DARK DUNE SPOTS: POSSIBLE BIOMARKERS ON MARS?

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Abstract. *Dark Dune Spots (DDSs)* are transitional geomorphologic formations in the frost-covered polar regions of Mars. Our analysis of the transformations and arrangements of subsequent stages of DDSs into time sequence revealed their: (i) hole-like characteristics, (ii) development and formation from the bottom of the frosted layer till the disapperance of the latter, (iii) repeated (seasonal and annual) appearance in a pattern of multiple DDSs on the surface, and (iv) probable origin. We focused our studies on a model in which DDSs were interpreted as objects triggered by biological activity involved in the frosting and melting processes. We discuss two competing interpretations of DDSs: development by defrosting alone, and by defrosting and melting enhanced by the activity of *Martian Surface Organisms (MSOs)*. MSOs are hypothetical Martian photosynthetic surface organisms thought to absorb sunlight. As a result they warm up by late winter and melt the ice around them, whereby their growth and reproduction become possible. The ice cover above the liquid water lens harbouring the MSOs provides excellent heat and UV insulation, prevents fast evaporation, and sustains basic living conditions until the ice cover exists. When the frost cover disappears MSOs go to a dormant, desiccated state. We propose further studies to be carried out by orbiters and landers travelling to Mars and by analysis of partial analogues on earth.

Keywords: astrobiology, Dark Dune Spots (DDSs), frosting-defrosting, geomorphologic analysis of DDSs, life on Mars, Mars Global Surveyor, Mars Odyssey, Martian Surface Organisms (MSOs), Southern Polar Region of Mars, water ice and liquid water on Mars

1. Introduction

Images made by Mariner 7 (Murray *et al.*, 1971) and Mariner 9 (Cutts and Smith, 1973) already revealed dark-toned ‘splotches’ inside and around the craters of the southern polar region of Mars. Based on the Viking images it has been suggested that the dark ‘splotches’ are eolian dunes made up of fine-grained sediments of dark blue colour (Thomas *et al.*, 1992; Thomas and Veverka, 1986; Howard, 2000). The dark dunes in both polar areas have colours and albedo similar to that of the dunes at low latitudes, but they are dramatically different from the widespread bright dust on Mars (Thomas and Weitz, 1989).

[⋆] The first two authors have contributed equally to this work.

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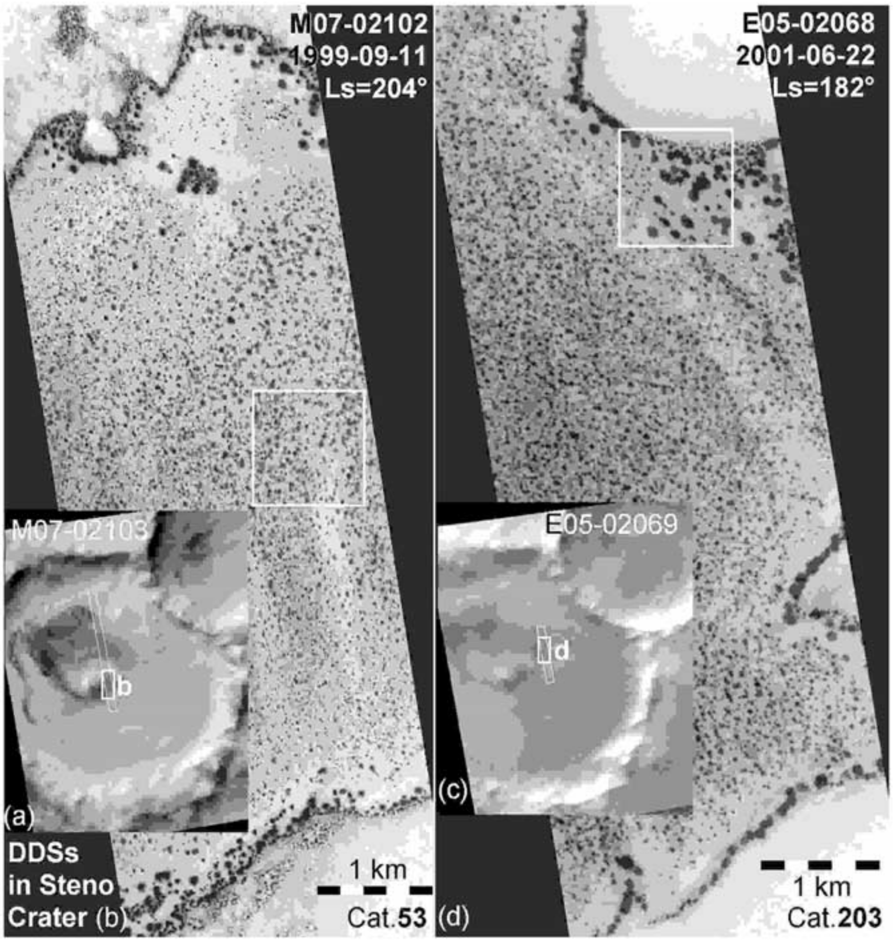

Figure 1. Characteristic intracrater, ice covered dark dune fields on Southern Polar Region of Mars. Dark dune spots (DDSs) appear on the surface of the frost covered dune hill in the Steno Crater (a, c) (105 km in diameter) at early spring (b, d). The enlarged regions within the white frames (1 × 1 km) can be seen in Figure 2. Sun illuminates from upper left and north is up.

The composition and origin of the dark dunes have been widely discussed. It is thought that the dark dunes are composed of low-albedo, sand-sized eolian sediments, mainly dense basaltic sand (Edgett and Malin, 1999).

Mars Global Surveyor (Albee *et al*., 2001) Mars Orbiter Camera (MGS MOC) images from 1998, 1999 and 2001 showed interesting features on the dark dune fields in the south polar regions of Mars (Figures 1–3). These dark dune spots (DDSs) and their clusters could be observed during winter and early spring. These dunes are the first surfaces to frost in the fall and latest to defrost during spring, frost may well persist on them until late spring or even early summer (Malin and Edgett, 2000a). Edgett *et al*. (2000) and Malin and Edgett (2000a), have made an

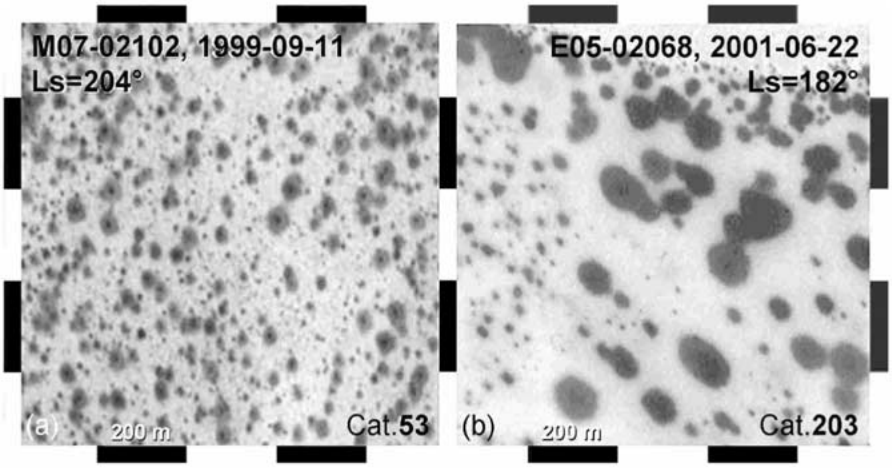

Figure 2. Typical circular DDSs can be observed on the surface of the frosted dune field in the Steno Crater at early spring. These images (a, b) are enlarged regions of Figure 1. Sun illuminates from upper left and north is up.

analysis of the whole defrosting process from the winter until the summer of the southern hemisphere, using images taken in 1999–2000 of the low-albedo dune fields. They and others (Bridges *et al.*, 2001) concluded that a complex process of CO_2 and H_2O sublimation and re-precipitation occurs as a function of season and local temperature, which is controlled by the surface and interior physical properties of the dunes.

In the first part of the paper we describe our observations on dark dune spots morphology, the patterns of DDSs, the formation and transformation of DDSs. Dark Dune Spots tend to have circular shape on the top of dark sand sheets (Figure 1); their diameter varies from a few dozen to a few hundred meters and they exhibit a characteristic inner structure (Figure 2). On slopes the spots are elongated downwards: they are ellipsoidal or fan-shaped and sometimes streams flow out from these spots. We observed that DDSs are shallow crater-like holes in the frosted layer and the DDS formation process is triggered from the bottom of the frost. We also observed seasonal and annual variation and recurrence of DDSs patterns, too.

In the second part of our paper we deal with the interpretation of the observational data. We interpret the sequence of DDS formation as a process of sublimation combined with melting and some kind of biological activity of putative Martian Surface Organisms (MSOs) (Horváth *et al.*, 2001, 2002d). In our model we suggest that, despite the adverse conditions, these Martian Surface Organisms could dwell below the surface ice, are heated up by the absorption of sunlight, grow and reproduce through photosynthesis and generate in part their own living conditions. The lifecycle of putative MSOs is consistent with observed features of the dynamics of DDS morphogenesis. We are not aware of any rival mechanistic hypothesis of comparable detail.

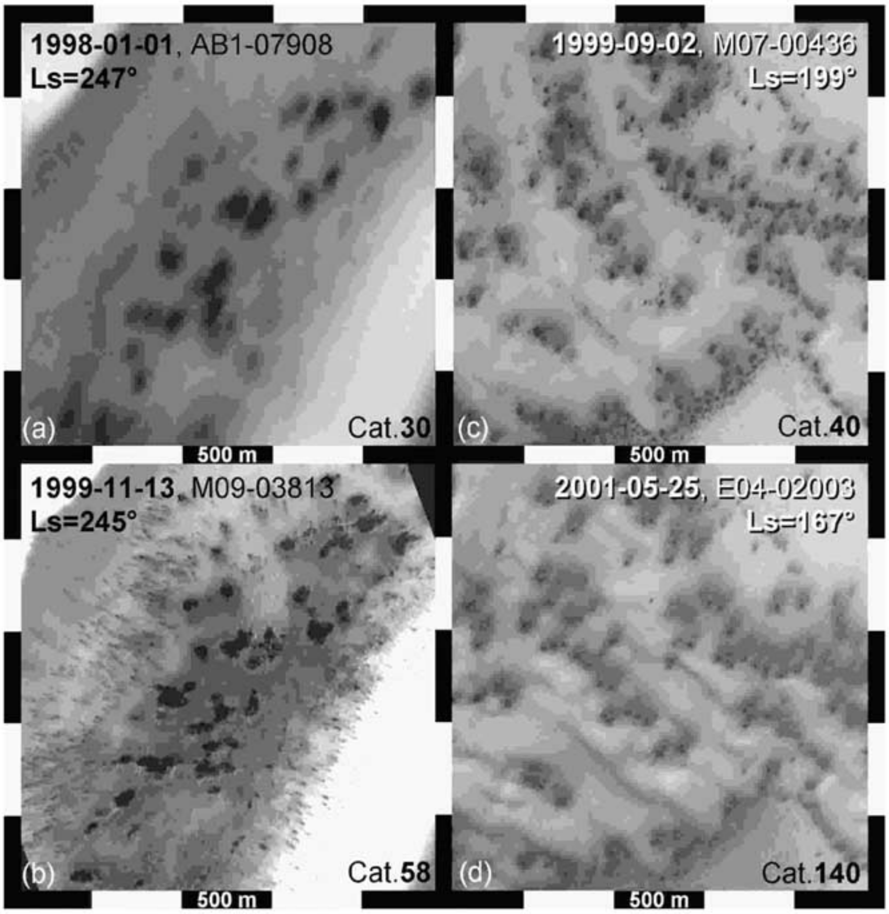

Figure 3. DDSs appear in three subsequent Martian springs and winters. The two images (a, b) show identical 2.5 × 2.5 km regions of the Martian 'Inca City' formation (II. 'cassettes') in springs of 1998 (a) and 1999 (b). Here the majority of the greater DDSs can be seen on the same place where they appeared earlier. See the detailed version of the Figures a and b on Figure 20. The other two images (c, d) also show identical 2.5 × 2.5 km regions of the Jeans Crater in springs of 1999 (c) and 2001 (d). Sun illuminates from upper left and north is up.

Living systems basically function as fluid (chemical) automata: their component reactions proceed in solution (Gánti, 1997, 2003). Under Martian circumstances the only possible solvent is liquid water. After the Viking missions it has become widely accepted that living systems cannot operate on the Martian surface because either water is frozen on the surface due to extreme cold, and that the eventually arising liquid water would very quickly evaporate thanks to the very low atmospheric pressure (reviewed by Horneck, 2000). Thoughts about Martian life so far have been severely constrained by the general surface conditions. Very low temperature and extreme low atmospheric pressure were thought to prohibit the existence of liquid water, and, consequently, currently active life. Speculations concentrated, therefore, on the Martian soil or even deeper layers of the planetary surface (cf. Horneck, 2000; Wynn-Williams and Edwards, 2000). We do not challenge these ideas but point out a potential alternative. The fact that the surface in general is not hospitable to life does not mean that there can not be particular habitats, where the special circumstances can support life for relatively long periods. Dark Dune Spots in the southern polar regions of Mars seem to qualify for such special habitats. We argue that their appearance by late winter-early spring, and their further morphological development are indicative of life processes within (Horváth *et al.*, 2002c).

2. Observations

We have analyzed more than two hundred MGS MOC pre-processed images and more than two dozen MGS MOLA laser height-measurements published on the World Wide Web by the Malin Space Science Systems (http://www.msss.com/moc_gallery/) and by Jet Propulsion Laboratory in the Planetary Image Atlas (http://www-pdsimage.jpl.nasa.gov/PDS/public/Atlas/). As the two polar regions of the Mars are quite different from each other (Malin and Edgett, 2000c), the southern polar region was chosen for the primary morphological analysis of the DDSs. The dark dunes give a background behind the light, precipitated, frosted layer and this fact made it far easier to observe the changes of the spots. We also note that photographic coverage of the south Polar Regions by MGS MOC images is better than that of the northern one.

MOC wide-angle context images (wavelengths 600–630 nm) helped orientation, while MOC narrow-angle images (wavelength 500–900 nm) were used for detailed analysis of the DDSs. Figure 25 shows the Map of the Southern Polar Region of Mars with places of craters of DDSs and the number of MGS MOC images in our Catalogue by Appendix. The table in Appendix/*Catalogue of Dark Dune Spots(DDSs) on Southern Polar Region of the Mars*/provides details of those MGS MOC narrow angle images which were used in our analysis along with a list of craters in which we observed DDSs. The narrow-angle images usually cover a 1–3 km wide and 7–57 km long area, with a high resolution of 1.4–5.5 m (except images Nos. 26, 30, 45c, see in table in Appendix, their resolution is only 15–25 m).

After enlargement and identification of interesting areas, the contrast and brightness of the images have been improved using Paint Shop Pro 6 software. These modifications only increase the contrast and the accessibility of visual information of the images.

The analyzed MGS MOC narrow-angle images were taken between May 1999 and June 2000 from winter to autumn of the southern hemisphere of Mars (besides plus three from 1997–1998 and five from 2001), and cover areas between 58–82°S latitudes (except images Nos. 42 and 47 in Appendix).

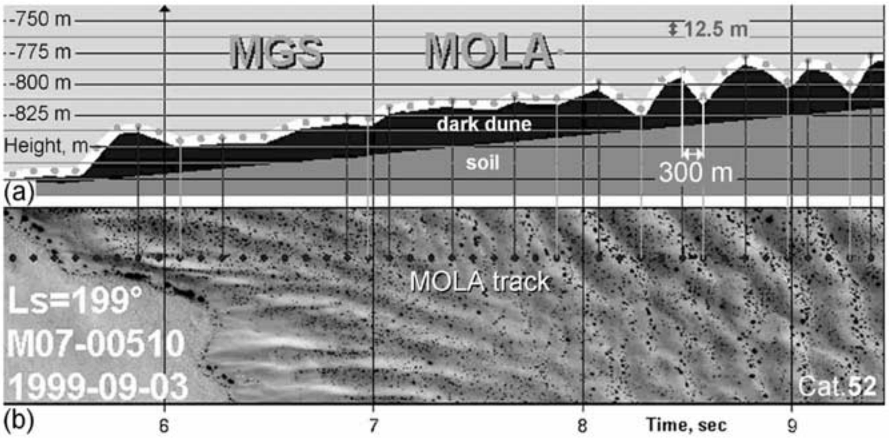

Figure 4. Thickness, size and hypothetical cross-section of the DD-field in the 175 km diameter Phillips Crater of the Martian South Polar Region. The image (a) shows our model cross-section obtained by using MGS MOLA laser height-measurements and MGS MOC narrow angle images (b). The average minimal dark dune height is alternating between 10–50 m. Sun in (b) illuminates from upper right and north is right down.

3. Geomorphological Analysis of DDSs

The horizontal size of the *dark dune (DD)* regions falls in the range from a few to some dozens of kilometres. The thickness of dark dunes varies from 10 to 200 m on average, as seen from comparisons of MGS MOLA laser height measurements and MOC images (Figures 4 and 5), although in some places attained 500 m. In our cross-section model of DDs we assumed that they sit on a surface apparent in the surrounding territory.

The diameter of DDSs varies between a few dozen and a few hundred meters and they have an interesting inner ring-structure (Malin and Edgett, 2000b; Edgett *et al.*, 2000), which can be seen only on the highest-resolution images (Figure 6). The thickness of the CO_2 and H_2O ice depends on the latitudes. It is increasing towards the polar region and may reach some decimetres at lower latitudes and one meter at the South Pole (Smith *et al.*, 2001).

MOC images of Figure 7 illustrate that the circular shape of DDSs is superimposed on (so they are independent of) the local micro-topography.

This superimposition suggests the local determination of circular DDS formation by some previously unidentified process, because the preferential sites for sublimation would be surfaces receiving the highest radiation flux from the Sun. For this reason we can say that spots formed by sublimation only ought to have diverse, irregular, rather than circular, shapes.

On all images we studied, the overwhelming majority of DDSs are nearly circular on the horizontal surfaces of the dark dunes (Figures 1–8, 12–16, 18–19). This circular shape of DDSs also holds information about their formation process and it

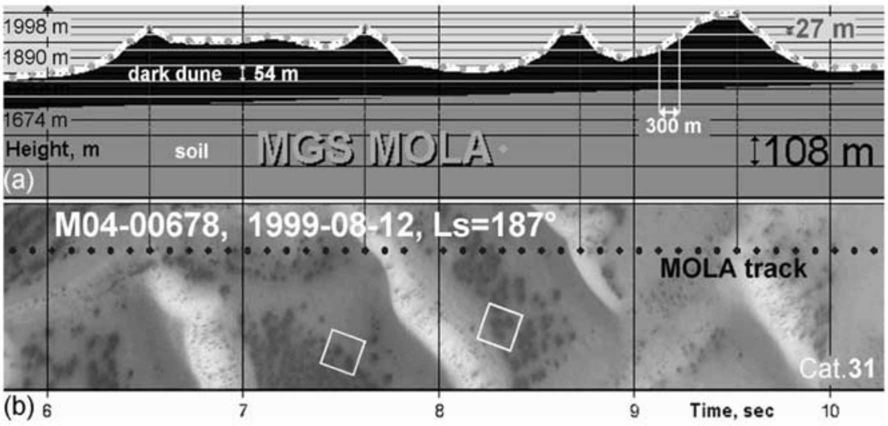

Figure 5. We show thickness and configuration of the dark dunes in the Martian 'Inca City' formation. The image shows our model cross-sections obtained by comparing the MGS MOLA laser height-measurements (a) and MGS MOC narrow angle images (b). The minimal heights of the dunes in the 'Inca City' are between 50–250 m. In (b) we can observe that elongated or fan-shaped narrow flows emanate from DDSs on the illuminates side of DD. Sun in (b) illuminates from upper right and north is right down.

indicates that spots are formed not only by sublimation, but also by some radially spreading process (e.g. water leaking into homogeneous sandy soil). However, on slopes with meaurable tilt this circular shape is modified.

3.1. HOLES, ELONGATED DDSS, SEEPAGES OR FLOWS

It is another important observation that the DDSs are shallow crater-like holes in the frosted layer (in the precipitated snow-ice layer). On Figures 8 and 12b we can see that the surrounding grey annulus on the side illuminated by the sun is lighter than on the opposite side. This means that the DDSs are holes.

The central region of a DDS is dark because it is deep and exhibits the dark dune surface. The surrounding grey annulus is the slope around the central hole and it is grey because of the gradually thinner frosted precipitation layer (Horváth *et al.*, 2002a).

Another observation is that on slopes the spots are elongated downwards: they are ellipsoidal or fan-shaped (Figures 5b, 9, 10, 14c, 15c, d and 17b); depending on the steepness of the slope, indicating that gravitational force does affect spot morphogenesis (Gánti *et al.*, 2002).

Finally, there are spots from which extensions originate (Figure 11), indicating some downward seepage or flow. All these observations confirm that some transport of a fluid phase (most likely water) plays a fundamental role in spot morphogenesis. The fact that transport of something in liquid phase (water) occurs below the frosted ice cover, rather than on the naked (defrosted) surface, is visible on Figures 11c and d. The migration of water in the soil results in a seepage-like

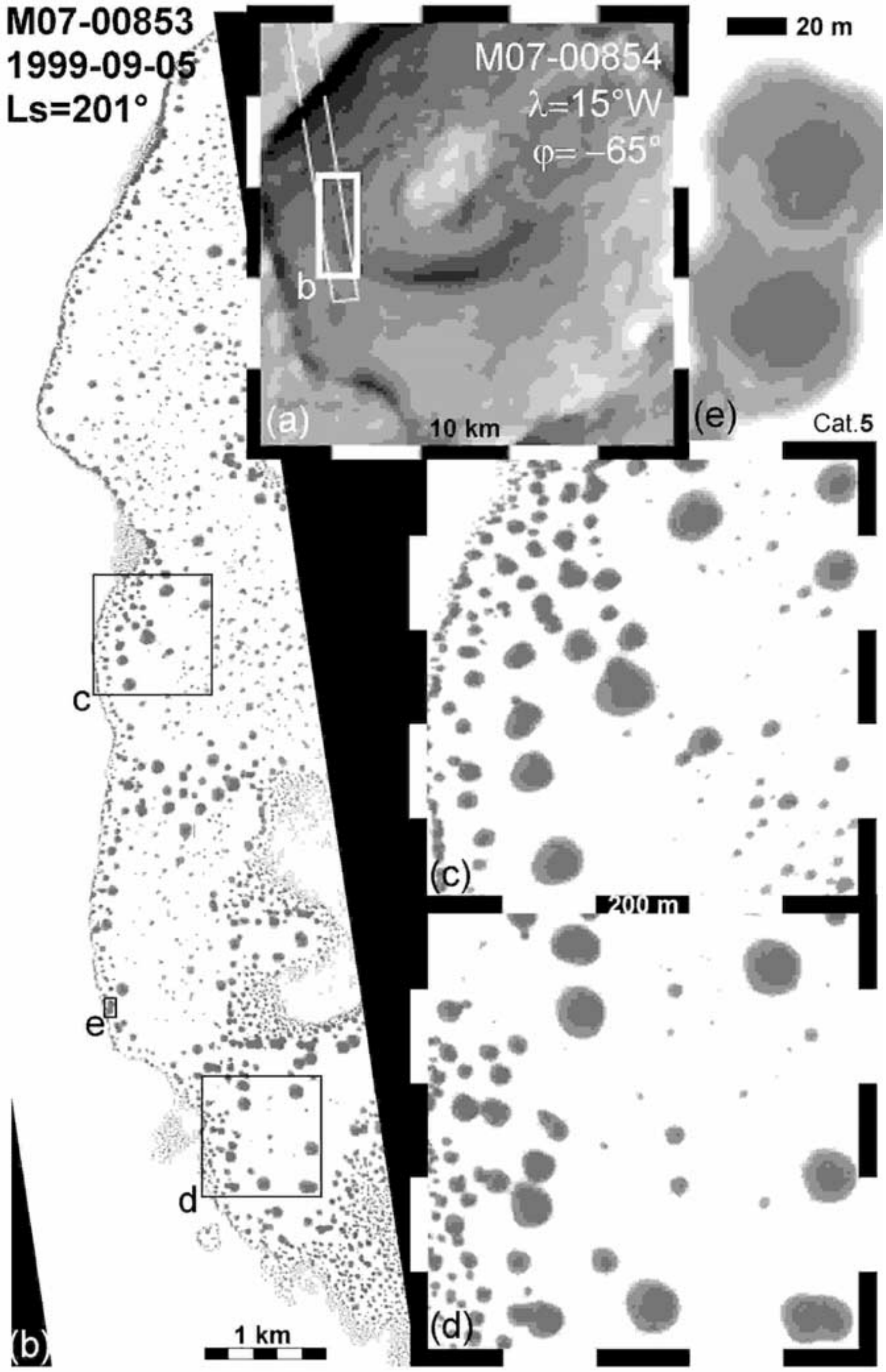

Figure 6. Martian dark dune spots with circular or rounded shape and inner ringed structure. (a) A 50 km wide crater with intracrater dark dune field. Early spring DDSs can be seen along the edges and on the top (b) of the intracrater dune field. Nearly circular DDSs are on the flat (c, d) dune field. Enlarged inner ring structures of two DDSs can be seen in (e). Sun illuminates from upper left and north is up.

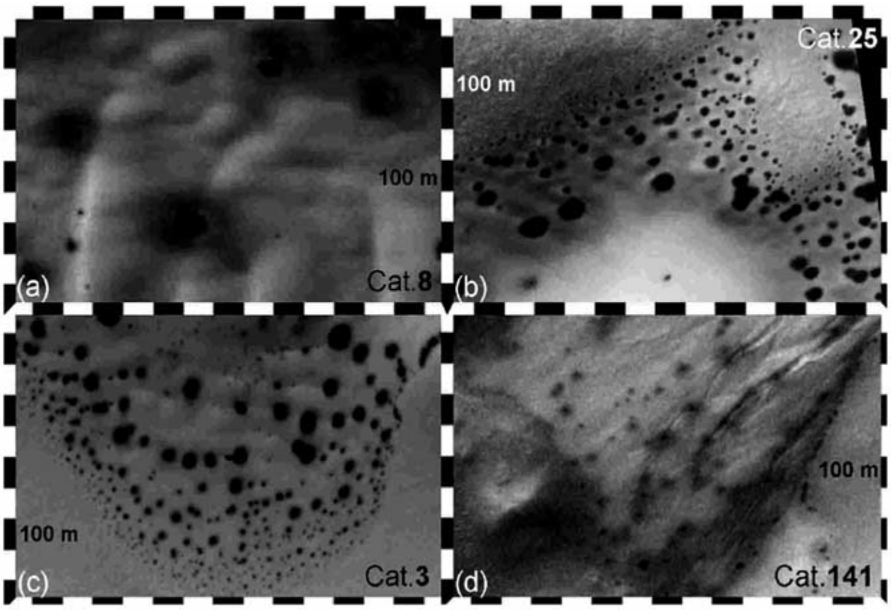

Figure 7. DDSs are superimposed on the local topography i.e. small-scale groove structure of the frosted surface of snow/ice cover. (a) The DDSs cut across the crest of the dunes. (b) DDSs are superimposed on the small-scale grooves of the frost (in Jeans Crater). (c) The rounded shape of the DDSs overprints local dune crests. (d) DDSs superimpose on the frosted gullies in the anonymous crater of 5 km diameter. Sun illuminates from upper left and north is up.

surface expression of the process, in the form of elongation of DDSs on the dark dune slopes. There is an image that shows DDSs, which are not only elongated but are arranged in several hundred meters long, winding stripes. We suggest these stripes follow the tracks of such water seepage in the soil. It is remarkable that some of these under-ice flow tracks can reach a length of a few hundred metres. From other types of sites Malin and Edgett (2000d) have already found overwhelming evidence for recent groundwater seepage and surface runoff on Mars.

3.2. DDS FORMATION BEGINS FROM THE BOTTOM

Figure 12 shows a surface pattern of grooves on the top of the frost, remaining undisturbed while grey and dark spotting is already in progress. Based on this and the other observation that the DDSs are shallow, hole-like objects (Figure 8), we conclude that DDS formation is not a slow sublimation of the frosted layer (beginning on the top), but it is a process triggered and promoted from the bottom of the frost.

The interpretation that DDSs form at the boundary of the frost cover and the dune surface is in accord with our other observation, shown in Chapter 3.4; namely that the collective pattern of multiple DDSs behaves as a recurrent seasonal pattern

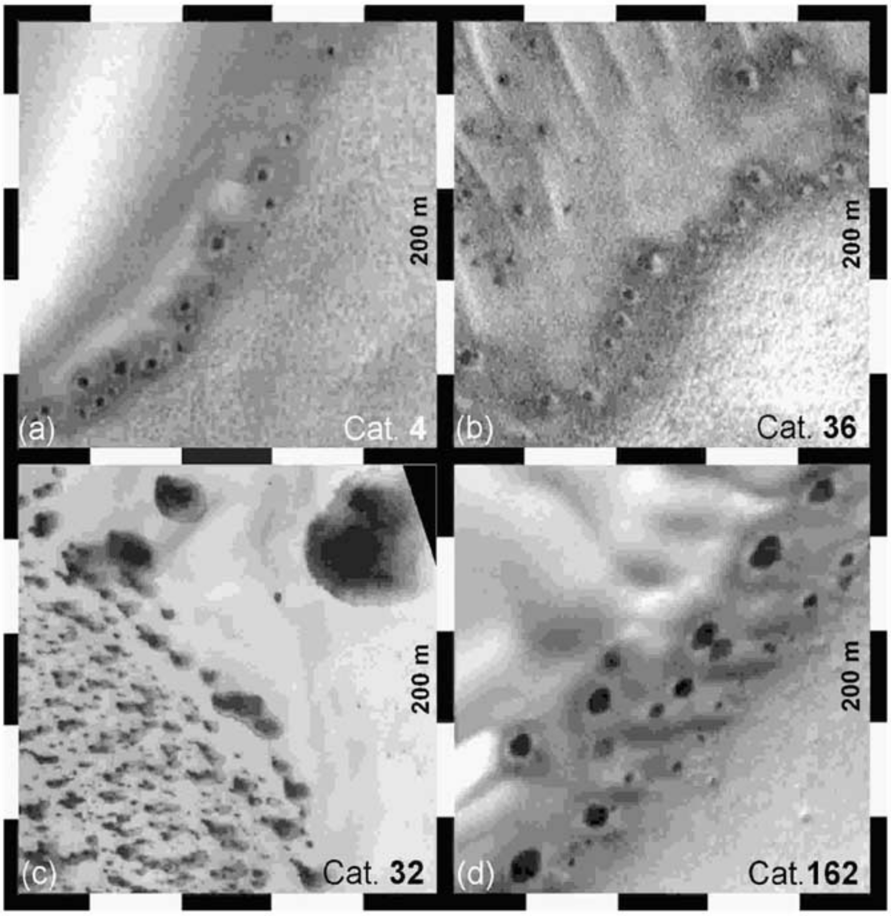

Figure 8. DDSs appear and become shallow crater-like holes in the ice cover layers. (a, b, d) In the winter DDS-holes appear at the margin of the frosted dark dune field and they are surrounded by light grey halos (c) In middle of spring, in a crater nearer to the South Pole, together with smaller DDSs larger ones also appear, but frosted covers without DDSs also occur in this DD-field. Sun illuminates from upper left and north is approximately at the top in all these figures.

or configuration, showing also that some formative cause is tied to the soil-frost boundary.

This conclusion is also in accord with the observation that the circular shape of DDSs is independent from the local small-scale surface topographic variations (Figure 7), because DDSs grow radially rather than follow fine-scale topographic highs or lows on the *surface* of the frost.

All these observations may imply that the melting/evaporation process ‘eats up’ the frosted layer from the bottom where the DDS centres develop, which later become the dark holes of the DDSs. The central region of DDSs is dark because it is deeper than the frosted layer, and it exhibits the dark dune surface (Figures 6–8).

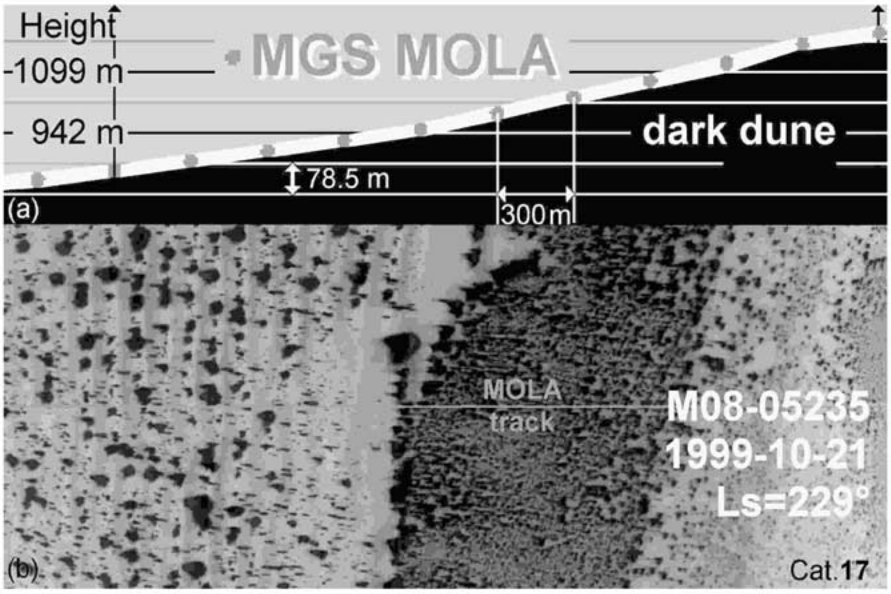

Figure 9. Elongated DDSs and flows originating from them can be seen in the Lyell Crater. On the undulating dark dune surface, which is tilted (4 degrees according to the MOLA measurements, (a) many elongated flow-tracks of DDSs can be observed (b). In (b) on MOC image the Sun illuminates from upper right and north is approximately right lower corner.

3.3. ‘INCA CITY’: TIME SEQUENCE OF THE CHANGING DDSs

The studies of the narrow angle MGS MOC images, between late winter through spring, summer and early autumn of 1999–2000, has shown that in the Martian Southern Polar Region there are two terrains where many images are made about the time sequence of the DDSs formation. One site is the Richardson Crater (located at 72.4°S, 180.0°W) dark dune field region, and the other is a place bearing the informal name ‘Inca City’ at 81.5°S, 64.7°W.

We selected (Horváth *et al.*, 2002b) for detailed analysis the ‘Inca City’ region (Malin and Edgett, 2000a), instead of Richardson Crater (Edgett *et al.*, 2000; Supulver *et al.*, 2001), because there is far better coverage of this place at various times of the seasons (Figure 13). Here, on the slopes with average inclination of 11–12 degrees (Figure 5a), associated with almost every dark dune spot, elongated or fan-shaped narrow extensions can be observed (Figures 14a–d and 17b).

In the ‘Inca City’ ‘cassettes’ with various slope directions are apparent on the same image, therefore we may conclude that the extensions are triggered by some downhill motion rather than blown by the wind (Figures 14c, d).

On the basis of the time coverage of six images of ‘cassettes’ II. and III. of the ‘Inca City’ we constructed a tentative time sequence of the changing DDSs in order to sketch their morphogenesis (Figure 14).

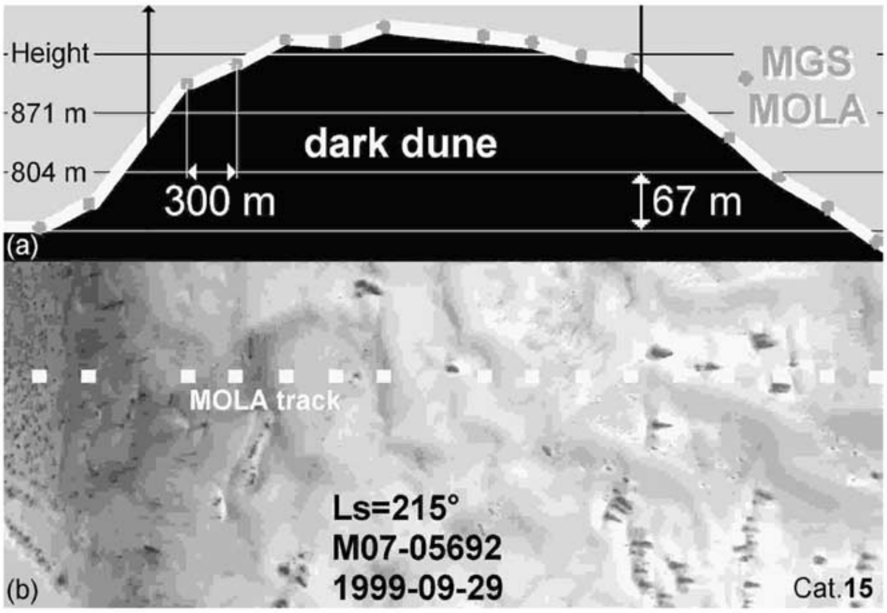

Figure 10. On the steep slopes, in spring the shape of DDSs is elongated and fan-like on the DD field (b) inside the Jeans Crater. The dark dune hill itself is also tilted (on the left 13 degrees, on the right 8 degrees), as shown by MOLA measurements (a). In (b) on MOC image the Sun illuminates from upper right and north is approximately right lower corner.

In many places the appearance of 'proper' DDSs is preceded by grey fuzzy spots or fields (Figures 15a and 16a). Later the grey fuzzy spots become sharper and greyer (Figures 15b and 16b). Later yet they become increasingly darker (Figures 15c, d and 16c): DDSs develop on the grey background. Finally, their centres become black and sometimes the central dark spots gradually coalesce. When initial spotting begins on the slopes of the local heights, ellipsoidal or thin fan-shaped forms of the DDSs develop (Figures 15c, d and 17b).

We must add another period of formation stage to the DDS morphogenesis. In summer in some places on the dark dune fields clusters of *lighter grey patches (LGP)* appear at the sites where in spring the DDSs configuration was seen (Figures 17 and 19). The details of lighter grey patches can be seen on Figures 15e and 16d. The inner structure consists of a lighter ring and a darker centre (Figures 15e and 17c). However, at the end of summer no remnants of these light structures are visible in these sites (Figure 15f).

On Figures 15b–d, 16c, d and 17 we can see interesting formations, the so-called 'spider-ravines' (Ness and Orme, 2001, 2002), with connection to DDSs.

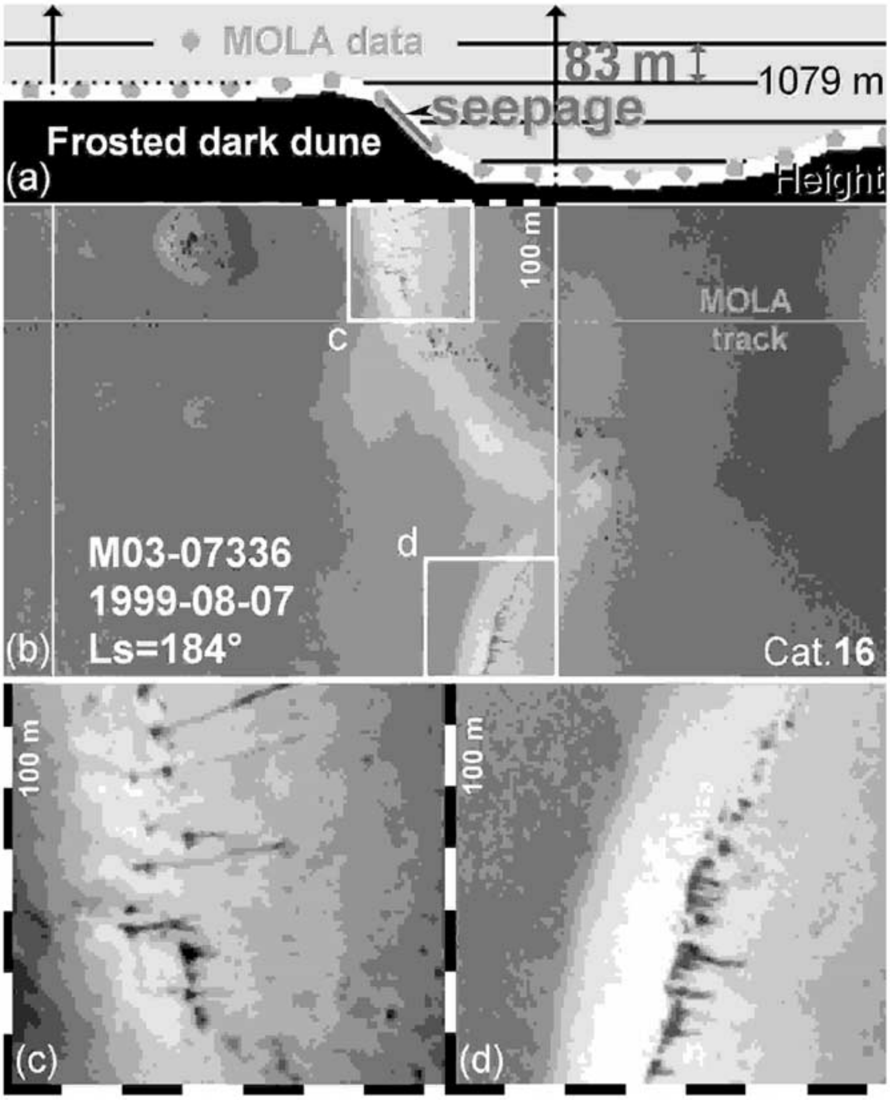

Figure 11. Many creek-like flows originate from the DDSs where the slope of the dark dune is steeper. Many creek-like flows can be observed clearly on the dark dune (c, d) inside the Lyell Crater (b) at the site where the slope has 21° steepness according to MGS MOLA data (a). On MGS MOC (images b, c and d) the Sun illuminates from upper right and north is approximately right lower corner.

3.4. PATTERNS OF DDSs

Not only the single DDSs, but also the collective patterns of multiple ones exhibit important characteristics to be interpreted. The most important observation is the following. Year by year the DDSs appear almost at the same place with almost the same configuration. This was observed in images made in two subsequent years

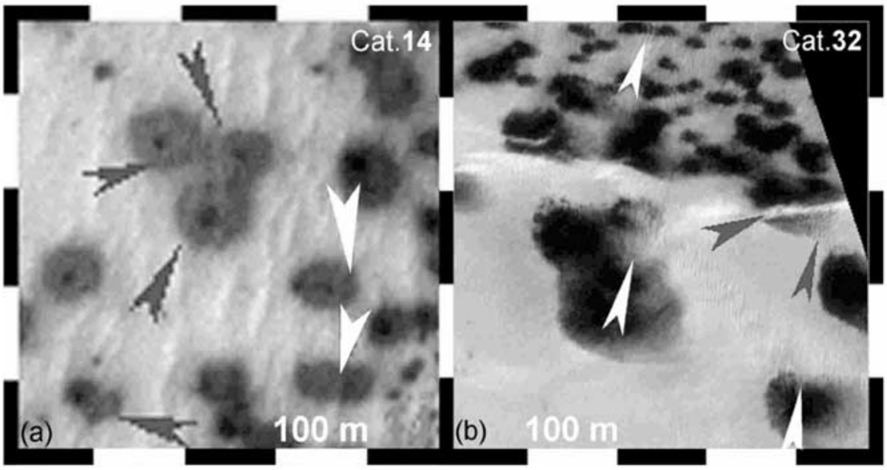

Figure 12. Grooves formed during freezing on the ice cover can be seen even above the grey spots. Eventually this shows that the spotting process begins at the bottom of the ice cover, as was suggested by the DDS-MSO theory (Horváth *et al.*, 2001). (a) The ice grooves (arrows) continue on the top of the grey parts of the DDSs in the thin frosted dunes of the Jeans Crater, as can be seen well at the triplet group of spots in the centre. (b) The groove structure of the original ice surface on top of the grey DDSs can be clearly observed (arrows) on this detail of another MOC image, too. Sun illuminates from upper left and north is approximately at the top in these figures.

(Figures 3a–b). The occurrence of DDS patterns in the same place with the same configuration of spots suggests that the cause of their appearance is fixed on the surface (or subsurface) of the locality on the dark dune fields (Figure 20). We call this phenomenon *the annual pattern* or configuration of DDSs.

It is an interesting observation (Malin and Edgett, 2000a) that the ice cover on dark dune fields survives for longer time than on the surroundings crater floor without DDs (Figures 18c–d). Therefore, the DDS pattern in the frost cover also survives for the same long time. But the pattern of DDS configuration survives in another form, too.

Another collective phenomenon of DDS pattern is that the spring configuration of DDSs appears in the form of the summer configuration of light grey patches on the dark dune fields. Counterparts of not only the big DDSs, but of the dark streaks of the late spring image (Figure 19a) can be observed in the form of light grey patches and streaks on the summer images (Figure 19b) of the same site. This repeated occurrence of the configuration of spots strengthens our previous suggestion of fixed causes of the spots on the dark dune surfaces. We refer to this phenomenon as the *seasonal pattern* or configuration of DDSs and the corresponding light grey patches (Horváth *et al.*, 2002b).

In many places the pattern of the multiple DDSs has a uniformly scattered arrangement on the dark dune fields (Figures 1, 2, 3c and 4). The evenly scattered

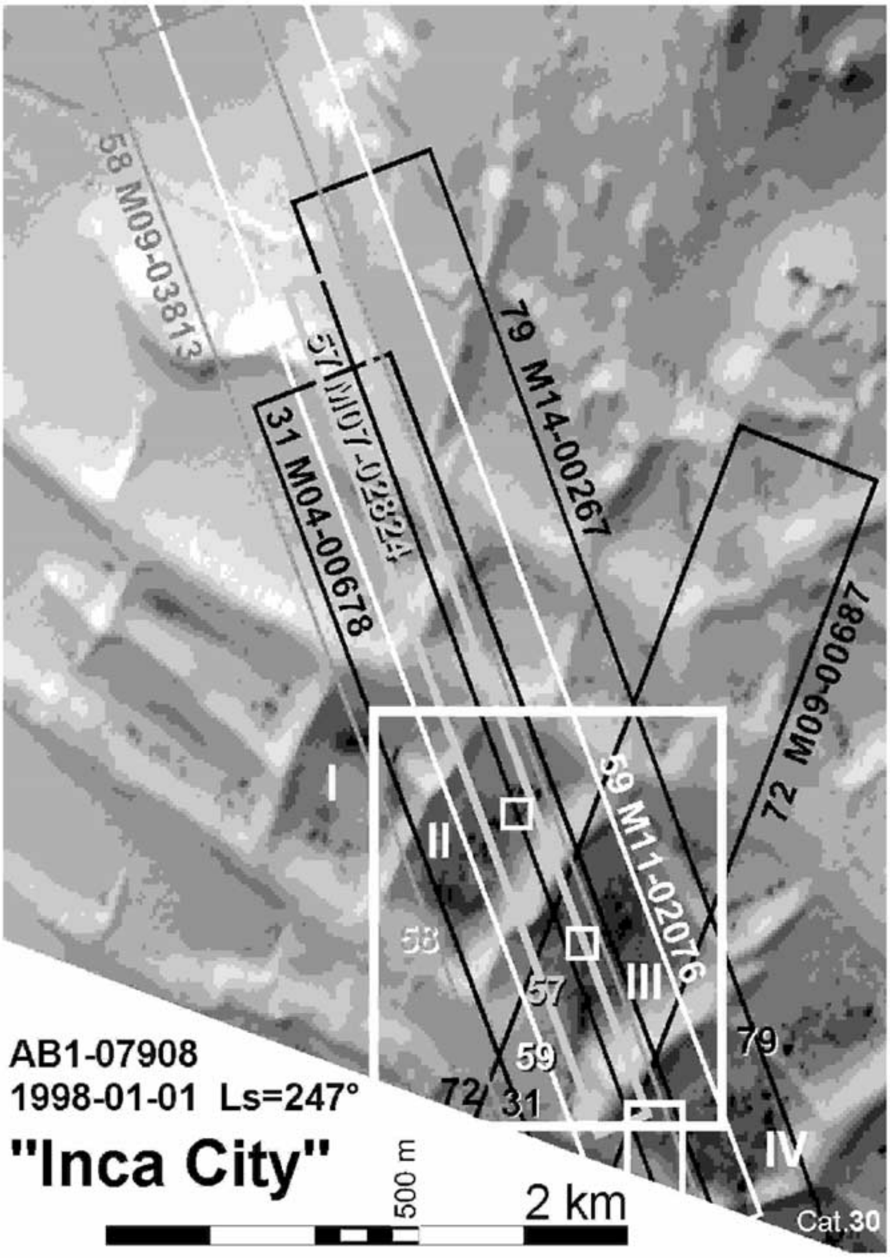

Figure 13. Frosted dark dunes with DDSs of the Southern Polar 'Inca City' Region of Mars in 1998. We marked the localities of the subsequent MGS MOC narrow angle images (see on Figures 14–17) by frames. Roman numerals refer to 'cassettes' of the 'Inca City'. Sun illuminates from upper left and north is up.

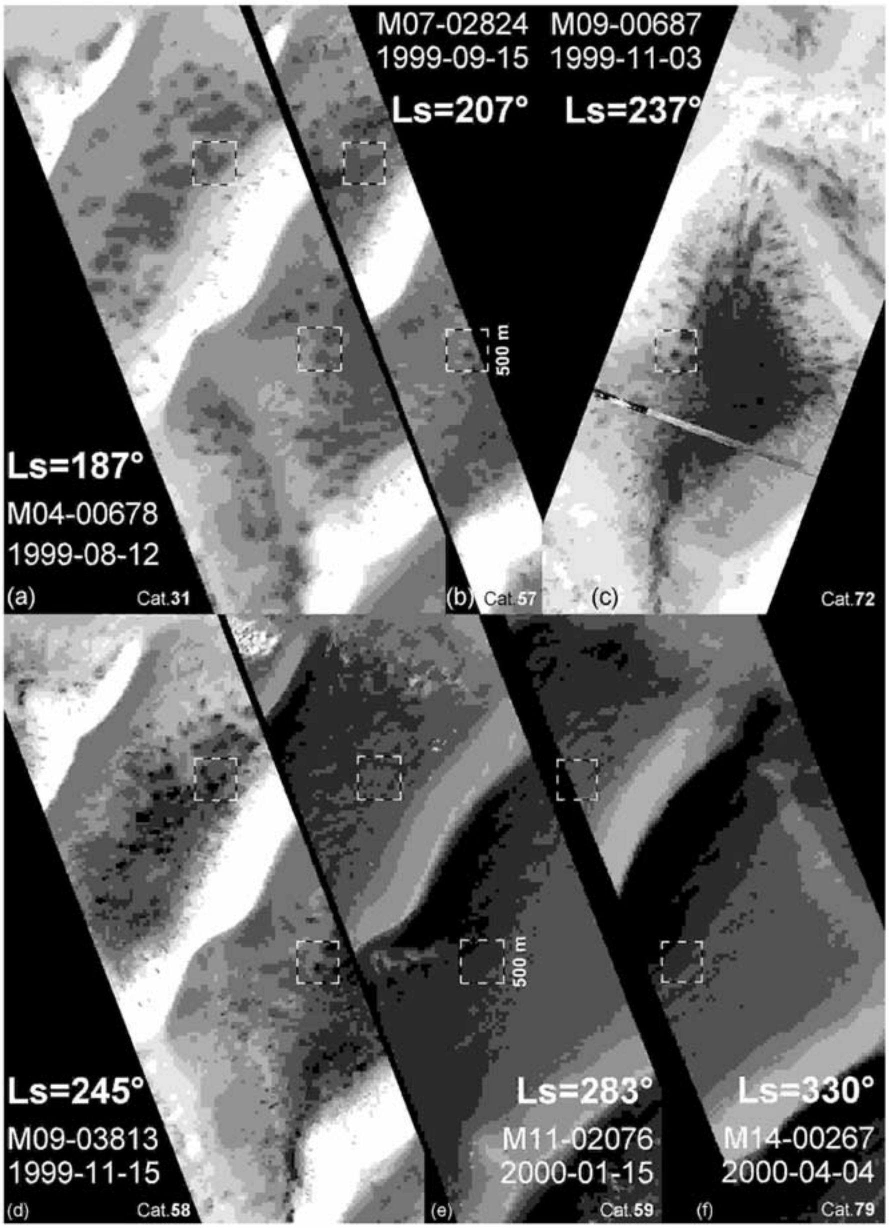

Figure 14. On this series of images we can observe seasonal changes of DDSs on the frosted and defrosted dark dunes in the II. and III. 'cassettes' of the 'Inca City' from early spring till late summer. All images marked black and white frames on Figure 14 are enlarged on Figures 15 and 16. Sun illuminates from upper left and north is approximately at the top in all this figures.

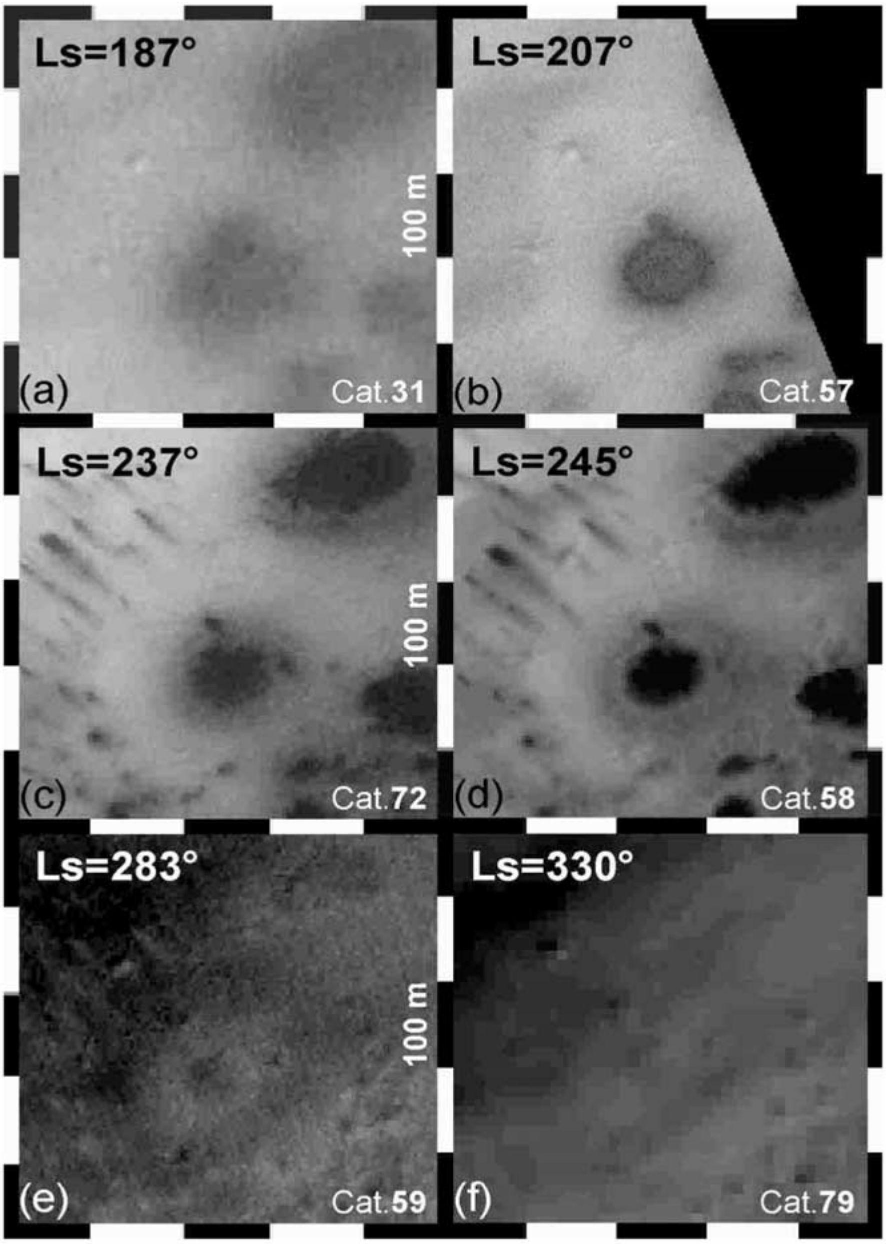

Figure 15. On this series of enlarged images we can see the stages of the development of some DDSs on the frosted and defrosted dark dunes in the III. 'cassette' of the 'Inca City' from spring till summer. The place of these images are marked with the lower frames in Figure 14. Sun illuminates from upper left and north is approximately at the top in Figures a–b and d–f.

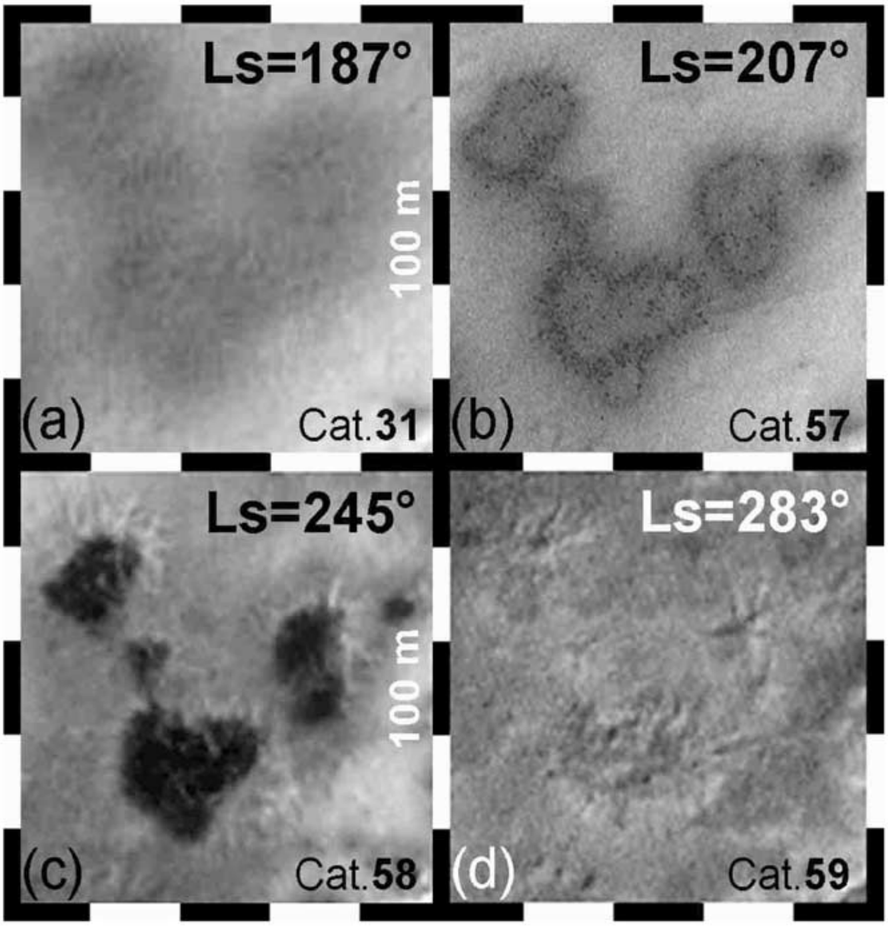

Figure 16. On this series of enlarged images we can see also the development of some DDSs on the frosted and defrosted dark dunes in the II. 'cassette' of the 'Inca City' from spring till summer. (a) At the beginning of spring grey fuzzy spots appear in the frosted surface of DDs. (b) In the middle of the first half of spring from the grey fuzzy spots DDSs with expressed margin develop. (c) By the second half of the spring the inner region of the spots become totally dark. (d) Till the beginning of summer the defrosting finishes in this region and we can see the naked soil of the dark sand dune; however, lighter rings with darker central portions (LGP) still mark the localities of DDSs. The place of these images is marked in Figure 14 (see the upper frames). Sun illuminates from upper left and north is approximately at the top in all this figures.

DDSs on the field have a pattern similar to some colonies of living beings on the Earth. Hence this spatial distribution awaits statistical analysis.

3.5. CONCLUSION OF MORPHOLOGICAL ANALYSIS OF DDSS

Analysis of several thousand DDSs on more than 200 MGS MOC narrow-angle images supports the following list of conclusions about the general features of

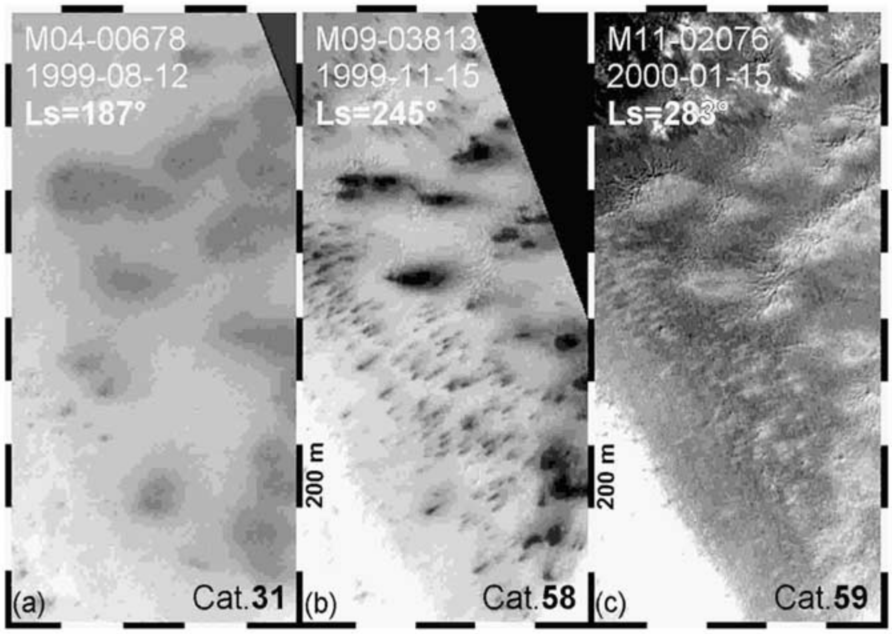

Figure 17. Spring ‘configuration’ of DDS (a, b) appears at summer as of light grey patches in IV. ‘cassette’ of the DD fields of ‘Inca City’ (c). Fan-shaped DDSs with tails on the tilted side (b) can be seen in summer (c). Sun illuminates from upper left and north is approximately at the top in all this figures.

individual (i–vi) and collective (or multiple) pattern (vii–viii) of the development of dark dune spots.

(i) DDSs are only to be found on dark dunes to the extent that sometimes the border of their occurrence matches exactly the boundaries of the latter. They *never form outside* the surface of the dark dunes (Figures 1, 3c, 4b, 6, 8c and 18).

(ii) On flat or nearly flat sites the spots are nearly *circular* (Figures 1–8, 12–16 and 18–19).

(iii) The most important new observation is that the DDSs are shallow *crater-like holes* in the frosted layer (Figures 8 and 12b). The central region of a DDS is dark because it is deep, exhibiting the dark dune surface.

(iv) The existence of the DDS-holes in the frosted layer is important evidence that the process of DDS *formation begins from the bottom*, because the effect of defrosting by sublimation, acting always on the top of the frost, is uniform.

(v) On mild slopes the spots are *elongated* downhill, thus forming large-axis elongated ellipsoid shapes in parallel orientation (Figures 9b and 17b and in upper part of 18c).

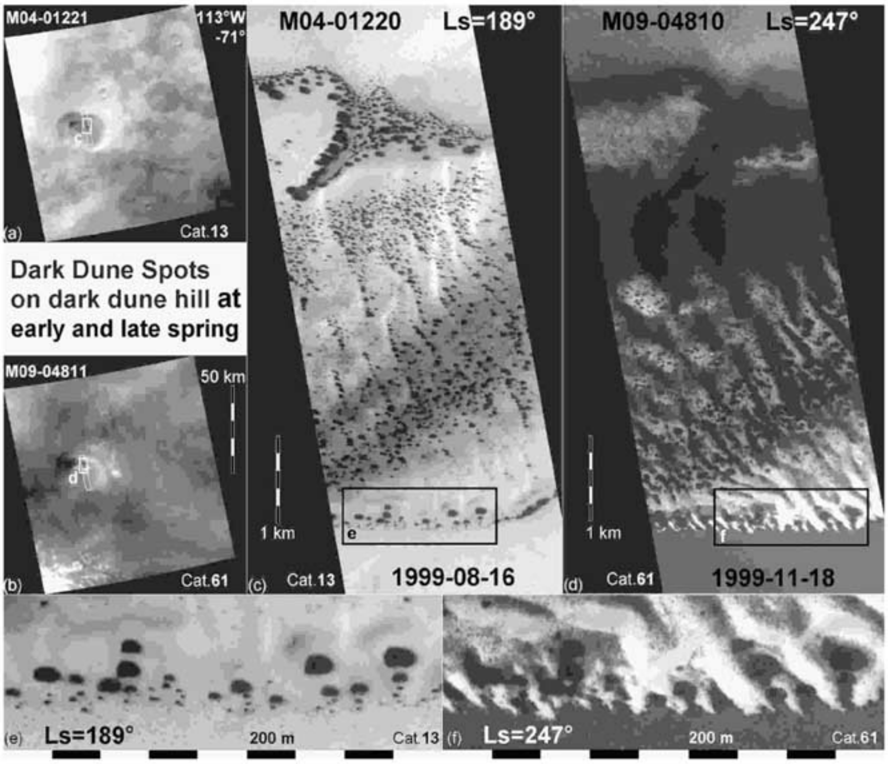

Figure 18. The ice cover on dark dune fields (a, b) survives for longer time than on the surrounding crater floor without DDs. The DDS holes, forming a conspicuous pattern in this frost cover (c), also survive for a long time (d), seen in particular on the middle and lower part of dark dune fields (e, f). Sun illuminates from upper left, north is up.

(vi) On steeper slopes DDSs are tail- or fan-shaped (Figures 9b, 10b, 15c, d and 17d) and *flow-like* extensions originate from the spots pointing downhill (Figures 11b–d).

(vii) A marked phenomenon of DDS pattern is that the spring configuration of DDSs appears as the summer configuration of light grey patches on the DD fields (Figures 17 and 19). This repeated occurrence of the DDS and LGP configuration of spots supports our suggestion of localized-biological-causes of spot formation.

(viii) Several years of MGS imaging resulted in the recognition that year by year DDSs ‘renew’ on the same place with almost the same configuration (Figures 3a and b).

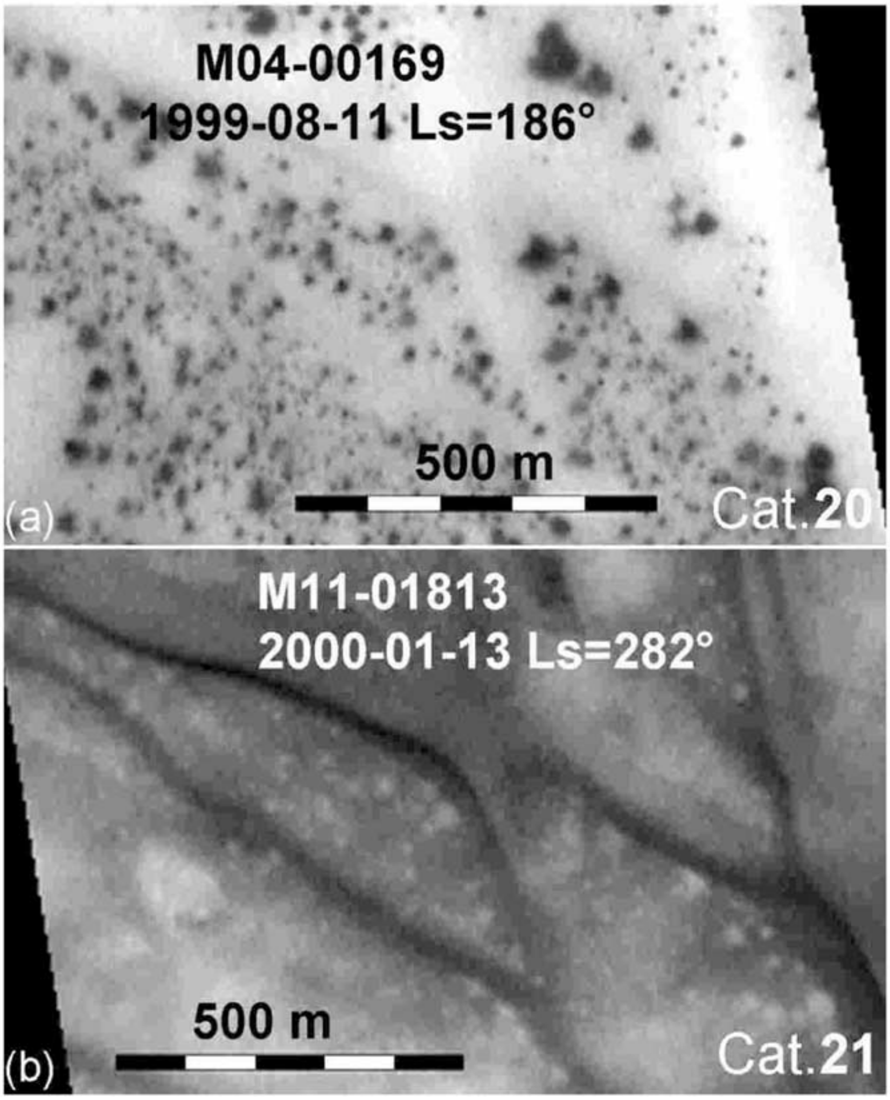

Figure 19. Comparison of images of the same territory of the dune field in the Charlier Crater in early spring and summer. Where there were DDSs in early spring (a) there are lighter grey patches (LGP) on the dark soil in early summer (b). This suggests that a layer with a different albedo covers the dark soil. We interpret this as a layer of desiccated MSO colonier. Sun illuminates from upper left and north is approximately at the top.

4. Biological Interpretation

The central question of Martian life is the persistent prevalence of liquid water. If liquid water exists for long periods on the surface Mars, then living systems may also exist there. If it does not, then life cannot exist. The Viking missions testified

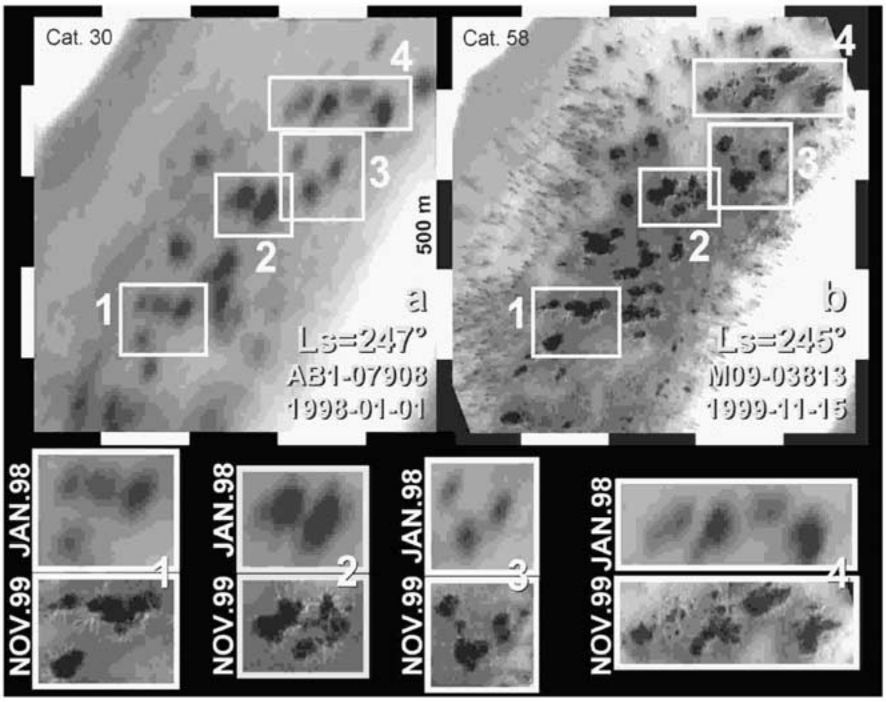

Figure 20. In the cassette II of the Inca City region (see Figure 13) we can observe annual changes of the appearance of DDSs. The image (a) (with 16 m resolution) was taken on 1 January 1998; the image (b) (with 4 m resolution) was taken one Martian year later, on 15 November 1999, during the second half of the southern spring on Mars (at Ls = 247 and 245°). At the bottom we compare four detailed and enhanced regions. There the DDSs appear in a pattern following the one from the previous year.

that the Martian surface is very cold and dry; the atmospheric pressure is very low (6–7 mbar). Under such conditions liquid water, if formed by some process on the surface, quickly evaporates. These results seem to suggest that no ecosystems can exist on the Martian surface today. On the other hand, several orbiters have recorded traces of extensive water flows. Repeated investigations have shown that these flows result not from unique events; rather, they are recurrent phenomena. What is more, independent suggestions (Mangold *et al.*, 2002; Reiss and Jaumann, 2002) argue for the current occurrence of such flows on the basis of MOC images. But these flows are too ephemeral to sustain life.

According to the currently held view, early Mars witnessed a much wetter and warmer climate, which could have favoured the emergence of life. But the climate has drastically changed due to reasons not yet fully understood. Much of the atmosphere has disappeared, surface temperatures have markedly dropped; atmospheric pressure has sunk to low values. In consequence the planet has turned cold and dry. One can assume that if life has arisen at all on Mars, it has maximally adapted to the global environmental changes. Of course, such an adaptation has its limits; in the absence of liquid water life cannot function. However, the last survivors of the Martian biota could dwell at places where liquid water still recurs. This is why some assume that living or viable organisms could exist in the solid or nearby hydrothermal systems. We are not concerned here with putative under-surface organisms. Rather, we consider possible extant surface life forms. We have found that at certain localities under special conditions liquid water appears year to year for several months. These sites could provide habitat for some of the last survivors of the Martian biota adapted to those conditions. These sites are the dark dunes.

4.1. STABLE LIQUID WATER ON THE SURFACE OF MARS

The spots appearing by late winter mainly on intracrater dark dunes whose morphology was discussed above have raised our attention. Malin and Edgett (2000a) thought to explain the morphogenesis of the DDSs by sublimation processes (defrosting). We have found, based on reasons given below, that this explanation is insufficient to explain the formation and development of spots. In contrast, the appearance of fluid water is a necessary ingredient of a successful explanation (Gánti *et al.*, 2003). We corroborate our opinion with the following arguments:

(i) As we have shown in Section 3.2, the appearance of DDSs begins at the bottom of the frost layer, where DDSs also develop (Figure 12) until they lose the ice/snow layer above (Horváth *et al.*, 2002b). This by itself excludes sublimation as the only decisive component of spot formation, since the latter process begins at the soil/frost boundary; in sharp contrast to defrosting that would start at the outer surface of the frost. To sum up, one should be looking for a mechanism that could act independent from sublimation; i.e. beneath the frost cover.

(ii) The fact that DDSs form only on the surface of the eolian DDs indicates that the formation of the former is somehow linked to the material of the latter. This may be attributable to either the chemical composition and/or the physical structure (porosity) of the dunes. The process of the frosting may depend on the quality of the soil, because the soil grains may act as crystallization seeds for frost formation. Defrosting is, however independent from the soil, because it happens on the surface of the ice/snow cover. This again shows that defrosting alone is insufficient to explain the phenomenon.

(iii) The fact that on flat sites the spots are circular and that they grow radially indicates that spot formation is isotropic in the plain of the surface (Figures 3, 6, 8 and 12). Spot formation thus cannot result from mere defrosting, because the sublimation process depends on wind, the angle of insolation, etc. Such type of radial growth is, however, readily explainable in terms of capillary diffusion of some liquid in the porous regolith. Under the *pT* (pressure-temperature) conditions of Mars that fluid cannot be anything else but liquid water.

(iv) The fact that the spots on mild slopes become ellipsoids pointing downwards, indicates that spot spreading is affected by gravity (Figures 9b, 17 and 18c above). In the given size range sublimation processes are independent from gravity. Again, the only sensible interpretation is the active role of fluid phase, namely (as explained above) liquid water.

(v) On steeper slops regular flows are apparent (Figures 9–11). These cannot be interpreted as open creeks, however: it is much more likely that melted water slowly percolates downwards in small canals below the ice. According to the listed facts (Gánti *et al.*, 2002) we may accept that besides defrosting some liquid phase must also play a main role in spot formation. Under the given Martian conditions this can only be liquid water. This liquid comes in form of a water lens appearing between the frozen DD soil and the ice layer above it; first forming in the hiatuses of dune sand. It appears by late winter and is maintained until the beginning of summer; which under Martian conditions guarantees the existence of liquid phase for 150 to 250 Martian days (sols).

4.2. A POSSIBLE MECHANISM FOR DDS FORMATION BY MARS SURFACE ORGANISMS (MSOs)

The hypothetical mechanism should explain the phenomena listed in Section 4.1. Furthermore, it should account for the following observations.

(i) It is apparent on the images that the spatial pattern of spot arrangement remains the same year to year; i.e. spots form where they formed last year (Figures 3a, b and 20). Their reappearance is not random.

(ii) In the summer, when the frost disappears completely, at the sites where the spots appeared, grey spots (against the dark dune material) are apparent. This indicates that something, different from windblown dust, covers the dunes at these sites (Figures 15e, 16d, 17c and 19b).

(iii) The spots have a fine internal structure. This means that in the centre of the originally grey spots a black core develops with time (Figure 15), and later (in some cases) a light thin ring appears between the black core and the grey outer ring (Figures 6, 7a, 8, 12 and 17a).

It can be seen that the mechanism for DDS formation must explain a set of several, independently observed phenomena. Furthermore, it has to explain how liquid water can form at temperatures obviously below freezing, and if formed, why does it not freeze immediately? Furthermore, if some mechanism produces liquid water, why does it not evaporate immediately in the very thin Martian atmosphere? We want to show below that all these problems can be solved if we suppose the existence of Martian Surface Organisms who have adapted to an above-ground,

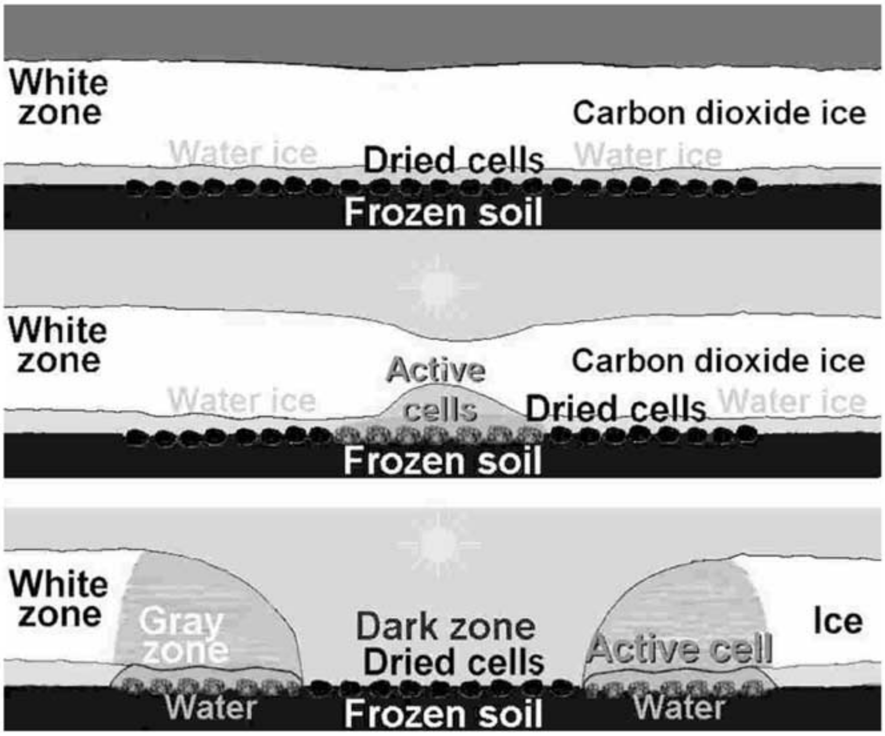

Figure 21. DDS-MSO model: dynamics of biogenic spot morphogenesis. In the first phase of spot development organisms on the soil, below the ice, warm up by the absorption of sunlight (a) and melt the H_2O ice around them (b). The CO_2 ice cover first disappears in the center, where the melting starts (c). When water evaporates the organisms (MSOs) desiccate and the dark naked soil can be seen.

below-ice lifestyle (for which we have some earthly analogue). We emphasize that the form of life described here should be distinguished from hypothesized non-photosynthetic ecosystems beneath the Martian north polar ice cap (Skidmore *et al*., 2000).

In order to understand the mechanism for the origin of DDSs, one should start with two observations. The first one is that the pattern of the spots is the same year to year, i.e. they form at the same sites; therefore the cause of their formation is associated with these sites (Figures 3a and b). The second is that by the middle of summer, when the frost is gone and the dark surface of the dunes (thought to consist of basaltic sand) is revealed, some lighter spots are apparent where the dark spots have grown, i.e. some layer still covers the dunes at these sites (Figures 15e, 16d, 17c and 19b). In principle, this layer could be of eolian origin, but the shape and pattern of the spots contradict this. The second possibility is that the layer covering the sand is of biological origin, resembling bacterial mats or lichens that strongly stick to the sand. We prefer this interpretation through which the morphology of spots, their seasonal and annual development and spatial pattern are readily and consistently explainable. Since we do not have a clue about the exact nature of these organisms (i.e. which earthly species they resemble most), we coin the term Mars Surface Organism and will refer to these hypothetical organisms by this name.

If life indeed exists on Mars then it must have adapted to the conditions and to the changes thereof. It follows that photoautotrophic MSOs must have evolved pigments with high absorbance. We suggest they conduct the following lifecycle (Figure 21). During winter the soil below the spots is deep-frozen and some form of ice/frost covers them. MSOs must occupy a layer between the soil surface and the ice sheet. Because ice is transparent to light, MSOs intensely absorb the emerging sunlight (which is continuously available in the polar region from spring to summer, and the length of the sunlit period depends on the latitude) and thus warm up at the end of the winter. From a frozen state they pass to a molten one, which also applies to part of the ice around them. Thus MSOs find themselves in a liquid solution with contact to the underlying soil, enabling them to take up the necessary nutrients. The volume and extension of the liquid body increase with the intensity of the insolation. The ice cover above the forming liquid water provides excellent heat insulation and prevents fast evaporation that otherwise would be inescapable due to the low atmospheric pressure. The fact that the spots mainly appear in the polar region indicates that a long period of sunlight is a necessary condition for their formation, which prevents night frosting of water around the MSOs. Thus the most basic living conditions of the MSOs prevail until there is sunlight and until the ice sheet above them does not evaporate.

This period is the phase when the grey spots appear. Later the ice disappears from the centre of spots due to the faster sublimation caused by the heat coming from the activity below, where the soil with its biological cover is revealed. We observe this on the images as the black centres of the spots. This black core increases with time. Obviously water, necessary for the life of MSOs, quickly evaporates from the black centres. The MSOs freeze and they desiccate in the frozen state. This corresponds to the freeze-drying (liofilisation) of microorganisms on Earth whereby they are made capable of long-term storage. The vaporized water partly precipitates on the ice cover of the grey region, hence the light thin ring between the black centre and the grey zone (Figures 6c–e, 7a, 8a and b). Meanwhile a crater-like ditch forms in the frost, centred at the black core. By the summer the whole frost cover sublimates/evaporates, the material of the DDs becomes visible, and at the sites of the former DDSs shows a layer, which is also dark but still lighter than the dunes. We reckon that these are the freeze-dried MSO colonies. The proposed mechanism of spot formation is shown in Figure 21.

4.3. WHY DO THE SPOTS FORM ON THE DARK DUNES?

The set of images by MOC includes many examples of spots, geometrical formations, and other surprising phenomena, collected recently (Ness and Orme, 2001, 2002). Analysis of their morphology and formation mechanism has barely star-

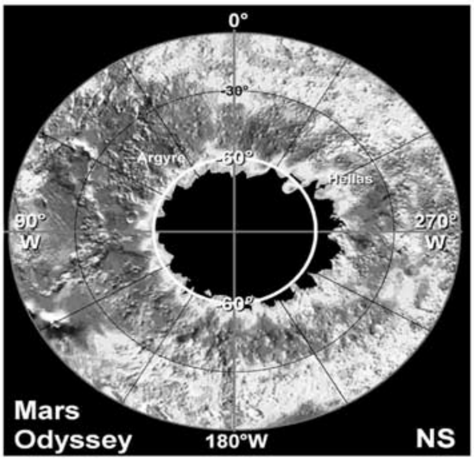

Figure 22. The water ice on the Southern Polar Region of Mars as determined by the NS instrument of the Mars Odyssey spacecraft. The maximal water ice content is shown by the black region inside the 60° southern latitude (in February, 2002). These data are gained from the upper 60 cm layer of the soil (Feldman *et al*., 2002, http://grs.lpl.arizona.edu/results/publications/).

ted yet. The spots, the DDSs appearing at the end of the winter on the dunes, investigated here, strongly differ from the spots found elsewhere and form a coherent group. The DDSs are found strictly on the dunes, their population often demarcating the dune edges (Figures 1a, 3c, 4b, 6b, 8c and 18c). This means that there is some causal connection between the composition of the dunes and the appearance of the DDSs. Since the material of the dunes is thought to be eolian basaltic sand, this cause is unlikely to be found below the dune surface (such as hydrothermal activity, vapour outburst or degassing). The location of such activity ought to be independent from the dunes. Therefore, the real cause must be sought in the material nature of the dunes themselves, their chemical and physical traits (such as porosity), and in the interaction between the dune surface and frost formation.

MOLA data indicate that the southern frost cover is 0.1–1 m thick (Smith *et al*., 2001). These are average values, from which significant deviations may occur locally. The frost cover may consist of three components: frozen carbon dioxide, carbon dioxide clathrate and water ice (Carr, 1996; Hoffman, 2000). Unfortunately, we do not have any data on the relative composition and internal structure of the frost. The common assumption had been that the quantity of water ice is very low. Surprisingly, data provided by the Gamma-Ray Spectrometer on the Mars Odyssey spacecraft, by the Neutron Spectrometer (NS; Figure 22) and the High-Energy Neutron Detector (HEND; Figure 23) consistently indicate that water in some form is prevalent in the south polar region (Boynton *et al*., 2002; Feldman *et al*., 2002; Mitrofanov *et al*., 2002). This prevalence ranges from the Pole up to –60°, which surprisingly coincides with the range of DDSs. From this we conclude that water in some form is relatively abundant in the region of the DDSs. We reach the

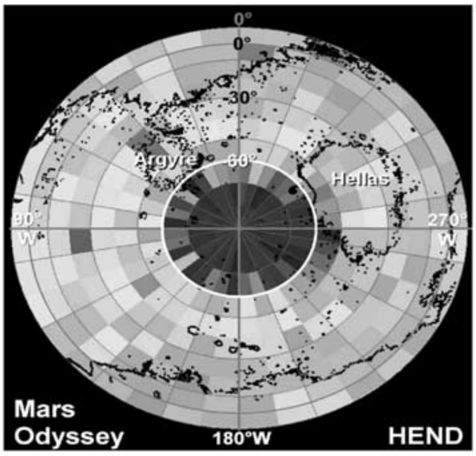

Figure 23. The calculated water ice content from the measurements of the Russian HEND instrument of the Mars Odyssey spacecraft also shows the largest amount of water ice inside 60° southern latitude. This water ice content refers to the upper 2 m of the soil (Mitrofanov *et al*., 2002, http://www.iki.rssi.ru/hend/).

same conclusion when we monitor the change of the water content of the Martian atmosphere, which shows that in the winter the quantity of water vapour drops considerably, indicating that it precipitated to form the frost cover (Carr, 1996).

Supulver *et al*. (2001) show that in the winter the dunes are covered by white frost below the freezing point of CO_2 ($\sim$148 K), until the end of winter when the sun rises to the horizon. Then small grey spots appear on the dunes that grow in number as well as size as spring proceeds. As the temperature reaches the melting point of water ice, frost-free regions appear. The albedo of the dunes decreases from 0.4 (when covered by white frost) to 0.1 (when naked, by the middle of summer). In autumn, when the sun sinks below the horizon, frost settles on the dunes again.

Although we are not aware of data on the composition and layered structure of the Martian frost in the investigated region, we venture into outlining a mechanism for the annual reappearance of frost; based on the literature cited above and the laws of physics. When sunshine ceases and the surface temperature of the dunes sinks below the freezing point of water, frosting begins. But at the beginning this can be water frost only. On one hand, it is known that frosting starts at seeds for crystal formation. On the other hand, different surfaces differ in the degree of providing such seeds. It is know from the Earth that first the plants accumulate frost, and the uncovered soil follows much later when the temperature has decreased further. We must assume that the dunes provide much better crystallization seeds and that is why frosting appears there first. In the autumn this water frost stays there; it grows thicker until the temperature drops to a degree where carbon dioxide clathrate and later carbon dioxide also freeze. This means two things. First, the frost on the dunes will have a layered structure: water, carbon dioxide clathrate and carbon dioxide, from bottom to top. Second, the water layer of the frost will be significantly thicker on the DDs than elsewhere.

In winter and spring, when the sun shines again, the solar radiation begins to heat up the dune surface under the frost cover. The temperature can be significantly higher at this interface due to the excellent isolation capacity of the frost/snow above. The lowermost part of the water ice cover may melt to form thin water lenses that partly penetrate into the underlying soil. Continued and increased sunshine prevents this water from freezing. It is here where the Mars Surface Organisms (MSOs) may find their habitat. This is valid until the frost above the MSOs disappears. This period may last for 150–250 sols, which allows ample time for MSO growth.

With increased surface temperature the layers of frost sublimate in the order of CO_2, CO_2 clathrate and, finally, water. Since, as we have seen, the DDs are covered by the thickest water ice, they must be the last to defrost completely. That is why one sees images with dunes still covered with white frost when the bottom of craters is already free of frost (Figures 18d and f).

4.4. NUTRIENTS AND WASTE PRODUCTS

Mineral nutrients are obviously accessible from the basaltic sand material of the dunes. Atmospheric CO_2 is the carbon source, just like in most cases on Earth. CO_2 supply depends on the partial pressure of this gas. The atmospheric pressure on the Martian surface is very low, but 95.32% of it is CO_2. In contrast the air has a pressure of 1000 mbar, but only 0.03% of it is CO_2. This means that the partial pressure of carbon dioxide, so crucial for autotrophic organisms, is about six times as high as on Earth. This is in the range of partial pressure realized in horticulture in so-called carbon dioxide fertilization. Thus, at least from the point of view of the partial pressure of CO_2, conditions for life would be excellent on Mars even for photosynthetic organisms from the Earth.

All this of course does not provide information about the exact conditions below the ice, in the microenvironment of the DDSs. The gas pressure there could be significantly higher than or equal to the atmospheric pressure, depending on the density and porosity of the ice. Even in the latter case the composition of the local gas mixture may deviate from that of the Martian atmosphere. Unfortunately, data about this are simply absent.

Photosynthesis requires a hydrogen donor, and nitrogen also must be incorporated somehow. It is very likely that water serves as hydrogen donor, which is locally abundant, as discussed above. In this case oxygen is released as a by-product. Part of this may be recycled for breathing by the MSOs and by heterotrophic organisms associated with them (see the Discussion Section). Another part of the produced oxygen may reach the atmosphere, containing 0.13% O_2.

The nitrogen content (2.7%) of the Martian atmosphere is sufficient to support nitrogen fixation.

4.5. THE PROBLEM OF UV RADIATION

Since Mars does not have an ozone shield like Earth, which would protect it from UV radiation above 190 nm (below this value the Martian atmosphere also protects), putative surface organisms face a high radiation hazard. It is justified to ask how MSOs could cope with this situation.

One must divide the problem in two parts: the answers in the periods of growth and dormancy (with and without the ice cover, respectively) are different. We have shown that during growth MSOs are under an ice cover of appreciable thickness, which efficiently absorbs the UV rays. The protection efficiency by the ice cover should depend on the nature of ice. At 300 nm the following extinction efficiencies hold (Zolotarev, 1984): pure ice crystals 10%, water-bubbled ice 50%, and snow 90% (all 2 cm thick). This means that an ice cover in the dm range would be a perfectly sufficient UV shield.

The situation is different when there is no ice above the MSO colonies but they are in a freeze-dried state. In such a state they do not have a protective layer above them. But MSOs have the option to send their propagules by active biological motion (propelled by flagella, for example) in the protective environment of the soil, before they are exposed to the Martian atmosphere and with it the dangerous UV radiation. A layer of a few centimetres would be sufficient to protect the propagules from UV damage (cf. Horneck, 2001). Similar examples are known from the Earth (Cockell *et al.*, 2001).

4.6. COMPARABILITY WITH CASES ON EARTH: PARTIAL ANALOGUES

When we contemplate life on Mars we naturally do this on the basis of our knowledge of the biosphere on earth, since that is the only form of life about which we have information. There is a strong temptation, therefore, to determine the life conditions of putative Martian organisms on the basis of the conditions on earth. This may mislead us, however, since if there was or still is a Martian biota, its species must have undergone evolution markedly different from that on Earth. It may be assumed that the conditions for the origin of life had been rather similar on the two planets. Therefore the basics trait of metabolism may also be similar on them. Conditions have strongly diverged subsequently, however. Therefore we stress that if analogues to the conditions and way of life of Mars Surface Organisms can be found on Earth, this makes the hypothesis stronger. At the same time, should such analogues not be found, this would not invalidate the idea. We show below that partial analogues to the life of the MSOs can indeed be found on Earth.

With this in mind, the obvious place where one should look for partial earthly analogues are the Arctic/Antarctic regions. The importance of Antarctica for comparison with putative life forms of Mars has been addressed in general by the late

Wynn-Williams (e.g. Wynn-Williams and Edwards, 2000). Here we would like to stress a particular example of microbial life below a permanent ice cover. Priscu *et al.* (1998) have found that the 3–6 m thick ice cover of the lakes in the dry valleys of Antarctica contains wind-blown sediments in the middle region. Photosynthetic organisms on the surface of these sediment grains absorb sunlight and melt the ice around them, thus partly creating their own living conditions (Priscu *et al.*, 1998; Pearl and Priscu, 1998). A multispecies consortium is found on the grains, able to perform continuous photosynthesis, nitrogen fixation and decomposition, forming a small ecosystem with nutrient cycling.

Another life form with potential similarity to MSO-centred consortia is the lichens, also living under extremely harsh conditions in the Antarctic (Friedmann and Thistle, 1993). Remarkably, lichens become active before the snow disappears above them, and their temperature can rise significantly above the external air temperature. Although we would be surprised to find life at the eukaryotic level on Mars (note that one component of lichens, namely the fungi are by definition eukaryotes), bacterial consortia functionally similar to lichens on Earth may well have evolved on Mars.

A striking common feature of many Antarctic cyanobacteria and lichens is the black colour. It is known that it serves as an effective sunscreen, protecting the cells from UV radiation: the photosynthetic pigments are masked by the dark shield. Given the high UV dose on Mars, similar protective screens are likely to cover the MSOs. Note that the same black layer would be efficient in absorbing the sunlight for warming up at the beginning of the MSO life cycle.

Finally, stromatolites may also be a case in point. Certainly, the analogy in this case may be more remote than for below-ice consortia and lichens, but we should not forget that the MSO-based consortia, when active, form an ecosystem in water. Their sticking to the DD surface, as evidenced by the images, allows for the possibility of the formation of metabolically layered consortia of a few centimetres (decimetres?) thick, in partial analogy to stromatolites.

A cyanobacterial component figures in all examples mentioned. One may therefore think that the photosynthetic MSOs could in fact be cyanobacteria. One must be careful with this idea, though. Cyanobacteria are derived Gram-negative bacteria, with two photocentres for water-splitting photosynthesis. The claim that the oldest fossils of cyanobacteria are 3.5 billion years old (Schopf, 1993) has recently seriously been questioned (Brasier *et al.* 2002). Molecular and cytological investigations also seem to indicate that the cyanobacterial lineage on Earth is only about 2.5 billion years old (Gupta *et al.*, 1999; Gupta, 2000; Cavalier-Smith, 2002). Although it is not impossible that frequent and relatively safe travel from Mars to Earth (much more so than the other way round) was widespread about 3.5 billion years ago (Davies, 1998; Weiss *et al.*, 2000), it does not seem likely that MSOs (if they exist) would be close relatives to earthly cyanobacteria. It is perhaps more likely that oxygenic photosynthesis has been an independent evolutionary innovation on Mars.

5. Measurements and Landing Site Proposal

'Extraordinary claims require extraordinary evidence'. Obviously, we are unable to come forth with such evidence at the moment; that is why we present a hypothesis rather than a theory. But time lags between hypotheses and attempts at their falsification are normal in science. The hypothesis of life in Martian polar dunes can, in principle, easily be tested. If life forms are associated with DDSs, then they have to exhibit a significant light absorption at well-defined wavelengths, which is only characteristic of organic material rather than the surrounding Martian sand and dust. These pigments may play the role of biomarkers in spectroscopic observations. If a Martian Lander in the South Polar region is equipped with such an instrument, its landing site is selected on the dark dunes, then *in situ* measurements can decide with great confidence about the existence of MSOs.

The planned British Beagle 2 exobiology Lander of the ESA Mars Express Mission (http://www.beagle2.com/) and NASA Mars Exploration Rover 2003 (http://mars.jpl.nasa.gov/ and http://www.athena.cornell.edu/) will carry out exploration on Martian surface. It is our recommendation for these missions to plan a strategy with the onboard instruments to observe dry-frozen, wind transported spores – desiccated MSOs – (or any large molecules of biological materials) probably originating from DDSs. Our proposal for later missions is the landing to these southern polar DDS regions to measure biological activity we described here.

It is encouraging that Pershin (2000) has observed a colour index value of 763/554, suggestive of photosynthetic pigments, during analysis of the Martian images made by the Hubble Space Telescope. As to the basic mechanism of spot formation outlined in this paper, experiments using the Mars Chamber at the Astrobiological Centre in Madrid would be welcome.

6. Discussion

We want to return to three issues here: the question of UV tolerance, the problem of temperature, and that of alternative (non-biological) explanations.

During the active phase of the MSO life cycle the ice cover would protect MSOs from intense UV radiation. Although atmospheric CO_2 filters out UV below 190 nm, the flux of UVB (280–320 nm) and UVC (200–280 nm) radiation is higher on Mars than on present-day Earth, which must constrain life processes, especially photosynthesis, whether of earthly or endemic origin (Rothschild and Cockell, 1999). Furthermore, laboratory experiments confirm that the aggressive chemical reactivity of the Martian soil at the Viking landing sites is likely to be due to superoxide ions that form under UV irradiation (Yen *et al*., 2000). Thus shielding from UV irradiation should also reduce the concentration of harmful superoxide ions in the habitat of the MSOs, in addition to the fact that the colour of the dunes indicates a local depletion of iron, necessary for the formation of superoxide. Moreover, it

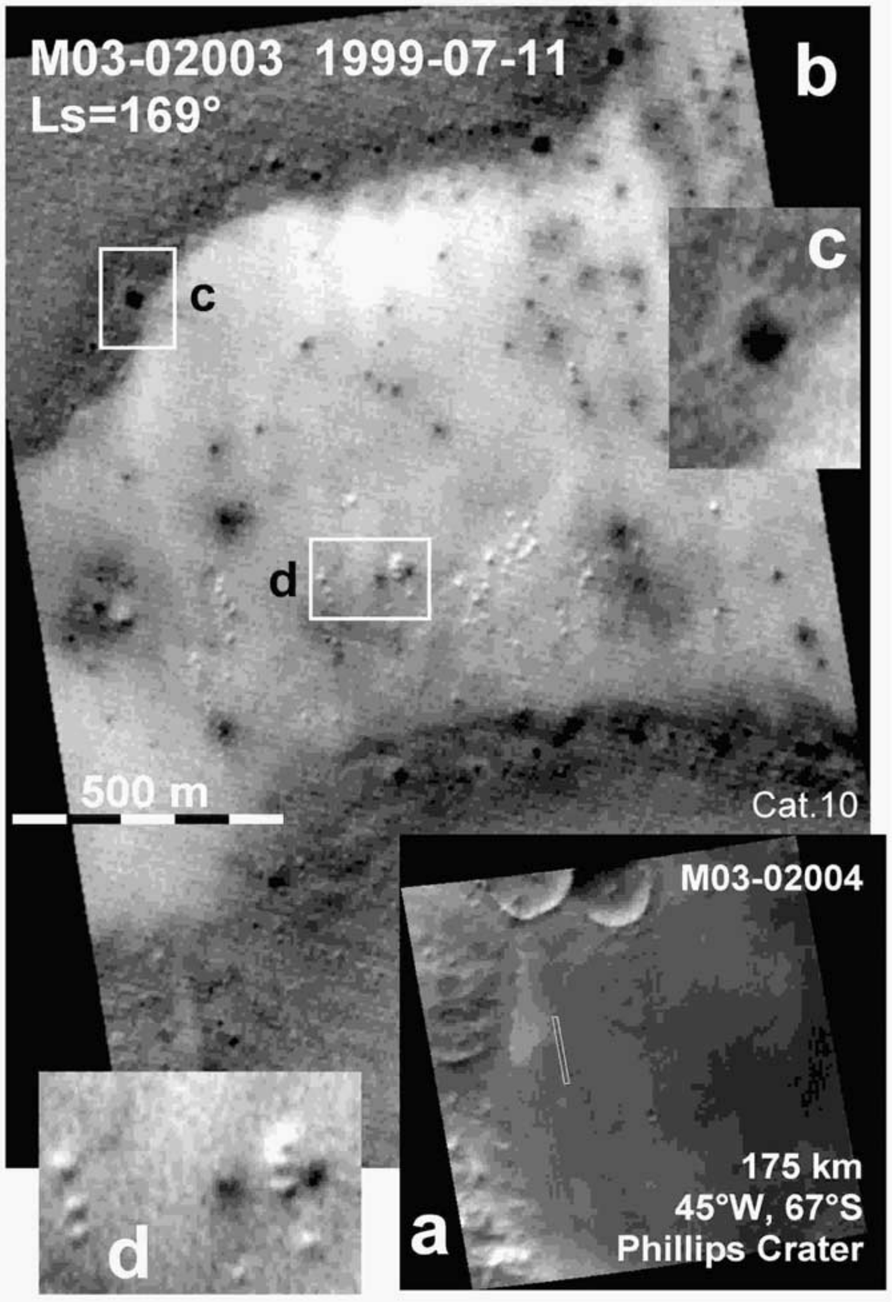

Figure 24. DDSs and rocks (b) appearing in the Phillips Crater (a) in late winter. There is no correlation between the locality of DDSs and the rocks, or elevated sites (c, d).

must be borne in mind that the present-day UV exposure of the Martian surface to UV radiation is comparable to that of the Archean Earth (Cockell, 1998; Rothschild and Cockell, 1999). There is evidence in the fossil record for Archean microbial mats in marine benthic environments (Pierson, 1994), potentially exposed to a high UV radiation. Whereas early exposure to UV of the surface is likely to have been much larger on the early Earth, the converse is likely to hold for early Mars with its thicker atmosphere and a roughly 1:1 ratio of O_2 to CO_2 during periods of low obliquity (Lindner and Jakosky, 1985). Thus Martian organisms could easily have adapted to present-day UV conditions through billions of years. Note that even on Earth today one finds organisms such as *Deinococcus radiodurans* (Battista, 1997) or *Rubrobacter radiotolerans* (Asgarani *et al*., 2000), tolerant of enormous levels of radiation, including UV. *Deinococcus* is able to survive a dose of 1.5 million rads, and-remarkably for our topic-after cooling and freezing it may survive 3.0 million rads (Battista, 1997). In fact the extreme radio-tolerance may be a by-product of extreme desiccation tolerance. Coupling of desiccation and UV tolerance has also been reported for the cyanobacterium *Nostoc commune* (Hill *et al*., 1997). All in all, it has been concluded that UV could not be the limiting factor for Martian surface organisms, in contrast to cold and low pressure (Cockell, 1998; Rothschild and Cockell, 1999), exactly the conditions that do *not* hold below the ice cover under sunshine (Figure 21).

When cells are inactive, protection against UV may be secured by three strategies: escape in the upper layer of the soil, protection by the upper layer of cells at the expense of their death, and sporulation. Any combination of these strategies is feasible. If MSOs exist, then they must be eminently adapted to their peculiar lifestyle. This would mean that these protective mechanisms would be triggered *before* they are exposed to the external conditions by the disappearance of the ice cover. Any environmental cue could trigger such an adaptive response. We hypothesize that the increased insolation (due to the combined effect of increasingly strong sunshine and decreasing thickness of the ice) could be the required cue to trigger the onset of sporulation/escape reaction.

The permissible temperature under which MSOs could start to warm up is a very serious question. Unfortunately, we do not have data for the *surface* temperature at the onset of spotting. Bolometric measurements indicate a temperature of –60 °C for the Russell Crater (Reiss *et al*., 2002), but significantly less for the Richardson Crater (Malin and Edgett, 2000c; Supulver *et al*., 2001). The problem is that this information comes from a remote region that cools down due to the intense defrosting of the carbon dioxide cover. Therefore, we do not think that temperatures permissive to life could not occur below the ice, in *tiny surroundings* of the MSOs. Finally, we note that Antarctic examples point to the possibility of melt water down to temperatures of –50 °C (Wynn-Williams and Edwards, 2000). But, of course, we do not know anything of the salinity of the dune fields.

It is not excluded that the discussed peculiar phenomena, associated with DDSs, could be produced by 'bizarre' geology rather than biology. We are not aware of any such explanation that would fit *all relevant observations*. The one that could come close is a variant of a hypothesis put forward by Ness and Orme (2001, 2002). We could thus imagine that there are cracks in the dunes that in the summer fill up with gas. Then, as temperatures drop, the gas in the cracks also cools down and finally freezes. Layered ice covers the dunes in winter. Then, when sunlight appears, the dark dunes slowly heat up; the pressure in the cracks rises. Vapour and liquid material (including water) may form and would start to melt the ice layer *from below* at the openings of the cracks. The greyish material seen in the summer would be a deposit of material (salt?) brought up by the gas/liquid mixture from within the dunes.

This hypothesis could explain the annual pattern of the spots and their formation from below. But there are problems: first, the conspicuous lack of explosive formations associated with the DDSs does not favour such a scenario; second, the greyish residual spots do not show any features consistent with the blow of such outbursts. We also note that much more regular observation of DDS growth could falsify this hypothesis. The growth of spots *after the formation of the black centre* would be utterly different by the two mechanisms. In the biological case they would grow at the same speed, since the grey ring harbours living/reactivating MSOs, whereas in the geological case simple defrosting would follow the initial phase of the re-opening of the cracks.

It is a frequent suggestion that the DDSs may appear at the site of blocks or peaks of rocks (boulders) standing out from the dark dune fields. The explanation is that because of the larger heat capacity of these protruding sites, sublimation or melting is quicker there. However, the observations prove that DDSs are not related to these protruding sites. We have a number of MGS MOC images where it is apparent that there is no correlation between the DDSs sites and the protruding boulders (Figure 24).

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Appendix

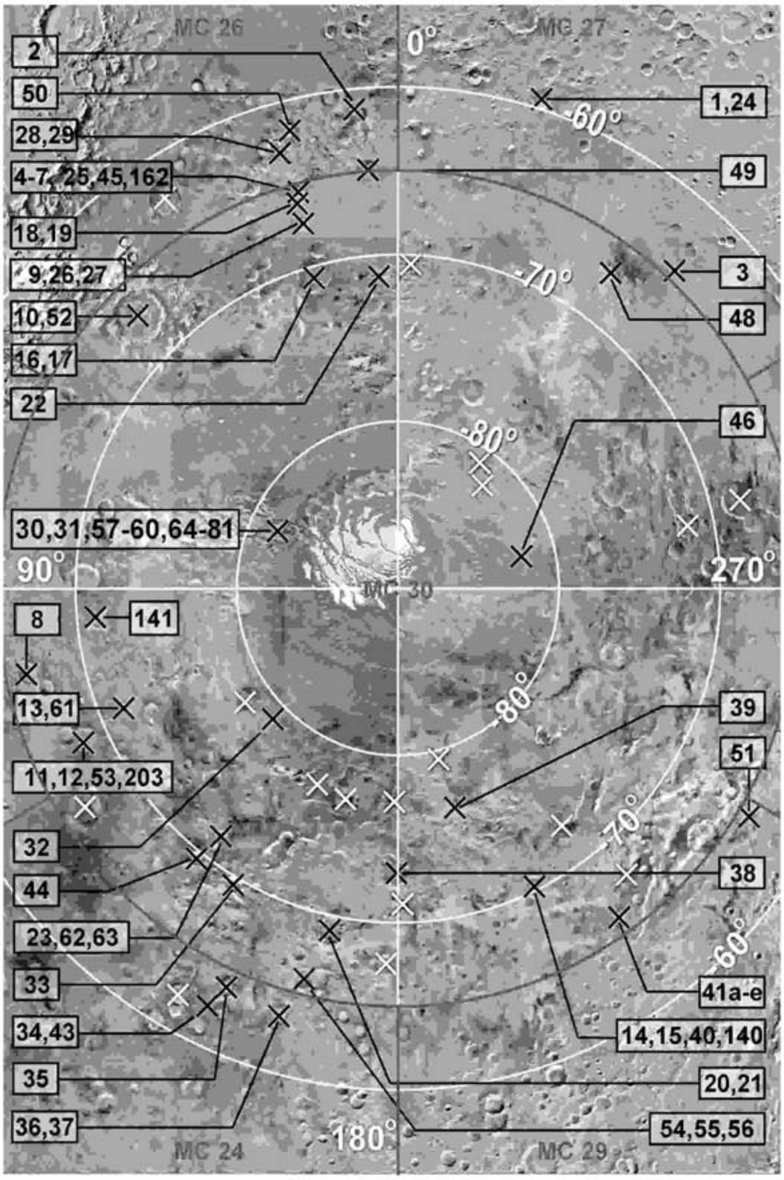

Figure 25. Photomap of the South Polar Region of Mars, on which we indicate with black crosses the sites and the numbers of MGS MOC narrow angle images in our Catalogue (see the data in the table in the Appendix). Black numbers are our catalogue-numbers in Appendix. White crosses indicate sites not in our Catalogue where DDSs can also be observed. (On the map there are no black crosses corresponding to entries Cat. 42 and 47, because these are at low latitudes.)

TABLE I

Catalogue of Dark Dune Spots (DDSs) on the Southern Polar Region of Mars (Ls: 90° ≤ winter < 180° ≤ spring < 270° ≤ summer < 360° ≡ 0° ≤ autumn <90 °)

No.Catal. */another images*	***MGS MOC*** *No.*	***Date***	***Ls***	***Pixel*** *m*	*Width x length imag.*	***Crater*** *name & sign*	***Lat.S***	***Long.W***	*Diam.Crat*	*Cat.No.,* ***Figs.***
1 /24	M02-02528--29	1999-06-19	157°	4.2 m	2.80 x30.04 km	Cr 343W-59	59.3°	343.8°	70 km	1
2	M03-06104--05	1999-08-01	180°	2.8 m	2.85 x19.82 km	Cr 5W-61	60.7°	5.3°	30 km	2
3	**M03-07564--65**	**1999-08-09**	**185°**	**4.1 m**	**2.79 x32.88 km**	**Cr 318W-64**	**64.0°**	**317.8°**	**20 km**	**3, Fig. 7c**
4 /5-7,25,45,160-2	**M02-02175**	**1999-06-17**	**156°**	**2.8 m**	**2.14 x23.79 km**	**„AB1”Cr 15W-65**	**64.9°**	**15.1°**	**50 km**	**4, Fig. 8a**
5 /4-7,25,45,160-2	**M07-00853--54**	**1999-09-05**	**201°**	**2.8 m**	**2.85 x40.68 km**	**- „ -**	**65.0°**	**15.5°**	**- „ -**	**5, Fig. 6**
6 /4-7,25,45,160-2	M08-02047--48	1999-10-09	221°	1.4 m	2.14 x11.32 km	- „ -	65.0°	15.3°	- „ -	6
7 /4-6,25,45,160-2	M12-00838--39	2000-02-07	297°	4.2 m	2.80 x24.33 km	- „ -	65.1°	14.8°	- „ -	7
8 /197	**M02-04639--40**	**1999-06-29**	**162°**	**5.5 m**	**2.83 x57.40 km**	***Smith 103W-66**	**66.1°**	**102.6°**	**75.5 km**	**8, Fig. 7a**
9 /26-7,155-157	M03-01162--63	1999-07-06	166°	2.8 m	2.85 x46.39 km	„AB1-b”Cr 15W-67	66.8°	15.6°	46 km	9
10 /52	M03-02003--04	1999-07-11	169°	1.4 m	1.42 x19.22 km	*Phillips 45W-67	66.4°	47.6°	190.2 km	10
11 /12,53,92-4,203-4	M02-03457--58	1999-06-23	159°	1.4 m	1.06 x19.25 km	*Steno 115W-68	67.8°	115.1°	106.9 km	11
12 /11,53,92-4,203-4	M03-03751--52	1999-07-20	174°	1.4 m	1.42 x14.33 km	- „ -	67.9°	- „ -	- „ -	12
13 /61	**M04-01220--21**	**1999-08-16**	**189°**	**4.1 m**	**2.79 x21.50 km**	**Cr 113W-71**	**71.1°**	**113.2°**	**15-33**	**13, Figs. 18a, c**
14 /15,40	**M04-03317--18**	**1999-08-26**	**195°**	**4.1 m**	**2.79 x35.64 km**	***Jeans 206W-70**	**70.0°**	**207.0°**	**80.2 km**	**14, Fig. 12a**
15 /14,40	**M07-05692--93**	**1999-09-29**	**215°**	**2.8 m**	**2.13 x25.99 km**	**- „ -**	**- „ -**	**206.8°**	**- „ -**	**15, Fig. 10b**
16 /17	**M03-07336--37**	**1999-08-07**	**184°**	**4.2 m**	**2.80 x35.63 km**	***Lyell 15W-70**	**69.5°**	**17.4°**	**131.0 km**	**16, Figs. 11b-d**
17 /16	**M08-05235--36**	**1999-10-21**	**229°**	**1.4 m**	**1.43 x13.27 km**	**- „ -**	**70.3°**	**15.5°**	**- „ -**	**17, Fig. 9b**
18 /19	M03-07643-*0700854*	1999-08-09	185°	2.8 m	2.85 x19.81 km	„AB1-a”Cr15W-66	65.6°	14.6°	12 km	18
19 /18	M09-02963--64	1999-11-12	243°	2.8 m	2.85 x21.51 km	- „ -	- „ -	- „ -	- „ -	19
20 /21	**M04-00169--70**	**1999-08-11**	**186°**	**2.8 m**	**2.12 x28.85 km**	***Charlier 169W-69**	**68.2°**	**168.8°**	**113.1 km**	**20, Fig. 19a**
21 /20	**M11-01813--14**	**2000-01-13**	**282°**	**2.8 m**	**2.12 x23.78 km**	**- „ -**	**68.3°**	**- „ -**	**- „ -**	**21, Fig. 12b**
22 /205-10,214	M03-05739--40	1999-07-30	179°	4.2 m	2.80 x37.42 km	„Polar Pit” 6W-71	70.7°	5.9°	PPS	22
23 /62-3,82-3,182-3	M03-06160--61	1999-08-01	181°	2.8 m	2.84 x14.13 km	Cr 144W-71	71.3°	144.2°	50 km	23
24 /1	M03-02916	1999-07-15	171°	2.8 m	2.85 x23.23 km	Cr 343W-59	59.3°	343.9°	70 km	24
25 /4-7,26,45,160-2	**M03-02430--31**	**1999-07-13**	**170°**	**1.4 m**	**1.43 x13.30 km**	**„AB1”Cr 15W-65**	**64.9°**	**15.2°**	**50 km**	**25, Fig. 7b**
26 /9,27,155-7	AB1-07708	1997-12-29	246°	25.1 m	25.83 x72.84 km	„AB1-b”Cr15W-67	66.9°	16.0°	46 km	26
27 /9,26,155-7	M10-03316--17	1999-12-28	272°	2.8 m	2.85 x26.59 km	- „ -	66.9°	16.1°	- „ -	27
28 /29	M03-07645-*0302433*	1999-08-09	185°	2.8 m	2.85 x23.24 km	Cr 16W-63	62.8°	15.6°	47 km	28
29 /28	M09-02965--66	1999-11-12	243°	2.8 m	2.85 x23.50 km	- „ -	62.9°	- „ -	- „ -	29
30/31,57-60,64-81,171-9	**AB1-07908**	**1998-01-01**	**247°**	**15.5m**	**31.88x32.87 km**	**„Inca City”64W-82**	**81.5°**	**64.6°**	**ICP**	**30, Figs. 3a, 13**

TABLE II

Catalogue of Dark Dune Spots (DDSs) on the Southern Polar Region of Mars (Ls: 90° ≤ winter < 180° ≤ spring < 270° ≤ summer < 360° ≡ 0° ≤ autumn <90 °)

No.Catal. */another images*	***MGS MOC*** *No.*	***Date***	***Ls***	***Pixel*** *m*	*Width*x*length imag.*	***Crater*** *name & sign*	***Lat.S***	***Long.W***	*Diam.Crat*	*Cat.No.,* ***Figs***
31/30,57-60,64-81,171-9	**M04-00678--79**	**1999-08-12**	**187°**	**2.8 m**	**2.83 x33.88 km**	**„Inca City”64W-82**	**81.7°**	**64.1°**	**ICP**	**31, Figs. 5, 14-17a**
32	**M08-03419--20**	**1999-10-15**	**225°**	**1.4 m**	**1.07 x15.72 km**	**Cr 136W-79**	**78.7°**	**135.8°**	**15-20 km**	**32, Figs. 8c, 12b**
33	M02-04119-*0906541*	1999-06-26	161°	1.4 m	2.13 x17.34 km	Cr 151W-69	69.1°	151.0°	60 km	33
34 /43	E05-00762--60-61	2001-06-08	175°	4.2 m	2.83 x21.49 km	Cr 155W-62	62.1°	155.2°	20 km	34
35	M02-00104--05	1999-06-05	150°	2.8 m	2.84 x21.50 km	Cr 156W-63	63.4°	156.1°	55 km	35
36 /37	**M02-00556--57**	**1999-06-08**	**151°**	**2.8 m**	**2.80 x18.13 km**	**Cr 164W-63**	**62.9°**	**164.2°**	**55 km**	**36, Fig. 8b**
37 /36	M03-00845--46	1999-07-05	165°	2.8 m	2.13 x19.25 km	- „ -	63.0°	164.5°	- „ -	37
38 /187-190	M03-02972--73	1999-07-16	171°	4.1 m	2.79 x49.20 km	*Richardson 180W-72	72.4°	179.1°	80 km	38
39	M03-05345--46	1999-07-27	178°	4.1 m	2.79 x54.80 km	„MPL” 195W-76	76.0°	195.0°	ICP	39
40 /14-5,139-41	**M07-00436--37**	**1999-09-02**	**199°**	**2.8 m**	**2.84 x26.62 km**	***Jeans 206W-70**	**69.9°**	**206.1°**	**80.2 km**	**40, Fig. 3c**
41b /41c,d,e,107-9	M00-02906--07	1999-04-30	132°	4.1 m	2.77 x32.90 km	Cr 216W-66	65.5°	215.2°	25-30	41b
41c /41b,d,e,107-9	M02-02258--59	1999-06-17	156°	2.8 m	2.83 x23.23 km	- „ -	65.4°	215.3°	- „ -	41c
41d /41b,c,e,107-9	M03-02564--65	1999-07-14	170°	1.4 m	0.71 x20.80 km	- „ -	65.3°	215.4°	- „ -	41d
41e-a /41b,c,d,107-9	M04-00011--12	1999-08-10	185°	2.8 m	2.83 x17.77 km	- „ -	- „ -	215.1°	- „ -	41e-a
42 /137	M02-02711--12	1999-06-20	157°	2.8 m	2.84 x 52.34 km	*Proctor 330W-48	47.9°	329.8°	168.2 km	42
43 /34	M03-06791--92	1999-08-04	182°	1.4 m	1.42 x 9.92 km	Cr 155W-62	62.1°	155.6°	20 km	43
44	M04-04056--57	1999-08-30	197°	2.8 m	1.42 x 7.16 km	Cr 141W-69	68.9°	141.4°	47 km	44
45ac /5-7,25,160-2	AB1-07707	1997-12-29	246°	24.5 m	25.16 x71.12 km	„AB1”Cr 15W-65	65.1°	15.3°	50 km	45ac
46	M08-04688	1999-10-19	228°	5.5 m	2.83 x20.46 km	ICP 284W-82	82.1°	284.3°	ICP	46
47	M02-01663--64	1999-06-14	154°	4.2 m	2.80 x13.63 km	Cr 342W-52	52.1°	342.1°	48	47
48	M03-03084--85	1999-07-16	171°	1.4 m	1.42 x 9.92 km	ICP 325W-66	66.3°	325.1°	ICP	48
49 /85	M04-02186-*0704581*	1999-06-20	192°	2.8 m	2.14 x10.94 km	*Wegener 4W-65	64.7°	5.3°	76.8 km	49
50 /84-5,211-2,211-2	M0300094--95	1999-07-01	163°	1.4 m	1.43 x13.31 km	Cr 14W-62	61.5°	14.1°	50 km	50
51	M03-00740--41	1999-07-04	165°	1.4 m	1.42 x14.36 km	Cr 238W-64	63.8°	237.9°	50 km	51
52 /10	**M07-00510--11**	**1999-09-03**	**199°**	**2.8 m**	**2.84 x29.45 km**	***Phillips 45W-67**	**66.4°**	**47.9°**	**190.2 km**	**52, Fig. 4b**
53 /11-2,92-4,203-4	**M07-02102--03**	**1999-09-11**	**204°**	**2.8 m**	**2.84 x45.09 km**	***Steno 115W-68**	**67.8°**	**115.6°**	**106.9 km**	**53, Figs. 1, 2**
54 /55-6,86,202	M07-01643--44	1999-09-08	203°	2.8 m	2.84 x26.57 km	Cr 166W-66	65.1°	166.4°	55 km	54
55 /54,56,86,202	M11-01099--100	2000-01-08	279°	2.8 m	2.12 x25.37 km	- „ -	65.3°	166.6°	- „ -	55
56 /54,55,86,202	M12-00311--12	2000-02-03	295°	4.1 m	2.79 x30.44 km	- „ -	65.4°	- „ -	- „ -	56
57/30-1,58-60,64-81,171-9	**M07-02824--25**	**1999-09-15**	**207°**	**1.4 m**	**1.06 x16.67 km**	**„Inca City”64W-82**	**81.5°**	**64.5°**	**ICP**	**57, Figs.14b,15-17b**

TABLE III

Catalogue of Dark Dune Spots (DDSs) on the Southern Polar Region of Mars (Ls: 90° ≤ winter < 180° ≤ spring < 270° ≤ summer < 360° ≡ 0° ≤ autumn <90 °)

No.Catal. */another images*	***MGS MOC*** *No.*	***Date***	***Ls***	***Pixel*** *m*	*Width x length imag.*	***Crater*** *name & sign*	***Lat.S***	***Long.W***	*Diam.Crat*	*Cat.No.,* ***Figs***
58/30-1,57-60,64-81,171-9	**M09-03813--14**	**1999-11-15**	**245°**	**4.1 m**	**2.78 x29.89 km**	**„Inca City”64W-82**	**81.5°**	**64.4°**	**ICP**	**58,Figs.3b,14-16c**
59/30-1,57-60,64-81,171-9	**M11-02076--77**	**2000-01-15**	**283°**	**2.7 m**	**2.82 x30.53 km**	**- „ -**	**- „ -**	**64.3°**	**- „ -**	**59,Figs.14-15e,17c**
60 /30-1,57-9,64-81,171-9	M15-01795--96	2000-05-27	358°	2.8 m	2.83 x18.64 km	- „ -	- „ -	64°	- „ -	60
61 /13	**M09-04810--11**	**1999-11-18**	**247°**	**2.8 m**	**2.84 x19.80 km**	**Cr 113W-71**	**71.1°**	**113.2°**	**15-33km**	**61, Figs. 18b, d**
62 /23,63,82-3,182-3	M08-01939--40	1999-10-08	221°	2.8 m	2.84 x21.47 km	Cr 144W-71	71.2°	143.3°	50 km	62
63 /23,62,82-3,182-3	M09-00968--69	1999-11-04	238°	2.8 m	2.13 x26.01 km	- „ -	71.2°	143.9°	- „ -	63
64/30-1,57-60,65-81,171-9	M03-03137	1999-07-17	172°	5.5 m	2.83 x47.42 km	„Inca City”64W-82	81.2°	65.7°	ICP	64
65/30-1,57-60,64-81,171-9	M03-04585	1999-07-24	176°	4.1 m	2.79 x44.87 km	- „ -	81.3°	64.2°	- „ -	65
66/30-1,57-60,64-81,171-9	M07-01552--53	1999-09-08	203°	5.5 m	2.83 x143.94 km	- „ -	- „ -	65.7°	- „ -	66
67/30-1,57-60,64-81,171-9	M07-03428--29	1999-09-18	208°	2.8 m	2.84 x17.51 km	- „ -	82°	63°	- „ -	67
68/30-1,57-60,64-81,171-9	M07-05947	1999-09-30	216°	4.1 m	2.79 x44.88 km	- „ -	81.6°	64.4°	- „ -	68
69/30-1,57-60,64-81,171-9	M08-02675--76	1999-10-12	223°	2.8 m	2.83 x21.47 km	- „ -	81.5°	65°	- „ -	69
70/30-1,57-60,64-81,171-9	M08-04693--94	1999-10-19	228°	2.8 m	2.83 x44.65 km	- „ -	- „ -	64.1°	- „ -	70
71/30-1,57-60,64-81,171-9	M08-06605	1999-10-27	233°	2.8 m	2.13 x16.37 km	- „ -	- „ -	64.9°	- „ -	71
72/30-1,57-60,64-81,171-9	**M09-00687--88**	**1999-11-03**	**237°**	**2.8 m**	**2.84 x23.73 km**	**- „ -**	**81.6°**	**64.1°**	**- „ -**	**72, Figs.14c, 15c**
73/30-1,57-60,64-81,171-9	M09-05442--43	1999-11-22	249°	2.8 m	2.83 x20.97 km	- „ -	81.4°	63.8°	- „ -	73
74/30-1,57-60,64-81,171-9	M09-05545--46	1999-11-23	249°	2.8 m	2.84 x14.11 km	- „ -	81.4°	65.1°	- „ -	74
75/30-1,57-60,64-81,171-9	M10-01405--06	1999-12-12	262°	2.8 m	2.83 x28.22 km	- „ -	81.5°	- „ -	- „ -	75
76/30-1,57-60,64-81,171-9	M11-01795--96	2000-01-13	282°	2.7 m	2.12 x23.74 km	- „ -	80.6°	70.9°	- „ -	76
77/30-1,57-60,64-81,171-9	M13-00047--48	2000-03-01	311°	2.8 m	2.83 x30.50 km	- „ -	81.5°	65.5°	- „ -	77
78/30-1,57-60,64-81,171-9	M13-01966--67	2000-03-28	326°	2.7 m	2.83 x26.57 km	- „ -	- „ -	65.3°	- „ -	78
79/30-1,57-60,64-81,171-9	**M14-00267--68**	**2000-04-04**	**330°**	**5.5 m**	**2.82 x33.92 km**	**- „ -**	**- „ -**	**64.4°**	**- „ -**	**79, Figs.14f, 15f**
80/30-1,57-60,64-81,171-9	M14-02193--94	2000-04-30	344°	2.8 m	2.83 x33.92 km	- „ -	81.7°	63.8°	- „ -	80
81/30-1,57-60,64-81,171-9	M16-00825	2000-06-16	8°	4.1 m	2.78 x24.30 km	- „ -	81.5°	65.3°	- „ -	81
140 /14-5,40,139	**E04-02003--04**	**2001-05-25**	**167°**	**4.2 m**	**2.81 x26.84 km**	***Jeans 206W-70**	**69.8°**	**205.9°**	**80.2 km**	**140, Fig. 3d**
141	**E05-01421**	**2001-06-15**	**179°**	**4.2 m**	**2.81 x 9.88 km**	**Cr 96W-71**	**71°**	**96°**	**5 km**	**141, Fig. 7d**
162 /4-7,25,45,160-1	**E04-01607**	**2001-05-21**	**165°**	**4.2 m**	**2.82 x 9.90 km**	**„AB1”Cr 15W-65**	**65°**	**15°**	**50 km**	**162, Fig. 8d**
203 /11-2,53,92-4,204	**E05-02068--69**	**2001-06-22**	**182°**	**2.8 m**	**2.86 x21.48 km**	***Steno 15W-68**	**68.0°**	**115.6°**	**106.9km**	**203, Figs.1c,d, 2b**

Notations

No. Catal./another images the same site under different MGS MOC-image numbers in our catalogue. *MGS MOC No.* is the *MSSS-number* of the image ID of the Mars Global Surveyor spacecraft (MGS) Mars Orbiter Camera (MOC) narrow-angle and wide-angle context image. *Date* is the *time of observation* (year-month-day). *Ls* is a term to specify Martian seasons: the *planetocentric longitude of the Sun* measured from the autumn equinox in degrees. *Pixel m* is the *resolution* of the image in meters. *Width x length imag.* are the width and length of the MGS MOC narrow-angle image in kilometers. *Crater name & sign* with coordinates. *Lat.S* is the aerographical *latitude* of the crater or the intercrater plain (ICP). *Long. W* is the aerographical *longitude* of the crater or the intercrater plain, increasing to the West. *Diam. Crat* is the *diameter* of the crater in kilometers. *Cat.No.* is number of the MGS MOC-image in our Catalogue. *Figs.* are number of figures. Data from the Mars Nomenclature: http://wwwflag.wr.usgs.gov/USGSFlag/Space/nomen/mars/marscrat.html/

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