

# The martian soil as a planetary gas pump

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**Mars has an active surface, with omnipresent small dust particles and larger debris. With an ambient pressure below 10 mbar, which is less than 1% of the surface pressure on Earth, its CO<sub>2</sub> atmosphere is rather tenuous. Aeolian processes on the surface such as drifting dunes, dust storms and dust devils are nevertheless still active<sup>1–3</sup>. The transport of volatiles below the surface, that is, through the porous soil, is unseen but needs to be known for balancing mass flows<sup>4,5</sup>. Here, we describe a mechanism of forced convection within porous soils. At an average ambient gas pressure of 6 mbar, gas flow through the porous ground of Mars by thermal creep is possible and the soil acts as a (Knudsen) pump. Temperature gradients provided by local and temporal variations in solar insolation lead to systematic gas flows. Our measurements show that the flow rates can outnumber diffusion rates. Mars is the only body in the Solar System on which this can occur naturally. Our laboratory experiments reveal that the surface of Mars is efficient in cycling gas through layers at least centimetres above and below the soil with a turnover time of only seconds to minutes.**

As a terrestrial planet, Mars shares many geological and physical processes with Earth<sup>6</sup>. However, the martian environment is unique with respect to at least one point. It is the only Solar System body with an atmosphere of significant but low surface pressure of on average 6 mbar. Consisting mostly of CO<sub>2</sub>, this surface pressure corresponds to a mean free path of the gas molecules of 10 μm at a temperature of 218 K. Of central importance is that this mean free path is comparable to the size of the dust particles and to the pore size within the martian soil<sup>7</sup>. A concept from the early days of rarefied gas physics is that under these conditions—mean free path comparable to or larger than the size of a structure—a pore can act as an efficient pump, purely by applying a temperature difference to its ends<sup>8</sup>. In other words, if one side of a thin channel is warmer than the other side, this channel transports gas from the cold to the warm side along its walls<sup>8–10</sup>. This effect is called thermal creep, which can be understood as follows. Let there be a closed reservoir of gas at a temperature  $T$ . If a small hole is provided, the gas flow rate (number of particles per time and area) through this opening is proportional to the thermal velocity of the gas molecules multiplied with the density ( $v_{\text{therm}} \times n$ ). Assuming an ideal gas, this is proportional to the pressure over the square root of the temperature  $p/\sqrt{T}$ . The lower the temperature at a given pressure, the higher the gas flow. If two reservoirs of the same pressure but at different temperatures are now connected, a net flow from the cold to the warm reservoir results. This argument applies only if the connection between the two reservoirs is smaller or comparable to the mean free path of the molecules and no interaction between gas molecules occurs within. On the basis of this effect, in 1909 Knudsen<sup>8</sup> measured a compression ratio in gas pressure of about a factor of 10 between the two ends of a series of small channels with a diameter of 0.6 mm at sub-millibar pressure. If the pore or the channel is too large compared with the mean free path, a backflow of gas in the centre of the channel inhibits the efficient transport along the channel<sup>9,11</sup>. Therefore, for a dusty soil with micrometre

particles, this effect is seen only at millibar pressure. This enables thermal creep through the porous soil of Mars with its low-pressure atmosphere to act as an efficient pump if temperature gradients are present. Thermal creep is similar to, but not to be confused with thermophoresis of gas molecules in a temperature gradient. This has also been considered for transport in soil as thermodiffusion, but has been estimated to be very inefficient on Mars<sup>12</sup>. Gas flow in martian soil also occurs owing to the expansion and contraction during diurnal temperature variation. This also occurs between the two reservoirs at two different temperatures as considered above, but these are one-time equilibrations. In contrast, thermal creep occurs continuously along a temperature gradient. It should be noted that pumping on Mars usually refers to net vertical transport of H<sub>2</sub>O in diurnal temperature cycles<sup>13</sup>. The thermal creep soil pump considered here has to be distinguished from this.

The gas mass flow rate  $M$  through channels due to thermal creep has been quantitatively described as<sup>11</sup>

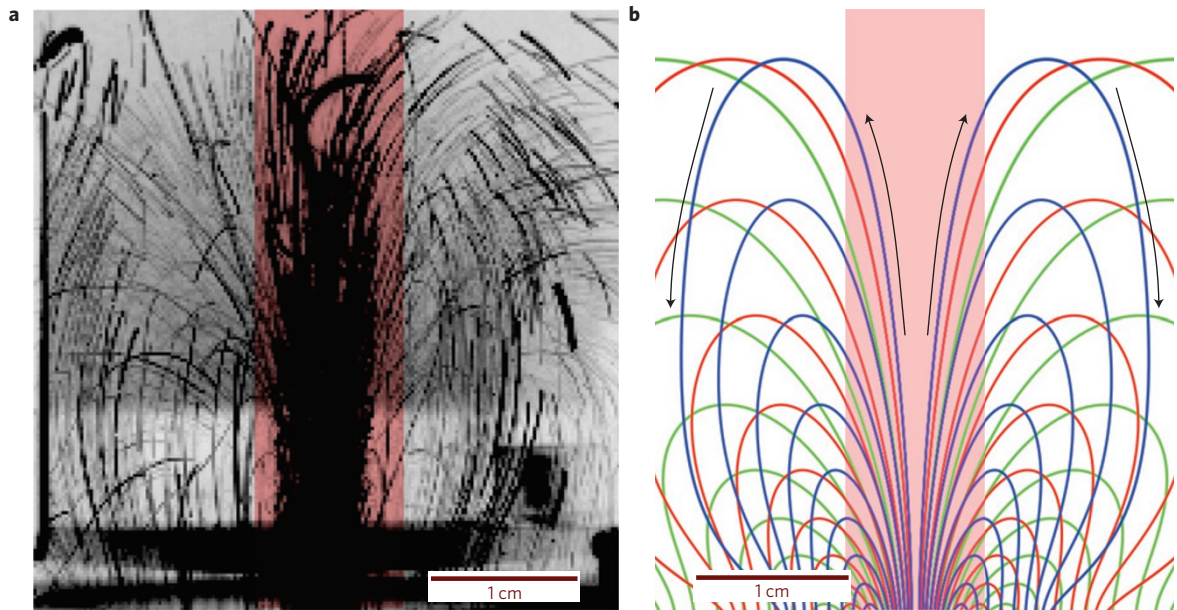
$$M = p_{\text{avg}} \sqrt{\frac{m}{2 k_{\text{B}} T_{\text{avg}}}} \pi \frac{r^3}{l} \frac{\Delta T}{T_{\text{avg}}} Q \quad (1)$$

where  $p_{\text{avg}}$  and  $T_{\text{avg}}$  are the average ambient pressure and temperature,  $r$  is the channel radius and  $l$  is its length.  $\Delta T$  is the temperature difference between the channel ends,  $k_{\text{B}}$  is the Boltzmann constant and  $m$  is the mean molecular mass of the ambient gas.  $Q$  is a factor depending on the Knudsen number. It specifies the balance between thermal creep and pressure-induced backflow. It is  $Q \sim 0$  at high pressure where the mean free path is much smaller than the pore size as, for example, on Earth.

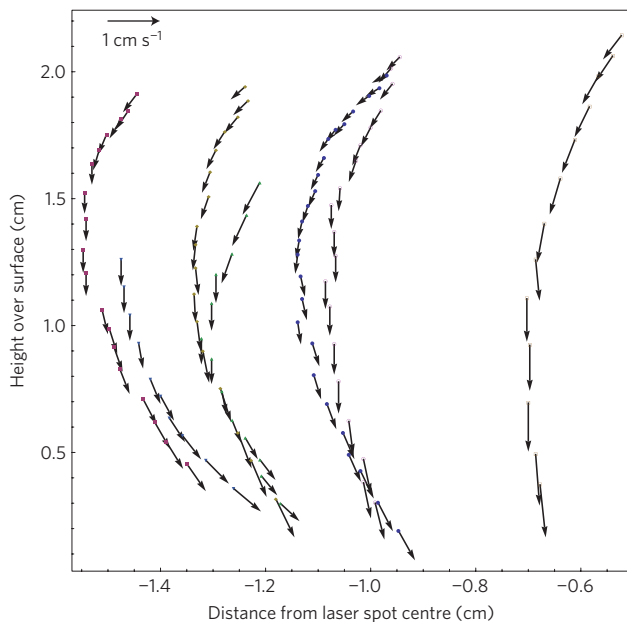
Under gravity the dominant gas flow above an illuminated and hence heated dust bed is the thermal convection. This motion is restricted to the space above the soil. A component due to gas flow through the soil by means of thermal creep is not easily discerned under gravity in the face of thermal convection. We therefore carried out experiments with an illuminated dust bed at the drop tower in Bremen (Germany) where residual gravity is below 10<sup>−6</sup> g for approximately 9 s (Methods). We used basalt with a broad size distribution up to 125 μm and a gas atmosphere with a 4 mbar ambient air pressure. In the work reported here we analyse the gas flow by observing the motion of tracer dust particles. We use particle eruptions similar to those discussed in refs 14 and 15 to generate tracer particles to study the gas flow through the porous dust bed on illumination.

Without gravity thermal convection does not exist and gas flow due to thermal creep can be observed unbiasedly. An absence of convective eddies can be demonstrated in the experiments for an illuminated solid surface. The tracer particles move only within the illuminated spot owing to photophoresis—a particle motion by light-induced temperature differences over the dust particles. No motion is visible for dust particles if not illuminated directly. This translates to no significant gas flow being present.

This changes once the basaltic dust bed is exposed to the light source. A convective flow pattern becomes visible (Fig. 1a). We note again that the experiments are carried out without gravity and the



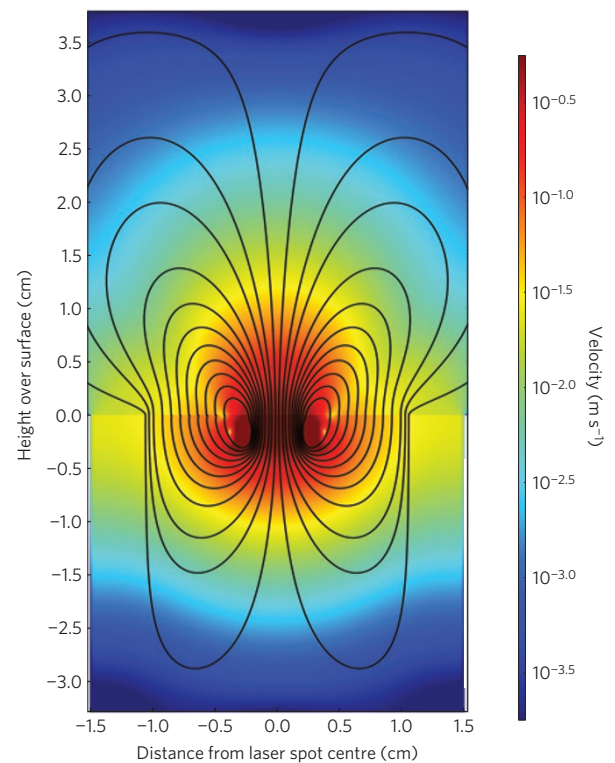
**Figure 1 | Particle trajectories above an illuminated dust bed consisting of basalt particles. a,b,** The trajectories seen in the experiments (**a**) are consistent with a simulation of the gas flow (**b**) assuming a volume force in the dust bed due to thermal creep. The light red bar marks the diameter (8 mm) of the light source (laser, 655 nm,  $13 \text{ kW m}^{-2}$ ). The direction of the particle motion is represented by the black arrows on image **b**. Owing to the illumination, dust particles leave the surface within the laser beam. The lines outside the laser (red bar) mark the downward directed particle and gas flow. These particles are not illuminated and trace only the streamlines. Streamlines enter the dust bed's surface outside the illuminated area. The illumination of the dust bed leads to a convective flow through the soil.



**Figure 2 | Velocities of a sample of tracer particles along their streamlines.** The x axis shows the distance from the centre of the laser spot and the y axis the height over the dust bed.

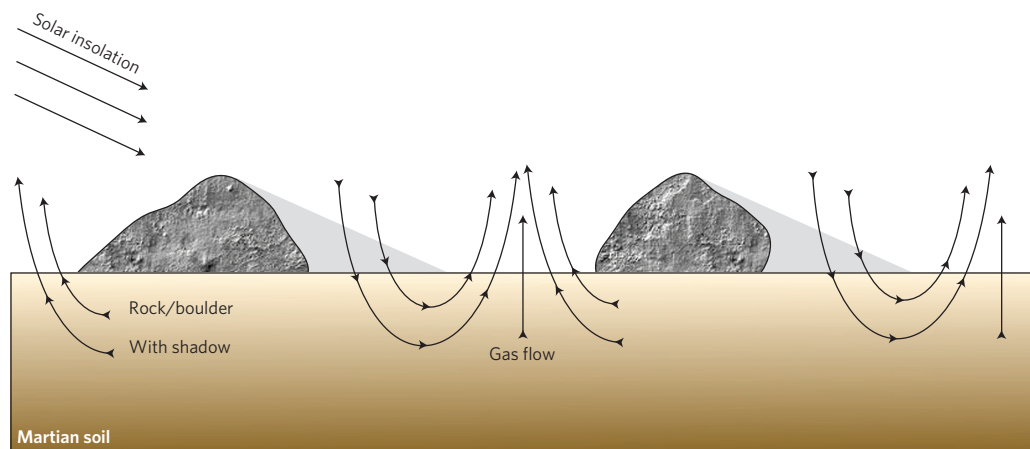
convection is not a thermal convection. The tracer particles follow the gas streamlines and enter the dust bed in the non-illuminated part tracing a gas flow into the soil (Fig. 1).

At a radiation flux of  $13 \text{ kW m}^{-2}$  the upward velocity is about  $10 \text{ cm s}^{-1}$  within the illuminated spot and downward velocities outside the illuminated spot are about  $1 \text{ cm s}^{-1}$  (Fig. 2). The inflow of gas extends to the outer end of the dust bed. The fact that gas also enters the soil at the outer extension 1.5 cm away from the spot indicates that the flow within the soil is reaching down

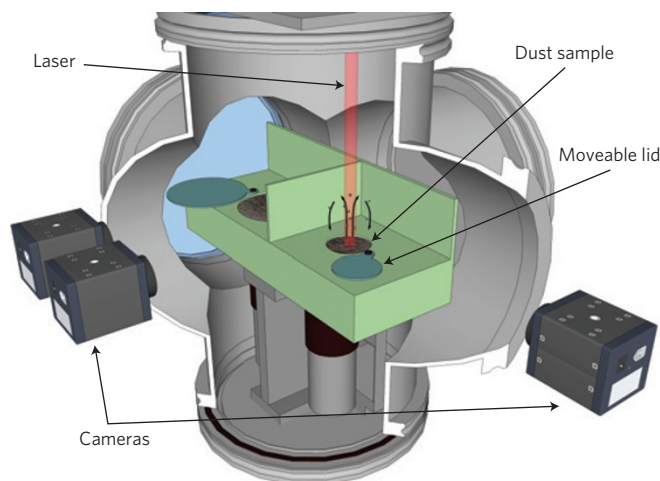


**Figure 3 | Simulation of particle velocities along their streamlines below and above the surface of the dust sample.** The height 0 marks the surface of the dust bed. The coloured scale gives the velocities, ranging from  $10^{-0.0687}$  to  $10^{-11.237} \text{ ms}^{-1}$ .

to the bottom of the dust bed 2 cm below the surface. This is consistent with a model of forced flow through the porous medium as seen in Figs 1b and 3.



**Figure 4 | The natural soil pump on Mars.** Owing to solar insolation thermal creep leads to a gas flow from the cool deeper layers up to the surface. The resulting pressure difference in the dust bed soaks up atmospheric gas from shadowed surfaces into the soil and pumps it underneath the surface towards insulated (heated) surface regions.



**Figure 5 | Schematic diagram of the drop tower experiment.** The small container for basalt powder has a diameter of 3 cm and is 2 cm deep. A red laser with 655 nm is focused on a spot diameter of 8 mm on the dust bed. Two cameras observe the movement of the dust particles at an angle of 90°.

As the experimental conditions compare well to the martian environment (detailed below), the results can readily be applied to Mars and reveal the following picture: if the martian soil is heated by solar insolation, gas will be pumped from the colder soil layers beneath the heated layers towards the surface.

At shadowed places on the surface, gas will efficiently be soaked up into the soil, traverse the underground and will be pumped up again to the heated (insolated) surface as shown in Fig. 4. Therefore, the resulting gas flow below the surface is a mixture of a vertical and a horizontal flow. In this simple picture, shadowed regions are needed as a continuous (atmospheric) reservoir of gas. As pores in soil act like micro-channels and as dust particles and pores exist in the micrometre range, the low atmospheric pressure on Mars is ideally suited to provide its soil with the ability for natural thermal creep pumping. The capability of gas flowing through heated or insolated dust layers can also lead to a significant pressure increase. It can even be sufficient to levitate large dust aggregates or to eruptively eject particles from the surface, which has been shown in ground-based laboratory experiments<sup>10,14–17</sup>.

To evaluate the gas mass flow in the drop tower experiments we use equation (1), with  $p_{\text{avg}} = 4$  mbar and  $T_{\text{avg}} = 300$  K. For a length of

$l = 2$  cm (depth of the dust bed) and basaltic powder with a thermal conductivity of  $0.01 \text{ W K}^{-1} \text{ m}^{-1}$  (ref. 18), we get  $\Delta T = 300$  K (ref. 15). In a simple model of hexagonally packed spheres, the radius of a capillary is about 20% of the sphere radius; therefore, we assume  $r = 0.2r_{\text{particle}}$  with  $r_{\text{particle}} = 50 \mu\text{m}$ . The molecular mass of the air is  $m = 28.96 \text{ AMU}$  and  $k_B = 1.37 \times 10^{-23} \text{ J K}^{-1}$ . The mean free path of air in the experiments is  $\lambda = 17.5 \mu\text{m}$ . This results in a Knudsen number  $Kn = (\lambda/2r) = 0.875$ . For this Knudsen number, we take the  $Q$ -value from ref. 11 of  $Q = 0.36$ . This leads to a gas mass flow of  $10^{-14} \text{ kg s}^{-1}$ . Divided by the cross-section of one capillary  $A = 10^{-10} \text{ m}^2$  and the density of air at 4 mbar ambient pressure  $\rho = 4.8 \times 10^{-3} \text{ kg m}^{-3}$ , we get a mean gas velocity of  $9 \text{ cm s}^{-1}$ , which is consistent with the velocities measured in the experiment.

Scaling this to martian conditions we have to consider  $\text{CO}_2$  instead of air, which has a molecular mass of  $m_{\text{CO}_2} = 44 \text{ AMU}$ . With a geometric radius of  $4.63 \times 10^{-10} \text{ m}$  (ref. 19) the molecule has a cross-section of  $\sigma = 1.6 \times 10^{-19} \text{ m}^2$ . At  $p = 6$  mbar,  $T = 218 \text{ K}$  and a particle density  $n = p/k_B T$ , the mean free path of  $\text{CO}_2$  is  $\lambda = (1/\sqrt{2}n\sigma) = 21 \mu\text{m}$ . According to this mean free path, the Knudsen number is 1.05 and hence  $Q = 0.31$  (ref. 11). Owing to the lower insolation of about  $700 \text{ W m}^{-2}$ , a smaller temperature difference than in the experiment is obtained. As a first estimate, we assume the typical diurnal surface temperature variation as  $\Delta T = 50 \text{ K}$ . Assuming the same thermal conductivity of  $0.01 \text{ W K}^{-1} \text{ m}^{-1}$ , a length of 2 cm and an average particle radius of  $50 \mu\text{m}$ , the  $\text{CO}_2$  gas mass flow is the same as the air mass flow in the experiments with  $10^{-14} \text{ kg s}^{-1}$ . Divided by the cross-section  $A \sim 10^{-10} \text{ m}^2$  and the density of  $\text{CO}_2$  at 6 mbar ambient pressure  $\rho = 14.6 \times 10^{-3} \text{ kg m}^{-3}$ , the result is a mean gas velocity of  $1.6 \text{ cm s}^{-1}$  on Mars.

The details of the martian gas pump will depend on the local light flux, which varies with daytime and shadow-casting landmarks. It also depends on the detailed soil characteristics such as pore size, albedo and thermal inertia.

Mars is known to have buried ice within its subsurface<sup>20</sup> and water vapour can be transported by diffusion to the surface<sup>12</sup>. Ref. 21 estimated the diffusion constant of water vapour in a martian simulant (JSC Mars-1 Dust) at 6 mbar ambient pressure to  $1.5 \text{ cm}^2 \text{ s}^{-1}$ . Diffusive flow might roughly be estimated to  $0.3 \text{ cm s}^{-1}$  for a 5 cm layer then. This is below the pump velocity found in the experiments scaled to martian conditions. The thermal creep gas flow hitherto unconsidered might therefore be a dominant transport mechanism for water vapour in large parts of the martian soil as it is dragged along with the  $\text{CO}_2$ .

Basalt dust beds were studied here, which we regard as a suitable analogue to martian dust<sup>22</sup>. However, essentially all light-absorbing



dust samples show effects of thermal creep in ground-based laboratory experiments on illumination (Methods).

The natural soil pump on Mars is probably leaky, acting locally in many different ways. This natural, potentially planet-wide pump is tied to the ambient pressure and has no analogue on Earth or any other planet known in the Solar System. It certainly has an influence on the gas cycle and the soil atmosphere interaction on Mars. As the directed CO<sub>2</sub> gas flow carries along the other gas species as well, it also has to be considered for water transport through the soil.

## Methods

**The experiment.** The experiments were carried out at the drop tower in Bremen (Germany) in a catapult mode. A sketch of the experiment is shown in Fig. 5.

A basaltic dust sample is placed inside a vacuum chamber. This chamber is evacuated after preparation to a preset value of 4 mbar.

During the launch the dust bed is covered by a lid to prevent particle loss during tension release. After 300 ms in microgravity the lid is opened. The dust sample is illuminated by means of a red laser (655 nm) with a spot diameter of 8 mm. The light flux is varied between 13, 9 and 6 kW m<sup>-2</sup>. The laser is turned on 4 s before the launch. The light flux is chosen as high so that once the lid is opened, particle eruptions due to a solid-state greenhouse effect and photophoresis occur<sup>10,14,16</sup>; the solid-state greenhouse effect is mostly known for transparent bodies such as dirty ice<sup>23</sup>. Visible radiation enters the medium and the absorption heats it within. As thermal radiation cannot escape because ice is opaque at this wavelength, the ice heats up below and is cooler at the surface (greenhouse effect). The same can occur for dust samples as visible light enters through the pores or forward scattering and thermal radiation cannot leave the same way<sup>17,24</sup>. In this study, this is a minute detail, as it influences only the top dust layer of about 100 μm and does not change the coarser temperature structure of the sample. However, the temperature gradient is sufficient to lead to an upward-directed photophoretic force on particles in the top layer that can eject particles from the surface at high light flux<sup>24</sup>.

At 4 mbar, a 50 μm size particle couples to the gas flow on a timescale of 50 ms. Therefore, in accordance with the observations, they rapidly slow down and then essentially trace the gas flow. A photophoretic motion is superimposed on the particle motion. This is visible when the dust bed is closed again by the lid 1 s before hitting the ground and returning to laboratory gravity. Particle motion by photophoresis can be stronger than the gas flow. Such particles are, for example, seen moving towards the dust bed rapidly within the laser beam. In any case, particles outside the direct light beam are not subject to photophoresis but are visible within the stray light. They move along with the gas and trace the streamlines.

**The sample.** We used three different dust bed samples: black spherical particles (150–250 μm in size), basalt with a broad size distribution up to 125 μm and a mixture of basalt and transparent glass spheres of 150–250 μm size. All basalt samples were heated for 48 h at 200 °C to remove any water. Neither sublimation nor expansion led to an inflow of gas into the dust bed and to a directed convection through free-floating aggregates (also observed but not shown here). Earlier levitation experiments with basalt and other samples showed that gas flow and compression are not tied to water<sup>10,25</sup>. In fact, the earlier levitation experiments with basalt were carried out on a 500 °C hot surface and we rule out that water plays a role here. Most experiments were carried out with pure basalt but the other samples showed the same gas flow patterns.

**Model of dust bed gas flow.** To support the measurements we carried out a numerical calculation according to the experimental setting. For this we simulated a gas flow within the experiments.

The problem was solved using COMSOL to simulate the flow within the dust bed and in the space above. To drive the gas flow, we placed a volume force within which the light beam enters the dust bed and it was adjusted to obtain the measured mass flow rates. Everything else, that is, the convective pattern and the depth of the gas flow, is then determined self-consistently. The simulation is carried out to compare the general circulation to the experiments and to see the part below the surface not accessible by the observations. The simulated flow matches the general flow pattern as well as the measured inflow velocities. The simulations show that gas flow at least down to 1 cm is still larger than 1 mm s<sup>-1</sup> but this strongly depends on the spatial extent of the dust bed and illumination. A spatially scaled up version of the simulation shows that also the depth of the gas flow increases. Therefore, gas flow for the illuminated surface of Mars might reach larger depths.

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## Author contributions

C.d.B. and J.T. designed the experiment. C.d.B. performed the experiment with help from G.W., T.K., M.K., T.J. and J.T. M.K. simulated the gas flow with help from G.W. C.d.B. and G.W. wrote the paper with input from T.K., M.K., T.J. and J.T.

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## Competing financial interests

The authors declare no competing financial interests.