THEMIS VIS and IR observations of a high-altitude Martian dust devil

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[1] The Mars Odyssey Thermal Emission Imaging System (THEMIS) imaged a Martian dust devil in both visible and thermal-infrared wavelengths on January 30, 2004. We believe this is the first documented infrared observation of an extraterrestrial dust devil, and the highest to be directly observed at more than 16 kilometers above the equatorial geoid of Mars. This dust devil measured over 700 meters in height and 375 meters across, and the strongest infrared signature was given by atmospheric dust absorption in the 9-micron range (THEMIS IR band 5). In addition to having formed in the extremely low-pressure environment of about 1 millibar, this dust devil is of particular interest because it was observed at 16:06 local time. This is an unusually late time of day to find dust devils on Mars, during a period when rapid surface cooling typically reduces the boundary-layer turbulence necessary to form these convective vortices. Understanding the mechanisms for dust-devil formation under such extreme circumstances will help to constrain theories of atmospheric dynamics, and of dust lifting and transport mechanisms on Mars. **Citation:** Cushing, G. E., T. N. Titus, and P. R. Christensen (2005), THEMIS VIS and IR observations of a high-altitude Martian dust devil, *Geophys. Res. Lett.*, *32*, L23202, doi:10.1029/2005GL024478.

1. Introduction

[2] The first thermal observation of an extraterrestrial dust devil is also the highest observed in the solar system at >16 km above the mean equatorial datum of Mars where atmospheric pressure is about 1 millibar. The Mars Odyssey Thermal Emission Imaging System (THEMIS) observed this dust devil near the center of Arsia Mons' caldera floor, with a visible plume reaching more than 700 meters above the caldera floor, and a diameter spanning about 375 m. This is enormous when compared with dust devils on the Earth, but unremarkable in size by Martian standards [e.g., *Cantor and Edgett*, 2002].

2. Background

[3] Convective plumes form in the heat of the midday sun when air directly above the ground becomes warm and begins to rise. As a packet of warm air ascends through the atmosphere, cooler air converges beneath it from all sides, and a spinning vortex forms as each incoming particle tries to conserve angular momentum. A low-pressure core often forms at the center of a developing vortex, causing a difference in pressure between the top and bottom of the surface particle layer. This pressure differential creates a suction effect which easily entrains dust-sized particles as small as 1 μm on Mars [*Fisher et al.*, 2005; *Ferri et al.*, 2003; *Greeley et al.*, 2003] which are typically lifted only by high winds combined with saltating sand-sized particles [*Greeley et al.*, 1992]. A visible dust devil forms if the vortex gains sufficient strength to entrain these particles from the surface.

[4] Tracks left by the passage of dust devils are found on nearly every region across the Martian surface [*Cantor and Edgett*, 2002], and nearly every orbiter and lander sent from Earth has directly observed active plumes, including: Viking Landers 1 & 2 (passage of vortex cores inferred by meteorological data) [*Ringrose et al.*, 2003], Viking Orbiters 1 & 2 [*Thomas and Gierasch*, 1985], Mars Pathfinder Lander [*Schofield et al.*, 1997; *Metzger et al.*, 1999] and Mars Global Surveyor (MGS) [*Edgett and Malin*, 2000]. Measured diameters were between 28–509 m, with heights of 170–8500 m. An extensive survey using 2 p.m. Mars Orbiter Camera (MOC) wide and narrow-angle images was conducted by *Fisher et al.* [2005], who determined that Martian dust devils exhibit some regional and seasonal dependence with a bias toward northern latitudes during the warmest seasons. To constrain estimates of time variability, this same survey examined 17 THEMIS images of the most active region (Amazonis Planitia) obtained between 15:55 and 17:25 local time, and found no clearly defined active dust devils. The apparent lack of activity during this time is probably because rapid surface cooling during late afternoon reduces the boundary-layer turbulence necessary to form such vortices [*Fisher et al.*, 2005].

3. Arsia Mons

[5] Dust devils appear to be common on Arsia Mons' caldera floor during late summer (shown by *Fisher et al.* [2005] to be an active dust-devil season everywhere they occur on Mars). Numerous tracks are observed by THEMIS between L_s 342° and 357°, but are absent from identical locations observed at other times of the year. Additionally, MOC narrow-angle observations show increasingly frequent tracks on the caldera floor in images acquired between L_s 238° and 339°, but they are absent during other seasons. Figure 1b shows many of these tracks and an active dust devil (not the same dust devil that prompted this analysis) in a section of THEMIS VIS image V01453002

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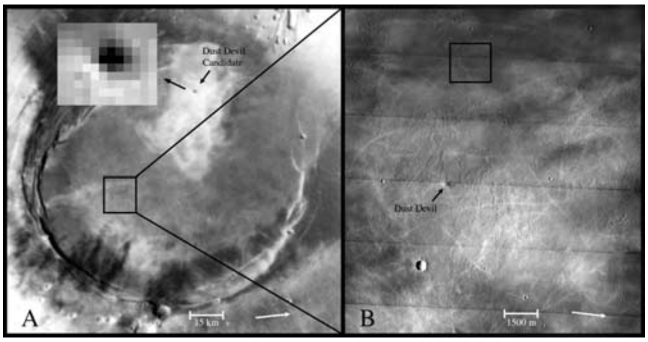

Figure 1. Arrows indicate direction of illumination. A: Extracted from MOC wide-angle image R130-4630 (L_s 342°, 13:30, ~509 meters/pixel). This context image of Arsia Mons' caldera region shows the location of [1-B]. The shadow of a possible (though unlikely) active dust devil is in the upper part of the image with an enlargement shown at its observed resolution. B: Extracted from THEMIS VIS image V01453002 (L_s 357°, 15:25, ~18 m/pix). Box shows location of the THEMIS VIS/IR dust-devil observation used in this analysis (shown in Figure 2). This image shows an additional active dust devil and numerous dust-devil tracks (most Martian dust-devil tracks are darker than the surrounding surface, and it's not well understood why some of them are brighter as they are here).

(L_s 357°, 15:15). Figure 1a is a wide-angle MOC image (R13-04630, 13:43, L_s 342°) of the entire caldera floor shown to provide regional context at 509 meters/pixel. The bright (transient) albedo feature in the northern portion of this image shows what is possibly the shadow of a very broad dust devil. However, its large size indicates that this is probably a dust cloud rather than an actual vortex. Unfortunately, the event causing this shadow is mostly indistinguishable from the bright background.

[6] The seasonality of Arsia Mons' dust-devil tracks suggests that some other dust-transporting agent effectively covers the tracks each year. Mesoscale cyclonic dust storms have been observed, and successfully modeled by *Rafkin et al.* [2002] to form above Arsia Mons' caldera each year on or around L_s 180°, which could be an important mechanism for covering the tracks each year.

4. Data

[7] The dust devil that prompted this investigation was observed by THEMIS in both visible and infrared wavelengths at 16:06 local Mars time on January 30, 2004, which was late summer on the southern hemisphere (L_s 342°). Located at 239.18° E, 9.38° S, the dust devil and its shadow in Figure 2a were observed by the THEMIS VIS camera in the red band (0.65 μm) at a resolution of 18 meters/pixel, and simultaneous infrared data were collected in 10 bands by the THEMIS IR camera (6.78–15.32 μm at 100 m/pix). While the dust devil is clearly defined in the VIS image, infrared data are approaching limitations of the instrument's detection ability, and are somewhat noisy, with the strongest signature showing as absorption at 9.35 μm (IR band 5) by the plume's enhanced atmospheric dust (Figure 2d). We examined additional THEMIS VIS coverage of the same area at different times (Figure 2b) to dismiss the possibility that this could be a misinterpreted surface feature. Figure 2c shows the image from Figure 2b overlain with a colorized version of Figure 2a to show relative brightness differences between the dust devil, its shadow and the ground.

[8] Surface pressure is calculated from the altitudes given by the MGS-Mars Orbiter Laser Altimeter (MOLA) 1/4° × 1/4° topographic map. Assuming a 10 km scale height, pressures are adjusted for the seasonal CO_2 sublimation cycle and normalized to the pressure curves observed by the Viking and Pathfinder landers [*Conrath et al.*, 2000]. Using this technique, surface pressures at the Arsia Mons caldera are found to vary annually between 0.85 mb and 1.22 mb. The estimated surface pressure at the time of observation is 1.08 (±.02) mb.

[9] The time-of-day and low-pressure environment of this observation are both noteworthy. While THEMIS daytime observations (generally limited to times between 15:30–17:30) observed no active dust devils in the most productive region studied by *Fisher et al.* [2005], at least 3 were

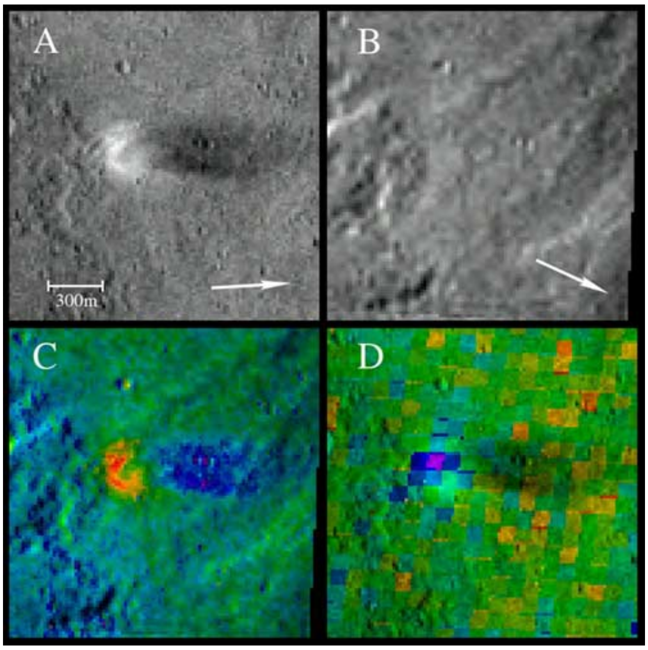

Figure 2. A: THEMIS VIS image V09442001 projected to 18 meters/pixel (approximate observed resolution) showing the dust devil and its shadow (solar incidence angle = 60.8°). The dust column is approximately 714 m tall and 376 m in diameter. Arrows indicate direction of illumination. B: The same area as [A], shown by THEMIS VIS image V12824002 (observed resolution is approximately 36 m/pix). This image and others of the same region were examined to verify the dust devil was not an anomalous surface feature. C: Image [B] overlaid with a colorized version of image [A] to show relative brightness differences between the dust devil, its shadow and the ground. D: Image [A] overlaid with a map of 9.35-micron apparent emissivity derived from THEMIS IR image I09441024 (observed simultaneously with image [A] at approximately 100 m/pix). Coolest colors (dark blue, purple) indicate regions where 9.35-μm thermal radiation is absorbed by enhanced atmospheric dust. The region of maximum absorption clearly corresponds to the center of the dust devil.

recorded by this instrument on the caldera floor of Arsia Mons. Observations of multiple late-afternoon dust devils in this extremely low-pressure environment suggest conditions that allow dust devils to either form or persist unusually late into the day. This may be related to extreme climactic and thermophysical properties on the caldera floor, a thermally exotic place on Mars that sits at nearly 2 atmospheric scale heights, and is mantled by a layer of fine dust with low thermal inertia which gives rise to particularly high thermal gradients [*Cushing and Titus*, 2005]. TES observations of the caldera floor show temperatures that vary diurnally by a factor of nearly 2 each day of the year; CO_2 frost forms on the floor every night, and 2 p.m. summer temperatures often exceed 290 K (for comparison, 274 K is the maximum TES-observed temperature for Amazonis Planitia). It should be noted that no previous dust-devil investigation has concentrated on Arsia Mons or any other region of extremely high elevation.

5. Discussion and Conclusion

[10] Dust devils on Mars are crucial mechanisms responsible for continuously injecting dust into the atmosphere [*Fisher et al.*, 2005; *Ferri et al.*, 2003], which is then heated to drive all scales of atmospheric motion [*Zurek et al.*, 1992]. Additionally, the surface evolution of Mars is currently dominated by the atmospheric dust cycle, which governs the rate of exhumation, transportation, and deposition of dust on the surface [*Christensen and Moore*, 1992; *Thomas and Gierasch*, 1985]. Regional and global dust storms were originally assumed to dominate this cycle, but *Pollack et al.* [1979] showed that dust settles from the atmosphere too rapidly after such events to account for the continuous opacity caused by suspended particles. Dust devils have been shown to help maintain this perennial atmospheric haze [*Fisher et al.*, 2005], and are important mechanisms for redistributing substantial amounts of the Martian surface over short geological time periods [*Ringrose et al.*, 2003].

[11] Dust devils on Arsia Mons appear to occur later in the afternoon than is typical for previously examined regions, which could be a result of extremely low atmospheric pressures and/or low thermal inertia at the surface. Cursory surveys of other high-elevation regions (Olympus Mons, Ascraeus Mons, Pavonis Mons and Elysium Mons) showed either very few dust-devil tracks or none at all, which suggests Arsia Mons as the only fertile ground for conducting high-elevation dust devil surveys. Future observations of active dust devils at various times and elevations will help to constrain theories of Martian dust-lifting mechanisms. Furthermore, additional modeling of Arsia Mons (including the walls and flanks) will provide insights about possible contributions from mesoscale topography to local boundary-layer instabilities, and will provide a greater understanding of local Mars atmospheric dynamics.

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