LETTERS

CO_2 jets formed by sublimation beneath translucent slab ice in Mars' seasonal south polar ice cap

Hugh H. Kieffer[1,2], Philip R. Christensen[3] & Timothy N. Titus[2]

The martian polar caps are among the most dynamic regions on Mars, growing substantially in winter as a significant fraction of the atmosphere freezes out in the form of CO_2 ice. Unusual dark spots, fans and blotches form as the south-polar seasonal CO_2 ice cap retreats during spring and summer. Small radial channel networks are often associated with the location of spots once the ice disappears. The spots have been proposed to be simply bare, defrosted ground[1–3]; the formation of the channels has remained uncertain. Here we report infrared and visible observations that show that the spots and fans remain at CO_2 ice temperatures well into summer, and must be granular materials that have been brought up to the surface of the ice, requiring a complex suite of processes to get them there. We propose that the seasonal ice cap forms an impermeable, translucent slab of CO_2 ice that sublimates from the base, building up high-pressure gas beneath the slab. This gas levitates the ice, which eventually ruptures, producing high-velocity CO_2 vents that erupt sand-sized grains in jets to form the spots and erode the channels. These processes are unlike any observed on Earth.

The vast majority of spots and fans occur in the south polar region of Mars[1,2], and are common in 'cryptic' terrain identified in Mars Global Surveyor Thermal Emission Spectrometer (TES) data as having CO_2 slab ice and anomalously low albedos[4]. Spots and fans (Fig. 1) are often associated with dunes but are common on mesas and individual layers of the polar layered materials[1–3]. Spots are remarkably repeated from year to year[2,5], and often correspond to the centres of radially branching 'spiders' eroded into the substrate (Fig. 2)[6,7]. Blotches are larger than spots, hundreds of metres to tens of kilometres in size, with less distinct boundaries, and, unlike most spots, have albedo patterns that are similar whether CO_2 ice is present or not.

Previous studies have suggested that these dark features are areas of early ice defrosting and exposing dark soil[3,5,8,9]. Mars Odyssey Thermal Emission Imaging System (THEMIS)[10–13] infrared images of the temperature of spots and fans that show that they are within 3–5 °C of the CO_2 ice temperature (~145 K), and remain at these temperatures for more than 120 days after sunrise. These temperatures are far too cold to be bare soil, which warms to >225 K within days of CO_2 ice removal[4,14]. Thus, the spots must be on, under, or within a layer of CO_2 ice, and an alternative to defrosting is necessary to explain their formation.

We selected a representative mesa and trough system (nicknamed 'Manhattan Island') for an intense monitoring campaign (Fig. 3). In this region some spots were present at sunrise (Fig. 3a) and increased in number significantly over the next week (Fig. 3b). Some regions remained spot-free for up to 100 days then developed a large number of spots within one week (Fig. 3c, d). Fans were rarely present when spots first form, typically forming days to weeks later. Some fans lengthened by up to 1 km in multiple events, suggesting surface transport at rates well within reasonable wind velocities.

Two major brightenings occurred at Ls 201° and 241° (Ls is the aerocentric longitude of the Sun and Ls 180° is the southern spring equinox) with a contrast reversal between 'Manhattan Island' and the surroundings (Fig. 3c, e). TES albedos increased to ~0.29 and ~0.32 in dark and bright regions respectively; temperatures in all regions remained near 150 K. Many spots and fans became indistinct, suggesting the deposition of a thin veneer of bright material. Over the next several weeks the spots and fans reappeared in their previous positions, suggesting the removal of the overlying bright material or, which is less likely, the formation of new fans in the same positions.

Blotches, unlike spots, have similar albedo patterns in winter with CO_2 ice present and in summer when the ice is gone. This suggests that the ice is translucent, allowing the underlying surface albedo to be seen in winter.

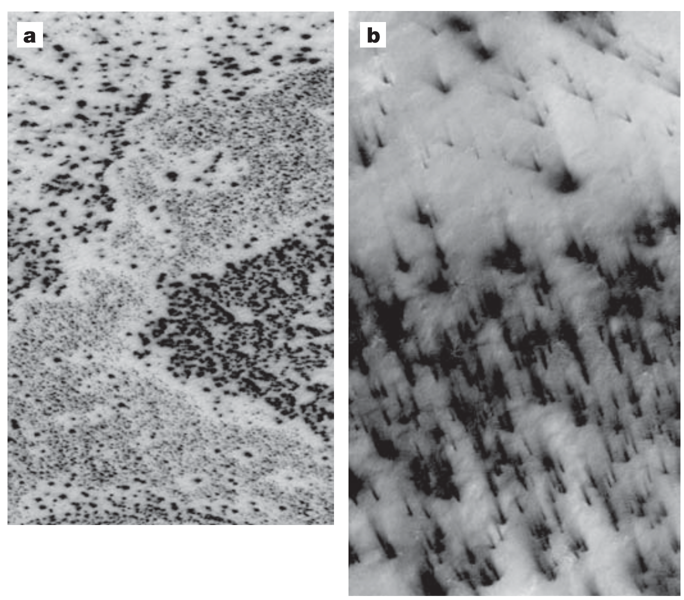

Figure 1 | Examples of spots and fans in the south polar region of Mars. **a**, MOC image E09-00231 at Ls 248° is ~3 km × 5 km in size, centred near 85.2° S and 181.4° E at ~3 m per pixel. **b**, MOC image E07-00159 at Ls 207° is ~3 km × 6 km in size centred near 86.3° S and 94.4° E at ~11 m per pixel. The dark fans are typically tens to hundreds of metres in length, 10–30° in angular size, originate from a dark spot, and point in a similar direction within a given area, sometimes with curvilinear trends influenced by topographic slopes. Occasionally fans form in multiple directions from a single spot. Some multiple fans have one diffuse edge, suggesting subsequent transport at an angle to the initial orientation. Fans are typically dark relative to the surrounding surface, although relatively bright fans also occur.

[1]Celestial Reasonings, Carson City, Nevada 89703, USA. [2]US Geological Survey, Flagstaff, Arizona 86001, USA. [3]Department of Geological Sciences, Arizona State University, Tempe, Arizona 85287, USA.

Throughout the spring and summer the surface temperatures of spots and blotches, adjusted for the presence of a relatively warm atmosphere[4], were only 3–5 °C warmer than CO_2 ice (~145 K) (Fig. 3). Assuming a 50/50 mixture of spots and ice within an infrared pixel, the temperature of the spots must be ≤153 K. The temperatures of the dark terrains remained near 150 K until the ice began to disappear at Ls 260° (~160 days after sunrise), at which time the surface rapidly warmed to temperatures consistent with bare soil (~235 K); see Fig. 3f. The duration of ice persistence requires an ~1-m-thick slab[14], consistent with elevation, neutron and gamma-ray observations[15–17].

The observation that spots are only 3–5 °C warmer than CO_2 ice requires that they be on the surface in order to produce the observed warming, yet they can only be ~1 mm thick to remain in adequate conductive contact with the CO_2 ice. The occurrence of fans with their apexes originating at spots and the similarity of their orientations indicate material on the surface that is transported by wind[6,7]; the orientations in Manhattan match the expected slope wind flow patterns towards the deep trough of Chasma Australe (Fig. 3).

The similarity in albedo patterns between winter and summer both regionally and locally (that is, blotches) suggests that in some regions the ice is transparent or translucent to a sufficient degree that surface albedo contrasts are visible through the ice. This would not be the case for a fine-grained, highly scattering CO_2 frost. There is also evidence from the infrared spectral properties that the CO_2 ice in the cryptic region is much larger-grained than the typical CO_2 frosts, and may be in the form of a translucent slab[4,18].

A model has been developed for the formation of spots, fans and blotches that accounts for their observed characteristics[6,19] (Fig. 4). Dark, granular materials lie at the surface during summer. Approximately one metre of CO_2 ice[15,16,20–22] forms the residual cap during winter (Fig. 4a). This ice anneals to form a slab[4,6,18]. With spring sunrise, the fine dust particles incorporated during cap condensation are heated by sunlight and become mobile through the slab; these dust particles can exit the slab after ~20 martian days (sols), creating an impermeable, translucent layer that allows sunlight to penetrate to the subsurface and, in the case of blotches, allows the substrate to be visible (Fig. 4b). Insolation reaches and heats the substrate, leading to sublimation of the CO_2 ice from the base. Basal sublimation results in pressures at the base of the impermeable slab that levitate the cap. Eventually the slab ruptures locally to form jets of CO_2 gas; this gas converges towards the jets beneath the slab at lateral gas velocities of

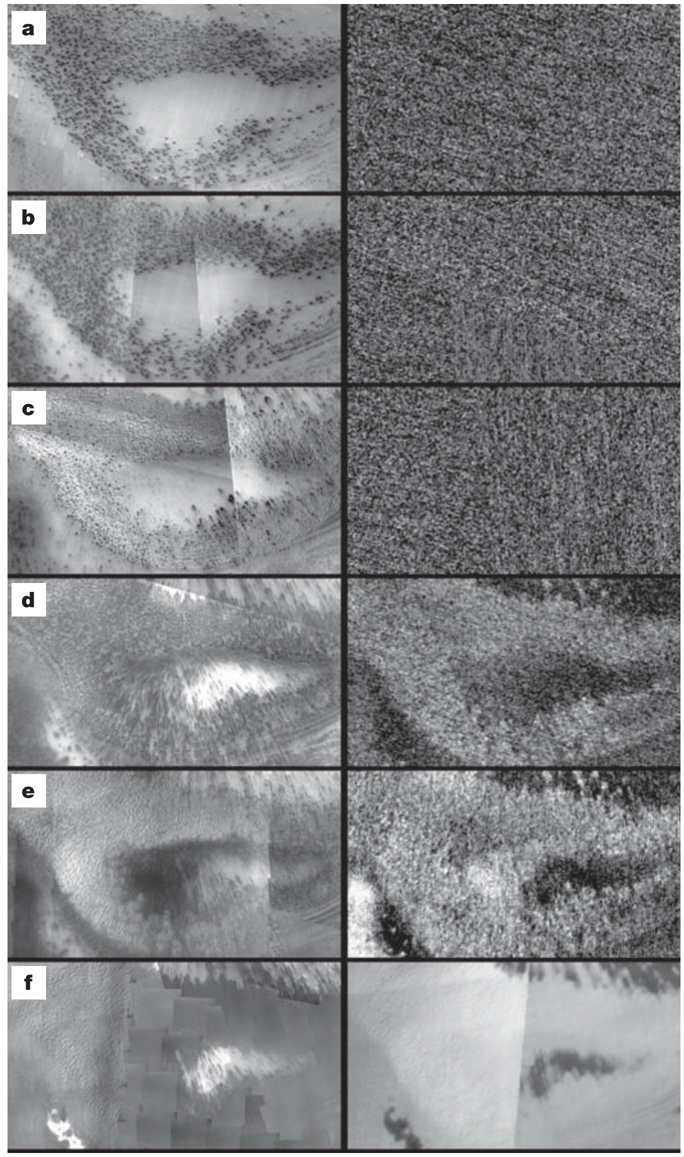

Figure 3 | The time evolution of spots and fans of a selected region of interest as seen in THEMIS visible and thermal infrared images. The ‘Manhattan Island’ region is centred at 99° E, −86.25° S. These images are a subset of over 200 THEMIS infrared and visible image pairs obtained from the end of southern winter (Ls = 176°) through midsummer (Ls 315°). This region follows the classic TES ‘cryptic’ behaviour of low albedo while remaining near the CO_2 ice temperature[4]. Simultaneous TES visible bolometer data gave well-calibrated albedo measurements at 5-km scales[13,28]. Significantly, the spot-free ice typically had a TES albedo of 0.23–0.25; spot-covered areas were only slightly darker with an albedo of 0.22–0.24. Assuming 30% spot cover, the albedo of the spots themselves is ~0.21. The high precision of the THEMIS camera allows these subtle albedo differences to be highly exaggerated. The visible albedo (left column) in all images varies from ~0.21 (black) to 0.30 (white). The temperature (right column) varies from 145 (black) to 155 K (white) in **a** to **e**. The temperatures in **f**, after the CO_2 is mostly gone, vary from 145 K (black) to 235 K (white). Temperatures in all cases have been corrected to remove the atmospheric component. Despite the formation and evolution of dark spots and fans (**a**, Ls 182°; **b**, Ls 190°; **c**, Ls 201°) the temperatures throughout the region are within ~3 °C of the CO_2 ice temperature. Even when dark spots and fans are abundant (**d**, Ls 229°; **e**, Ls 241°), the maximum temperatures are ~150 K. Therefore, the dark materials must be in thermal contact with CO_2 ice and be on top of the cap. When the surface has completely defrosted (**f**, Ls 268°), the temperatures rapidly rise to >255 K.

Figure 2 | Dendritic ‘spiders’ that form beneath spots in the south polar cryptic region. This image was acquired in Mars’ southern hemisphere summer (Ls 270°) after the CO_2 ice had completely sublimated. The MOC image (R09-04023) is ~3 km × 4 km in size, centred near −86.3°S, 99.5° E at 4.3 m per pixel.

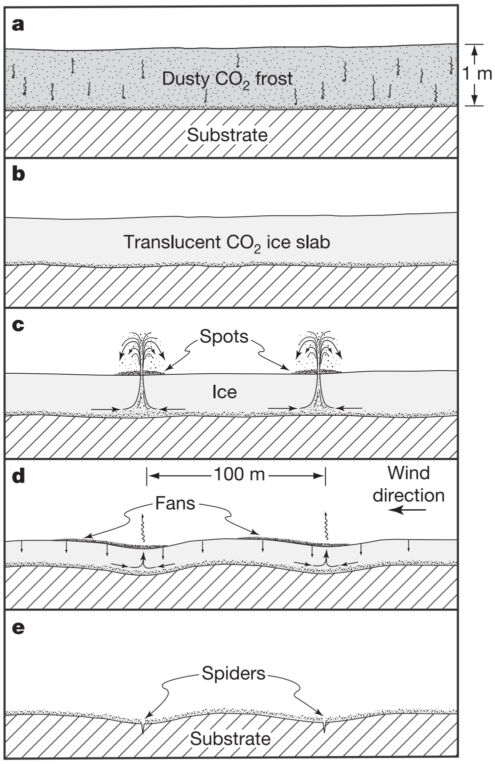

Figure 4 | A model for the formation of polar spots, fans and spiders. CO_2 ice formed during winter (**a**) self-cleans and anneals to form a translucent slab (**b**). Jets form as the pressure builds at the base of the slab, carrying sand and dust aloft to form dark spots (**c**). Dark material is transported downwind, forming fans (**d**). Because of the near equality in sublimation rates between spot and spot-free regions, the entire upper surface lowers evenly (**d**). The high-velocity gas flow at the base of the ice erodes the spiders whose centre lies beneath a spot (**d**). Eventually the ice is completely removed and the dark granular material is back on the surface (**e**).

the order of $10\,m\,s^{-1}$ at 10 m from the vent (Fig. 4c). The spots are granular materials that have been carried to the top of the ice by these jets. The dark material in spots and fans is relatively coarse (>100 μm), initially falls near the vent, is <1 mm thick, and is subsequently transported across the surface by the wind to form fans (Fig. 4d).

The small differences in albedo between the dark spot material on the surface (~0.23) and the dark substrate beneath the ice (~0.24) results in nearly equal solar energy input and nearly equal sublimation in spot and spot-free regions. In the spots the dark sand absorbs sunlight, resulting in sublimation at the surface, whereas over the rest of the cap the sublimation occurs at the base. As a result of this near equality in sublimation rates, the dark spots do not burrow down to the substrate, but instead the entire upper surface lowers evenly (Fig. 4d). The high-velocity gas flow at the base of the ice erodes the 'spiders' whose centres lie beneath vents[7,19]. Once established, this spider morphology is responsible for the year-to-year repeatability of the spot locations. Eventually the ice is completely removed and the dark granular material is back on the surface (Fig. 4e). Finally, the formation of some spots the following year before sunrise is probably due to residual subsurface summer heat, with the rapid increase in number after sunrise due to solar input that begins the process again.

Near-infrared spectra from Mars Express Observatoire pour la Mineralogie l'Eau, les Glaces et l'Activite (OMEGA)[23] support several elements of this jetting model. CO_2 ice is indeed observed in cryptic terrain near "Manhattan" from Ls 197° to Ls 242°. The observed spectra at Ls 197° require significant dust contamination at the surface of the CO_2 ice layer. At the time of this first OMEGA observation the vents and spots had already been active for about 30 days, and in many cases have reached their final configuration (Fig. 3a–c). Between Ls 197 and 223° this surface became contaminated by a thin veneer of dust (7 wt%; 0.5–1 mm)[23], in excellent agreement with the THEMIS observations and the model presented here; virtually all spots and fans have formed by Ls 223° (Fig. 3d). Furthermore, the dust contamination seen by OMEGA probably formed by the same venting process that formed the spots. Late in the season sand and dust accumulation may reduce the sunlight penetration into the ice[23], consistent with the reduction in spot activity following Ls 229° (Fig. 3). However, this surface dust layer is strongly scattering[23] and some of the obscuration of the CO_2 spectra bands may be by water ice[24], with the result that a significant fraction of the solar energy probably penetrates into the slab even during the waning phase of ice sublimation after Ls 229°.

The regional brightening and disappearance of some fans at Manhattan could be due to the condensation of a thin veneer of bright water ice and/or dust at several times throughout the spring. Poleward transport of water from the edge of the retreating cap has been suggested to account for the observed annulus of brightening near the retreating cap edge, and may be the source of these surface frosts. Areas of exposed water ice[14,25] around the south polar cap may provide an additional potential source of water.

The formation of translucent slab ice, basal sublimation and cap levitation, high-velocity CO_2 gas jetting, and eruptions of sand are unlike any phenomena observed on Earth, although a related process of solar-powered geysers has been proposed for Triton[26,27]. Each year, this process will winnow out the finest-grained materials that can be carried away by the wind in suspension, resulting in a layer of material that has been well sorted by a unique aeolian process that operates vertically.

The erosion and vertical stirring of surface materials under seasonal slab ice may have significantly altered the metre-scale sedimentary structures in the polar-layered deposits in a manner similar to bioturbation on the Earth. This erosion and redeposition of the surface material on vertical scales of a few metres may have produced sedimentary structures that reflect this modification process, rather than the initial depositional environment. If so, this process may present major complications to the interpretation of the sedimentary record observed in upcoming Polar Lander observations, and must be considered in relating this record to the climate history of Mars.

Received 4 April; accepted 30 May 2006.

1. Malin, M. C. & Edgett, K. S. Mars Global Surveyor Mars Orbiter Camera: Interplanetary cruise through primary mission. *J. Geophys. Res.* 106, 23429–23570 (2001).
2. Cantor, B., Malin, M. & Edgett, K. S. Multiyear Mars Orbiter Camera (MOC) observations of repeated Martian weather phenomena during the northern summer season. *J. Geophys. Res.* 107, doi:10.1029/2001JE001588 (2002).
3. Edgett, K. S., Supulver, K. D. & Malin, M. C. Spring defrosting of martian polar regions: Mars Global Surveyor MOC and TES monitoring of the Richardson crater dune field, 1999–2000. In *2nd International Conference on Mars Polar Science and Exploration (University of Iceland, Reykjavik, 21–25 August 2000)* 34 (Univ. Iceland, Reykjavik, 2000).
4. Kieffer, H. H., Titus, T., Mullins, K. & Christensen, P. R. Mars south polar cap behaviour observed by TES: Seasonal cap evolution controlled by frost grain size. *J. Geophys. Res.* 105, 9653–9700 (2000).
5. Malin, M. C. & Edgett, K. S. Early defrosting of the 1999 south polar seasonal frost cap: Evidence of interannual climate change? *Lunar Planet. Sci.* [CD-ROM] XXXI, abstr. 1052 (2000).
6. Kieffer, H. H. Annual punctuated CO_2 slab-ice and jets on Mars. In *2nd International Conference on Mars Polar Science and Exploration (University of Iceland, Reykjavik, 21–25 August 2000)* 93 (Univ. Iceland, Reykjavik, 2000).
7. Piqueux, S., Byrne, S. & Richardson, M. I. Sublimation of Mars's southern seasonal CO_2 cap and the formation of spiders. *J. Geophys. Res.* 108, 5084, doi:10.1029/2002JE002007 (2003).
8. Supulver, K. D., Edgett, K. S. & Malin, M. C. Seasonal changes in frost cover in the martian south polar regions: Mars Global Surveyor MOC and TES monitoring of the Richardson Crater dune field. *Lunar Planet. Sci.* XXXII, abstr. 1966 (2001).
9. Kossacki, K. J. & Leliwa-Kopystynski, J. Non-uniform seasonal defrosting of subpolar dune field on Mars. *Icarus* 168, 201–204 (2004).

10. Christensen, P. R. *et al.* The Thermal Emission Imaging System (THEMIS) for the Mars 2001 Odyssey Mission. *Space Sci. Rev.* **110,** 85–130 (2004).
11. Christensen, P. R. *et al.* Morphology and composition of the surface of Mars: Mars Odyssey THEMIS results. *Science* **300,** 2056–2061 (2003).
12. Christensen, P. R., Gorelick, N. S., Mehall, G. L. & Murray, K. C. THEMIS Public Data Releases. Planetary Data System node. ⟨http://themis-data.asu.edu⟩ (Arizona State Univ., Tempe, Arizona, 2006).
13. Christensen, P. R., Kieffer, H. H. & Titus, T. Infrared and visible observations of south polar spots and fans. *Eos (Fall Meeting Suppl.)* **86**(52), abstr. P23C–04 (2005).
14. Titus, T. N., Kieffer, H. H. & Christensen, P. R. Exposed water ice discovered near the south pole of Mars. *Science* **299,** 1048–1051 (2003).
15. Smith, D. E., Zuber, M. T. & Neumann, G. A. Seasonal variations of snow depth on Mars. *Science* **294,** 2141–2146 (2001).
16. Feldman, W. C. *et al.* CO_2 frost cap thickness on Mars during northern winter and spring. *J. Geophys. Res.* **108,** 5103, doi:I0.1029/2003JE002101 (2003).
17. Boynton, W. V. *et al.* Distribution of hydrogen in the near surface of Mars: Evidence for subsurface ice deposits. *Science* **297,** 81–85 (2002).
18. Titus, T. N., Kieffer, H. H., Mullins, K. F. & Christensen, P. R. TES Pre-mapping data: Slab ice and snow flurries in the Martian north polar night. *J. Geophys. Res.* **106,** 23181–23196 (2001).
19. Kieffer, H. H. Behaviour of solid CO_2 on Mars: A real zoo. *6th Int. Conf. Mars (Pasadena, California, 20–25 July 2003)* abstr. 3158 (California Institute of Technology, Pasadena, 2003).
20. Kieffer, H. H. & Titus, T. N. TES mapping of Mars' north seasonal cap. *Icarus* **154,** 162–189 (2001).
21. Mitrofanov, I. G. *et al.* CO_2 snow depth and subsurface water-ice abundance in the northern hemisphere of Mars. *Science* **27,** 2081–2084 (2003).
22. Haberle, R. M., Mattingly, B. & Titus, T. N. Reconciling different observations of CO_2 ice mass loading of the martian north polar cap. *Geophys. Res. Lett.* **31,** L05702, doi:10.1029/2004GL019445 (2004).
23. Langevin, Y. *et al.* No signature of clear CO_2 ice from the 'cryptic' regions in Mars' south seasonal polar cap. *Nature* doi:10.1038/nature05012 (this issue).
24. Kieffer, H. H. Interpretation of the martian polar cap spectra. *J. Geophys. Res.* **75,** 510–514 (1970).
25. Bibring, J.-P. *et al.* Perennial water ice identified in the south polar cap of Mars. *Nature* **428,** 627–630 (2004).
26. Soderblom, L. A. *et al.* Triton's geyser-like plumes—Discovery and basic characterization. *Science* **250,** 410–415 (1990).
27. Kirk, R. L., Soderblom, L. A. & Brown, R. H. Subsurface energy storage and transport for solar-powered geysers on Triton. *Science* **250,** 424–429 (1990).
28. Christensen, P. R. *et al.* The Mars Global Surveyor Thermal Emission Spectrometer experiment: Investigation description and surface science results. *J. Geophys. Res.* **106,** 23823–23871 (2001).

Acknowledgements We thank the members of the Odyssey and THEMIS mission teams and the ASU and USGS software development group for their efforts in obtaining and processing the THEMIS data used in this work.

Author Information Reprints and permissions information is available at npg.nature.com/reprintsandpermissions. The authors declare no competing financial interests. Correspondence and requests for materials should be addressed to P.R.C. (phil.christensen@asu.edu).