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CO_2-driven formation of gullies on Mars

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Introduction and summary

Since their discovery by the Mars Observer Camera [1], Martian Gully landforms have attracted considerable attention because they resemble terrestrial debris flows formed by the action of liquid water [1,2]. They have thus been argued to be evidence for relatively recent potential liquid-water habitat on Mars. This interpretation is now questioned by the discovery of ongoing gully formation occurring in conditions much too cold for liquid water, but with seasonal CO_2 frost present and defrosting [3-5]. However, how a relatively thin seasonal dry ice cover could trigger the formation of decameter large debris flows exhibiting levees and sinuosities as if they were liquid-rich remained mysterious

Using a thermo-physical model of the Martian soil, we have found that, during the defrosting season, the pores below the ice layer can be filled with CO_2 ice, and subject to extreme pressure variations. The subsequent gas fluxes destabilize the soil and create gas-lubricated debris flows with the observed geomorphological characteristics of the Martian gullies. Moreover, such subsurface activities are precisely predicted at latitudes and slope orientations where gullies are observed. This shows that Martian gullies likely result from geological dry ice processes with no earthly analogs.

Modeling

We have developed a model able to compute the seasonal evolution of a column composed of an underlying regolith, a CO_2 ice layer, and the atmosphere above [6,7]. Below the surface, in the CO_2 ice layer (when present) and in the regolith, the model simultaneously solves the heat conduction and the radiative transfer through the ice [7] as well as the diffusion, condensation and sublimation of CO_2 and the related latent heat exchanges. A characteristic of the locations where CO_2 ice is predicted to condense (above 50° latitude on flat surface and down to ~30° latitude on pole-facing slope) is that a subsurface water ice table in equilibrium with the atmospheric water vapor is always expected to be present below a dry material layer of several centimeters to a few tens of centimeters [8]. We modeled the regolith accordingly, with a dry porous layer lying above an impermeable, ice-cemented, high thermal inertia soil.

Exemple on the Russell Crater megadune

Simulations were first performed to model the Russell crater megadune (54.5°S, 12.7°E), one of the key locations where recent gully formation has been observed [3,5]. While CO_2 condenses on the surface in late fall, it is observed that the albedo remains low [9], suggesting that the solid CO_2 forms a translucent slab of ice. In the model, as the daytime solar light penetrates into the CO_2 ice slab and heats the underlying regolith, the temperature at the base of the CO_2 ice slab increases. Some CO_2 sublimes and diffuses down to keep the porous layer sandwiched between the CO_2 ice and the impermeable permafrost in vapor pressure equilibrium with the CO_2 ice slab (Fig.1). The gas is trapped and the pressure can rise significantly. At the end of winter, the thickness of the CO_2 ice layer reaches 30 cm while the solar flux at midday increases. Around Ls=149°, the temperature in the regolith substrate increases from 153 K in the morning up to about 158 K in the afternoon. Accordingly the pressure rises daily from 1200 to 2300 Pa, well above the atmospheric pressure at 590 Pa. Two interesting phenomena then occur during daytime. First, the temperature within the regolith tends to be lower than at the top of the regolith where the solar flux is absorbed. As a consequence, CO_2 condenses in the coldest pores of the soil a few cm below the CO_2 ice slab base. Second, the pressure below the ice can overcome the cryostatic pressure exerted by the CO_2 ice layer and lift it. Eventually the slab should rupture to form jets of CO_2 gas [10] potentially carrying some regolith material with it. The pressure within the pores then drops down to the atmospheric pressure, leading to a much lower condensation temperature than prior to the ejection (T_{cond} ~148 K). The CO_2 ice that is present within the pores and at the base of the slab sublimes rapidly.

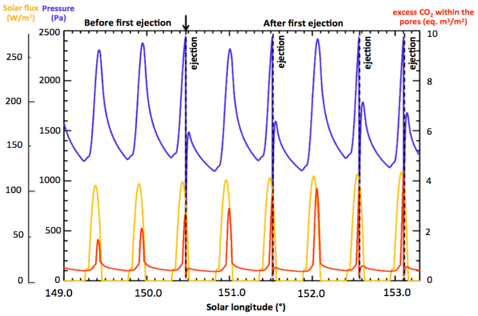

Figure 1: Evolution of the CO_2 gas pressure and total amount of CO_2 (pressurized gas and ice, converted to a volume at atmospheric pressure) in the porous soil below the seasonal CO_2 ice sheet simulated on the Russell crater megadune over an 8 sol period in late southern winter, at the time of the first CO_2 gas ejections and ice layer ruptures. This illustrates the large amount of gas in excess that must flow through the soil porous medium and which can destabilize and fluidize the subsequent debris flow.

When occurring on slopes, this process is likely to destabilize large amount of soil material. The volume of gas that has to flow up through the soil pores is considerable because it combines the depressurized excess gas (up to 1 m^3 per m^2 in our example) with the gas produced by the sublimation of the CO_2 ice present within the regolith and which becomes suddenly unstable (up to 3 m^3 per m^2). Furthermore, a large part of the gas will flow laterally through the porous medium to reach the location of the vent in the slab.

While this process has no exact analog on Earth, it can be related to terrestrial pyroclastic flows, which are gas-particle mixtures generated during volcanic eruptions. A wide range of pyroclastic flows exists, depending on the proportion of gases, and our case can be compared to the denser ones dominated by particle friction [11]. These have been found to exhibit levees [11] which are very similar in size to the ones observed on Mars [2]. The viscosity of typical flows in our simulations can be estimated to range from a few tens to a few thousands of Pa.s, similar to water triggered debris flows. In our simulation this process can repeat multiple times throughout the defrosting season. On the Russell crater's dune, CO_2 induced debris flows are thus predicted to occur between Ls=150° and Ls~205°, in agreement with the available observations [5]. However, each ejection will not generate a debris flow. As on Earth where debris flows triggered by melting snow are rare, stochastic events, it is likely that an uncommon combination of conditions are required to destabilize the slopes.

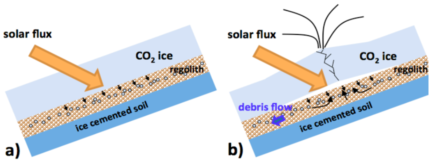

Figure 2: the sequence of events leading to the formation of CO_2-regolith viscous flows

Spatial distribution of gullies

We performed model calculations for a wide range of latitudes and slope orientations. These simulations reveal that high-pressure CO_2 gas trapping in the subsurface and the subsequent formation of ice within the regolith pores can occur where gullies are observed, and not elsewhere. In particular the model explains why gullies are only observed on pole facing slopes between 30° and 45° latitude, and with no orientation preference above 45° latitude [12].

Acknowledgements

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