THEMIS observes possible cave skylights on Mars

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[1] Seven possible skylight entrances into Martian caves were observed on and around the flanks of Arsia Mons by the Mars Odyssey Thermal Emission Imaging System (THEMIS). Distinct from impact craters, collapse pits or any other surface feature on Mars, these candidates appear to be deep dark holes at visible wavelengths while infrared observations show their thermal behaviors to be consistent with subsurface materials. Diameters range from 100 m to 225 m, and derived minimum depths range between 68 m and 130 m. Most candidates seem directly related to pit-craters, and may have formed in a similar manner with overhanging ceilings that remain intact. **Citation:** Cushing, G. E., T. N. Titus, J. J. Wynne, and P. R. Christensen (2007), THEMIS observes possible cave skylights on Mars, *Geophys. Res. Lett.*, *34*, L17201, doi:10.1029/2007GL030709.

1. Introduction

[2] The existence, physical properties and possible benefits of extraterrestrial caves have been a subject of scientific discussion for as long as spacecraft have observed planetary surfaces. *Oberbeck et al.* [1969] compared lunar and terrestrial lava-tubes, and *Carr et al.* [1977] examined similar structures on Mars. *Horz* [1985] suggested using lunar lava tubes as shelters for human habitation, and *Boston et al.* [2004] discussed the same for Mars–along with favorable implications for astrobiology. Even now, engineers are developing technologies to allow both human and robotic missions to physically explore extraterrestrial caves [*Boston et al.*, 2004; *Boston and Dubowsky*, 2005]. Unfortunately, cave detection by spacecraft is difficult because their instruments have limited resolution and generally point nadir (straight downward), requiring detectable cave entrances to face skyward and be large enough to be resolved from orbit.

[3] The Martian surface experiences a range of significant hazards. Micrometeoroids, solar flares, UV radiation, high-energy particles from space and intense dust storms regularly bombard the surface [*Mazur et al.*, 1978; *Kuhn and Atreya*, 1979; *Frederick et al.*, 2000; *Boston et al.*, 2004; *Schulze-Makuch et al.*, 2005], where absolute temperatures can double over a single diurnal cycle [*Cushing et al.*, 2005]. Caves may be among the only structures on Mars that offer long-term protection from such hazards.

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[4] We have identified seven candidate cave entrances (skylights) located on or near the flanks of Arsia Mons (southernmost of the three massive shield volcanoes of Tharsis Montes, Figure 1). This region has widespread pit craters and grabens, suggesting an abundance of subsurface void spaces [*Ferrill et al.*, 2003; *Wyrick et al.*, 2004]. These candidates may have formed in a manner comparable to pit craters (which are usually found nearby) except that an area of competent surface materials may have remained intact to form a ceiling as subsurface materials collapsed and drained into the subterranean voids below (see Figure 2 and auxiliary material).[1] These candidate skylights appear to descend 100 meters or more beneath the surface and may either (1) open laterally into cavernous spaces; (2) plunge deeply into subsurface faults; or (3) may not be caves at all, instead being deep cylindrical shafts with sheer vertical walls. With currently available data, we cannot determine which of these cases is correct because THEMIS only observes from nadir and can't see whether the candidates have vertical or subvertical walls. In any case, these are extremely unusual and interesting features worthy of further investigation.

2. Observations

[5] The majority of data were collected by THEMIS, which observes the surface from nadir at both visible and thermal-infrared wavelengths. The thermal-infrared camera (IR) observes nine bands ranging between 6.3–15.3 μm with a spatial resolution of 100 meters per pixel. The visible-wavelength camera (VIS) observes at 18 or 36 m/pixel in 5 bands, though only band-3 images ($\sim$0.65 μm) are used for this investigation. THEMIS observes with both VIS and IR cameras late in the afternoon ($\sim$1500–1700 hrs, when the sun has past transit and doesn't shine as deeply into the candidates). Only the IR camera is used for predawn observations ($\sim$0300–0500 hrs) which are necessary to provide a diurnal range of thermal coverage [*Christensen et al.*, 2004].

[6] Cave entrances detectable by THEMIS are probably rare because they must face skyward and have minimum diameters of $\sim$100 m. While VIS observations can resolve smaller features than this, they do not show sufficient detail to verify definite cave-like characteristics. We therefore use 100-meter IR observations to confirm that each candidate exhibits smaller amplitudes of diurnal temperature variations than the immediately surrounding terrain. This requirement of minimum 100-m diameters and skyward facing should seriously limit the number of cave entrances detectable by THEMIS (the only thermal imaging system currently orbiting Mars.).

[1]Auxiliary materials are available in the HTML. doi:10.1029/2007GL030709.

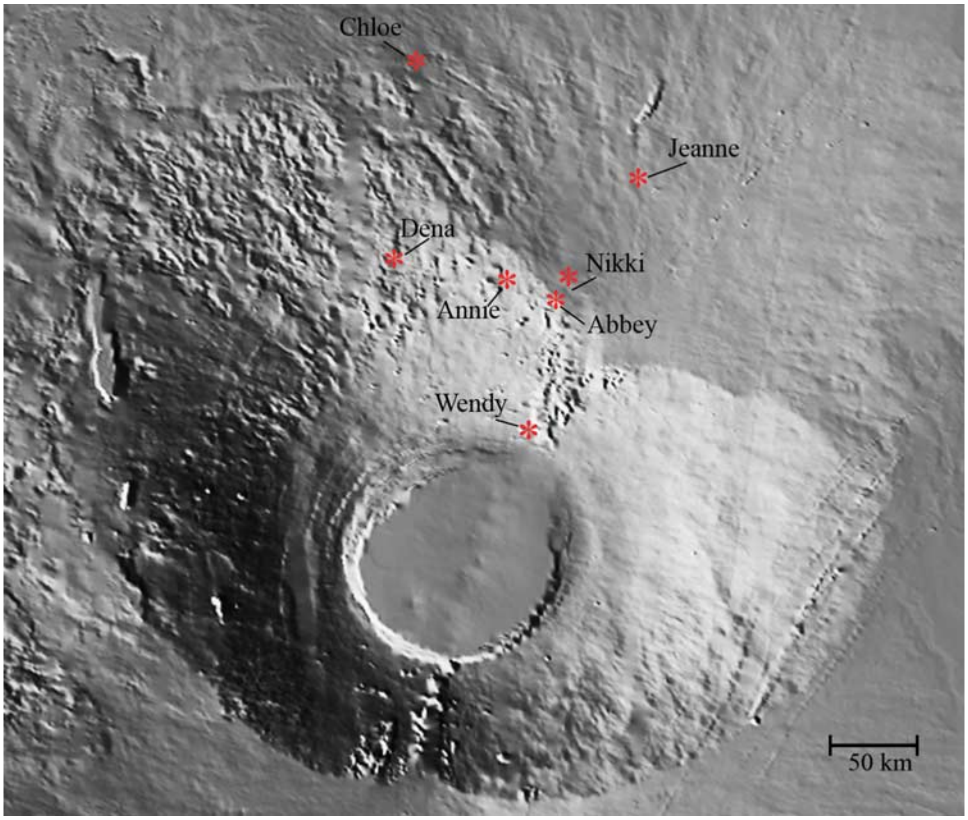

Figure 1. MOLA shaded relief map of Arsia Mons. Caldera floor is centered at approximately 239°E, 9°S. Locations of the seven candidate cave skylights are labeled.

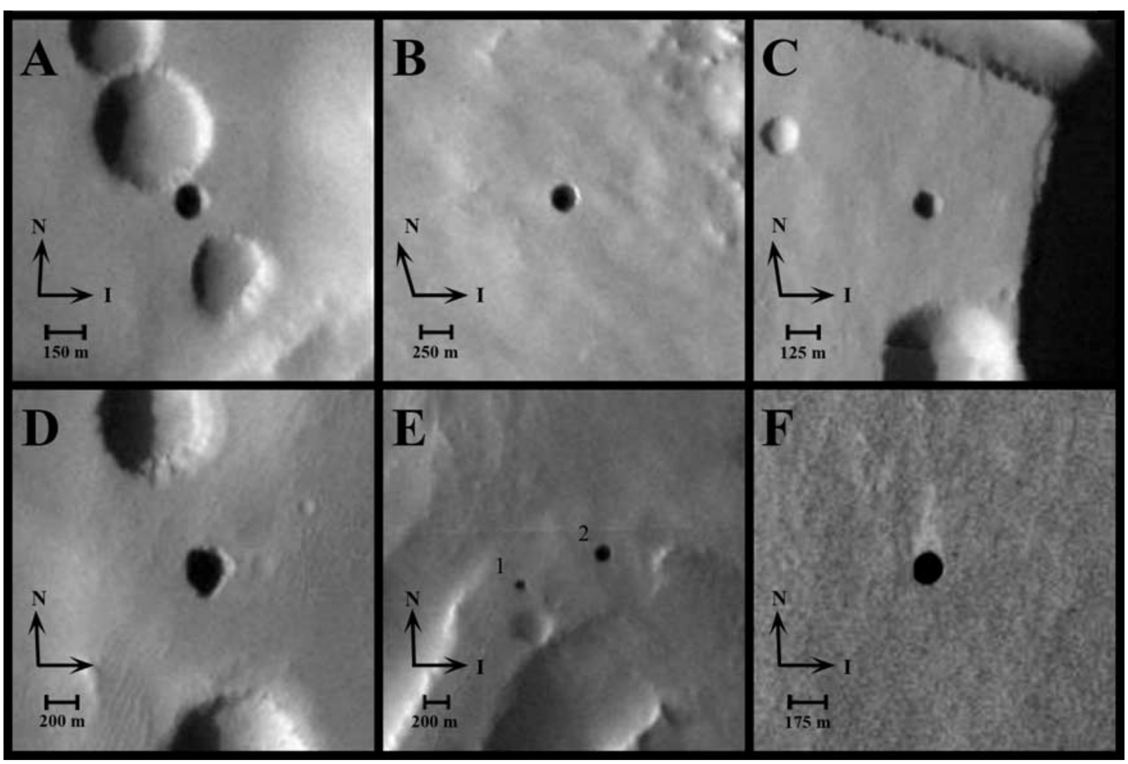

Figure 2. Seven candidate cave skylights: (a) Dena, (b) Chloë, (c) Wendy, (d) Annie, (e) Abby (1) and Nikki (2), and (f) Jeanne. Arrows signify directions of solar illumination and of North. To facilitate our photoclinometry routine, each candidate is map-projected with sunlight coming from the 9 o'clock direction.

Table 1. Physical Parameters of Candidate Skylights[a]

Name	Longitude	Latitude	Diameter	Incidence Angle	Minimum Depth	Minimum d/D Ratio	Elevation	THEMIS VIS ID
Annie	240.03°E	6.52°S	225 m	65.9°	101 m	0.44	11055 m	V18340001
Dena	239.02°E	6.31°S	162 m	63.6°	80 m	0.49	9100 m	V18053001
Jeanne	241.38°E	5.57°S	165 m	65.7°	75 m	0.45	9970 m	V18315002
Wendy	240.32°E	7.84°S	125 m	61.5°	68 m	0.54	15500 m	V17716001
Chloe	239.21°E	4.29°S	252 m	83.1°	N/A	N/A	5700 m	V13448001
Abby	240.54°E	6.713°S	100 m	84.4°	N/A	N/A	11150 m	V14334002
Nikki	240.55°E	6.708°S	180 m	84.4°	N/A	N/A	11150 m	V14334002

[a]Diameter, D; depth, d. Minimum depths are not calculated for observations with very high solar incidence angles (>80°). Minimum d/D ratio is the ratio of minimum depth to the diameter of each candidate. Small impact craters on Mars typically have d/D ratios of about 0.2.

[7] VIS images showing dark, circular features in the midst of pit-crater chains gave our first indication of potential skylight openings. These candidates are obviously distinct from typical pit craters because of their lack of sloped walls or visible floors, and they also lack the visible characteristics (such as raised rims or ejecta patterns) that would associate them with impact craters. Additionally, thermal behaviors confirm these are not misidentified surface features such as dark sand or rock (analysis section). Illuminated upper-rims can be seen in several THEMIS VIS images, and off-nadir observations from other orbiting instruments (possibly HiRISE) will image these candidates from the side, (and at much higher spatial resolution) showing us the interior wall structure, and possibly providing ceiling thicknesses if such ceilings exist. Observations at earlier times of day will allow us either to see the floors or to constrain minimum depths to deeper values than we have at present (analysis section). Observations of illuminated floors will provide us with definite depth values, but will not necessarily determine cave-like characteristics.

3. Analysis

[8] For a convenient aid in identification and visualization, we informally identify these 'seven sisters' on Arsia Mons as: Dena, Chloë, Wendy, Annie, Abby, Nikki and Jeanne (Figures 1 and 2, Table 1). Diameters of these candidates are estimated by taking an average of several measurements using the ~18 m/pixel resolution of THEMIS VIS, and range between 100–252 meters. Only minimum values of each candidate's depth can be estimated because the floors are completely in shadow during THEMIS observations. These minimum depths (d_{min}) are easily constrained using observed diameters (D) and their respective solar incidence angles (i) where $d_{min} = D/\tan(i)$. Our 'useful' incidence angles ranged between 61.5°–69.9° and returned respective d_{min} values between 68–101 m (Table 1), though actual depths could be considerably greater. We also model topographic profiles across each candidate using a 1-dimensional photoclinometry (shape from shading) routine described in the auxiliary material.

[9] The Mars Orbiter Camera (MOC) observed 'Dena' with a partially illuminated floor earlier in the afternoon with an incidence angle of 40.15° (~1430 hrs, Figure 3b). This valuable observation allows us to tightly constrain the floor's depth at the edge of the shadow to ~130 m while the THEMIS minimum depth is only ~80 m.

[10] THEMIS IR shows that diurnal temperature variations are much smaller in the candidate skylights than on any of their surrounding surfaces. In Figure 4, notice how 'Annie' is warmer in the afternoon than the shadows of adjacent collapse pits, while cooler than the sunlit portions. Nighttime temperatures, meanwhile, are warmer than all nearby surfaces. This behavior is consistent in all seven candidates, and would be expected of cave interiors that

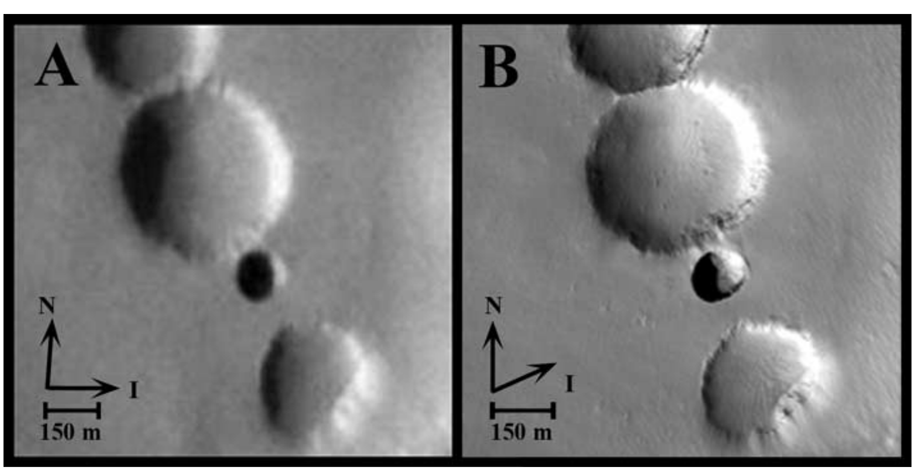

Figure 3. (a) A THEMIS observation of Dena at 18-m resolution with an incidence angle of 63.6° and a minimum depth of ~80 m. (b) A MOC observation (R0800159) at 6-m resolution with a partially illuminated floor (40.15° incidence angle). The depth at the edge of the shadow is ~130 m.

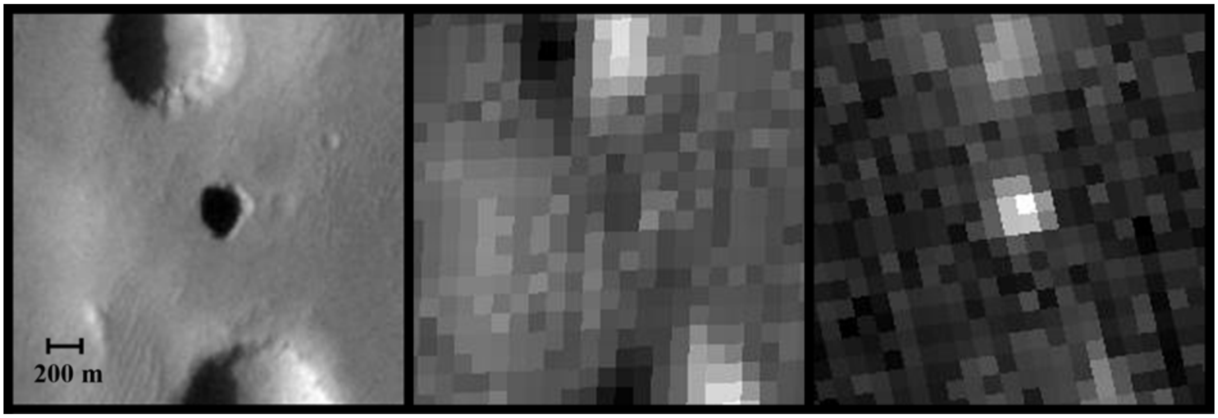

Figure 4. THEMIS VIS and IR images show diurnal thermal behavior of the candidate 'Annie'. (left) The visible image, (middle) an afternoon IR image observed concurrently with the VIS (~1500 hrs), and (right) an early-morning observation at 0400 hrs. This example shows the thermal behavior typical of all seven candidates.

receive little or no daily solar insolation [*Howarth*, 1980; *Pflitsch and Piasecki*, 2003].

[11] The candidates Wendy, Dena, Annie and Jeanne have both VIS and diurnal IR coverage, and are large enough to give distinct IR signatures at 100-m resolution. Chloë, Abby and Nikki have the same visible and thermal characteristics as the others, and are also strong candidates, but their minimum depths could not be constrained to useful values because they were observed late in the afternoon when sunlight comes from the side and doesn't shine deeply into them (observed incidence angles >83°).

4. Formation Mechanisms

[12] Most of the candidates are either adjacent to pit craters, or are directly in-line with pit-crater chains, suggesting similar formation processes, though pit craters consistently show distinct walls that slope inward at the angle of repose (~30°). Recent investigations and some terrestrial analogues suggest these pits are likely caused by the drainage of loosely consolidated surface materials into deep extensional fractures or faults that could reach down to 5 km into the crust [*Ferrill et al.*, 2003; *Wyrick et al.*, 2004].

[13] Some terrestrial pit craters found in Hawaii are visibly similar to our candidates [*Okubo and Martel*, 1998]. These form in young basalt with walls that collapse inward over short geologic timescales. If these Hawaiian pit craters are truly analogous to the candidates discussed here, then seismic activity could possibly be an ongoing process on Arsia Mons at the present time. It's also possible that these candidates are much older and fairly stable, and might be a halted intermediate stage in pit-crater formation. In either case, some of these Hawaiian pits such as 'Devil's Throat' [*Okubo and Martel*, 1998] may still be excellent terrestrial analogues (the Hawaiian pits do not open into cavernous spaces, but have been observed to crosscut lava tubes). Some suggested causes for Martian pit-crater chains include dike intrusion [e.g., *Wilson and Head*, 2002; *Scott et al.*, 2002], and collapsed magma chambers [*Mege et al.*, 2000]. See *Wyrick et al.* [2004] for a more detailed explanation of possible pit-crater formation mechanisms. Regardless of the mechanism, there is general consensus that subsurface void spaces with sufficient volume are necessary to accommodate the immense volume of collapsed materials, which may be up to tens of km^3 for a single pit [*Wyrick et al.*, 2004].

[14] Because Annie and Dena lie directly along the centerline of pit-crater chains (and Abby, Nikki and Wendy are immediately adjacent to similar chains), we propose these candidates may have formed through a similar process of collapse that has either halted or is still in progress. Local topography indicates a possibility that these candidates have intact ceilings above laterally extending cavernous spaces, or may extend deeply into subsurface voids that have not been completely filled by the collapsed materials. Chloë and Jeanne are unique from the other candidates because they have no nearby collapse features to indicate a local presence of subsurface void spaces. This could indicate a different formation mechanism, but otherwise, their sizes, appearances and thermal behaviors are identical to the other candidates. These two skylights may still open into subsurface voids although local topography does not indicate such spaces. Many cave skylights on Earth expose subsurface voids such as lava tubes or sink-holes that are not otherwise discernible by local terrain features [*Calvari and Pinkerton*, 1999; *Miyamoto et al.*, 2005].

5. Conclusion

[15] Appearances and thermal behaviors of all seven candidates are consistent with those we should expect from skylight openings into subsurface cavernous spaces, and the terrain surrounding most of the candidates indicates a likely presence of subsurface voids. There is much more to be learned about these features and future observations will look into these candidates at different angles, different wavelengths, higher resolutions and at different times of day which may show internal structures and possibly provide more clues about how they formed and why they exist.

[16] As exploration targets, these candidates are too small and too high in elevation (>5.7 km) to reach with our current landing technologies. Astrobiological possibilities may also be poor at these locations because if microbial life ever did flourish on Mars, it may not have migrated to these elevations. Furthermore, if these candidates happen to be

cylindrical shafts without protective overhanging ceilings, then microbial life would probably not survive due to direct exposure to sunlight during those seasons and times of day when the sun is directly overhead.

[17] Evidence of past fluvial activity has been documented in the Tharsis Montes region [*Mouginis-Mark and Christensen*, 2005; *Basilevsky et al.*, 2006], and water-ice clouds are observed nearly every day of the year around Arsia Mons [*Benson et al.*, 2003]. Accordingly, further research and modeling could give valuable insights about whether these clouds affect conditions at the surface (or in the candidate skylights). Additionally, possible evidence of liquid water reaching the surface was recently identified in Centauri Montes by *Malin et al.* [2006]. If this is true, then caves found at lower elevations (probably below 0 km) could hold some of this moisture, providing a potential resource for future explorers and improving the possibility of finding past or present microbial life.

[18] The discovery of potential skylight openings into Martian caves is an exciting step towards exploration and discovery. Future observations will provide more detailed information and inspire deeper insights about the characteristics and history of these features. A detailed search covering other volcanic regions across Mars is currently underway for similar targets—especially for those at lower elevations which are easier to reach and have a greater potential for holding some form of water and/or life. This discovery challenges us with fresh insights and new possibilities for the future of Mars exploration.

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