 m long terminal parts of the streaks (e.g., Fig. 7).
streaks ∼ the ages. Sullivan distances. 4.4. Fig. gentler slope: if some parcel of material is mobilized by some mechanism or event on a slope steeper than the dynamic angle of repose, this may trigger run-away movement of material, while on a slope gentler than the dynamic angle of repose, the mobilized material will settle, and no triggering would be possible. The 18–20° slope is too gentle for the dynamic angle of repose of any natural terrestrial dry granular materials. However, the dynamic angle of repose has been argued to be gentler under a lower gravity (e.g., Kleinhans et al., 2011), and if this is the case, ∼20° might be a reasonable value for some types of dry granular material under martian gravity, although martian-gravity experiments with dry sand by Kleinhans et al. (2011) showed still steeper values (25–30°).

In the frame of “wet” mechanisms it is naturally to expect that streaks are easier to initiate on steeper slopes, therefore they less frequently triggered on gentler slopes; however, the presence of a sharp threshold of initial slope is not expected. However, the observed apparent threshold does not reject “wet” mechanisms: it is possible that there is no sharp physical threshold, and continuous decrease of streak formation frequency on gentler slopes mimics a threshold in our data.

To reconcile the ∼20° threshold for slope streak initiation with the stable propagation of the streak front on slopes of 18° or less we need to assume that there is some physical quantity that characterizes the “power” of the front: for example, a newly triggered propagating front has an initial low “power” and gains “power” while propagating downhill; the front with high “power” can stably propagate down a gentle slope. For a percolation front, the amount of liquid phase per unit length would naturally play the role in such a front “power”. Therefore, the difference between slopes required for initiation and stable propagation is naturally explained in the frame of “wet” mechanisms. For known types of granular flows, momentum per unit length of the front plays the role of such a “power”:

4.4. Interaction with small obstacles

Stereo views of streaks propagating through rugged MFF or MFF-like material as well as analysis of DTMs clearly show that the streaks do propagate over 1–2 m high topographic obstacles and therefore can climb ∼ 1–2 m uphill over short (a few meters) distances. This behavior of slope streaks has been described by Sullivan et al. (2001) on the basis of visual inspection of MOC images. We confirm this with quantitative evidence from topographic measurements and higher-resolution images. Although the elevation difference of 1–2 m only slightly exceeds the intrinsic inaccuracy of our stereo measurements, the number of examples is so high, and the examples are so clear, that there is no doubt that this is indeed the case. For example, the streak in Fig. 3 ends at a ∼4 m high knob and climbs about halfway between the base and the summit of the knob. The DTM in Fig. 4 reveals several isolated ∼2 m tall knobs within the dark streak that are clearly dark from their base to their summits. We see a number of examples where streaks propagated along long narrow valleys, and streak lateral margins (edges) were located on the valley walls at an elevation clearly above the valley floors.

5. Implications for slope streak formation mechanisms

In this section we assess the consistency of the observations outlined above with two types of slope streak formation mechanisms: “dry” mechanisms involving some kind of granular flow, and “wet” mechanisms involving propagation of a percolation front.

The apparent presence of a minimum 18–20° slope threshold for slope streak initiation is consistent with a “dry” mechanism. In this case the dynamic angle of repose is the natural threshold
to the observation that the observed edges are perfectly sharp at the best HiRISE resolution (~30 cm); however, fine-tuning of specific darkening mechanisms might be able to reconcile the particle cloud model to produce sufficiently sharp edges.

In the framework of “wet” mechanisms, climbing over meter-size obstacles could be explained by wicking. It is difficult to predict plafonds of wet areas that wicking would produce in the rugged MFF surfaces and to determine whether or not the observed streaks are consistent with wicking. On smooth slopes in Antarctic Dry Valleys (Head et al., 2007) shallow-subsurface percolation in the presence of wicking does produce sharp linear edges of wet surface and lobate termini, similar to plafonds of martian slope streaks in similar topographic settings.

6. Conclusions

We performed a series of topographic measurements and visual stereo observations of slope streaks using HiRISE stereo images. With robust quantitative analysis, we confirmed that the slope streaks cover 1–2 m tall obstacles and can climb 1–2 m uphill over short (meter-scale) distances, but do not propagate uphill over longer (tens of meters) distances. We also confirmed that the streaks can propagate stably for long (many hundreds of meters) distances and turn following the topographic gradient on ~1° and steeper slopes; however, they can also terminate at much steeper slopes. We found that the streaks can initiate only on slopes steeper than ~18°–20°.

We used these findings to assess the viability of “dry” (some kind of dry granular flow) and “wet” (some kind of percolation of brines in the shallow subsurface) mechanisms of slope streak formation. These results contribute to the documentation of the nature of slope streaks and their environment, but are not uniquely definitive in distinguishing between the two mechanisms. No specific observation unambiguously proves or rejects either of the two mechanisms. Some observations are readily explained by the “dry” mechanism and are somewhat difficult to reconcile with the “wet” mechanism, specifically, climbing over small obstacles and the presence of the slope threshold (~20°) for streak initiation. Other observations, specifically, propagation on gentle slopes, coexistence of short and long streaks on the same steep slopes, and the very wide range of slopes at the tips and termini, are more readily explained by “wet” mechanisms and are difficult to reconcile with the “dry” mechanism.

This paradoxical situation might be explained by equifinality, a suggestion that slope streaks, despite their morphological similarity, are formed by different physical mechanisms: long streaks on gentle slopes are “wet”, while short streaks on steep slopes are “dry”. However, formation concurrence and exact coincidence of the regions of occurrence taken together with the striking morphological similarity of short and long streaks make this explanation unlikely.

It is still possible that some modifications to either the “dry” or “wet” mechanisms can provide a coherent explanation for this enigmatic phenomenon. For example, rolling of round dust particle aggregates (Sullivan et al., 2008) or boiling of percolating brines (Massé et al., 2016) may play some role. Finally, it is also possible that neither of the two envisioned mechanisms adequately describes the physics of slope streaks, and new ideas are needed to understand the process(es) involved.

Acknowledgments

This work was carried out in Moscow State University of Geodesy and Cartography (MIIGAIK) and supported by the Russian Science Foundation, project 14-22-00197.

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