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# Formation of recurring slope lineae on Mars by rarefied gas-triggered granular flows

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## Abstract

Active dark flows known as recurring slope lineae have been observed on the warmest slopes of equatorial Mars. The morphology, composition and seasonality of the lineae suggest a role of liquid water in their formation. However, internal and atmospheric sources of water appear to be insufficient to sustain the observed slope activity. Experimental evidence suggests that under the low atmospheric pressure at the surface of Mars, gas can flow upwards through porous Martian soil due to thermal creep under surface regions heated by the sun and disturb small particles. Here we present numerical simulations to demonstrate that such a dry process involving the pumping of rarefied gas in the Martian soil due to temperature contrasts can explain the formation of the recurring slope lineae. In our simulations, solar irradiation followed by shadow significantly reduces the angle of repose due to the resulting temporary temperature gradients over shaded terrain and leads to flow at intermediate slope angles. The simulated flow locations are consistent with observed recurring slope lineae that initiate in rough and bouldered terrain with local shadows over the soil. We suggest that this dry avalanche process can explain the formation of the recurring slope lineae on Mars without requiring liquid water or CO<sub>2</sub> frost activity.

Dark flow type RSL occurs in the warmest areas of Mars, during the warm season [1, 2]. The activity of RSL seems to be linked with solar irradiance. In the  $\sim 11^\circ\text{S}$  latitude of Melas Chasma, the activity is observed mainly around  $L_s = 90^\circ$  (Southern hemisphere Winter solstice) at a slope oriented toward North and around  $L_s = 270^\circ$  (Southern hemisphere Summer solstice) at a slope oriented toward South [2]. This slope dependent seasonal activity is also confirmed

by more recent observations, including Garni crater, central Melas chasma [3]. Thus high local temperature or local irradiance seem to be the trigger of the flow.

The temperature and insolation dependence has been recognized very early, and has been mainly interpreted as an effect of humidity [1, 2]. Indeed, RSL activity occurs in the closest point to liquid water in the phase diagram, at present time on Mars [3]. Various sources of liquid water have been proposed : subsurface aquifers, melting of ice dams, deliquescence of salt recharged by atmospheric water [4]. The transport phenomenon itself seems to be very puzzling. Recently, metastable boiling water [5] has been proposed. If liquid water, even transient, is currently present on Mars, its habitability would be relatively high.

**Wet versus dry formation** Nevertheless, the location of RSL is near the equator which is the driest place on Mars and where atmospheric water vapor is at the lowest [6]. In this place, surface condensation of atmospheric water vapor never occurs [7]. Subsurface ice is not stable [8], as also confirmed by indirect detection [9]. The source of water seems still a mystery because an internal source, such as a subsurface aquifer, has also been excluded especially when RSL occurs near the crater rim [3]. The actual amount of atmospheric water required to recharge the RSL's source each year seems not sufficient. The precise thermal calculations from remote sensing thermal infrared measurement of the THEMIS instrument show no evidence of liquid water [10] and there is no spectroscopic direct evidence of liquid water [4]. Recently discovered diurnal CO<sub>2</sub> frost could also trigger the flow [11] by sublimation in early morning. Nevertheless this process is not consistent with RSL growths observed in Valles Marineris at  $L_s = 270^\circ$ . At this period, diurnal CO<sub>2</sub> frost is only present in the bright terrains between Arsia Mons and Mangala Fosse [11]. We propose here a re-interpretation of the RSL features and a new process to explain the RSL activity without involving phase change of chemical compounds. This process aims to reconcile all available data.

Geomorphologically, the RSL consists of the following parts: (1) a concentrated source from bedrock outcrops, (2) a linear channel that is a few meters large and several 100 m long, (3) a terminal part with elongated tongues (figure 1). The main channel exhibits a rather streak-like shape without levees (at the HiRISE resolution of 25 cm). The source has been often attributed to the outcrops but the outcrops themselves are not changing. Moreover, the steepest parts of the walls always stay unchanged. Dark features appear to be surprisingly young and do not exhibit any meandering, anastomosing patterns or ramifications. Of particular interest, some sinuosities are reported on some dry granular flows on Earth [12] but without any cyclic variations like meandering. These sinuosities on RSL were previously described as a diversion around obstacles like in some dry granular flows [13]. The terminal point of RSL is usually determined by a slope angle of  $\sim 28^\circ$ . In summary, RSLs exhibit a narrow streak shape, an observed runout distance and distal morphology with

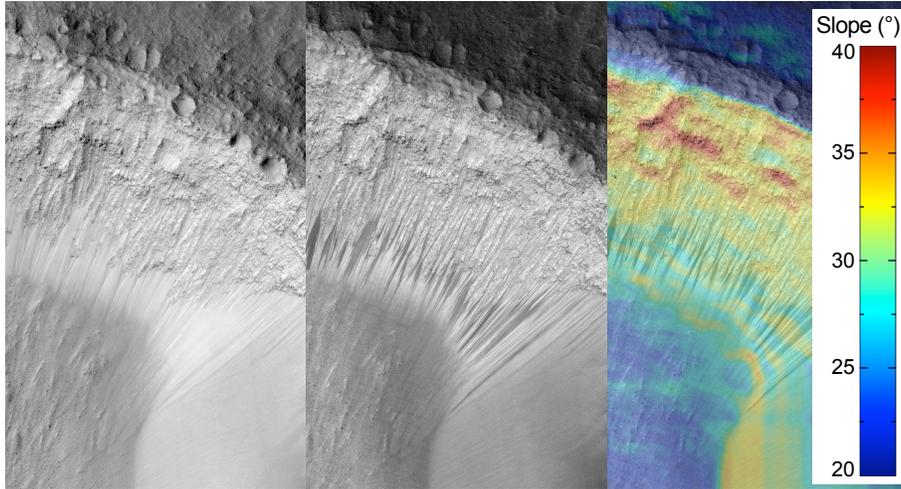


Figure 1: Evolution of RSL at Garni crater, Valles Marineris, Mars. Left: ESP\_029213\_1685 at Ls = 191.5° Middle: ESP\_031059\_1685 at Ls = 280.8° Right: slope angle map using stereoscopic DTM (see sup. mat. for details) Image MRO, HiRISE, NASA/JPL/University of Arizona. Scale: width=500 m.

exactly the same corresponding morphological characteristics of most terrestrial dry rock avalanches. Some laboratory simulations show the possibility to have some levee-channel deposits on dry granular flows [14]. Unfortunately, the resolution of HiRISE images is not enough to detect the morphometry of levees at the scale of these RSL. A fluvial or viscous flow like debris flows would show visible terminal levees at the HiRISE resolution and a much larger channel [15]. The lack of any lateral or terminal levees strongly favors a dry granular flow hypothesis. RSLs appear darker than the surrounding terrains for a few weeks and then they fade away. Vertical inverse grading is a common process in clastic flows due to kinetic sorting [16, 17, 18]. We interpret the relative darker albedo appearance of the RSL as an effect of the sorting of the grains during the flow. Finer grains could also be ejected during the flow. The fading is then due to the finer eolian grain deposition from the atmosphere. In conclusion, most of the RSL exhibit morphological characteristics that do not necessarily involve liquid phase for their formation, but are mostly in agreement with dry granular flows like the ones typical of terrestrial rock avalanches.

**Knudsen pump in the Martian soil** Recently, some experimental works demonstrated that thermal creep is able to lift grains at low pressure, only by irradiating the surface [19, 20]. This photophoretic (or thermophoretic or thermal creep) effect on the porous space of the soil (figure 2 B) has been proposed to be at the origin of dust lifting on Mars [21]. A more precise experimental work at reduced gravity proved that this process should occur on Mars in the

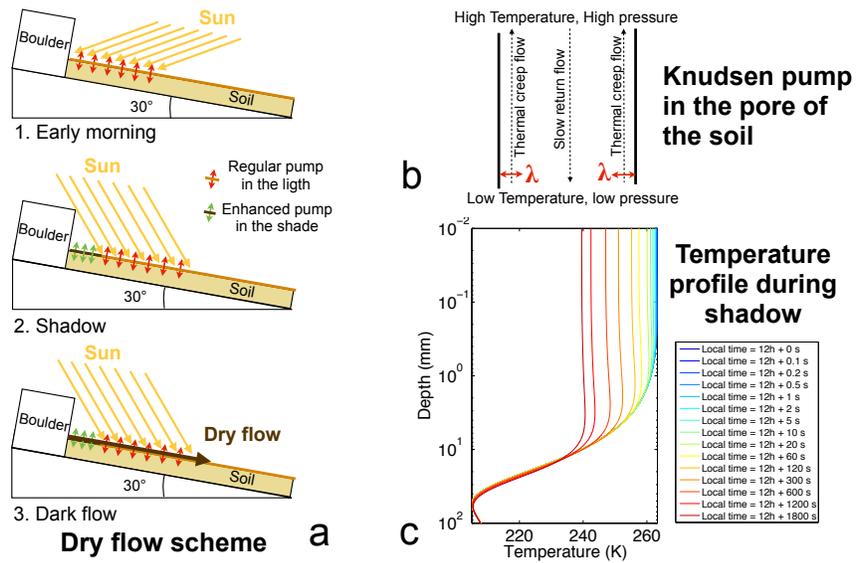


Figure 2: Knudsen pump in the Martian soil. (a) Scheme of the dry flow triggered by the Knudsen pump. The regular pump occurs in the irradiated soil. The enhanced pump occurs few minutes after the appearance of the shadow of a boulder. (b) Scheme of the thermal creep flow in the porous space of the Martian soil, driven from the cold end to the hot end of the tube, close to the wall.  $\lambda$  is the free mean path of the gas, about 20 microns in the Martian soil. (c) Temperature profile at local 12h (before shadow) and after a shadowing period (from 0.1 to 1800s after noon), for a facet at slope  $30^\circ$  toward North at  $L_s = 90^\circ$ .

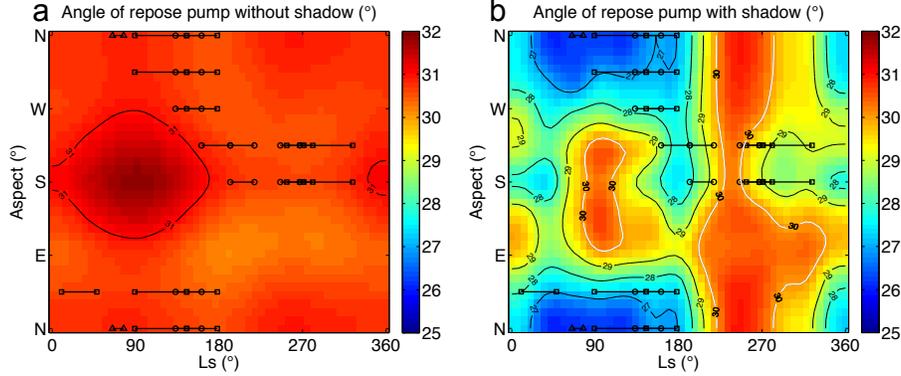


Figure 3: Angle of repose, modified by the Knudsen pump as a function of slope aspect (expressed as the clockwise angle from the North) and season (expressed in angle  $L_s$ ). (a) case of a regular pump (b) case of an enhanced pump. Black lines represents actual RSL activity as observed by the HiRISE instrument in the Garni crater [3]. Each activity is encompassed by two images: before and after. The circles represent Martian year 31 (MY31) while the squares MY32. The triangles represent the activity in the middle of the slope toward North, without clear boulder at the origin of the RSL.

form of a Knudsen pump [22]. The temperature field within few grains has been modeled and is enough for photophoretic effect [23]. The precise near-surface temperature field in granular medium has been estimated numerically [24, 25], taking into account the penetration depth of incoming light. On Mars, rough estimates of the thermal balance demonstrate that the thermal creep creates an active layer 100-200 microns thick for a particle size of 67 microns [26, 27, 28]. This effect decreases by 10% the wind speed threshold for saltation. This effect has also been proposed to produce larger dust devils by self shadowing of the dust devil itself. More generally, Knudsen pump has been recognized to be very promising to understand geomorphological features on Mars [29] but until now, no specific applications have been proposed.

**Modified angle of repose** We put forward that the photophoretic effect, triggered by the sun radiation, modifies seasonally the angle of repose of the granular material. Since the slopes of granular material are stable near  $30^\circ$ , even a minor change in the angle of repose due to the air flux could significantly change the stability. Figure 2 (A) summarizes our model to trigger RSL flows, by a simple Knudsen pump (regular pump) and by shadowing from a boulder (enhanced pump).

Knowing the direct solar flux, the one scattered by the atmosphere, and the thermal infrared flux from the Mars Climate Database [30], we can estimate the slope effect [31] on the three incoming energy fluxes. By using these values

as boundary conditions on precise thermal surface balance model [24, 25], we aim at estimating both regular (without shadow) and enhanced (with shadow) Knudsen pump effects on RSL sites [26, 27, 28]. Both regular and enhanced pumps are estimated in the most favorable conditions, when the surface temperature is higher at maximum solar elevation. Figure 2 (C) shows an example of a temperature profile for the regular pump (at local maximum solar elevation). The maximum enhancement effect occurs when the thermal gradient is maximum in the upper part, usually 1 to 5 minutes after shadow over passed.

By adapting a dry granular flow model [32], we estimate the slope angle required to flow  $\theta_{start}$  (limit angle of repose to start the flow) from the pumping effect. In this model,  $\theta_{start}$  is in the range 23°-36° and is dependent on the thickness of the flowing granular material. The thickness is determined by the upper layer of the thermal profile. Grain radius is set to 50 microns in agreement with the analysis of the infrared observations [10]. The observed slope is around 30° (see fig. 1). We choose to compute the model for the Garni crater, significantly better documented than other places on Mars [3] and offering a variety of slopes in a very localized place. We choose thermal parameters in accordance with previous analysis [10] (see sup. mat.). Since the observed slope is 30°, we will consider here that an angle of repose strictly lower than 30° will provoke the flow.

**Modelled flow activity on Mars** We computed the modified angle of repose as a function of season and slope orientation (aspect). The main results are summarized in fig. 3. The regular pump is never efficient enough to trigger a flow. Conversely, if a boulder creates a shadow near local maximum solar elevation, the enhanced pump is efficient enough to trigger a flow by reducing the angle of repose down to 26.2°, significantly less than the observed slope. The comparison with actual observations at Garni crater gives a very good agreement. The general pattern of slopes towards South near Ls=270° and towards North near Ls=90° is captured. Slopes towards East seem always inactive, as predicted with our model. These slopes have a lower thermal gradient due to less absorbed energy before the shadow (at local maximum solar elevation) at 10AM in the East, instead of noon in North/South and 14PM in the West. The flow activity in the middle of the Northern slope at Ls=80° is in the local maximum efficiency of the enhanced pump. We propose that self shadowing of the granular material itself may be at the origin of this activity.

In summary, our new model is compatible with most observational facts: (i) From HiRISE images, most of the sources of RSL are in rough terrains with slope  $\sim 30^\circ$ . Highest slopes  $> 40^\circ$  remain unmodified. (ii) Most of the flow seems to originate from boulders. (iii) The activity of RSL occurs at low slope angle ( $< 34^\circ$ ), lower than the usual angle of repose of wet/dry granular flow. We propose that the required lubrication to flow is provided by the Knudsen pump. (iv) The seasonality and slope facing activity is well reproduced by our model. (v) We can observe a slight advantage in West facing facets compared to East facing ones [3]. We argue that Western slopes accumulate more heat leading them to

be at higher maximum temperature; moreover, even in shaded conditions these slopes will have a higher temperature gradient. (vi) Our model does not require water (nor CO<sub>2</sub> ice), which is difficult to explain in the equatorial region of Mars.

A new dry exotic flow, based on Knudsen pump, occurring only near the equator of Mars is proposed to explain the cryptic RSL features. It constitutes an alternative hypothesis without pure liquid water nor brines. If confirmed, the absence of surface liquid would significantly modify our understanding of the Martian environment and the current habitability should be reassessed. Future experimental studies will be conducted in order to better quantify this process. As a perspective, this exotic dry flow mechanism could also occur in other planetary environments, in extremely rarefied gas such as those of Pluton, Triton or even the Moon.

## 1 Method

### 1.1 Irradiance on a sloped surface

The direct solar irradiance  $I_0$  reaching the top of the atmosphere at the longitude, latitude,  $L_s$  and local time  $(\delta, \phi, t)$  is computed using standard equations [33]. The direct irradiance reaching the surface  $D_0$  is deduced knowing the local atmospheric opacity from the Mars Climate Database 5.2 [30, 34, 35], based on average TES dust optical retrieval [36]. The total irradiance scattered by the atmosphere reaching the surface  $S_0$  is also estimated from the Mars Climate Database.

For each facet, at a slope  $\theta$ , and azimuth of slope (or aspect)  $\xi$ , the local incidence  $\mu_s = \cos \alpha_s$  can be estimated from the incidence  $\mu = \cos \alpha$  on a flat facet:

$$\mu_s = \max \left( 0, \mu_0 \cos \theta + \sqrt{1 - \mu_0^2} \sin \theta \cos (\xi - \xi_0) \right) \quad (1)$$

Using optical properties of the aerosols [37], we can deduce the irradiance of the direct beam  $D$ , the beams reflected by surrounding surfaces  $R$  and the beams scattered by the atmosphere  $S$  [31]. The total irradiance reaching the facet is thus  $I = D + R + S$ .

The thermal infrared incidence flux  $I_T$  is estimated from the Mars Climate Database [30, 34, 35].

### 1.2 Thermal model within the soil

In order to determine the precise thermal profile in a granular material, one has to solve the heat transfer equation, taking into account the penetration of light in the near surface [24, 25].

$$k \frac{\partial^2 T(t, h)}{\partial h^2} - \frac{\partial q_r(t, h)}{\partial h} = \rho C \frac{\partial T(t, h)}{\partial t} \quad (2)$$

where  $T(t, h)$  is the temperature field depending on time and depth,  $k$  is the thermal conductivity,  $\rho$  is the density,  $C$  the specific heat and  $q_r$  is the radiative flux from direct attenuated beam and diffused beam inside the soil. We estimate  $q_r$  using radiative transfer model [24], with optical properties of the grains [38, 39] and a grain radius of 50 microns. We solved eq. 2 numerically as previously described [24, 25].

We simply adapt the model, initially designed for constant illumination, to Martian daily illumination on a sloped facet by inserting  $I$  and  $I_T$  in the corresponding equations.

### 1.3 Knudsen pump model

At low pressure, temperature gradients are very important to conduct molecular flow in a tube. The Knudsen pump equation describes the mass flow  $\dot{M}$  through a capillary tube of length  $L_x$ , derived from the linearized Boltzmann's equation [40, 41] :

$$\dot{M} = P_{avg} A \sqrt{\frac{m}{2k_B T}} \left( \frac{L_r}{L_x} \frac{\Delta T}{T_{avg}} Q_T - \frac{L_r}{L_x} \frac{\Delta P}{P_{avg}} Q_P \right) \quad (3)$$

where  $\Delta P$  is the pressure difference,  $\Delta T$  is the temperature difference,  $P_{avg}$  is the average pressure,  $T_{avg}$  is the average temperature,  $A$  is the capillary cross section area,  $L_r$  is the radius of the capillary tube,  $L_x$  is the length of the capillary tube,  $m$  the molecular mass of the gas,  $k_B$  the Boltzmann's constant,  $Q_T$  is the thermally driven flow coefficient,  $Q_P$  is the pressure driven return flow coefficient. Those coefficients have been numerically evaluated [41].

From thermal calculation, the temperature gradient of a granular medium when the surface is irradiated can be considered as constant at the near surface for a length  $L_{x2}$  (upper domain 2) and then decreases at depth for a length  $L_{x1}$  (lower domain 1) [26]. We can thus estimate the pressure increase at the limit between domain 1 and 2 [26]:

$$\Delta P = \frac{L_{x2}}{L_{x2} + L_{x1}} P_{avg} \frac{\Delta T_1}{T_{avg}} \frac{Q_T}{Q_P} \quad (4)$$

When the irradiation stops, surface temperature decreases, creating a gradient in the upper domain 2, leading finally to an amplification of the Knudsen pump [28]. The enhancement factor is [28]:

$$E = \frac{\Delta P_{enhanced}}{\Delta P} = 1 + \frac{\Delta T_2}{\Delta T_1} \frac{L_{x1}}{L_{x2}} \quad (5)$$

### 1.4 Flow model

A fundamental aspect of granular flow is that there is an hysteresis in the slope stability: a metastable state exists between the static and the flowing states, where a flow can be triggered by a finite disturbance [42]. In this article, the physical modeling of the destabilization of the material and the granular flow is

based on an empirical formulation of a Coulomb-type friction law [32, 43], built on two functions  $h_{stop}(\theta)$  and  $h_{start}(\theta)$  that are determined experimentally.  $h_{stop}(\theta)$  is the thickness of granular media necessary to observe a steady uniform flow on an inclined plane at the inclination  $\theta$ , and  $h_{start}(\theta)$  is the minimum thickness of a granular layer necessary to generate a flow on the same plane.

To take into account the addition of an uplifting force due to the Knudsen pump effect, we chose to consider a rotation of the coordinate system, as if the lifting force that is perpendicular to the surface acted as a change in the gravity field. This approach is justified because the forces that apply to the flowing layer are depth averaged in the physical model considered [42].

For a given slope angle  $\theta$  (considered here to be  $30^\circ$ , as determined using the DTM), we determine if an uplifting force  $F_{lift}$ , caused by the Knudsen pump, can destabilize a granular layer of thickness  $h = L_{x2}$ . Considering that the granular material in the slopes has friction properties similar to sand, [43, 14, 42] we estimate the critical angle  $\theta_{start}$ :

$$\tan \theta_{start} = \frac{L \tan \theta_4 + h \tan \theta_3}{L + h} \quad (6)$$

with  $\theta_3$ ,  $\theta_4$  and  $L$  determined experimentally. Taking into account the lifting force  $F_{lift}$  and the gravity force  $F_{grav}$ , we estimate the equivalent slope angle  $\theta_{eq}$  using:

$$\tan(\theta_{eq} - \theta) = \frac{F_{lift} \sin \theta}{F_{grav} - F_{lift} \cos \theta} \quad (7)$$

The layer is destabilized by the Knudsen pump effect if  $\theta_{eq} > \theta_{start}$ .

## 1.5 Angle of repose

We compute the angle of repose as a function of (i) season from  $L_s=0^\circ$  to  $330^\circ$  each  $30^\circ$ , which is the resolution of the Mars Climate Database, and aspect from  $0^\circ$  to  $315^\circ$  each  $45^\circ$ . The angle of repose represents the angle to start a flow. In the case of the enhanced pump, it represents the angle of repose of a soil when shadow passed over, near the local maximum solar elevation, for instance due to the presence of a boulder.

## 1.6 Data availability

The authors declare that the data supporting the findings of this study are available within the article and its supplementary information files.

## 1.7 Code availability

The code is available from the corresponding author upon request.

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### **Author contributions**

F.S has led the project. F.A. was in charge of the angle of repose theory. F.C. has interpreted the RSL geomorphology. M.K., A.G.M. and F.S. adapted the thermal profile calculation. All co-authors contributed to the analysis of the results and the redaction of the article.

### **Competing financial interests**

The authors declare no competing financial interests.