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A Case for Using Ground-Based Thermal Inertia Measurements to Detect Martian Caves

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Abstract

Martian caves are regarded as one of the most interesting locations in which to search for life on the planet. Data obtained during the MARS2013 expedition at Hamar Laghdad Ridge in the Tafilalt region of Morocco indicate that even small cavities can display thermal behavior that is characteristic for caves. For example, temperature in a cavity equaled 14°C ± 0.1°C before sunrise, which was higher than the temperature of the ambient air (10°C ± 0.1°C) and proximate rocks (9°C ± 0.1°C) at the same time. Within 30 min after sunrise, when the temperature of surrounding rocks corresponded to 15°C, this thermal relationship reversed. Measurements were conducted under simulated spaceflight conditions, including near-real-time interpretation of data that were acquired in a complex flight planning environment. We conclude that using ground-based thermal contrast measurements, in 7–14 μm band before and after sunset, is an effective method for Mars astronauts to identify caves, possibly superior to usage of space-based or ground-penetrating data. Key Words: Mars—Caves—Thermal inertia—Detection—Human exploration. Astrobiology 14, 431–437.

1. Introduction

Since some workers have identified lunar rilles as collapsed lava tubes (Oberbeck *et al.,* 1969; Greeley, 1969, or more recently, Haruyama *et al.,* 2009), extraterrestrial caves have been widely discussed (*e.g.,* Boston *et al.,* 2003). Since martian basaltic volcanism is considered to be analogous to terrestrial processes (Glaze *et al.,* 2005), volcanic caves are believed to be a common phenomenon on Mars (Horz, 1985).

As an example, Bleacher *et al.* (2007a, 2007b) identified numerous tube-fed lava-flow systems in the Tharsis region, using Mars Express High Resolution Stereoscopic Camera images, and inferred that some collapsed lava-tube sections were skylights.

Other cave formation mechanisms that may occur on Mars include mass wasting (*e.g.,* undercutting of scarps) and tectonic processes that led to subsurface cracking (Boston *et al.,* 2004). The dissolution of soluble rock has also been considered, which occurred during the late Noachian period, when Mars is generally believed to have been much wetter (Baker, 2001). On Earth, such solution caves are common in limestones, evaporites, quartzites, granites, and sandstones (Boston *et al.,* 2004).

Carbonates have been predicted to exist on Mars (*e.g.,* Pollack *et al.,* 1987); this is supported by ground-based evidence of extensive evaporates that were observed by the Mars Exploration Rovers. More recently, Ehlmann *et al.* (2008) identified carbonate deposits on a relatively small ($<10\,\mathrm{km}^2$) scale in Compact Reconnaissance Imaging Spectrometer for Mars (CRISM, an instrument on the Mars Reconnaissance Orbiter) data sets of Nili Fossae, which are associated with olivine-rich outcrops where magnesite appears to be the dominant mineral. Evidence for significant quantities of surface carbonate deposits even in high northern latitudes was found at the 2007 Phoenix Mars landing site, in which alkaline soils were found to contain between 3 and 5 wt % calcite ($CaCO_3$) (Boynton *et al.,* 2009).

Caves are important with regard to human exploration of Mars since they are considered to provide efficient shelters from radiation (Horz, 1985; Coombs and Hawke, 1992), impacts, and temperature fluctuations, and are able to maintain high humidity compared to the surface. Frederick *et al.* (2000) hypothesized that martian caves might also provide an environment that supports stable ice. Williams *et al.* (2010) demonstrated, using a numerical Lattice-Boltzmann model, that cave ice should be stable over significant portions of the subsurface of Mars. The ice sources include wind-blown snow, frozen ponded rainwater, atmospherically deposited frost, or a combination of these. These authors calculated that ice could survive in caves on timescales of as long as 100,000 years. This would mean that the stability of the water resources over time could be greater than *the duration of* the average martian obliquity cycle where significant changes of

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the martian rotational axis (*e.g.,* Schorghofer, 2008) cause the polar caps to resupply lower latitudes with fresh ice (Laskar, 2004; Head *et al.,* 2006).

1.1. Astrobiological relevance

As organic materials cannot continuously withstand the chemical, thermal, impact, and radiative stress of the surface, caves on Mars may preserve paleomicrobiological evidence should it exist there (Leveille and Datta, 2010). Although the search for life or life's past traces on Mars is a priority within the astrobiology community, Boston *et al.* (1992, 2003) argued that any present martian life is more likely to be analogous to Earth's subsurface biosphere than anything currently found on Earth's surface.

However, until recently, the limited spatial resolution and viewing perspective of orbiters and the limited range of ground-based vehicles have resulted in only a small number of potential caves being detected (Cushing *et al.,* 2007).

1.2. Identification of caves

Detecting martian caves is nontrivial when using current techniques. The spectrum of terrestrial possibilities includes orbital reconnaissance, aerial reconnaissance, geophysical methods [such as ground-penetrating radar (GPR), seismic techniques, microgravity anomaly mapping], locating of outgassing sources that may be indicative of subsurface access, geomorphological evidence (*i.e.,* geological settings conducive to subsurface cavity formation). Fortunately, direct orbital imaging has already revealed lava tubes on Mars and the Moon.

Although well-established as a method, GPR has the distinct disadvantage of having to choose between either poor spatial resolution when obtaining data from orbital platforms or having to measure on site. Further, the data interpretation requires at least some assumptions about the geoelectric properties of the strata on the surface.

Current spacecraft GPR devices do not yet have the spatial resolution required for cave detection from orbit, for example, in the range of tens of meters. However, concepts for aerial platforms (*i.e.,* gliders, aerostats, zeppelins, etc.) that could put such an instrument within relative proximity to the surface are strong contenders to ground-based GPR surveillance.

However, either the resolution of the methods mentioned above is insufficient, or the methods providing satisfactory resolution require physical proximity of the sensor to the surface. We argue that ground-based thermal inertia measurements provide a simple means by which to detect potential cave entrances and cavities, including those that are not visible from orbit or aerial reconnaissance. This claim was put to a validation test in a high-fidelity Mars analog environment during the MARS2013 campaign.

2. The MARS2013 Field Simulation

From February 1 to 28, 2013, the Austrian Space Forum, in partnership with research teams from 23 nations, conducted a Mars analog field test in the Moroccan Sahara near Erfoud (31°21'N, 004°04'E). Seventeen experiments were performed by a crew of ten field researchers, supported by a Mission Support Center in Innsbruck, Austria. The tests were conducted under simulated martian conditions, including the usage of space suit simulators, rovers, a 10 min time delay in communications, and realistic work flows in a simulated operational spaceflight environment (Groemer *et al.,* 2014 in this issue). During this mission, the concept of identifying cave entrances was put to the test.

2.1. Geological context

The eastern Anti-Atlas of Morocco consists of a Precambrian crystalline basement, which is covered by Palaeozoic and undeformed Cretaceous and Tertiary sedimentary rocks (Cavalazzi *et al.,* 2008). One of the geologically and paleobiologically interesting features in the field test area is the Kess Kess mud mounds (Kess Kess Formation), which are exposed at the Hamar Laghdad Ridge in the Tafilalt region east of the city of Erfoud, Morocco (Fig. 1). Carbonate mounds occur as localized clusters of different size and shape and show typical features such as stromatactis and zebra cavity structures, fenestral fabrics, fractures, and veins in which some microbial mediation occurred during formation and early lithification of these carbonate formations (Monty *et al.,* 1995). We observed these mounds to have circular, sub-elliptical morphological shapes with generally steep (20–60°) asymmetrical flanks.

The elevation of the mounds does not exceed 55 m, and the average diameter is around 20–30 m. The mud mounds are of Lower Devonian age and represent shallow water deposits in an aphotic environment. The current topography closely reflects the initial topographic situation on the seafloor. On the basis of their lithology, architecture, isotope geochemistry, and clustered occurrence on top of a volcanic formation, Mounji *et al.* (1998) proposed that the fine crystalline material that forms the mounds and the intermound beds was precipitated from hydrothermal fluids and that accretion of the material was driven by hydrothermal venting. Cavalazzi *et al.* (2008) identified laminated carbonates in the vicinity, which they attributed to microbially mediated processes that suggest a direct biological contribution to the deposition of veins (crystalline streaks embedded in the rock matrix) fed by the hydrothermal solution.

We identified several mud mounds that seemed to have cavities; one of them was chosen by the MARS2013 Mission Support Center Remote Science Support team to be observed by the field crew. Because a divergence of thermal inertias between ambient surfaces and cave entries is well known (*e.g.,* Wynne *et al.,* 2008), this particular cavity was selected due to its small size to test under unfavorable conditions, since larger caves exhibit a larger thermal inertia and maintain their temperature difference throughout longer periods.

In addition, the aim was to put the concept of cave entry or cavity detection to the test in a field setting that simulated operational aspects of a human Mars mission. This was realized by processing the field data near real time into a complex flight planning workflow, enabling a revisiting of the site and verifying the usability of the forward-looking infrared (FLIR) camera with a high-fidelity space suit simulator (Groemer *et al.,* 2012).

3. Method

Measurements were made with a Draeger UCF9000 FLIR camera, an amorphous Silicium (Si) Microbolometer Array with 384 × 288 pixels and sensitivity between 7 and 14 μm.

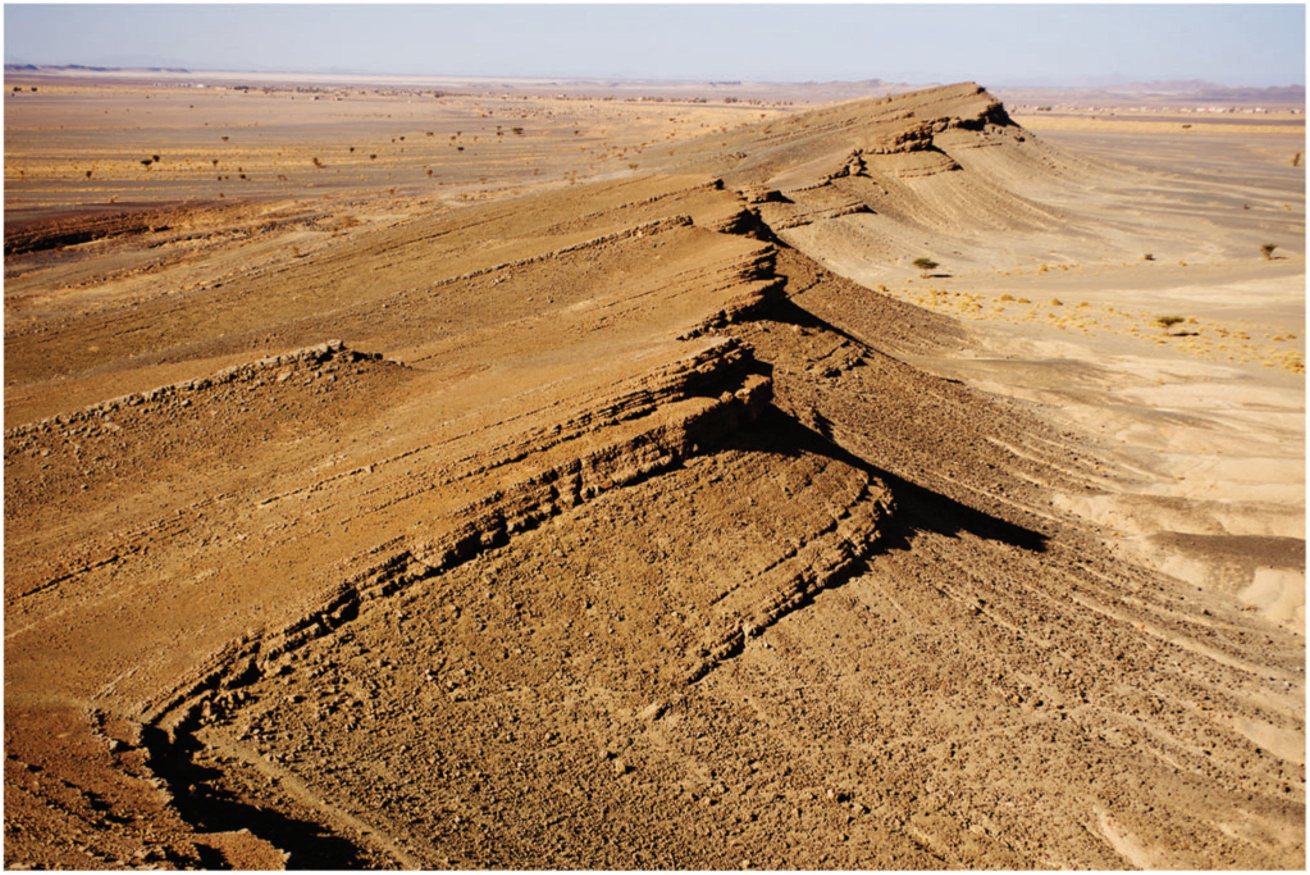

FIG. 1. The Hamar Laghdad Ridge in the Tafilalt region, Morocco, with a view of the inclined mud mounds. Color images available online at www.liebertonline.com/ast

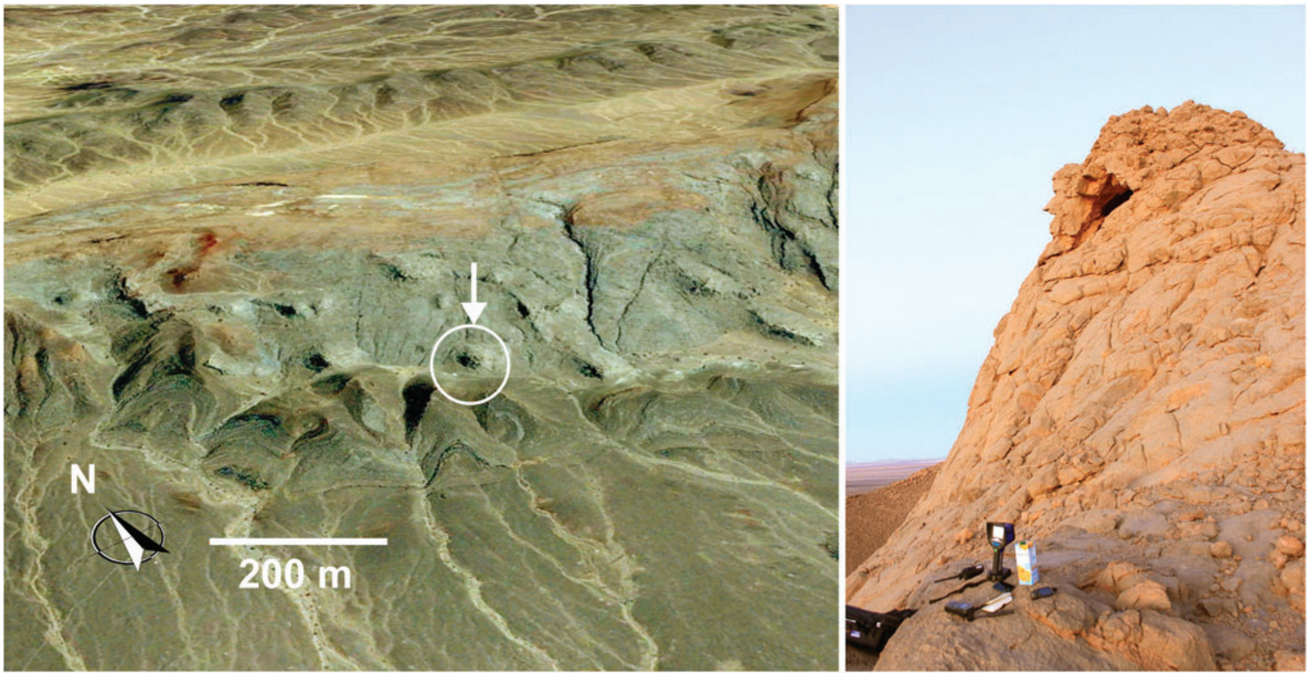

FIG. 2. Context satellite photo and close-up of the cave. The entrance shown in the right image is facing east. Color images available online at www.liebertonline.com/ast

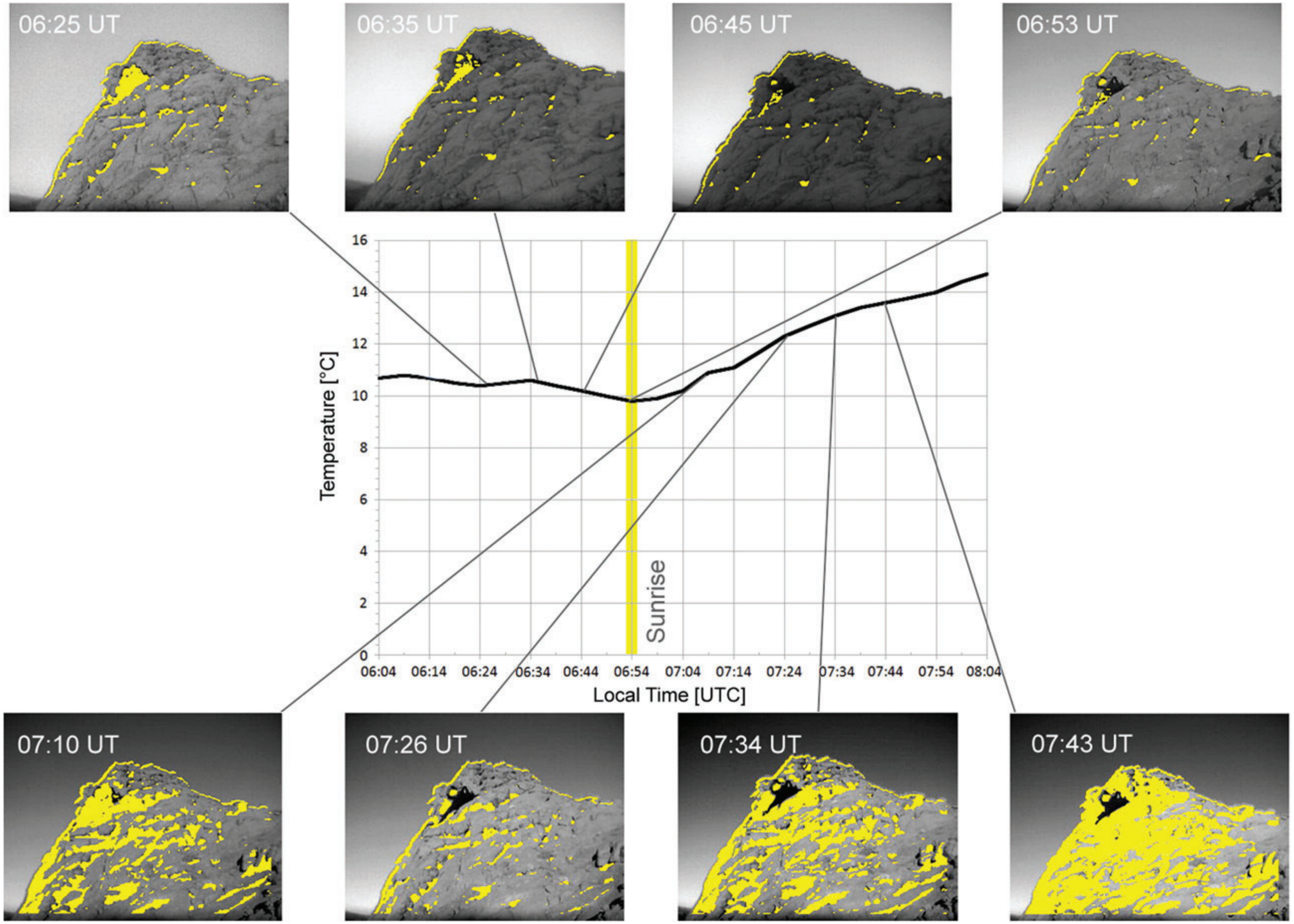

FIG. 3. Ambient air temperatures are shown together with the thermal threshold imagery. Regions above the threshold temperature are shown in yellow, superimposed on the optical context image. Threshold was set at 12°C until thermal equity with the ambient surface was reached at 07:26 UTC, then set at 15°C to identify the cooler cavity entry while the environment was heated above 15°C. Color images available online at www.liebertonline.com/ast

Temperature sensitivity was ±0.035°C. Local environmental data (temperature, pressure, and relative humidity) were obtained with a Voltcraft DL-180THP data logger every 5 min throughout the field campaign.

First, it was demonstrated that the camera can be used by an analog astronaut in the Aouda space suit simulator in accordance with the 3-D working envelope previously studied with motion capture techniques in a laboratory environment (Groemer *et al.,* 2012), and this has now been demonstrated in an actual field setting. Usability tests included screen readability, pointing accuracy, and the ability to operate the instrument software under representative physiological workload conditions. Additional measurements were taken out-of-simulation by unsuited crew members from a distance of approximately 100 m from the cave entry to fully exploit the resolution and field of view of the FLIR system.

The data detailed here were obtained on February 24, 2013, between 06:04 and 08:04 UTC for the sunrise period and between 17:49 and 19:00 UTC for the sunset period. Local sunrise was at 06:54 UTC, local sunset at 18:15 UTC. No wind activity was observed during either observation period.

The cavity investigated is located at 31°22.551N, 4°03.280W (Fig. 2) and has a southeast-facing, 2×5 m entry, as well as two sky-hole openings of 1.5 and 3 m diameter each.

The thermal imagery obtained is a threshold map, where pixels above a defined threshold are marked. The resulting map is superimposed on a near-infrared/optical reference image (Fig. 3). The threshold selected was at 12°C to discriminate the ambient surface structures (at about 10°C±0.1°C before sunrise) versus the cavity entrance (at 14°C±0.1°C before sunrise).

The thermal imagery clearly identifies the cave opening, which is warmer during the period before sunrise and then stays cooler than the surrounding surface as it heats up to above 14°C±0.1°C within 1 h after sunrise. Thermal equity was reached about 30 min after sunrise. After that the cavity stayed cooler, although the rock surface was heated by the Sun to above 15°C±0.1°C, corresponding to 0.3°C above the ambient air temperature. Subtracting the thermal images before (marking regions above the rock temperature and inverting that image) and after sunrise (marking regions below rock temperature) permits identification of the cave entrance (Fig. 4).

4. Discussion

These observations performed while using ground-based thermal inertia measurements in a simulated Mars spaceflight environment demonstrated that

(1) only a modest hardware effort, such as the use of a handheld device, is necessary to identify suitable cavity candidates for follow-up observations. Such an imaging bolometer could be available during a human Mars surface mission due to its dual use also for engineering purposes. In addition, devices like this can easily be tele-operated, for example, on robotic rover platforms.

(2) the workflow of sending data to a remote science support team (having them interpret the data in near real time) leaves enough margin for adapting a flight plan to allow for a site revisit; small cavities display thermal inertia characteristics sufficient to detect cave

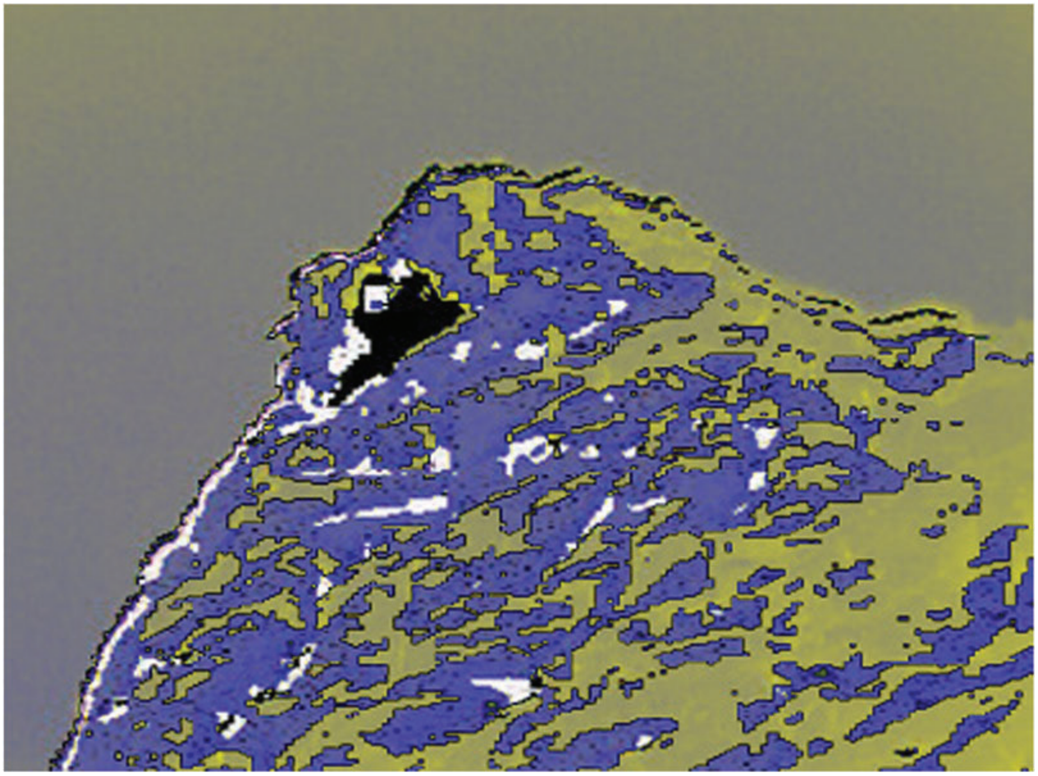

FIG. 4. Differential image of the thermal images at 06:25 UT and 07:43 UT, superimposed on an optical image for reference. The cave entrance appears in black. The black line at the horizon is caused by a slight change of the perspective between the images. Note that none of the dark areas from the optical image (Fig. 2) (caused by the shadows in the bedding of the rock) are present in this differential image. Color images available online at www.liebertonline.com/ast

openings as small as several cubic meters in diameter. This allows, among other things, for cataloging potential shelter areas for radiation protection of astronauts.

Due to the diurnal temperature variations on Mars, it would be expected that the effect described here is even more prominent on that planet than it is on Earth. In our observations, the temperature increase was 5°C within 1 h. *In situ* data collected over a period of 100 sols with the Mars Science Laboratory's Rover Environmental Monitoring Station (MSL REMS) indicate a total diurnal variation of 80°C, and 10°C changes within 1 h were observed (de la Torre Juárez, 2013). As to wind effects, due to the low density of the martian atmosphere, the temperature of the surface is controlled primarily by solar heating, and infrared cooling to the atmosphere and space, rather than heat exchange with the atmosphere (Martín-Torres *et al.,* 2013). Hence, environmental effects pertinent to the terrestrial application of the method are less relevant on Mars.

None of the caves observed during the MARS2013 mission could have been detected by orbital reconnaissance due to the limited resolution of thermal imaging systems and the local topography, which blocks the line of sight from above. Side-looking, remote thermal imaging would increase the footprint and hence result in undesirably poor spatial resolution.

Putzig and Mellon (2007) argued that thermal inertia derivation techniques generally assume that surface properties are uniform at horizontal scales below the footprint of the observing instrument and to depths of several decimeters.

Hence, using thermal inertia measurements for identifying cave entry candidates should be applied with at least a basic understanding of the diurnal cycle of ground temperatures related to energy fluxes due to surface solar radiation fluxes, wind-driven heat exchanges, thermal emission behavior of the atmosphere, heat dissipation into the soil, and surface properties. Additionally, the detection efficiency also depends on the choice of the wavelength, cave entry size versus instrument footprint, viewing geometry, strength of the actual thermal signal, and the choice of the timing for obtaining the data (Wynne *et al.,* 2008).

In summary, the method described here offers efficient, low-cost (in terms of mass) data-processing capabilities, less time consumption, and less stringent astronaut training requirements, and it identifies caves that would not otherwise be observable with orbital reconnaissance.

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Author Disclosure Statement

The authors state no competing financial interest.

Abbreviations

FLIR, forward-looking infrared; GPR, ground-penetrating radar.

References

Baker, V.R. (2001) Water and the martian landscape. *Nature* 412:228–236.

Bleacher, J.E., Greeley, R., Williams, D.A., Cave, S.R., and Neukum, G. (2007a) Trends in effusive style at the Tharsis Montes, Mars, and implications for the development of the Tharsis province. *J Geophys Res* 112, doi:10.1029/2006JE002873.

Bleacher, J.E., Greeley, R., Williams, D.A., Werner, S.C., Hauber, E., and Neukum, G. (2007b) Olympus Mons, Mars: inferred changes in late Amazonian aged effusive activity from lava flow mapping of Mars Express High Resolution Stereo Camera data. *J Geophys Res* 112, doi:10.1029/2006JE002826.

Boston, P.J., Ivanov, M.V., and McKay, C.P. (1992) On the possibility of chemosynthetic ecosystems in subsurface habitats on Mars. *Icarus* 95:300–308.

Boston, P.J., Frederick, R.D., Welch, S.M., Werker, J., Meyer, T.R., Sprungman, B., Hildreth-Werker, V., Thompson, S.L., and Murphy, D.L. (2003) Human utilization of subsurface extraterrestrial environments. *Gravit Space Biol Bull* 16: 121–131.

Boston, P.J., Frederick, R.D., Welch, S.M., Werker, J., Meyer, T.R., Sprungman, B., Hildreth-Werker, V., and Thompson, S.L. (2004) Extraterrestrial subsurface technology test bed: human use and scientific value of martian caves. *AIP Conf Proc* 699:1007–1018.

Boynton, W.V., Ming, D.W., Kounaves, S.P., Young, S.M., Arvidson, R.E., Hecht, M.H., Hoffman, J., Niles, P.B., Hamara, D.K., Quinn, R.C., Smith, P.H., Sutter, B., Catling, D.C., and Morris, R.V. (2009) Evidence for calcium carbonate at the Mars Phoenix landing site. *Science* 325:61–64.

Cavalazzi, B., Barbieri, R., and Ori, G.G. (2008) Chemosynthetic microbialites in the Devonian carbonate mounds of Hamar Laghdad (Anti-Atlas, Morocco). *Sediment Geol* 200:73–88.

Coombs, C.R. and Hawke, B.R. (1992) A search for intact lava tubes on the Moon: possible lunar base habitats. In *The Second Conference on Lunar Bases and Space Activities of the 21st Century*, Vol. 1, edited by W.W. Mendell, NASA Conference Publication 3166, Lyndon B. Johnson Space Center, Houston, pp 219–229.

Cushing, G.E., Titus, T.N., Wynne, J.J., and Christensen, P.R. (2007) THEMIS observes possible cave skylights on Mars. *Geophys Res Lett* 34:L17201.

de la Torre Juárez, M., Ramos, M., Sebastian, E., Armiens, C., Gómez-Elvira, J., Carrasco, I., Haberle, R.M., Hamilton, V.E., Jurado-Molina, A., Lepinette, A., Martín-Torres, J., Martínez Frías, J., Mischna, M., Mora, L., de Pablo, M.A., Peinado, V., Rodríguez-Manfredi, J.A., Urqui O'Callahan, R., Vasavada, A.R., Zorzano M., and María, P. (2013) Preliminary analyses of the REMS ground temperature data in Gale: exploring thermodynamic processes behind the diurnal variability [abstract EGU2013-6733]. In *EGU General Assembly 2013*, European Geosciences Union, Munich.

Ehlmann, B.L., Mustard, J.F., Murchie, S.L., Poulet, F., Bishop, J.L., Brown, A.J., Calvin, W.M., Clark, R.N., Des Marais, D.J., Millikeb, R.E., Roachl, L.H., Roush, T.L., Swayze, G.A., and Wray, J.J. (2008) Orbital identification of carbonate-bearing rocks on Mars. *Science* 322:1828–1832.

Frederick, R.D., Billings, T.L., McGown, R.D., and Walden, B.E. (2000) Martian ice caves [abstract 6062]. In *Concepts and Approaches for Mars Exploration*, Lunar and Planetary Institute, Houston.

Glaze, L.S., Anderson, S.W., Stofan, E.R., Baloga, S., and Smrekar, S.E. (2005) Statistical distribution of tumuli on pahoehoe flow surfaces: analysis of examples in Hawaii and Iceland and potential applications to lava flows on Mars. *J Geophys Res* 110, doi:10.1029/2004JB003564.

Greeley, R. (1969) On the origin of lunar sinuous rilles. *Modern Geology* 1:75–80.

Groemer, G.E., Hauth, S., Luger, U., Bickert, K., Sattler, B., Hauth, E., Foeger, D., Schildhammer, D., Agerer, C., Ragonig, C., Sams, S., Kaineder, F., and Knoflach, M. (2012) The Aouda.X space suit simulator and its applications to astrobiology. *Astrobiology* 12:125–134.

Groemer, G., Soucek, A., Frischauf, N., Stumptner, W., Ragonig, C., Sams, S., Bartenstein, T., Häuplik-Meusburger, S., Petrova, P., Evetts, S., and Sivenesan, C. (2014) The MARS2013 Mars analog mission. *Astrobiology* 14:360–376.

Haruyama, J., Hioki, K., Shirao, M., Morota, T., Hiesinger, H., van der Bogert, C.H., Miyamoto, H., Iwasaki, A., Yokota, Y., Ohtake, M., Matsunaga, T., Hara, S., Nakanotani, N., and Pieters, C.M. (2009) Possible lunar lava tube skylight observed by SELENE cameras. *Geophys Res Lett* 36:L21206.

Head, J.W., Marchant, D.R., Agnew, M.C., Fassett, C.I., and Kreslavsky, M.A. (2006) Extensive valley glacier deposits in the northern mid-latitudes of Mars: evidence for Late Amazonian obliquity-driven climate change. *Earth Planet Sci Lett* 241:663–671.

Horz, F. (1985) Lava tubes: potential shelters for habitats [abstract A86-30113 13-14]. In *Lunar Bases and Space Activities of the 21st Century,* edited by W.W. Mendell, Lunar and Planetary Institute, Houston.

Laskar, J. (2004) Long term evolution and chaotic diffusion of the insolation quantities of Mars. *Icarus* 170:343–364.

Leveille, R.J. and Datta, S. (2010) Lava tubes and basaltic caves as astrobiological targets on Earth and Mars: a review. *Planet Space Sci* 58:592–598.

Martín-Torres, J., Paz Zorzano, M., Pla-García, J., Rafkin, S., Lepinette, A., Sebastián, E., and Gómez-Elvira, J. (2013) Nighttime infrared radiative cooling and opacity inferred by REMS ground temperature sensor measurements [abstract EGU2013-12230]. In *EGU General Assembly 2013*, European Geosciences Union, Munich.

Monty, C.L.V., Bosence, D.W.J., Bridges, P.H., and Pratt, B.R., editors. (1995) *Carbonate Mud-Mounds: Their Origin and Evolution*, Special Publication of the International Association of Sedimentologists No. 23, Blackwell Science, Oxford.

Mounji, D., Bourque, P.-A., and Savard, M.M. (1998) Hydrothermal origin of Devonian conical mounds (kess-kess) of Hamar Lakhdad Ridge, Antiatlas, Morocco. *Geology* 26: 1123–1126.

Oberbeck, V.R., Quaide, W.L., and Greeley, R. (1969) On the origin of lunar sinuous rilles. *Modern Geology* 1:75–80.

Pollack, J.B., Kasting, J.F., Richardson, S.M., and Poliakoff, K. (1987) The case for a wet, warm climate on early Mars. *Icarus* 71:203–224.

Putzig, N.E. and Mellon, M.T. (2007) Thermal behavior of horizontally mixed surfaces on Mars. *Icarus* 191:52–67.

Schorghofer, N. (2008) Temperature response of Mars to Milankovitch cycles. *Geophys Res Lett* 35:L18201.

Williams, K.E., McKay, C.P., Toon, O.B., and Head, J.W. (2010) Do ice caves exist on Mars? *Icarus* 209:358–368.

Wynne, J.J., Titus, T.N., and Chong Diaz, G. (2008) On developing thermal cave detection techniques for Earth, the Moon and Mars. *Earth Planet Sci Lett* 272:240–250.

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