SLOPE STREAKS ON MARS: AN ASSESSMENT OF "WET" SCENARIOS AND THE ROLE OF CONCENTRATED BRINES.
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Introduction: Dark and bright streaks without any apparent topographic expression are observed on steep slopes on Mars [1 - 5]. They occur in wide regions in the equatorial zone; these regions are characterized by high albedo, low thermal inertia and thick fine-dust coverage. Formation of dark slope steaks is an ongoing process; new streaks were revealed by repeating imaging. The slope streaks are mostly interpreted as results of some kind of dry mass wasting of fine dust [e.g., 2, 5]; it was also suggested that the streaks are results of some "wet" processes, namely brine-rich debris flows [1]; in [6] is was suggested that *some* streaks result from springs formed by salty groundwater discharge. In [3] it is shown that some features of slope streak distribution suggest some role of H_2O phase transition in formation of the streaks. Recently, striking morphological similarity of the slope streaks on Mars and in Antarctic Dry Valleys was demonstrated [7,8]. Antarctic slope streaks are formed by percolation of water and dilute brines above the ice table and wicking to the surface. The source of water is seasonal transient melting of snow. Because no fresh snowpacks associated with the streaks have been detected on Mars, the complete Antarctic analogy cannot be immediately applied. However, the striking morphological similarity impels us to consider the possibility of "wet" scenarios [7,8].

Here we assess the principal physical possibility of "wet" scenarios for the slope streak formation. We do that by simply considering metastable liquid phases that can survive for a time long enough to produce flow. These considerations are not intended to distinguish between "wet" and "dry" scenarios, which should be done with detailed studies of morphology, environment, etc. We postulate that streaks result from some flow involving a liquid phase and figure out how basic physics constrains possible modes of the process.

Under what conditions the streaks form? The slope streaks are observed in a wide range of elevations. The highest location where the slope streaks are observed on Mars is at the walls of mesas just above the circumferential scarp of Olympus Mons, where the elevation is ~6000 m above the datum. At these elevations the maximal atmospheric pressure is below 4 mbar, that is well below the triple point of H_2O.

Since the metastability of aqueous phases is very sensitive to temperatures, we undertook special efforts to obtain accurate estimates of the maximal and average surface temperatures. To do this, we collected TES retrievals of the spectral temperature measurements [9] for several selected locations in the slope streak regions over different seasons, excluding periods of dusty or cloudy atmosphere and non-nadir measurements. To convert day-time (1 - 3 pm local time) and night-time (1 - 3 am) into daily-maximum and daily-average temperatures, we fit the collected measurements with a thermal model of the surface. The model included insolation, thermal radiation of the surface, one-dimensional thermal conduction in a homogeneous upper surface layer and a simple parameterization of the net heat exchange between the surface and the atmosphere. Tunable parameters were surface thermal inertia and one parameter of atmospheric heat exchange. For each location, we matched the night- and day-time temperatures for different seasons and slightly different local times with a single set of tunable parameters. In this way we obtained a precise daily temperature curve for each location and each season, and retrieved extremal and average temperatures.

The low thermal inertia of the surface causes a very wide diurnal temperature amplitude. Despite the high albedo in the regions, the surface temperatures reach 270 - 315 K every day. We confirm, that (as noted in [3]) the maximal temperatures in the warmer season are always above 273 K.

Due to high albedo and low thermal inertia, the *day-average* temperatures in the regions are the lowest in the equatorial zone, 190 - 230 K with minor (up to 20 - 30 K) seasonal variations. The year-maximum day-average temperatures are within 210 - 230 K range.

Nature of the liquid phase. Some streaks form at elevations where the pressure never exceeds the triple point pressure of H_2O; hence pure water cannot exist as a metastable liquid phase, and cannot be obtained through either melting or condensation. Discharge of groundwater can lead to the presence of transient liquid phase on the surface for a short time; however, streak morphology and location of at least some streaks are not consistent with groundwater discharge. Thus, the streak-forming process cannot involve pure water.

A wide range of organic compounds (e.g., high-molecular hydrocarbons) are in liquid phase under the conditions we consider, but we do not see any rationale for the existence of such compounds on Mars.

Concentrated aqueous solutions of many substances have saturation water vapor pressure noticeably lower than that of pure H_2O at the same temperature, and such solutions can be metastable at the lowest atmospheric pressure under which the streaks are formed. Concentrated aqueous solutions of sulfuric acid have been considered as good candidates for liquid phases occurring in the past under present-day martian conditions [10]. If, however, any H_2O - H_2SO_4 phases were present currently in contact with the atmosphere, there would be some sulfur species in the atmosphere, which are not observed. Hydrogen peroxide is a result of atmospheric photochemical processes. The H_2O - H_2O_2 system at proper concentrations can also exist in liquid phase for the pressure - temperature conditions of interest. However, the atmospheric abundance of gaseous H_2O_2 [11] is too low and contradicts the existence of aqueous H_2O_2 solutions as a phase.

The only viable candidates for liquid phase we see are concentrated aqueous solutions of salts (brines). We consider them below.

Brines on the surface. Even if the temperature does not exceed the boiling point of brine for a given pressure and brine composition and concentration, the H_2O evaporation from the brine would occur rather rapidly, because the saturated vapor pressure at high afternoon temperatures is high and exceeds the partial pressure of H_2O vapor in the atmosphere by many orders of magnitude. Thus, had liquid aqueous phases formed at the surface, they would evaporate quickly. Ongoing formation of the slope streaks would require replenishing H_2O at the surface to compensate daytime evaporation, and there is no apparent mechanism capable of providing such replenishment. In the Antarctic Dry Valleys the slope streaks are re-supplied with moisture from melting of accumulated windblown snow, a source not observed in the equatorial region of Mars. A tiny amount of H_2O frost might be accumulated at the surface at night; however it would inevitably sublimate after sunrise. The absence of winter seasons with persistently low temperatures in the equatorial zone precludes accumulation and concentration of this frost. Thus, the streaks cannot be formed by brines flowing immediately on the surface.

On the same reason, the observed darkness of the streaks is unlikely to be caused by the presence of moisture in the surface material. The contrast of the slope streaks is not high, and some change in sub-mm-scale structure of a dusty surface can easily account for the observed brightness variations.

Brines in the subsurface. A dry layer at the surface can effectively reduce the net evaporation rate of brines hidden at some depth and allow prolonged existence of metastable liquid aqueous phases. Extremely low thermal inertia of the surface layer in the region is necessarily accompanied by low thermal diffusivity, which defines a very thin diurnal thermal skin depth (~ 7 mm). We calculated that at a depth of a few mm, day-time heating is unable to supply enough heat to melt a noticeable amount of ice. Thus, the "wet" slope streak scenario should not rely on high day-time surface temperatures and has to deal with much lower day-average temperatures persisting deeper than the diurnal thermal skin layer.

Low temperatures constrain severely possible compositions and concentrations of dissolved salts that can keep brines liquid at least during the warmer season. Sulfates abundant in the martian soils do not provide the necessary depression of the melting point at any concentrations. Chlorides work much better; among the most abundant cations, Ca and Fe provide the lowest eutectic temperatures. In particular, for the $CaCl_2$ - H_2O system the eutectic point is at a temperature of 218 K and concentration of 30% $CaCl_2$ by weight. In the terrestrial salt deposits, Ca cation is typically present in carbonates and sulfates. This is caused by the low solubility of these salts, which precipitate first from evaporation of dilute solutions. As discussed in [12], on Mars, where dilute solutions may have never existed and salt deposition occurred by freezing of concentrated brines, association of Ca cation with Cl should be expected. This happens, for example, in the never-freezing Don Juan Pond in the Antarctic Dry Valleys [12], at the base of the slope below the slope streaks [7,8].

For a significant part of the slope streak region the warmer season day-average temperatures exceed 218 K, the $CaCl_2$ - H_2O eutectic. Accurate estimates of the day-average temperatures inferred from TES measurements gave, however, temperature as low as 210 K for some regions, measurably lower than the eutectic point.

We do not believe that this discrepancy is critical for the "wet" scenario. First, TES measurements with their rather low resolution represent mostly horizontal surfaces, while the slope streaks occur on steep slopes. Slopes are warmer at night, because of partial shielding of cold sky, and may be either warmer or colder during the day, depending on location, slope orientation, and season. Thus, depending on season and orientation, the day-average temperature on the slope can be higher than inferred from TES data. Second, thermal inertia of the soil increases with the temperature, which may lead to temperatures at depth being a little higher than the day-average temperature at the surface. Third, admixture of other salts would somewhat decrease the eutectic point in comparison to the pure binary $CaCl_2$ - H_2O system.

Amount of brines. Neutron and gamma-ray spectrometers onboard Mars Odyssey provided estimates of abundances of all components of the $CaCl_2$ - H_2O system.

Almost all areas of slope streak occurrence have hydrogen concentration of 6-10 wt. % water equivalent [13], higher than areas at these latitudes without slope streaks. Some streaks in the eastern part of Tharsis Regio are in areas of very low hydrogen abundances. We believe that this is not critical, because neutron and gamma-ray data have extremely low resolution (~ 300 km), and these streaks can easily be related to unresolved outliers of a high-hydrogen surface layer.

Gamma rays give widely varying Ca abundance from moderate to high in the slope streaks regions, from ~5 to ~9 wt % [14]. Cl abundances are moderately elevated in the slope streak regions and are typically about 0.6 wt%. [15].

Given these measured abundances, the amount of eutectic $CaCl_2$ - H_2O brine is limited by Cl abundance and is equal to ~3% by weight, which give ~4-5% by volume for porous soils. An increase of the temperature above the eutectic point (by 10-20 K) does not yield a significantly more dilute solution, and hence gives only a minor increase of the brine volume. At such low concentration of the liquid phase, liquid-assisted flow is barely possible.

Many factors, however, affect the reliability of these estimates. First, due to extremely low resolution of the gamma-ray data, large local concentrations of Cl are not ruled out. Second, the gamma-ray spectroscopy provides abundances averaged over a surface layer ~ 0.5 m thick; much higher abundances is the uppermost few cm are not excluded by the measurements. Third, due to high H abundance and the probable strong vertical variations of H and/or Cl abundances in the upper meter of the surface, the model used for absolute Cl abundance determination may be strongly biased [15]; therefore, significant systematic errors are probable for the slope streak regions.

Long-term stability. As we discussed above, the dry upper centimeter of the fine-grained soil effectively protects the hypothetical brines from immediate sublimation. However, it does not provide per se long-term stability of H_2O - bearing phases in the soil. Diffusion of H_2O vapor in the pore space of the soil may lead to gradual loss of water. In the frame of a first-order approach, the criterion of ground ice stability [e.g., 16] is that the year-average saturation vapor pressure at some depth is below the year-average atmospheric partial pressure of water vapor. On Mars, ground ice is stable in cold (in year-average sense) high-latitude areas. The slope streak regions are the coldest regions in the equatorial zone, and the atmosphere in these regions has the highest year-average water vapor abundance on the whole planet [17]. These facts led to the discussion of possible stability of ice or hydrated salts in these regions [e.g., 18, 19]. In the frame of the first-order approach, however, the ground ice is not stable: the year-average temperature is about 210 K, while the frost point corresponding to the year-average water vapor abundance is 199 - 200 K. Because of very steep dependence of the saturated vapor pressure on temperature, this temperature difference is not ignorable. The presence of salts does not change the situation, because close to the eutectic the saturation vapor pressure above brine is almost the same as above ice. The second-order approaches to ice stability analysis include models that trace the seasonal dynamics of H_2O in the pore space. Such calculations show that the actual stability boundary may deflect from the first-order predictions; however obtained maps [20-22] still do not show ground ice stability in the slope streak regions. These second-order models, however, still ignore some effects that may influence the result. Finally, the present-day moisture in the soil in the slope-streak regions may represent ongoing migration of H_2O from some depth, where ice was deposited or accumulated earlier under different climate conditions [e.g., 23]. The close similarity of the conditions in the regions to the stability boundary suggests that such conditions may have occurred in the very recent past [24].

Conclusions. We found that the only possible "wet" scenario for slope streaks formation on Mars may involve small amounts of highly concentrated chloride brines persisting seasonally or perennially below a few cm thick dry layer. The particular mechanism of streak formation may be the following: when the amount of brine reaches some threshold, brine droplets in the pore space coalesce and produce flow; the flow and wicking of moisture to the surface alters the soil sub-mm structure and composition, which causes darkening and, consequently, a positive feedback by facilitating some increase of liquid phase.

The persistence of brines in the soil is at the boundary of physical possibility (in terms of the available amount of chlorine, warm-season day-average temperatures and long-term stability). The direct first-order estimates clearly point to the "impossibility" side of this boundary; however, more detailed considerations may shift the situation to a marginal possibility. Such a marginal character of possibility may be in accord with the rather low rate of slope streak formation.

Our considerations show that the "wet" model cannot be readily rejected as impossible. Discrimination between "wet" and "dry" modes of origin of the slope streaks should be based, first of all, on further morphological observations. Such observations would be facilitated by the use of HiRISE images. Radar studies can potentially detect seasonal variations of electromagnetic properties of the surface caused by seasonal variations in brine amount. Due to the marginal character of the "wet" phenomena, detailed studies of places where the streaks are present and places where formation of new streaks occur, can potentially lead to tests for the "wet" scenario.

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