Moreover, Airapetian *et al.* find that the solar–atmospheric interactions produce abundant NO and NH, which then participate in chemical reactions that produce both N_2O and hydrogen cyanide (HCN) — potentially quite efficiently if the solar storms are as frequent as the researchers suggest. The authors' model predicts N_2O concentrations of 20 parts per billion by volume (ppbv) at 30 km in altitude if an atmospheric pressure equal to that of present (1 bar) is assumed. However, it has been suggested that the early atmospheric pressure may have been at least twice as high[9] and N_2O concentrations can reach 3000 ppbv if atmospheric pressure is doubled. Vertical motions in the atmosphere would have then transported this upper atmospheric N_2O downward to lower altitudes, where it could warm the surface through the greenhouse effect.

As for the other gas produced in the simulations, HCN, the implications for early Earth are no less important. HCN is an important molecule for life. Chains of these compounds are known to produce various amino acids — the building blocks of proteins. The simulated 2-bar atmosphere of Airapetian *et al.* produces HCN concentrations exceeding 10 ppbv. These levels of HCN, along with other nitrogen-bearing products of the atmospheric reactions, could have helped to fertilize early surface biology.

One potential question is whether this mechanism could have counteracted a dimmer younger sun at later times as solar magnetic activity weakened. Nevertheless, the processes proposed by Airapetian *et al.* may be critical to the early Earth environment, as well as influence planetary evolution elsewhere. Geologic evidence suggests that Mars was also paradoxically warm and wet around the same time[10]. Estimates of the early Martian inventory of N_2 range from 3 to 300 mb[11], potentially fuelling similar solar–atmospheric interactions to those seen in the Earth-based models.

Airapetian *et al.*[2] demonstrate that super solar storms on an active young Sun may have had a significant impact on both surface warming and biology almost 4 billion years ago. The findings may have implications for the climates and potential biology of terrestrial exoplanets orbiting very young Sun-like stars, particularly stars with exceptionally high magnetic fluxes and very intense super stellar storms. ❐

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References

1. Sagan, C. & Mullen, G. *Science* **177,** 52–56 (1972).
2. Airapetian, V. S., Glocer, A., Gronoff, G., Hébrard, E. & Danchi, W. *Nature Geosci.* **9,** 452–455 (2016).
3. Sheldon, N. D. *Precambr. Res.* **147,** 148–155 (2006).
4. Kuhn, W. R. & Atreya, S. K. *Icarus* **37,** 207–213 (1979).
5. Haqq-Misra, J. D., Domagal-Goldman, S. D., Kasting, P. J. & Kasting, J. F. *Astrobiology* **8,** 1127–1137 (2009).
6. Ramirez, R. M. *et al. Nature Geosci.* **7,** 59–63 (2014).
7. Wordsworth, R. & Pierrehumbert, R. *Science* **339,** 64–67 (2013).
8. Rosing, M. T., Bird, D. K., Sleep, N. H. & Bjerrum, C. J. *Nature* **464,** 744–747 (2010).
9. Goldblatt, C. *et al. Nature Geosci.* **2,** 891–896 (2009).
10. Craddock, R. A. & Howard, A. D. *J. Geophys. Res. Planets* **107,** 511 (2002).
11. Mckay, C. P. & Stoker, C. R. *Rev. Geophys.* **27,** 189–214 (1989).

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PLANETARY SCIENCE

Jumping grains on Mars

Liquid water on Mars may be an agent of surface change, but it is unstable under the thin atmosphere. Experiments suggest water percolating though Martian hillslopes ejects sediment as it boils under the low pressure, and modifies the landscape.

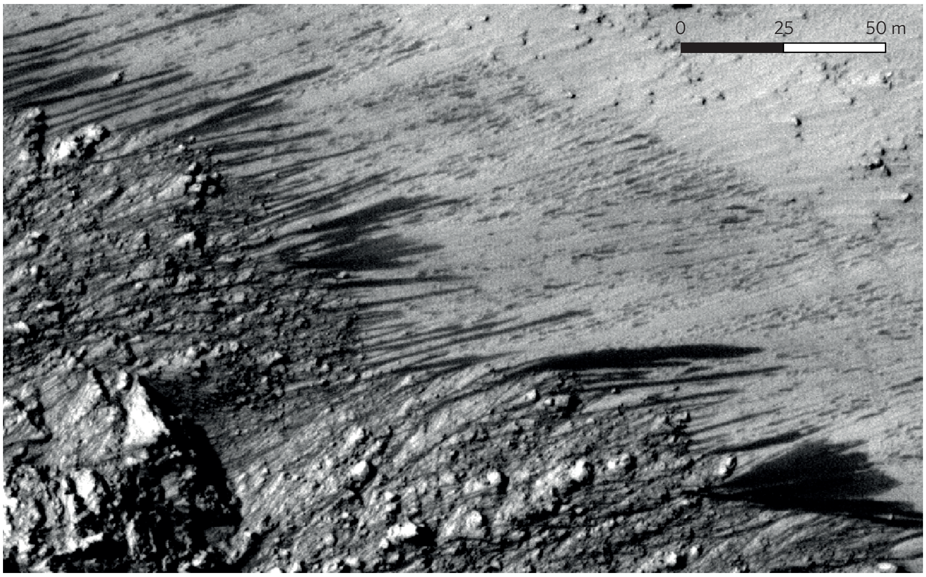
Wouter A. Marra

The surface of Mars reveals many clues about current and past geomorphological processes. The morphology and temporal changes of some surface features observed from orbit hint at the present-day activity of liquid water on or near the Martian surface. Our understanding of extraterrestrial surface processes is often biased towards what we know about analogous landforms on Earth. However, liquid water under the low pressure of the Martian atmosphere behaves very differently from Earth's surface water: it will quickly boil or freeze. As a result, it seems unlikely that water can play a large role in shaping the surface of present-day Mars. Writing in *Nature Geoscience*, Massé *et al.*[1] present the results of laboratory experiments conducted under Martian conditions and show that the vigorous boiling of water sends grains of sand airborne and results in significant geomorphological change.

Ancient channel systems on Mars are thought to have formed by vast quantities of liquid water under a dense early atmosphere[2,3]. Due to atmospheric loss[4], liquid water is no longer stable on the surface and a planet-wide hydrological cycle is now absent. Nevertheless, cyclic climate variations have resulted in infrequent periods where water sourced from snow, ice or the subsurface has transiently flowed over the surface, possibly aided by dissolved salts that lower the freezing point of water.

Remote sensing observations of the Martian surface over the turning seasons have revealed streaks that lengthen down steep slopes during warmer seasons (Fig. 1)[5]. The morphology of the streaks seems to be formed by flowing water, but water does not survive for long in liquid form under the climate conditions at the surface. Alternatively, these streaks could have formed by CO_2 processes[6], dry granular flows[7] or the transient flow of brines in the subsurface. The detection of hydrated salts in a few cases[8] points towards the latter explanation, but how the percolation of a small amount of water can cause morphological changes that are observable from orbit remains unclear.

Massé *et al.*[1] demonstrate that the morphological changes observed on the surface may be explained by the different behaviour of water under Martian atmospheric conditions. In their experiments, they let a block of ice melt on top of a sloping layer of sand in a chamber kept at the atmospheric pressure of Mars. The meltwater then percolated from the base of the ice block downslope through the sediment. This water boiled at the interface between wet sediment and thin air. In the experiment, the power of the escaping water vapour launched sediment into the air, resulting in the deposition of ridges over time. These ridges occasionally collapsed as they became too steep, and induced dry granular flows.



NASA/JPL/UNIVERSITY OF ARIZONA

Figure 1 | Slope streaks on Mars as observed from orbit. Massé *et al.*[1] produced similar morphologies in physical experiments conducted under the low surface pressure of Mars and found that the instability of water under such conditions leads to geomorphic processes unlike those reworking slopes on Earth where liquid water is stable.

The morphologies produced on the sandy slopes in these experiments are remarkably similar to the streaks observed on Mars (Fig. 1). Paradoxically, instead of requiring the stability of substantial water or brines, it is the instability of water on Mars that may explain the morphological activity needed to form the observed features. Furthermore, the wet process that induces the hopping of grains, followed by the dry process of granular flow in the experiments is consistent with a change in morphology observed between the upper and downstream ends of these features on Mars.

The experiments of Massé *et al.*, along with other experimental studies of Martian surface processes[9,10], yield valuable insights into the origin of Martian landforms. To explain the landscape of Mars, we need to extend our knowledge of geomorphological processes beyond Earth conditions. It is not easy to conduct fieldwork on Mars, so physical experiments are an important tool to explore how processes operate under Martian surface conditions and the geomorphic impact of these processes. Such experimental insights are essential to interpret what we see in satellite imagery and to provide information for numerical models attempting to reconstruct climate conditions on Mars.

Diagnostic morphological details observed in the experiments by Massé *et al.* cannot yet be identified on landforms on Mars as available spacecraft data are not at such a small resolution. Moreover, since the water is percolating just beneath the surface, direct spectral evidence for this water may be hard to find. Besides higher-resolution images from orbit or landers, measurements of the Martian subsurface in the vicinity of slope streaks are needed to test this hypothesis.

Massé *et al.*[1] propose a process that may explain the paradox of apparent ongoing aqueous surface processes under conditions at which liquid water is unstable. This process in which unstable boiling water causes grains to hop and trigger slope failures may underlie some of the active landforms observed on the Martian surface. The ability of water to cause surface changes under a thin atmosphere suggests that the role of water in shaping the Martian surface is not strictly limited to occasionally favourable climate conditions. ❐

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References

1. Massé, M. *et al. Nature Geosci.* **9,** 425–428 (2016).
2. Baker, V. R. & Milton, D. J. *Icarus* **23,** 27–41 (1974).
3. Craddock, R. A. & Howard, A. D. *J. Geophys. Res.* **107,** 5111 (2002).
4. Mahaffy, P. R. *et al. Science* **341,** 263–266 (2013).
5. McEwen, A. S. *et al. Science* **333,** 740–743 (2011).
6. Dundas, C. M., Diniega, S. & McEwen, A. S. *Icarus* **251,** 244–263 (2015).
7. Sullivan, R., Thomas, P., Veverka, J., Malin, M. & Edgett, K. S. *J. Geophys. Res. Planets* **106,** 23607–23633 (2001).
8. Ojha, L. *et al. Nature Geosci.* **8,** 829–832 (2015).
9. Marra, W. A., Hauber, E., de Jong, S. M. & Kleinhans, M. G. *GeoResJ* **8,** 1–13 (2015).
10. de Haas, T. *et al. Nature Commun.* **6,** 7543 (2015).

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CARBON CYCLE

A hump in ocean–air exchange

Semivolatile organic compounds from fossil fuels or incomplete combustion are ubiquitous. A suite of circumglobal measurements of their oceanic and atmospheric concentrations reveals large carbon fluxes through the deposition of these compounds.

Christopher M. Reddy

The Malaspina 2010 circumnavigation was a seven-leg research cruise to document global change and the inventory of ocean biodiversity[1]. The expedition was named after Alessandro Malaspina, the Italian-born Spanish naval officer who sailed the ocean in the late 1700s, collecting marine samples and observations that were then lost to history for 200 years. During the 2010 expedition, scientists took 108 atmospheric and 68 seawater samples in the tropical and subtropical Atlantic, Pacific and Indian oceans. Writing in *Nature Geoscience*, González-Gaya *et al.*[2] provide an invaluable global assessment of the relative abundance and composition of pollutants in areas neighbouring established, rapidly