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Solar Panel Clearing Events, Dust Devil Tracks, and in-situ Vortex Detections on Mars

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Abstract

Spirit rover solar array data, which if publicly-archived would provide a useful window on Mars meteorology, shows dust-clearing events coinciding with the onset of dust devil season in three Mars years. The recurrence interval of 100–700 days is consistent with the extrapolation of Pathfinder and Phoenix vortex encounters indicated by pressure drops of ~6–40 Pa (similar to laboratory measurements of dust lifting threshold) and with observed areas and rates of generation of dust devil tracks on Mars.

Keywords

Atmospheres; Dynamics; Mars; Atmosphere; Meteorology

Introduction

The first solar-powered vehicle to operate on Mars, the Sojourner rover in 1997, saw a progressive deposition of dust on its horizontal solar panel which declined in electrical power output by 0.2–0.3% per day (e.g. Golombek et al., 1999; Landis and Jenkins, 2000). This degradation set expectations for subsequent solar-powered missions such as the Mars Exploration Rovers (MERs) Spirit and Opportunity, which were designed for a 90-day nominal mission life. The much longer operation of these vehicles was made possible by unanticipated ‘dust clearing events’ (e.g. Vaughan et al., 2010) which are interpreted to be wind gusts or dust devils which removed much of the dust that had accumulated. Clearly, the existence of such events has a dramatic effect on the longevity and productivity of solar-powered missions, and thus they demand to be better understood. Sadly, the MERs were not equipped with meteorological instrumentation, so these events cannot be characterized directly. However, we can use the observed frequency of these events, supplemented by laboratory results and by data from landed missions which were equipped with meteorology sensors, to assess their consistency with dust devil vortices. Dust removal is also observed

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directly on Mars via the formation of dust devil tracks, which bring another quantitative dataset to bear on the question.

2. Dust Clearing Events

Vaughan et al. (2010) present a figure illustrating the occurrence of three dust-clearing events over the ~2000 sol Spirit rover mission, and document the solar energy per day before and after the events. We quantify these events, and interpret the before/after ratio as a simple attenuation opacity in table 1. Although this is in principle a rather austere dataset to work with, the occurrence of 3 events at more or less regular intervals offers some hope that the phenomenon is not purely stochastic. Although suspected of being related to dust devil activity, other causes (wind gusts, strong ambient winds) have been considered, yet table 1 shows a strong correlation of the clearing events and observations of dust devils by Spirit's camera (Greeley et al., 2006, 2010) – specifically, in each year of 669 sols, clearing was observed between 0 and 95 sols of the onset of dust devils, suggesting cause and effect, or a common cause.

The solar array data is not generally available, although a normalized dataset for year 1 was published in image form (figure 1). These data show there were in fact two major clearing events separated by ~100 sols (and possibly several minor ones) in the first dust devil season. Thus the events have a recurrence interval of between 100 and 700 sols.

3. Comparison with Barometric Pressure Drops

Clearly, if some meteorological process performs the dust clearing, then it must be a process that only occurs once every 700 sols or so, or occurs with an interval of >100 sols during a specific season. The only meteorological record on Mars this long is that of Viking 2, but this had too low a pressure-sensing resolution and was too poorly-sampled to reliably detect brief dust devil encounters. However, we can make extrapolations from the rather faster-sampled and higher-sensitivity measurements on Pathfinder and Phoenix. Specifically, localized brief pressure drops are a signature of atmospheric vortices, which may or may not be rendered visible by lofted dust. Lorenz (2012) showed that both the Pathfinder vortices (Murphy and Nelli, 2002) and those detected by Phoenix (Ellehoj et al., 2010) follow a rather systematic frequency distribution, specifically a power law with a differential exponent of about -2 . Thus, in cumulative terms, a $10\times$ bigger pressure drop will occur $10\times$ less often. We plot these cumulative distributions, expressed as an interval rather than a frequency, together with some terrestrial data (Lorenz and Lanagan, 2014) for comparison, in figure 2, and extrapolate the Mars observations to larger pressure drops. The missions lasted ~80 and ~150 days respectively : the largest drop actually observed (Murphy and Nelli, 2002) was 4.8 Pa (0.7% of ambient).

It can be seen that extrapolating the Mars Pathfinder data implies that drops of 8 Pa or more (1%) may be encountered at intervals of many hundreds of sols, although the Phoenix measurements imply the interval could be less than 100 days (there are of course differences in both the location and season of these records). In any case, it seems that a reasonable extrapolation to this pressure drop is consistent with the dust-clearing interval observed on Mars.

Neakrase et al. (2006) conduct vortex dust-lifting experiments at terrestrial and Mars pressures, and find (for a 10mb atmosphere representative of Mars) that the dust flux increased by an order of magnitude as the vortex pressure drop increased from 20 Pa to 40 Pa : a measurable amount of dust lifting did occur, even at 10 Pa. Thus it seems that a vortex passage with a pressure drop of >5 Pa might well clear a solar panel on Mars if the exposure was long enough : Neakrase and Greeley (2010) provide additional discussion. Since fine ($2\mu\text{m}$) dust was used, where the cohesion between particles will dominate over weight, the fact that the tests were made in terrestrial gravity likely makes little difference, but in principle the thresholds in Mars gravity might be slightly lower. Note that the formation of dust devils on natural surfaces (i.e. the lifting of dust from a porous regolith) may be facilitated by sand blasting or backventing ('suction' - see Balme and Hagermann, 2006) that does not occur on flat plates, allowing a lower threshold for dust devil formation than for dust removal from a solar panel. Nonetheless, the interval extrapolated from lander data of exceeding laboratory threshold pressure drops of 100–500 sols is at least circumstantial evidence that (a) the population of vortices can be extrapolated to longer periods and (b) that dust devils are responsible for the clearing events. Note that the Opportunity rover did not observe dust devils, but this may be related at least in part to dust availability – boundary layer vortices with pressure drops large enough to remove dust from the panels may well have been invisible, although this does not exclude other meteorological processes from contributing to solar panel clearing.

4. Comparison with Dust Devil Tracks

Dust devil tracks can in fact be recognized (after the fact, Lorenz and Zimbelman, 2014) in the first Mariner 9 images from 1972 that show sand dunes on Mars. However, their detailed quantification awaited higher-resolution images that became available after ~1998.

In Hellas, the number of observed dust devil tracks in a survey by Balme et al. (2003) increased from $\sim 0.6 \text{ km}^{-2}$ to 3.5 km^{-2} over about 30 sols (between the intervals of $L_s=285\text{--}300$ and $L_s\sim 300\text{--}315$). This corresponds to a track generation rate of about 0.1 km^{-2} per day. More typically the generation rate was about a fifth of this rate. Verba et al. (2009) find similarly at Gusev in 2006–2008 a peak formation rate of $0.103 \text{ tracks km}^{-2}/\text{sol}$, although as low as 0.0011. At Russell crater, track formation was rather more frequent, 0.04 to 0.95 tracks $\text{km}^{-2}/\text{sol}$.

Verba et al. (2009) report dimensions of dust devil tracks in Gusev crater, finding average widths of $\sim 40\text{m}$ and lengths of $\sim 2.5\text{km}$. The area swept by an 'average' track is therefore $\sim 0.1\text{km}^2$. The formation of a 0.1km^2 trail at a rate of 0.1 per km^2 per day implies a typical interval between cleaning events seen by a given point of 100 days during the most intense part of dust devil season, and ~ 500 days more typically.

This 100–500 day interval is reassuringly close to that of dust clearing events indicated at Spirit. This agreement between track formation rate, dust clearing, and observed vortex distributions again supports the notion that dust devils are responsible for clearing events.

While the notion of ‘average’ for a highly skewed population requires considerable care, it is instructive to compare this average trail area of 0.1km^2 with the area swept by a typical dust devil. Lorenz (2013) determines a longevity of a dust devil diameter d (in m) as $\sim 40d^{0.66}$ seconds, or for a 40m dust devil, about 8 minutes. With a $5\text{--}15\text{ ms}^{-1}$ ground speed typical of dust devils (e.g. Reiss et al., 2014a), a devil would migrate $\sim 2\text{--}6\text{km}$, spanning the average length noted by Verba et al. (2009). This suggests some overall consistency, and circumstantially implies that dust devils may be able to form trails for most of their observed lifetime. In this connection, Raasch and Franke (2011, their figure 6) plot the time histories of two vortices in a Large Eddy Simulation (LES) model of terrestrial dust devils: the two vortices were tracked over ~ 500 and $\sim 600\text{s}$ respectively, and had core pressure drops exceeding 20 Pa (a likely dust-lifting threshold) for over 80% of their lifetime.

Verba et al. (2009) note that observed tracks are wider than observed devils: HiRISE observations of track widths peak at around $40\text{--}60\text{ m}$ across, with a mean of 56 m ($N=640$), whereas the dust devils observed by the Spirit rover ($N=480$) are generally between 10 and 20 m in diameter (see e.g. Greeley et al., 2010). While there may be some systematic differences in detection efficiencies, this difference is suggestive that track formation is favored for large devils. While it is possible that larger devils are more intense (i.e. P and tangential windspeed correlate with diameter, such that larger vortices are better able to lift dust), modeling of terrestrial dust devils finds no correlation (Lorenz, 2014).

Another possibility, however, relates to a finite rate of dust removal. Assuming dust lifting occurs over the footprint of the devil (or at least over some region that scales with diameter - an annulus near the dust wall perhaps) then for a fixed advection speed a given spot of ground will endure a longer scouring period for a large devil than a small one. In the case of an infinite layer of uniform dust, this effect will not make a difference, but if the excavation rate is commensurate with a thin layer of dust removed in the typical advection time then larger devils will preferentially remove all the dust while small ones will not.

Reiss et al. (2014b) deduce dust removal rates from opacities determined by shadows in Mars orbital images of up to $1221\text{ mg m}^{-2}\text{ s}^{-1}$, roughly equal to the $\sim 1000\text{ mg m}^{-2}\text{ s}^{-1}$ ($1\text{E-}3\text{ kg m}^{-2}\text{ s}^{-1}$) measured by Neakrase et al. (2006) in the laboratory for $P\sim 20\text{--}36\text{ Pa}$. At this rate a monolayer of $2\text{ }\mu\text{m}$ dust (i.e. $\sim 2000\text{ mg m}^{-2}$, roughly the amount associated with the opacities in table 1) is removed in only $\sim 1\text{s}$ (the crossing time of a $\sim 5\text{--}20\text{m}$ dust devil at typical advection speeds of $5\text{--}15\text{ ms}^{-1}$). Kinch et al. (2007) estimate that a monolayer of dust was deposited in about 100 sols (an opacity of 0.44 after 150 sols).

It may be that both (or indeed other) mechanisms apply. Cantor et al (2006) suggests that only 14% of observed dust devils formed trails. Again this might be interpreted by most devils being advected too quickly to excavate a visible trail, or that only a small fraction of vortices that have visible dust (itself a small fraction of all vortices that may be barometrically-detectable - see Lorenz, 2014) have pressure drops low enough to form trails, or both. The formation of trails in different surface environments (e.g. dust layer thickness) by a population of dust devils with skewed (power-law, exponential, etc.) diameter and core pressure drop distributions and varying advection speeds will be explored in future work. Michaels (2006) simulates dust devil track formation in a Large Eddy Simulation: it is

notable that the width of the $\sim 1\ \mu\text{m}$ dust removal footprint in his figure 1 is only about half of the wall diameter of the vortex. As on Earth, different surfaces (depending on sand and dust thickness - see e.g. Reiss et al., 2010) on Mars may have different thresholds for visible track formation. Solar arrays on the other hand, have relatively uniform roughness and adhesion properties which usefully resemble laboratory surfaces.

5. Conclusion

We have found that rover dust clearing events occur with a 100~700 sol recurrence interval that is compatible with the rate of $\sim 6\text{--}40$ Pa vortex encounters extrapolated from lander measurements. It is furthermore consistent with observed dust devil track formation, suggesting dust devils are responsible for dust clearing, and that dust devil track densities might be useful for assessing clearing event frequency on different areas of Mars. Further laboratory experiments to understand the potential different dust-lifting thresholds for flat solid surfaces versus regoliths with a wide range of particle sizes would be a useful contribution to the problems discussed in this paper. Solar array performance information from Mars missions should be made available in a public archive since it provides important information on the Mars environment.

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Figure 1.

Solar array factor (a measure of the transmissivity of the accumulated dust layer) published in image form at <http://photojournal.jpl.nasa.gov/catalog/PIA03608> (downloaded 10/13/2014) showing the progressive decline in output over the first Mars year, punctuated by two jumps, indicating dust removal events (arrowed), at Sols 420 and 520–522. The shaded box denotes the dust removal season where the factor fluctuates. The curve at bottom is the relative dust devil density observed by Greeley et al. (2006,2010) in that year – the peak was 0.1 dust devils per sol per km². The correlation is striking.

Figure 2.

Cumulative intervals between of pressure drop encounters measured by the Pathfinder lander (Murphy and Nelli, 2002, solid line) and the Phoenix lander (Ellehoj et al., 2010, dashed line) expressed as a normalized pressure drop dividing by ambient pressures of ~650 and 800 Pa respectively. The normalization allows comparison with terrestrial barometric surveys by Lorenz and Lanagan (2014), shown by the points at left. Extrapolating (solid line) the Mars data to intervals of 100–700 days suggests a normalized drop of 1–5%, or 6–30 Pa, broadly consistent with laboratory measurements of dust lifting at Mars pressures.

Table 1 :

Dust clearing events documented on the Spirit rover (derived from Vaughan et al., 2010) and dust devils observed from the rover (Greeley et al., 2010).

Mars Year	27	28	29
Dust Devil Onset Sol ¹	421	1103	1785
Dust Clearing Sol	420 ²	1200	1880
Dust Clearing Season (L _s , deg)	173–234	233–274	259–294
Dust Devil Season (L _s , deg) ¹	173–340	181–267	189–355
Energy Before (W-hr/day)	400	400	330
Energy After (W-hr/day)	740	610	940
Opacity Removed ³	0.61	0.42	1.04
Median Diameter (m) ¹	19	24	39
Peak Density (km ⁻² sol ⁻¹) ¹	0.1	0.06	0.04
Median Horizontal Speed (ms ⁻¹) ¹	2.5	2.2	1.5

¹ From Greeley et al. (2010)

² Data in this row from Vaughan et al. (2010). Figure 1 in the present paper shows 2 major events, at Sols 420 and Sol ~520 respectively.

³ The removed opacity is simply ln(After)-ln(Before).