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**Characteristics of large Martian dust devils using Mars Odyssey Thermal
Emission Imaging System Visual and Infrared images.**

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Abstract

A search for martian dust devils has been carried out, using Mars Odyssey Thermal Emission Imaging System (THEMIS) visible-wavelength images. Simultaneous THEMIS thermal infrared wavelength images were then processed and analyzed, to investigate the thermal properties of the dust devils observed. 3079 images were checked, concentrating on northern spring, summer and autumn (L_S from 0° to 270° , 20°S to 50°N). Mars Express High Resolution Stereo Camera, Mars Global Surveyor Mars Orbiter Camera and other THEMIS visible images were used for comparison to potentially rule out any ambiguous geological features. Eight clear examples of dust devils have been found in five separate images, with a comparable number of unconfirmed possible devils. The rarity of dust devils observed is believed to result from a combination of the difficulty in identifying dust devils in medium resolution THEMIS data, and that the Mars Odyssey orbit flyover local time is later in the afternoon than would be optimum for dust devil searching. The temporal distribution of dust devil activity appears to be weighted more towards later afternoon, compared to Earth, but this may be a sampling effect due to size variation with time of sol, greater coverage later in the sol, or the small-number statistics. The thermal infrared images indicate that the lofted dust in the column is cooler than the surrounding surface, and must be equilibrating with the atmosphere in the dust devil. This energy transfer is estimated to be about 10% of the heat flux energy that is available to drive the systems. The ground shadowed by the dust column also appears colder than the surroundings, due to reduced solar illumination. From the visible-wavelength images, the shadows of the dust columns were used to estimate the column opacity, which in turn gave estimates of the dust loadings, which ranged from 1.9×10^{-5} to $1.5 \times 10^{-4} \text{ kg m}^{-3}$,

similar to lander-based observations. No thermal or visible trails are associated with the dust devils, indicating that the surface equilibrates quickly after the devil has passed, and that track counting as a dust devil survey technique must underestimate dust devil populations and consequently dust loading calculations, confirming previous work.

1. Introduction

Early studies of arid environments have noted the presence of convective vortices and dust devils [Baddeley, 1860; Flower, 1936], and their formation and occurrence has been studied for many years [Balme and Greeley, 2006; Fitzjarrald, 1972; Kaimal and Businger, 1970; Ryan and Carroll, 1970; Sinclair, 1966; Snow, 1987]. Convective vortices are symptomatic of atmospheric instability, requiring strong insolation to form [Ryan and Carroll, 1970; Ryan, 1972]. They have a low pressure, hot core, and a tangential wind gradient, and if powerful enough they are capable of entraining surface material and becoming dust devils. Terrestrial dust devil investigations have taken on a new interest relatively recently, primarily due to the observations of dust devils on Mars.

Dust devils appear to be a ubiquitous process on Mars, having been visually observed by the Viking Orbiters [Thomas and Gierasch, 1985], Mars Global Surveyor [Cantor *et al.*, 2001; Malin and Edgett, 2001], Mars Odyssey [Cushing *et al.*, 2005], Mars Express [Stanzel *et al.*, 2006; Stanzel *et al.*, 2008], and the landers Mars Pathfinder [Metzger *et al.*, 1999] and the Mars Exploration Rovers [Greeley *et al.*, 2004]. Currently, the surface boundary layer wind speeds on Mars are considered borderline to be sufficient to initially loft fine dust particles into the atmosphere [Greeley and Iversen, 1985], therefore particle lofting by impact saltation, including dust devil action, has been posited as one of the main mechanisms for moving and redistributing dust on Mars.

Consequently, they may be potentially hazardous to both robotic and manned missions to Mars. Terrestrial studies also indicate their potential to degrade the air quality, and occasionally damage light aircraft [*Hess and Spillane*, 1990].

Dust devils on Mars are believed to form and to be influenced by identical factors to those on Earth [*Renno et al.*, 1998], and detailed study of this hypothesis will enable terrestrial analogues and modeling to be successfully applied to Mars. Several diagnostic features such as size and temporal frequency statistics, and the detailed structure of the dust devil (the nature of temperature, wind and pressure changes within it) have been considered theoretically [*Renno et al.*, 1998] and directly compared between Mars and Earth (see [*Balme and Greeley*, 2006; *Cantor et al.*, 2006] and references therein for a review). A dust devil is special case of a convective vortex, and one meteorological diagnostic of a convective vortex is the presence of a hot core [*Fitzjarrald*, 1973; *Ives*, 1947; *Kaimal and Businger*, 1970; *Ringrose et al.*, 2003; *Sinclair*, 1964; 1973; *Tratt et al.*, 2003]. Data from the Mars Odyssey Thermal Emission Imaging System (THEMIS) offers the opportunity to provide insight into this structure from orbit, as this instrument observes simultaneously in visible wavelengths and in the thermal infrared. This provides the potential to extract the dust devil's core temperature, provided the core is large enough to be clearly resolved (i.e. greater than 100 m across). To investigate this, a targeted survey for dust devils on Mars was performed, intended to capture well-observed exceptionally large dust devils.

The statistics generated while searching for dust devils using THEMIS also help to address the issue of dust devil activity as a function of time of day; THEMIS is well

86 suited to this type of activity, as the instrument has moderate resolution and large
87 coverage. The THEMIS instrument is summarized in [*Christensen et al.*, 2004]).

88 On Earth, dust devils usually form in dry areas, such as deserts, on sunny days in
89 spring or summer [*Cooley*, 1971]. Surface heating is needed, but the atmospheric thermal
90 gradient (driven by the ground-air temperature difference) is more important than
91 absolute high temperatures, as dust devils have been recorded in sub-arctic climate where
92 the air temperature was about 18°C [*Grant*, 1949]. Most terrestrial dust devils are less
93 than 150 m tall and last only a few minutes, with exceptional observations of dust devils
94 up to a few thousand meters in height lasting up to an hour [*Ives*, 1947].

95 On Mars, similar formation criteria are expected, but due to the different
96 atmospheric environment (e.g. a larger boundary layer, and smaller Grashof number,
97 [*Fuerstenau*, 2006]), they tend to be larger. It is possible that the generally lower thermal
98 inertia of the martian surface means that it responds faster than the Earth to insolation
99 changes, which in turn implies that dust devils may begin to form earlier than on Earth,
100 and peak during midday to early afternoon. This appears to be supported by the limited
101 number of lander observations; *Ringrose et al.* [2003] discussed convective vortices at the
102 Viking Lander 2 site as early as 10 am, with a relatively flat temporal distribution, while
103 Mars Pathfinder data [*Murphy and Nelli*, 2002] shows a peak vortex rate at midday.
104 However, these meteorological instruments are measuring convective vortices, and
105 inferring the presence of true dust devils, so caution must be taken in comparing them to
106 visual observations of dust devils. On the Earth, the temporal distribution of dust devils
107 shows a distinct skew towards the afternoon [*Sinclair*, 1969]. THEMIS data can also help
108 to determine this temporal distribution on Mars, as it has a different local time of day

flyover to earlier orbital surveys [Cantor *et al.*, 2006; Fisher *et al.*, 2005]. A clear observation of a dust devil in THEMIS will simultaneously quantify dust devil dimensions, dust loading, and temperatures allowing comparison with terrestrial work.

2. Previous martian studies

On Earth, the larger dust devils are approximately 50-100 m in diameter and over a kilometer high [Balme and Greeley, 2006; Bell, 1967]. These are small compared to Mars, where dust devils have been observed that are over 1 km across and up to 10 km high [Fisher *et al.*, 2005; Thomas and Gierasch, 1985]. Tracks left by the passage of dust devils leave behind appear to be ubiquitous across Mars, and active vortices have been recorded in data from almost all Mars missions, including landers equipped with meteorology instrumentation or suitable imaging sensors. The two Viking Landers detected vortices in the late 1970s by their meteorological signal [Ryan and Lucich, 1983]. Ryan and Lucich's analysis has shown that the Viking Landers appeared to encounter about 0.6 dust devils per sol, as compared to the 2 dust devils per sol found in the Pathfinder data [Murphy and Nelli, 2002; Ringrose *et al.*, 2003].

In 1999, the Mars Pathfinder lander took images in which five different dust devils were ultimately identified [Metzger *et al.*, 1999], although Ferri *et al.* [2003] has expanded upon this number. More recent orbital images acquired by the Mars Global Surveyor Mars Orbiter Camera (MOC) detected many dust devils, allowing detailed viewing and statistics to be generated [Cantor *et al.*, 2006; Fisher *et al.*, 2005]. Estimates of dust devil movement traverse velocity have been made by Mars Express High Resolution Stereo Camera (HRSC) [Stanzel *et al.*, 2006], giving speeds on the order of 20 ms⁻¹. Mars Reconnaissance Orbiter has imaged dust devils at pixel resolutions of

about 6 m, (using the High Resolution Imaging Science Experiment, HiRISE), and at 20 m, (using the Context Camera, CTX), as noted on the mission web page but not as yet formally published. Dust devils appear to be very common on Mars: Thomas and Gierasch [1985] identified almost 100 dust devils in Acidalia Planitia in the Viking Orbiter images, although resolution limitations may have obscured the smaller dust devils. Additionally they appear to often leave tracks behind them on the martian surface [Edgett and Malin, 2000], at nearly all latitudes [Balme *et al.*, 2003b; Cantor and Edgett, 2002; Whelley and Greeley, 2006].

Of most interest to this study is the recent publication by [Cushing *et al.*, 2005], which reports the first detection of a dust devil in both THEMIS visible and infrared (and the only detection by THEMIS published to date). This particular dust devil had a diameter of approximately 375 m, but is only weakly visible in the infrared data. Intriguingly, it was detected at an altitude of more than 16 km above the Mars datum, where the atmospheric pressure is very low (about 1 mbar), and also occurred relatively late during the day (a local time of 16:06).

3. Approach

3.1 The THEMIS Instrument

The THEMIS Instrument is comprised of two parallel systems; a thermal infrared (IR) emission imager and a visible-wavelength imager [Christensen *et al.*, 2004]. Visible-wavelength images have resolutions of 18, 36 or 72 m/pixel, compared to the infrared at about 100 m/pixel. The two parallel multi-spectral systems operate independently, and can be used to observe the same target simultaneously. Standard radiometrically

calibrated images from the THEMIS dataset can be obtained from the public domain NASA Planetary Data System (PDS) online archive.

The visible-wavelength imager can observe in five bands, but typically only band 3 is used (centered at 654 nm). The infrared imager can observe ten bands, between 6.78 μm and 14.88 μm , with each differing in its ability to highlight different surface (or atmospheric) features [Christensen *et al.*, 2004]. IR bands 3 (7.93 μm) and 5 (9.35 μm) are believed to have the best contrast for detection of surface dust movement and transient features, based on spectral modeling work and previous observations of suspended dust [Cushing *et al.*, 2005; Smith *et al.*, 2003]. As noted by [Brumby *et al.*, 2003], band 3 is mostly insensitive to water and the atmosphere, and can be used for a good visualization of the ground surface, while the appearance of dust is enhanced in IR band 5 (due to the atmospheric dust strongly absorbing photons at 9.35 μm). Using Stephan's law (assuming a fixed surface emissivity and a transparent atmosphere) and the infrared data, a brightness temperature image of the surface (in Kelvin) can be constructed; this is provided as a derived data product on the NASA PDS for each infrared image.

3.2 Image selection and treatment

Considering the resolution of THEMIS IR observations, it is clear that directly detecting medium size (a few 100 m) dust devils would not be easy. Hence we decided to look initially in the higher resolution visible-wavelength imagery, and then compare to the infrared, whilst using other observations from THEMIS and other missions to rule out permanent or ambiguous geological features. This technique is supported by the results of [Cushing *et al.*, 2005] where the dust devil seen has a diameter of 375 m, and is clearly

resolved in the visible-wavelength data, but shows only a minor deviation from surface emissivity in the infrared image.

We decided that a semi-targeted search of particular regions was likely to be the most successful approach. The criteria for targeting consideration were based on two questions; ‘will there be dust devils there, and will they be observable in the visible and the infrared data?’ As such, ‘borderline’ dust devil producing areas, which might lack the required atmospheric instability and only produce a few dust devils (and hence very few exceptionally large dust devils) were not included [Ryan and Carroll, 1970]. The search therefore focused on areas previously noted as major dust devil producing areas with large dust devils observed, for example the Amazonis region [Cantor *et al.*, 2002; Cantor *et al.*, 2006; Fisher *et al.*, 2005]. The study region should also be close to the equator, as this is where conditions are most suitable for dust devil formation [Biener *et al.*, 2002]. However it is also important to consider a large enough percentage of the martian surface in order to give a reasonable chance of success and to produce statistically meaningful results.

With this in mind, a latitude range of 20°S to 50°N was selected, over the full longitude range, which favors warm areas and maximum levels of light per sol. (Although dust devil tracks are generally seen to be maximum in the 40-60 latitude bands [Balme *et al.*, 2003a; Whelley and Greeley, 2006], they are seen at all lower latitudes.) Dust devil activity is highest in the spring and summer, so images acquired between solar longitude (L_s) 0° to 270° (northern spring, summer and autumn) were used. Obviously dust devils will not occur at night, and the largest are expected to occur during the

brightest daylight hours, so only images acquired between local times of 11:00 to 16:30 were considered.

These constraints were applied to a search of the NASA PDS, and images were retrieved from the PDS and analyzed systematically at increasing magnification, investigating and recording features of interest at greater detail as required. Potential candidates were identified initially based on the criteria of just the presence of a dust cloud like object. These candidates were then compared with images of the same regions taken by HRSC, MOC, Mars Reconnaissance CTX, or other THEMIS data to confirm the presence of a dust devil (dust devils are transient features, and should not appear in other images of the same location acquired at different times). In a small number of cases, there were no comparable images. Those candidates were discarded from the list of confirmed dust devils, but are considered separately later. Rejection was based on a judgment that these particular anomalies were ambiguous – the features lacked a clear shadow, or a clear track/trail, and lacked structure indicating a dust column; if they were dust related, rather than geomorphological, then they were most likely dust flurries or fronts, lacking convective vorticity.

The visible representations of confirmed dust devils were then analyzed in detail; where possible the height of the dust devil was calculated using the shadow projection and the Solar Incidence angle (from the PDS label). Diameter was directly measured from the image.

Simultaneous observations through the THEMIS infrared system provide a derived brightness temperature record (BTR) of the same locale. These data give local

temperatures of the ground and dust devil, providing additional information on dust devil structure.

4. Results and discussion

4.1 Survey results

The PDS search generated 3079 images within the region of interest, from 2002-04-18 to 2006-03-03, from THEMIS datasets release_id 0001 to 0017 (the latest release at the time of beginning this work). In reality, observations taken earlier than 16:00 local time are only from the orbit phasing part of the mission, early in the spacecraft lifetime, and there are none after 2002-07-20. Observations with a local time from 16:00 to 16:30 are available throughout the mission. Initial analysis revealed 294 candidate images that warranted further investigation. Comparison of coexistent images from a variety of sources as discussed allowed removal of false positives by eliminating features that have not moved between images. Overall, only eight dust devils were reliably detected from five image frames (there are two frames which each have multiple dust devils). The locations of these are shown in Figure 1, and summarized in Table 1. Figure 2 gives detailed images of the dust devils detected, showing both the visible data, and the IR thermal results (discussed later). Due to the conservative approach taken to eliminating false positives, the numbers of dust devils confirmed here probably represents a lower bound, highlighting the clearest, most apparent events, with ambiguous or smaller events excluded. Events that were eventually unconfirmed as dust devils, primarily to a lack of supporting overlapping images are shown in Table 2, and examples of these are shown in Figure 3. These are discussed in more detail later.

243

244 <fig 1 here>

245 <table 1 here>

246 <fig 2 here>

247 <table 2 here>

248 <fig 3 here>

249 <table 3 here>

250

251 Only a few active dust devils were detected by THEMIS in this work, suggesting
252 that these detections are of relatively rare exceptional events, requiring a fortuitous
253 combination of size and time of day. No trend is seen with altitude above the Mars
254 datum. In Figure 2, dust devils 5, 6 and 7, appear more ambiguous, and it is possible they
255 are in fact dust fronts or flurries, due to the apparent lack of structure. Dust devils 5 and 6
256 have no clear shadow, so no estimate of height could be made. This ambiguity is
257 somewhat supported by dust devil 7, as close examination of the shadow cast, which
258 although distinct, appears to indicate a lower height than might be expected. It may be
259 that the dust loading is lower later in the day, possibly due to the effect of the time of day
260 itself (a less intense dust devil due to lower illumination), or of course it may just be that
261 these areas happen to have less available dust on the ground to loft. Table 3 summarizes
262 the survey statistics obtained from this search. From this and the PDS image local time
263 statistics, there is a clear observational bias due to the mean flyover time of Mars
264 Odyssey, of about 16:30, such that there are relatively few images to search before 15:30,

and none before 15:00, when dust devil activity is observed to be higher [*Cantor et al.*, 2006; *Christensen et al.*, 2004].

Statistically, it would seem that very few dust devils have been found. As noted by *Fisher et al.*, [2005], very few dust devils occur in the late afternoon on Mars, in contrast to the Earth. The survey of *Cantor et al.*, [2006] using MOC found dust devils in 0.4% of the images studied, far greater than observed here (MOC over-flight is at about 14:00 local time). For example, peak rates seen during northern spring in the Syria-Claritas region by [*Cantor et al.*, 2006] were about 1.4×10^{-3} dust devils km^{-2} , observed between 14:00 and 15:00. [*Fisher et al.*, 2005] find very similar peak values for Amazonis Planitia, again using MGS MOC data. One possibility is that the lack of dust devils later in the day is driven by the low surface thermal inertia and the thin atmosphere both losing heat very quickly once the Sun is past zenith, resulting in less energy to drive the process. Of the 498 dust devils seen by Spirit, [*Greeley et al.*, 2006], only two are after 15:30, but there may be some sampling effect due to the observing constraints of the rover, which is permitted to produce more images during the middle of day. When studying terrestrial dust devils in the southwestern USA, *Sinclair*, [1969] had noted a tendency for larger dust devils to appear later during the day; one might expect this to be applicable to Mars, and this would be consistent with the rate distribution shown in Table 3 above. *Greeley et al.*, [2006] detect no trend of diameter with time of day.

For comparison, the biggest dust devil seen by Spirit is about 280 m [*Greeley et al.*, 2006]. The survey conducted by *Fisher et al.*, [2005] (using MGS MOC Wide Angle images) detected even larger examples, with the largest being about 8.5 km high and about 500 m in diameter.

288 This survey concentrated on detecting large well-resolved dust devils that could be
289 visible in the infrared; as such some smaller candidates (that may have been real) were
290 discarded, as they lacked clear diagnostic features (shadow, track etc). This may skew the
291 perceived detection rate. Ultimately the smallest resolvable is 4-8 pixels in the visible
292 (approximately 80-160 m), but any dust devils this small will have very little expression
293 in the lower resolution THEMIS IR image. Table 2 lists dust devil candidates that were
294 ultimately rejected or remain unconfirmed. The majority are rejected purely on the basis
295 of size and image resolution; usually there is one single observation that is just not clear
296 enough to be useful. Figure 3a gives an example of this. In a few cases, signal to noise is
297 insufficient to resolve the candidate clearly against the background structure. Figure 3b
298 shows an example of such a candidate, where there may be changes between the two
299 images, but image saturation prevents confidence that this is a dust devil. Future data
300 releases giving increased coverage may help to clarify the status of some of these
301 candidates. Due to the small numbers of dust devils confirmed, statistics derived from
302 this study are sensitive to the rate of the largest dust devils, and one must be careful in
303 over interpreting such small number statistics.

304 A further consideration is that later afternoon dust devils have been suggested to be
305 less intense and ordered, and more flurry-like [S. M. Metzger, pers. comm., 2005].
306 Laboratory investigations by *Church et al.*, [1979] and *Mullen and Maxworthy*, [1977]
307 related the compactness of the structure of tornado-like vortices formed to a ‘swirl ratio’,
308 which compares horizontal to vertical momentum. The swirl ratio will evolve throughout
309 the day, via the atmospheric stability and average wind speeds, so one would expect a
310 variation in dust devil compactness through the day. Terrestrially this is demonstrated by

311 considering in Figure 4, where two extremes are presented. One should expect the same
312 variation on Mars, as the underlying mechanism for dust devil formation on the two
313 planets are probably very similar [Renno *et al.*, 1998; Renno *et al.*, 2000].

314
315 <fig 4 here>

316
317 It should be noted that none of dust devils found here have produced visible tracks.
318 This implies that track-counting alone cannot produce accurate population statistics. This
319 has also been noted by Cantor *et al.*, [2006].

320 The dust devil observed by Cushing *et al.*, [2005] on Arsia Mons is not captured by
321 this survey: It is within the proscribed latitude range (9.38°S), and local time of day
322 (16:06), but occurred at $L_s=341$, and as such it could be considered a ‘southern’ dust
323 devil, occurring in southern summer. It would be detected if this survey was repeated
324 with a southern hemisphere orientation. This might be worthwhile, given that the data of
325 Whelley and Greeley, [2006] indicated that the southern hemisphere has more visible dust
326 devil tracks than the northern during peak seasons, per unit area. (see also [Cantor *et al.*,
327 2006]). The Cushing dust devil appears similar in appearance to the later dust devils seen
328 here, with little or no expression in the infrared temperature data. However infrared
329 absorption is weakly seen for this devil in THEMIS band 5, indicating the presence of
330 suspended dust [Smith *et al.*, 2003]. There is clearly no question that the Arsia Mons
331 feature is a dust devil, given its structure: It has a well defined shadow and height,
332 ([Cushing *et al.*, 2005], fig 2), whereas the features here suspected to be gusts do not. The
333 high altitude at this point means that the atmosphere is thin, with a low dust loading, and

hence a low dust opacity. This would have acted to increase the apparent contrast in the IR band 5 and the brightness temperature data; however no temperature excursion is seen. If this structure and temperature difference is typical for this size of dust devils, then it implies that circumstances may have to be exceptionally fortunate at lower altitude for thermal anomalies to be observed, and so in some cases dust devil core temperatures may be difficult to extract from dust devil events seen in THEMIS data.

4.2 Infrared Temperature Data results

Figure 2, right hand column shows the derived temperature anomalies associated with the dust devils. The visible-wavelength image brightness is overlain as contour lines, while the color pixels are used to represent temperature data. In all images, the temperature pixels are 100 m across.

The suspended fine dust in the devil column (about 2-3 μm diameter, [Tomasko *et al.*, 1999]) will appear clearest in IR band 5 [Smith *et al.*, 2003], because suspended particles of this size interact with the incoming sunlight with wavelengths near to 9 μm . Band 3 is less sensitive to suspended dust, and observes the ground below the dust devil. As such, a comparison of IR data from bands 3 and 5 can be used as a check for the presence of lofted dust. The temperature data are derived from band 5, and so give the temperature of the dust devil dust cloud (or the dusty surface if the atmosphere is clear).

Dust devil 2 (Figure 2b) has the clearest classic dust devil structure. The temperature data shows clear evidence of the shadow cooling the ground, and of the lofted dust being cooler than the surface. However, although the core should be about 3-4 pixels across, it is not immediately obvious as an expected ‘hot spot’, instead appearing cold. This is even more apparent in dust devil 3 (Figure 2c), where the shadowed surface

is only slightly cooler than ambient, but the relatively weak visible dust plume slightly to the SW of the main core appears strongly-cooled in the temperature data. From previous terrestrial and martian meteorological work it is known that dust devils have a hot core, due to their convective nature, but on Earth the core is generally dust free above the saltation skirt [Ryan and Lucich, 1983; Sinclair, 1969], and as such would not be observed by the dust sensitive THEMIS infrared data. These observations are consistent with the suspended dust appearing cold relative to the hot surface, possibly due to the loss of heat into the dust devil air column. In a terrestrial context, Sinclair, [1966] discusses modeling to consider the heat flow from the relatively hot dust picked up into the surrounding air within the column, which would then act to heat the air column (and cool the dust). Fuerstenau, [2006] indicated that the solar warming of the suspended dust grains is a major component of the thermodynamics of dust devils, as these warmed grains will transfer heat into the atmosphere. This warming will be strongest on the edges of the dust column (dependent on the opacity), which may then result in the inner dust being shaded somewhat, and thus relatively cooler. It would appear that if this warming is occurring then the warmed outer layers are relatively thin, and THEMIS is observing the cooler-than-ambient inner layers of dust.

From the thermal data in Figure 2, the lofted dust column is about 1 K cooler than the surface in all cases. Given that the system is roughly in a steady state, and taking plausible values for the dust loading (derived in the following section), and using the specific heat capacity of basalt for the dust (840 J/kg-K, [Roberts-Austen and Rücker, 1891]), this temperature drop results in about 100 W/m² of heat loss from the dust, as once lofted the dust immediately and isometrically re-radiates this absorbed heat. This

compares to the total energy available to drive dust devil activity of about 430 W/m² from the later afternoon Sun on Mars. Because nearly 25% of the incoming insolation energy is dissipated by this process, the presence of the dust should be taken into account when modelling dust devils [Fuerstenau, 2006; Sinclair, 1966].

In reality, orbital instruments are unlikely to ever be able to see right down the dust-free core of the dust devil, since dust devils are not precisely vertical, but tend to show a tilt in the direction of ambient wind. A ring of slightly cooler air surrounding the dusty core has been reported previously in some cases [Ives, 1947; Ringrose *et al.*, 2003] (although this is somewhat tentative [Balme and Greeley, 2006]), but the resolution here is insufficient to confirm this.

Dust devils 4 and 7 show no significant temperature anomalies, and so is possible that they may not be thermally driven, but might instead be wind gusts capable of lofting dust but lacking convective vorticity, similar to very small local fronts or storms [Briggs *et al.*, 1979]. However, such storms generally lack the column-like structure seen here, and are larger, so it is more plausible that the temperature anomalies are merely not large enough to be detected by the instrument, or that the upper-dust-column temperatures are equilibrating with surface temperatures, effectively shielding any temperature anomalies closer to the ground. The contour data clearly shows that dust devil 7 has a apparent double brightness peak, and this may be a compound dust devil, made up of two (or more) vortices circling each other; such structures are relatively common terrestrially in less well defined dust devils such as Figure 4(b) [Balme and Greeley, 2006].

There are weak hints of a hot anomaly seen on the ground in immediate sunward direction of dust devil column in dust devils 1, 2, 3, and 6 (Figure 2), which could be a

result of the dust column absorbing sunlight and scattering light onto the surrounding surface, which is adding to the direct solar illumination of this area of the surface. These apparent anomalies are very weak, and near to the resolution of the instrument, so further work is required to confirm this effect. In the case of dust devil 2 it is just plausible that this weak hot anomaly may be a false positive caused by the existing apparent temperature patterns in the surrounding surface. On Mars one would expect these anomalies to be a weak effect, given the dust devil opacity, but it might be possible to further investigate these phenomena in terrestrial dust devils using appropriate instrumentation [Lorenz, 2004].

In no case does there appear to be any apparent cold (or hot) trail on the ground upwind of the dust devil, marking the passage of the dust devil. Either the heat being removed from the ground by the dust devil is below the resolution of the instrument, or the ground is equilibrating quickly, which might be expected due to the low thermal inertia of the dusty surface layer.

4.3 Opacity and dust loading from consideration of shadowing

A significant shadow is seen alongside most observed dust devils. Hence, it is clear that the dust devils have significant opacity, and the depth of this shadow can be used to approximate the dust loading. We summarize the technique here, for a more detailed description of the method, see *Fuerstenau*, [2006]. We assume a Lambertian surface with constant albedo and geometric properties, and that the drop in illumination caused by a dust devil's shadow is not influenced by surface variations (Figure 5). By quantifying this amount of light lost, it is possible to estimate column absorption along the line of illumination. The measured dust devil diameter combined with the sun altitude above the

horizon allows opacity to be derived, which can then be related to atmospheric dust loading using previous work ([*Landis*, 1996], [*Metzger et al.*, 1999]).

<fig 5 here>

Considering the schematic of a dust devil in Figure 5 the average radiances of the dust devil and surface (R_{dd} and R_s respectively) can be extracted from image data of the dust devil shadow and adjacent areas outside the shadow. As measured by THEMIS, these are both relative radiances, but both are linearly related to absolute radiance by the same factor, which cancels out when R_{dd} and R_s are ratioed. To compensate for variations in terrain reflectivity between areas with and without shadows, a separate THEMIS image of the scene (with dust opacity and viewing geometry as similar as possible to the dust devil image) was considered. Radiance values from areas of the second image corresponding to the previously defined dust devil shadow and well illuminated terrain are used to derive r , the compensating ratio of the reflectances of the two areas. Additionally, one must account for the relative amounts of direct and diffuse illumination because at least some of the radiance emitted from the dust devil's shadow is probably due to scattered light from the sky and other features [*Fuerstenau*, 2006]. To evaluate the effect of the diffuse illumination, a nearby area of terrain shadow (only illuminated by diffuse lighting) is considered. The pixel values from this terrain shadow are then subtracted from the dust devil shadow's pixel values. For this opacity calculation, byte-scaled pixel units are used, for convenience. All measurements needed to calculate opacity are relative, and from the same image, so byte-scaling of the absolute radiances

cancels out. This canceling can be shown from Equation 1 using simple algebra: Replace all terms of R (the byte-scaled radiances) with a linear scaling such as A_1x+A_0 , where A_1 and A_0 are constants, and x is the original, non-byte-scaled, radiance (in $\text{Wcm}^{-2}\text{Sr}^{-1}\mu\text{m}^{-1}$); after simple manipulation, A_1 and A_0 completely cancel out and disappear from the equation, provided all radiances come from the same image. However, the THEMIS data files from the PDS must be the radiometrically calibrated format (RDR), rather than the raw data, to account for instrumentation effects such as non-linear sensitivity and varying zero offset. Additionally, the brightly-lit dust devil column itself could act as a secondary illumination source, acting to apparently brighten the shadow. Such an effect would be small, due to the relatively low opacity of the dust devil (and hence the low ratio of scattered to direct light), and computationally difficult to deal with, and is neglected here. It would have the effect of making the shadow appear brighter, such that the dust loading of the devil would appear lower than reality.

From Figure 5, the ratio of the radiances is then approximately

$$\frac{r(R_{dd} - R_T)}{(R_s - R_T)} = \frac{I_{src} e^{-\tau}}{I_{src}} = e^{-\tau} \quad \text{(Equation 1)}$$

Where τ is the opacity, R_T is the diffusely lit terrain, and I_{src} is the source intensity (which is unknown, but cancels out). From *Landis*, [1996], who considered martian dust opacity with reference to solar panel loading, the opacity can be related to the number density of particles in the air by

$$\tau = QAN_o \quad \text{(Equation 2)}$$

470

471 Where Q is the scattering efficiency, A is the particle average cross sectional area,
 472 and N_o is the column number density. Due to the geometry of the situation, the path
 473 length measured is the dust devil diameter with a factor of the sine of the solar
 474 illumination angle, θ (A vertical dust column is assumed), so the number density, n,
 475 becomes

476

$$n = \frac{N_o}{D \sin \theta} \quad \text{(Equation 3)}$$

477

478 Where D is the dust devil diameter, giving

479

$$n = \frac{\tau}{QA_o D \sin \theta} \quad \text{(Equation 4)}$$

480

481 Q is taken as 2.98 at 600 nm [*Ockert-Bell et al.*, 1997], which is the closest
 482 wavelength data available to THEMIS visible band 3 (654 nm), as used for these
 483 observations. The lofted dust grain size distribution in a martian dust devil is not well
 484 known. The lower dust devil is assumed to be saltation dominated [*Greeley et al.*, 2003],
 485 so a mean grain diameter is taken as 75 μm , the size of the most easily saltated dust
 486 diameter on Mars [*Greeley and Iversen*, 1985]. Dust devils are believed to loft finer dust
 487 by a low pressure ‘sucking’ effect, as well as saltation [*Balme and Hagermann*, 2006;

Greeley et al., 2003], but this is not yet well understood in detail. Qualitative modelling implies that this effect should be strongest for small well-formed dust devils on the Earth, as opposed to the targets of this work, large dust devils on Mars [*Balme and Hagermann*, 2006]. If significant, this excess dust lofting effect might result in a smaller average dust grain size, by increasing numbers of smaller particles. *Landis*, [1996] assumed particle diameters of 24 μm for his calculations, but he derived this value from the weighted mean of the suspended dust in the full atmospheric column, as relevant to solar panel obscuration. A factor of three difference in particle diameters is probably within the intrinsic variability in dust loading seen in dust devils, as can be seen from dust loading estimates from the Spirit rover ([*Greeley et al.*, 2006], discussed in following section).

<table 4 here>

Table 4 gives the physical parameters measured from the images, and the calculated dust devil loading. For comparison, the Spirit rover in Gusev crater recorded values from 3.9×10^{-9} to $4.6 \times 10^{-4} \text{ kg m}^{-3}$, with a mean of $2.07 \times 10^{-5} \text{ kg m}^{-3}$ [*Greeley et al.*, 2006], while the estimated dust devil loading from Mars Pathfinder is $7 \times 10^{-5} \text{ kg m}^{-3}$ [*Metzger et al.*, 1999]. Our calculated values (derived from spacecraft observations) are reassuringly similar to the values derived from lander observations. The dust concentration derived here is similar to the values of *Greeley et al.*, [2006], but it is not possible to estimate a dust flux, as there is no record of the vertical dust devil wind speed. However, the concentrations and sizes are similar to those observed by Spirit [*Greeley et al.*, 2006], so one might expect the flux to be comparable. The values for visible-dust opacity

measurements, from 0.06 to 0.23 across the width of the column (typically a few hundred meters), are comparable to estimates of 0.03-0.40 for the full atmospheric column [Smith *et al.*, 2000], which illustrates how much greater than the average dust loading the devil dust loads are.

Although this approach is general, in the ideal it requires that the dust loading is strong enough to make a clear dust-devil shadow and that there is a compensating image (which should ideally be a THEMIS visible-wavelength image as well). The values for r in Table 4 are all very close to 1, which highlights the fact that the dust devils are moving across smooth plains, which have a low contrast. The inclusion of r in the calculations would be more important if a dust devil was amongst terrain with a variety of albedos which may have altered, such as on top of older dust devil streaks. In cases where no THEMIS compensating image exists, Mars Express HRSC (the nadir observing channel) could be used as a substitute, as this observes at 650 nm, compared to 654 nm for THEMIS band 3. However this should be used with caution, as the flyover time of day may be different, resulting in a different surface temperature and illumination angle: r would also be altered by variations in atmospheric opacity, or any surface albedo changes such as frost.

5. Conclusions

Because THEMIS observes simultaneously in both visible and thermal-infrared wavelengths, it provides a unique dataset for studying dust devils, allowing simultaneous analyses to be performed of both physical and thermal properties. To initially detect the dust devils, a survey of THEMIS visible-wavelength images was conducted for L_s from 0° to 270° and latitude 20°S to 50°N , initially using THEMIS visible-wavelength

observations. 3079 images were searched manually, and then cross-referenced against other images of the same areas to eliminate false positives. Eight dust devils in total have been identified, in five images, ranging in diameter from 170 to 335 m.

The number of dust devils detected is approximately two orders of magnitude fewer than were detected in previous studies [*Cantor et al.*, 2006; *Fisher et al.*, 2005]. This discrepancy probably reflects the later flyover local time of Mars Odyssey (typically 16:30), coupled with the fact that the formation of dust devils may be more clustered around midday on Mars than on Earth. Previous studies used Mars Global Surveyor data, which has a local flyover time of around 14:00.

It appears likely that the late afternoon dust devils are more disordered in structure than ones detected earlier in the afternoon, perhaps because of the weaker driving insolation. It is possible (although unlikely given their structure) that the latest two dust devils (numbers 6 and 7, Figure 2) seen are saltation capable wind gusts but lacking in convective vorticity.

Using the calibrated surface radiances from the visible-wavelength imagery, and observing the loss in radiance in the shadowed surface, we estimated that the dust loading in the columns ranges from 1.94×10^{-5} to $1.53 \times 10^{-4} \text{ kgm}^{-3}$, and are comparable to the values derived from surface measurements for Mars Pathfinder and Spirit ([*Greeley et al.*, 2006; *Metzger et al.*, 1999]). The values here are derived from orbit, of the largest dust devils, and yet the loadings are very similar to those from smaller lander-observed devils. Measurements from orbit provide a more broadly applicable method for estimating dust loading in martian dust devils than the spatially limited data acquired from landing craft observations.

THEMIS also observed the dust devils at infrared wavelengths, as well as visible wavelengths, and this infrared data can be used to derive surface temperature data. The dust devils observed do not have a hot temperature anomaly, although the air temperature in convective vortex cores has been shown to be higher [Balme and Greeley, 2006]. This lack of a visible hot core is probably a shielding effect resulting from the dust column blocking sight of the core, although THEMIS band 5 is primarily sensitive to dust, and the core may be dust free. THEMIS infrared data indicates that the dust column is cooler than the surrounding ground surface, implying that the dust has equilibrated with the atmosphere after lofting. This loss of energy may be a significant part of the energy flow of a dust devil [Fuerstenau, 2006; Sinclair, 1966]. There are also indications that the dust column briefly shadows and cools a small portion of the surface.

Thermal tracks on the surface upwind of the dust devils are not detected by THEMIS, indicating that the low-thermal-inertia surface equilibrates quickly after dust devils pass (or that temperature drop is below the resolution of the instrument). Additionally the dust devils discussed here did not produce visible tracks either, suggesting that track counting statistics may not accurately represent dust devil populations, as previously noted by Cantor *et al.*, [2006].

THEMIS 18-m visible-wavelength images can resolve most dust devils, but this is not an perfectly suited instrument for broad surveying (mostly because of the late observational times when most dust devils have expired). As more data released to the NASA PDS, more dust devils that have been captured should be available, and searches of the southern latitudes may be particularly promising, due to their high density of dust devil tracks at some times of the year compared to the north [Whelley and Greeley, 2006].

Very recently Mars Odyssey has moved to an earlier orbit, which should also improve the probability of observing dust devils. Dust devil orientated observations do require that THEMIS is observing simultaneously at infrared and visible wavelengths, which is not always the case, due to other mission requirements. Although events will be rare, such searches may be still be fruitful, as the combination of the simultaneous observation by THEMIS of visible, infrared spectral and infrared temperature data provides unique opportunity to explore martian dust devil properties, by comparing lofted dust loading and dust temperature with surface conditions.

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References

- Baddeley, P. F. H. (1860), *Whirlwinds and dust storms of India*, Bell and Daldy, London.
- Balme, M. R., S. M. Metzger, M. C. Towner, T. J. Ringrose, R. Greeley, and J. D. Iversen (2003a), Frictions wind speeds in dust devils: a field study, *Geophys. Res. Lett.*, *30*(16), 1830, DOI 10.1029/2003GL017493.
- Balme, M. R., P. L. Whelley, and R. Greeley (2003b), Mars: dust devil track survey in Argyre Planitia and Hellas Basin, *J. Geophys. Res.*, *108*(E8), doi:10.1029/2003JE002096.
- Balme, M. R., and R. Greeley (2006), Dust devils on Earth and Mars, *Rev. Geophysics*, *44*(RG3003), doi:10.1029/2005RG000188.
- Balme, M. R., and A. Hagermann (2006), Particle lifting at the soil-air interface by atmospheric pressure excursions in dust devils, *Geophys. Res. Lett.*, *33*(L19S01), doi:10.1029/2006GL026819.
- Bell, F. (1967), Dust devils and aviation, Meteorol. Note 27, Aust. Bur. of Meteorol., Melbourne, Victoria.
- Biener, K. K., P. E. Geissler, A. S. McEwen, and C. B. Leovy (2002), Observations of martian dust devils in MOC wide angle camera images, paper presented at 33rd Lunar and Planetary Science Conference, Houston, Texas, USA.
- Briggs, G. A., W. A. Baum, and J. Barnes (1979), Viking Orbiter Imaging Observations of Dust in the Martian Atmosphere, *J. Geophys. Res.*, *84*(B6), 2795-2820.

612 Brumby, S. P., D. T. Vaniman, and D. Bish (2003), Emissivity spectrum of a large "dark
613 streak" from THEMIS infrared imagery, paper presented at Sixth International
614 Conference on Mars, Lunar and Planetary Institute, Pasadena, USA.

615 Cantor, B. A., P. B. James, M. Caplinger, and M. J. Wolff (2001), Martian Dust Storms:
616 1999 Mars Orbiter Camera observations, *J. Geophys. Res.*, *106*(E10), 23653-23687.

617 Cantor, B. A., and K. S. Edgett (2002), Martian Dust Devils: 2 Mars Years of MGS MOC
618 Observations, *AGU Fall Meeting Abstracts*, *51*, 0331.

619 Cantor, B. A., M. C. Malin, and K. S. Edgett (2002), Multiyear Mars Orbital Camera
620 (MOC) observations of repeated martian weather phenomena during the northern summer
621 season, *J. Geophys. Res.*, *107*(E3), doi:10.1029/2001JE001588.

622 Cantor, B. A., K. M. Kanak, and K. S. Edgett (2006), MOC observations of martian dust
623 devils and their tracks (September 1997 – January 2006) and evaluation of theoretical
624 vortex models, *J. Geophys. Res.*, *111*(E12002), doi:10.1029/2006JE002700.

625 Christensen, P. R., B. M. Jakosky, H. H. Kieffer, M. C. Malin, H. Y. McSween Jr., K.
626 Nealson, G. L. Mehall, S. H. Silverman, S. Ferry, M. Caplinger, and M. Ravine (2004),
627 The Thermal Emission Imaging System (THEMIS) for the Mars 2001 Odyssey Mission,
628 *Space Science Reviews*, *110*(1-2), 85-130.

629 Church, C. R., J. T. Snow, G. L. Baker, and E. M. Agee (1979), Characteristics of
630 tornado-like vortices as a function of swirl ratio: A laboratory investigation, *J.*
631 *Atmospheric Sciences*, *36*, 1755-1776.

632 Cooley, J. R. (1971), Dust devil meteorology, NOAA Tech memo NWS CR-42.

633 Cushing, G. E., T. N. Titus, and P. R. Christensen (2005), THEMIS VIS and IR
634 observations of a high-altitude martian dust devil, *Geophys. Res. Lett.*, 32(L23202),
635 doi:10.1029/2005GL024478.

636 Edgett, K. S., and M. C. Malin (2000), Martian dust streaks and surface albedo controls:
637 thin, dark (and sometimes bright) streaks and dust devils in MGS MOC high resolution
638 pictures, paper presented at 32nd Lunar Planet. Sci., Houston, Texas, USA.

639 Ferri, F., P. G. Smith, M. T. Lemmon, and N. O. Renno (2003), Dust devils as observed
640 by Mars Pathfinder, *J. Geophys. Res.*, 108(E12), doi:10.1029/2000JE001421.

641 Fisher, J. A., M. I. Richardson, C. E. Newman, M. A. Szwast, C. Graf, S. Basu, S. P.
642 Ewald, A. D. Toigo, and R. J. Wilson (2005), A survey of martian dust devil activity
643 using Mars Global Surveyor Mars Orbiter Camera images, *J. Geophys. Res.*,
644 110(E03004), doi:10.1029/2003JE002165.

645 Fitzjarrald, D. E. (1972), The dust devil: a laboratory and field investigation, PhD thesis,
646 186 pp, University of California, Los Angeles.

647 Fitzjarrald, D. E. (1973), A field investigation of dust devils, *J. App. Meteorology*, 12,
648 808-813.

649 Flower, W. D. (1936), Sand devils, *Prof. Notes. Met. Office*, 71(5).

650 Fuerstenau, S. D. (2006), Solar heating of suspended particles and the dynamics of
651 martian dust devils, *Geophys. Res. Lett.*, 33(L19S03), doi:10.1029/2006GL026798.

652 Grant, C. G. (1949), Dust-devils in the sub-arctic, *Weather*, 4, 402-403.

653 Greeley, R., and J. D. Iversen (1985), *Wind as a Geological Process on Earth, Mars,*
654 *Venus and Titan*, Cambridge University Press, Cambridge.

655 Greeley, R., M. R. Balme, J. D. Iversen, S. M. Metzger, R. Mickelson, J. Phoreman, and
656 B. R. White (2003), Martian dust devils: Laboratory simulations of particle threshold, *J.*
657 *Geophys. Res.*, 108(E5), 5041, doi:5010.1029/2002JE001987.

658 Greeley, R., S. W. Squyres, R. Arvidson, P. Bartlett, J. B. Bell, D. Blaney, N. A. Cabrol,
659 J. Farmer, B. Farrand, M. P. Golombek, S. P. Gorevan, J. A. Grant, A. F. C. Haldemann,
660 K. E. Herkenhoff, J. Johnson, G. A. Landis, M. B. Madsen, S. M. McLennon, J. Moersch,
661 J. W. Rice, L. Richter, S. Ruff, R. J. Sullivan, S. D. Thompson, A. Wang, C. M. Weitz, P.
662 L. Whelley, and A. S. Team (2004), Wind-related processes detected by the Spirit rover
663 at Gusev crater, Mars, *Science*, 305, 810-821.

664 Greeley, R., P. L. Whelley, R. E. Arvidson, N. A. Cabrol, D. J. Foley, B. J. Franklin, P.
665 E. Geissler, M. P. Golombek, R. O. Kuzmin, G. A. Landis, M. T. Lemmon, L. D. V.
666 Neakrase, S. W. Squyres, and S. D. Thompson (2006), Active dust devils in Gusev crater,
667 Mars: Observations from the Mars Exploration Rover Spirit, *J. Geophys. Res.*,
668 111(E12S09), doi:10.1029/2006JE002743.

669 Hess, G. D., and K. T. Spillane (1990), Characteristics of dust devils in Australia, *J. App.*
670 *Meteorology*, 29, 499-507.

671 Ives, R., L. (1947), Behavior of dust devils, *Bull. Am. Meteorol. Soc.*, 28, 168-174.

672 Kaimal, J. C., and J. A. Businger (1970), Case studies of a convective plume and a dust
673 devil, *J. App. Meteorology*, 9, 612-621.

674 Landis, G. A. (1996), Dust obscuration of Mars solar arrays, *Acta Astronautica*, 38(11),
675 885-891.

676 Lorenz, R. D. (2004), Thermal imaging of a desert dust devil, *Journal of Meteorology*,
677 29(292), 275-276.

678 Malin, M. C., and K. S. Edgett (2001), Mars Global Surveyor Mars Orbiter Camera:
679 Interplanetary cruise through primary mission *J. Geophys. Res.*, 106(E10), 23429-23570.

680 Metzger, S. M., J. R. Carr, J. B. Johnson, T. J. Parker, and M. T. Lemmon (1999), Dust
681 devil vortices as seen by the Mars Pathfinder camera, *Geophys. Res. Lett.*, 26(18), 2781-
682 2784.

683 Mullen, J. B., and T. Maxworthy (1977), A laboratory model of dust devil vortices,
684 *Dynamics of Atmospheres and Oceans*, 1, 181-214.

685 Murphy, J. R., and S. Nelli (2002), Mars Pathfinder convective vortices: frequency of
686 occurrence, *Geophys. Res. Lett.*, 29(23), 18.

687 Ockert-Bell, M. E., J. F. Bell, J. B. Pollack, C. P. McKay, and F. Forget (1997),
688 Absorption and scattering properties of the martian dust, *J. Geophys. Res.*, 102(E4),
689 9039-9050.

690 Renno, N. O., M. L. Burkett, and M. P. Larkin (1998), A simple thermodynamical theory
691 for dust devils, *J. Atmospheric Sciences*, 55, 3244-3252.

692 Renno, N. O., A. A. Nash, J. I. Lunine, and J. R. Murphy (2000), Martian and terrestrial
 693 dust devils: test of a scaling theory using Pathfinder data, *J. Geophys. Res.*, *105*(E1),
 694 1859-1865.

695 Ringrose, T. J., M. C. Towner, and J. C. Zarnecki (2003), Convective vortices on Mars: A
 696 reanalysis of Viking Lander 2 meteorological data, sols 1-60, *Icarus*, *163*(1), 78-87.

697 Roberts-Austen, W. C., and A. W. Rücker (1891), On the specific heat of basalt, *Phil.*
 698 *Mag.*, *32*, 353-355.

699 Ryan, J. A., and J. J. Carroll (1970), Dust devil velocities: mature state, *J. Geophys. Res.*,
 700 *75*(3), 531-541.

701 Ryan, J. A. (1972), Relation of dust devil frequency and diameter to atmospheric
 702 temperature, *J. Geophys. Res.*, *77*(36), 7133-7137.

703 Ryan, J. A., and R. D. Lucich (1983), Possible dust devil vortices on Mars, *J. Geophys.*
 704 *Res.*, *88*(C15), 11005-11011.

705 Sinclair, P. C. (1964), Some preliminary dust devil measurements, *Monthly Weather*
 706 *Review*, *92*(8), 363-367.

707 Sinclair, P. C. (1966), A quantitative analysis of the dust devil, PhD thesis, 292 pp,
 708 University of Arizona.

709 Sinclair, P. C. (1969), General characteristics of dust devils, *J. App. Meteorology*, *8*, 32-
 710 45.

711 Sinclair, P. C. (1973), The lower structure of dust devils, *J. Atmospheric Sciences*, 30,
712 1599-1619.

713 Smith, M. D., J. C. Pearl, B. J. Conrath, and P. R. Christensen (2000), Mars Global
714 Surveyor TES observations of dust opacity during aerobraking and science phasing, *J.*
715 *Geophys. Res.*, 105(E4), 9539-9552.

716 Smith, M. D., J. L. Bandfield, P. R. Christensen, and M. I. Richardson (2003), Thermal
717 Emission Imaging System (THEMIS) infrared observations of atmospheric dust and
718 water ice cloud optical depth, *J. Geophys. Res.*, 108(E11), 5115.

719 Snow, J. T. (1987), Atmospheric columnar vortices, *Reviews of Geophysics*, 25(3), 371-
720 385.

721 Stanzel, C., M. Patzold, R. Greeley, and E. Hauber (2006), Dust devils on Mars observed
722 by the High Resolution Stereo Camera, *Geophys. Res. Lett.*, 33(L11202),
723 doi:10.1029/2006GL025816.

724 Stanzel, C., M. Patzold, D. A. Williams, P. L. Whelley, R. Greeley, G. Neukum, and E.
725 al. (2008), Dust devil speeds, directions of motion and general characteristics observed by
726 the Mars Express High Resolution Stereo Camera, *Icarus*, 197, 39-51.

727 Thomas, P. C., and P. J. Gierasch (1985), Dust devils on Mars, *Science*, 230(4722), 175-
728 177.

729 Tomasko, M., L. R. Dose, M. T. Lemmon, P. H. Smith, and E. Wegryn (1999),
730 Properties of dust in the martian atmosphere from the imager on Mars Pathfinder, *J.*
731 *Geophys. Res.*, *104*(E4), 8987-9007.

732 Tratt, D. M., M. H. Hecht, D. C. Catling, and E. C. Samulon (2003), In situ measurement
733 of dust devil dynamics: Toward a strategy for Mars, *J. Geophys. Res.*, *108*(E11), 5116.

734 Whelley, P. L., and R. Greeley (2006), Latitudinal dependency in dust devil activity on
735 Mars, *J. Geophys. Res.*, *111*(E10003), doi:10.1029/2006JE002677.

736

737

Figure Captions

Figure 1 – A plot of dust devil positions, with MOLA shaded relief as a background. Symbols indicate the positions of dust devils observed, while the symbol labels refer to the dust devil number in Table 1 and the text.

Figure 2 – Left-hand images show the THEMIS visible-wavelength scenes of dust devils, on the right are THEMIS IR temperature variations (overlain by visible-wavelength intensity contours derived from concurrent observations). In all images, Sun illumination is from the left, about 280-300 azimuth. (North is to the top). The scale bars are 1 km long. Absolute temperature varies from scene to scene, but in all cases the red-blue corresponds to a 3K temperature difference. (a) V02114009 (dust devil 1 in Table 1), (b) V02326010 (dust devil 2), (c) V02326010 (dust devil 3), (d) V02502006 (dust devil 4), (e) V03334003 (dust devil 5), (f) V03334003 (dust devil 6), (g) V03343003 (dust devil 7), (h) V02326010 (dust devil 8)

Figure 3 – Two examples of dust devil candidates that were not confirmed as definite. (a) Shows a low resolution dust devil candidate, with no other supporting coverage (THEMIS image V09950014). (b) Indicates a possible candidate obscured by the saturation of the image (THEMIS images V03343003 and V07837020). The scale bars are 1 km.

Figure 4 – Examples of terrestrial dust devils, ranging from well structured to more disordered. (a) shows the classic dust devil structure with a dust column made up of fine suspended particles and a slightly wider saltation skirt near the surface. (b) has a weaker structure, and lower dust loading, but is physically larger in diameter.

Figure 5 – The illumination geometry for dust devil imagery. θ is the solar incidence angle. I_{src} is solar illumination. R_s and R_{dd} are the radiances detected by the spacecraft from the unobstructed surface and of the dust devil’s shadow respectively.

Tables

	Image	Image resolution (m/pixel)	Latitude (N)	Longitude (E)	Height (± 50 m)	Diameter (m)	Altitude (m) ^b	Date (yyyy-mm-dd)	L _s	Local time	Correlating images
1	V02114009	36	26°24'10.4"	231°56'11.5"	1500	335	-812	2002-06-06	23.6	15:47	V13697011, 3115_0000 ^d
2	V02326010	36	34°26'19.7"	239°22'48.0"	1900	170	2252	2002-06-24	31.6	15:58	1576_0009 ^d , 1316_0000 ^d
3	V02326010	36	35°25'1.7"	239°41'23.6"	>1700 ^a	260	2252	2002-06-24	31.6	15:58	1576_0009 ^d , 1587_0009 ^d
4	V02502006	36	35°15'73.0"	203°40'46.1"	550	230	-3951	2002-07-08	38.2	16:05	P01_001393_2161_XN_36 N156W ^e
5	V03334003	72	24°51'20.3"	327°53'56.9"	? ^c	310	-3655	2002-09-15	68.4	16:29	V05244026
6	V03334003	72	24°38'43.3"	327°40'54.2"	? ^c	240	-3655	2002-09-15	68.4	16:29	V14717013
7	V03343003	72	6°58'46.3"	65°44'31.4"	250	225	1986	2002-09-15	68.8	16:24	V14414019
8	V02326010	36	36°12'27.6"	120°23'44.1"	350	110	2384	2002-06-24	31.6	15:58	V20336003

Table 1 – The results of dust devil survey. Dust devil height is inferred from shadow length and solar illumination angle. An estimate the accuracy in the diameter is given by the image resolution column.

^a, minimum size is constrained by shadow impinging on the edge of the image, but maximum unknown. ^b, is relative to Mars datum. ^c, there is no clear shadow seen. ^d, image from Mars Express HRSC. ^e, image from Mars Reconnaissance Orbiter CTX.

Image	Latitude (N)	Longitude (E)	Ls	Local time	Comments
V01770009	17°5'38.4"	71°30'7.2"	10.2	15:32	Too small to resolve clearly in THEMIS visible, no other coverage
V02055003	11°26'16.8"	131°20'56.4"	21.3	15:41	Too small to resolve clearly in THEMIS visible, no other coverage
V10398001	-9°19'33.6"	21°46'8.4"	21.2	16:29	Structure unclear due to surface features, other coverage lower resolution
V10259008	7°45'21.6"	44°52'58.8"	15.8	16:28	Too small to resolve clearly in THEMIS visible, no other coverage
V18471001	-4°16'55.2"	61°19'55.2"	10.6	16:26	Structure unclear due to surface features, no other coverage
V03014004	3°49'15.6"	193°37'40.8"	56.9	16:14	Bright spot but lack structure, interfering surface features, no other coverage
V02498007	25°23'9.6"	317°31'55.2"	38	16:01	Too small to resolve clearly in THEMIS visible, no other coverage
V09950014	17°16'33.6"	319°44'49.2"	3.5	16:22	Too small to resolve clearly in THEMIS visible, no other coverage
V03343003	6°13'28"	65°47'60.0"	68.8	16:24	Possible small dust devil, signal to noise too low to resolve clearly, no better coverage
V18311007	3°15'0"	328°57'39.6"	4.2	16:23	Bright spot but lack of dust devil structure, no other coverage

Table 2 – Discarded dust devil candidates, with a brief description of the reason for discard. Latitude and longitude refers to the image location.

Two examples of these are shown in Figure 3.

Time of Day	No. of dust devils	No. of THEMIS images	Total area imaged (km ²)	Rate of occurrence (km ⁻² hr ⁻¹)
Before 15:00	0	0	0	
15:00-15:30	0	211	219000	$< 1.82 \times 10^{-5}$
15:30-15:45	0	321	536000	$< 7.45 \times 10^{-6}$
15:45-16:00	4	287	533000	3.00×10^{-5}
16:00-16:15	1	242	526000	7.60×10^{-6}
16:15-16:30	3	2018	2609000	4.61×10^{-6}

Table 3 – A summary of detected dust devil survey statistics.

	THEMIS image	Compensation image	r	R_{dd}	R_s	R_T	Plume Opacity	Incidence angle	Dust load (kgm^{-3})
1	V02114009	V13697011	0.998	169.4	177.5	38.0	0.0594	55.8	1.94×10^{-5}
2	V02326010	H1316_0000	0.995	119	138.7	46.0	0.2436	57.8	1.53×10^{-4}
3	V02326010	H1576_0009	0.971	134.7	139.5	46.0	0.0823	57.8	3.39×10^{-5}
4	V02502006	^a		174.4	209.8	43.0	0.2384	58.1	1.14×10^{-4}
5	V03334003	H1619_0000		No shadow	No shadow			60.6	
6	V03334003	V05244026		No shadow	No shadow			60.6	
7	V03343003	V14414019	0.975	142.3	154.5	12.0	0.1083	65.8	4.78×10^{-5}
8	V02326010	V20336003	0.990	125.5	135.8	46.0	0.1317	57.8	1.28×10^{-4}

Table 4 – Opacity and dust loading estimates for confirmed dust devils. HRSC images are indicated by starting with H, while THEMIS images start with V. Dust devils 5 and 6 do not appear to have a significant shadow, as discussed further in text. ^a indicates that no THEMIS or HRSC compensation images exist, and r is assumed to be 1. The radiance values R_{dd} , R_s and R_T are byte scaled.

Fig 1

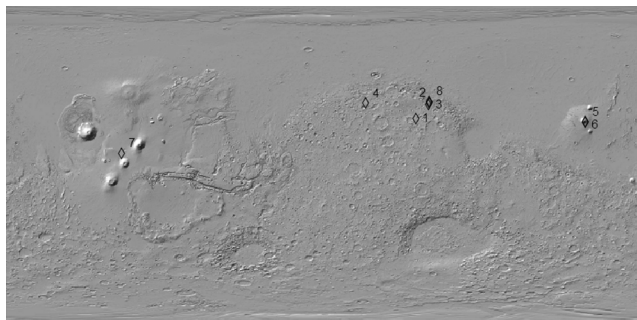


Fig 2

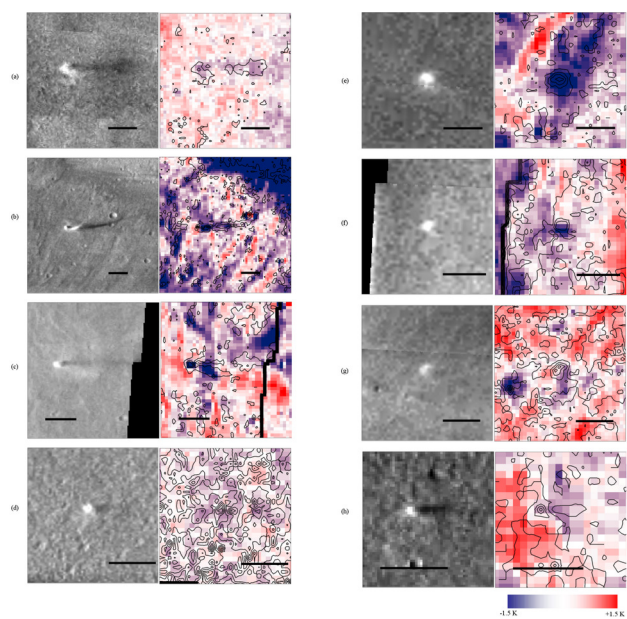


Fig 3

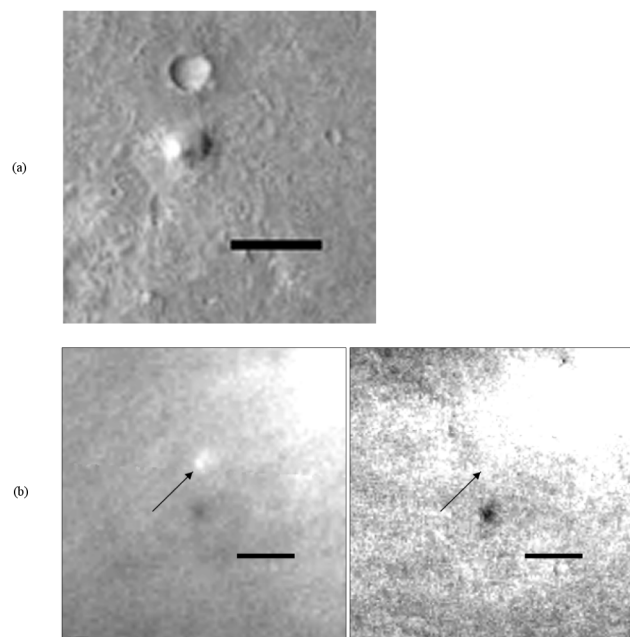


Fig 4



(a)

(b)

Fig 5

