Power law distribution of pressure drops in dust devils: Observation techniques and Earth–Mars comparison

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**A B S T R A C T**

Data from the Pathfinder and Phoenix landers on Mars show transient pressure drops (~1–4 per day) attributed to nearby encounters with dust devils or dust-free vortices. The distribution of pressure drop amplitudes is consistent with a truncated power law distribution with a slope of ~2, similar to that suggested previously for the optical diameters of dust devils. Comparable data from terrestrial field observations are very sparse: the only published dataset is half a century old and lists only 19 pressure drops. That dataset is too small to permit a robust comparison with Mars and likely suffers from a low detection efficiency at small dust devil sizes. Observed pressure drops in these fixed-station Mars datasets (30–300 μbar) are 10– lower than those typically observed on Earth (0.3–3 mbar): some higher drops have been reported for large terrestrial devils sampled by pursuing vehicles. The needed terrestrial data for comparison with Mars in-situ data (soon to be augmented, we hope, by the Mars Science Laboratory mission) is noted. Prospects for obtaining such data via field campaigns using new data acquisition technology, and with microbarographs for nuclear test monitoring, are discussed.

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1. Introduction

Dust devils (e.g. Sinclair, 1966; Balme and Greeley, 2006) are dry convective vortices that are rendered visible by lofted dust in arid regions. They play an important role in lofting dust into the atmosphere, with implications for air quality and sediment balance (e.g. Metzger et al., 2011). Dust devils can be a nuisance for outdoor activities and can occasionally cause structural damage or fire. A review of air accident statistics (Lorenz and Myers, 2005) indicates some 100 damaging – and in some cases fatal – incidents to aircraft that are attributable to dust devils. Dust devils are also the most prominent dynamic phenomena observed on the surface of Mars. They are major agents of surface change, forming tracks which not only are individually visible, but may lead to accumulated albedo changes over large regions (e.g. Cantor et al., 2006). Additionally, in the thin Martian atmosphere, they are a principal mechanism of dust-raising, with a resultant influence on the entire Martian climate. The operations of solar-powered vehicles on the Martian surface can be significantly affected both by the dust lofted planetwide, and by local dust removal events. Thus it is important that the frequency, intensity and behavior of dust devils be understood.

Dust devil populations have most frequently been discussed in the context of optical observations, where a visible diameter can be estimated from imaging data or more often (in the terrestrial case at least) naked-eye observations. It is well-known that large dust devils are less common than small ones—dust devils, like many other natural phenomena, have a highly skewed size distribution. It was suggested by Kurgansky (2006) that diameters might have truncated exponential or Weibull distribution. Lorenz (2009) found that Mars data with stronger statistics seemed better fit by a power law. Although there are indications that an exponential is still a good description of some observed populations (e.g. Pathare et al., 2010), a more extensive survey (Lorenz, 2011) shows that in fact most terrestrial data have been too coarsely-binned to permit a formal statistical discrimination of power law or exponential fits (or, for that matter, a test of whether the Mars and Earth population functions are similar). That paper also points out that estimates of population-integrated processes – especially those that are nonlinearly dependent on dust devil size, such as dust-raising – can be incorrect by orders of magnitude if the population function is not appropriately treated. Power laws often have an underlying physical basis (e.g. Bak, 1996; Newman, 2005) rather than being purely empirical functions. Lorenz (2011) notes that a randomly-truncated exponential growth as in Reed and Hughes (2002) might be a mechanism for producing a power-law population of dust devil diameters.

In this paper we open a new window onto dust devil populations, namely that from in-situ meteorological measurements and

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in particular from pressure sensors. Dust devil passage manifests itself in meteorological data by several clear signatures (e.g., Sinclair, 1973; Ryan and Lucich, 1983; Ringrose et al., 2003, 2007; Tratt et al., 2003)—most notably a pressure drop lasting a few seconds to hundreds of seconds and a rotation of the wind direction. The shapes of these signatures depend on the miss distance of the devil from the meteorological station and the diameter of the devil: usually the timebase of the recorded signatures is mapped into a spatial coordinate by an assumed constant translational velocity, which allows the signature to be normalized by the diameter of the devil. Additional signatures in windspeed, solar flux, temperatures and electrical activity are often encountered, but are rather variable in character.

The meteorological signatures of dust devils on Mars were noted in Viking lander data by Ryan and Lucich (1983), work which was extended by Ringrose et al. (2003). Dust devil passages were noted in an initial evaluation of Mars Pathfinder data (Schofield et al., 1997), and a comprehensive inventory of some 79 vortex passage events (>50 µbar) in 83 sols is given by Murphy and Nelli (2002). More recently, Ellehoj et al. (2010) document similar events detected by the Phoenix lander—502 events (>30 µbar) in 152 sols. The higher number of events per day is largely due to the lower detection threshold and in part due to a higher duty cycle of the Phoenix observations. It may be noted that many of the Phoenix events (and likely many of the Pathfinder ones) were not associated with a visible dust structure (i.e., they were vortices not at that point loaded with dust, ‘dustless devils’). Unfortunately, the Viking pressure data were not typically recorded with the cadence needed to resolve dust devils, so no meaningful catalog of pressure drops exists, and the Mars Exploration Rovers were not equipped with meteorological instrumentation.

Thus the catalogs reported by Murphy and Nelli (2002) and Ellehoj et al. (2010) are the only Martian ones available, and are presented as binned counts of peak pressure drops in Fig. 1. Following the approaches (Lorenz, 2011) for treating dust devil populations in the same way as other skewed data such as those of impact craters, these are presented in logarithmic size bins spaced by a factor of 2.05, and as differential and cumulative distributions. The binned data are shown in Table 1—the original unbinned catalogs can be found in the respective papers. The skewed nature of the populations is evident in the plots—as shown in Section 3 and in Fig. 1; the data can be well fit by power laws with a slope of about −2.

2. Observations of terrestrial dust devil pressure drops

Two principal approaches have been adopted in the acquisition of terrestrial in-situ dust devil data: by directed pursuit from a mobile platform and from fixed platforms. A familiar and instructive analogy is the capture of fish—one can actively hunt with a spear, or passively with a net. In order to make predictions that have utility for planetary applications (where a measurement...
system, or system whose operation might be affected by dust devils is fixed, or at least very slow-moving) the second type of data is more readily applicable. However, it is useful to review the history of these two complementary types of investigation.

Sinclair (1966, 1973) introduced the concept of an instrumented chase vehicle into dust devil studies (in his case a Willys Jeep with a 10 m mast and a microbarograph and other instrumentation wired to a chart recorder). When planetary dust devil studies were reactivated along with the Mars program in the late 1990s, this approach was again applied by several workers (e.g. Metzger et al., 2004; Tratt et al., 2003). While this methodology is somewhat efficient in yielding a useful number of in-situ measurement opportunities with a given set of instruments (‘trophies’, to continue the fishing/hunting analogy, and indeed data acquired this way provides the major foundation for theoretical work, e.g. Rennô et al. (1997, 2000)), and such ‘storm chasing’ has obvious visceral appeal and outreach utility, there are grave drawbacks in this approach for census purposes. First, and most serious, there are severe selection effects that bias the data: the largest, slowest and dustiest devils will be pursued (similar sampling biases are encountered in wildlife census processes, and even in the acquisition of Antarctic meteorites e.g. Harvey (1995)), and the properties of simultaneous or near-simultaneous devils are not explored. Second, the time–distance relationship between the center of the dust devil and the vehicle is often complicated and not always well-documented. Third, the vehicle itself can perturb the measurements by disrupting the airflow near the ground (an effect somewhat mitigated by vehicle-dropped platforms, or by masts or ladders on which instrumentation can be mounted a couple of meters ahead of the vehicle) and by introducing vehicle engine vibration and/or electrical noise into sensor signals (e.g. Tratt et al., 2003).

The alternate approach is to install fixed instrumentation and harvest whatever encounters occur (fishing with a net, or hunting with traps, to pursue the wildlife analogy). Although many meteorology stations exist worldwide, data are usually recorded with a 15-min or hourly cadence suitable for monitoring weather stations, each with instruments in a small shelter and on a mast, stations, each with instruments in a small shelter and on a mast, were spread in a line ~16 m wide orthogonal to the prevailing wind direction, and data were acquired by chart recorder in a trailer van some 35 m away. Although the site was known to experience ‘numerous’ dust devils, over a period of some 4 months (May 15–September 15, 1959) only 21 close encounters were made: results (pressure drops were recorded in only 19 cases) are shown in Fig. 1 and Table 1. The instrumentation and data acquisition systems of the time may have been a significant limitation e.g. Lambeth reports that wind vibration on the van could directly affect the chart recorder, and the response time of the wind vanes was too slow to properly capture the wind field of a close dust devil. He concludes, ‘dust devils can be measured in adequate quantities only using mobile sensors’ (and indeed Sinclair’s mobile work comes to the fore a few years later). As we discuss in the next section, this pessimistic outlook appears to be largely a result of a poor detection efficiency of small dust devils, which are by far the most numerous. Because data acquisition involved a consumable (paper on chart recorders) and instrumentation had a finite time constant that prevented characterization of small structures with rapid signatures, recording was triggered only when a significant dust devil made a close encounter with the array.

Ryan and Carroll (1970) set up a station in the Mojave desert and acquired a good set (some ~80 events) of in-situ data in a 30-day field period (i.e. 3–4 events/day): these data so far are the best for correlating some observed quantities such as diameter and wind-speed. Unfortunately pressure data were not reported.

Ryan and Lucich (1983) in their analysis of Viking dust devil signatures, rued ‘Unfortunately, we have been unable to find a terrestrial dataset that permits a one to one comparison with our Mars data’. Remarkably, this deficiency appears to remain today (at least in terms of publicly-accessible datasets). It is known that other workers on dust devils have made suitable fixed-station meteorology measurements in the field in support of other investigations (such as electromagnetic signatures of dust devils or vehicle campaigns). It is hoped that the full statistics of these observations may be published.

Besides, we may note that there is wide public interest in the superficially related phenomena of tornados, and some techniques for obtaining in-situ data that are related to those advocated later in this paper for dust devils have been applied. In-situ measurements of tornados are summarized in Karstens et al. (2010). Pressure drops between 5 and ~200 mbar have been measured. Corresponding wind speeds at 3 m height were 40–50 m/s.

### Table 1

Dust devil pressure drops recorded on Mars at the Pathfinder (Murphy and Nelli, 2002) and Phoenix (Ellehoj et al., 2010) landing sites, and on Earth at White Sands (Lambeth, 1996).

<table>
<thead>
<tr>
<th>System</th>
<th>Minimum pressure drop (mbar)</th>
<th>Maximum pressure drop (mbar)</th>
<th>Number detected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mars Pathfinder</td>
<td>50</td>
<td>71</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>91</td>
<td>100</td>
<td>141</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>200</td>
<td>282</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>400</td>
<td>564</td>
</tr>
<tr>
<td>Mars Phoenix</td>
<td>30</td>
<td>42</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>84</td>
<td>120</td>
</tr>
<tr>
<td></td>
<td>240</td>
<td>340</td>
<td>400</td>
</tr>
<tr>
<td>White Sands</td>
<td>0.4</td>
<td>0.56</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>0.8</td>
<td>1.12</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>2.26</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3. Results and discussion

The data from the two Mars studies and that from Lambeth above have been binned as described by Lorenz (2011) and plotted on logarithmic axes (Table 1, Fig. 1). The datapoints can be fit by a power law by simply performing linear (least squares) regression on the logarithms of the datapoints (i.e. number per bin). The data from the two Mars studies and that from Lambeth above have been binned as described by Lorenz (2011) and plotted on logarithmic axes (Table 1, Fig. 1). The datapoints can be fit by a power law by simply performing linear (least squares) regression on the logarithms of the datapoints (i.e. number per bin).
(with 1σ uncertainties estimated using the procedure in Taylor (1997) as 0.49 and 0.47, respectively). These results are both consistent at the ~0.5σ level with an exponent of −2, which is not only a succinct general description of these data, but is also in striking agreement with the exponent of −2 suggested in the Gusev dust devil diameter data (Lorenz, 2009) and in the size of convective cloud clusters on Earth (Machado and Rosson, 1993.)

The quality of the fit to the terrestrial data by Lambeth (1996) is much poorer, due to the poor counting statistics. The least-squares power law fit has an exponent of −0.76, with a 1σ uncertainty of 0.74. Thus a −2 slope is not excluded by the data at the 2σ level.

Inspection of the observed diameter of the 21 events indicates only a couple of small devils (3 m), yet if the size distribution followed the power law seen in optical surveys (Lorenz, 2009; Lorenz, 2011), then these small devils should outnumber the dozen ~30 m devils recorded by Lambeth (1996) by two orders of magnitude, i.e. ~1000 3 m devils should have been seen. This size discrepancy, and the overall low detection rate of ~0.16 events/day, suggests small devils were not being detected efficiently. Although some local variation, or perhaps an unusually dust-free season, cannot be excluded, a visual survey over several years at White Sands by Snow and McClelland (1990) yielded a dust devil density consistent with other Earth and Mars locations. If we postulate that more small devils exist than were reported, then the slope of the real distribution may well be closer to −2 than the observed −0.76.

In summary, both Mars and terrestrial data could be consistent with a distribution of peak pressure drops that follows a −2 power law, although better terrestrial data is needed to substantiate this proposal. As discussed in Lorenz (2011), there are some theoretical motivations, in addition to algebraic convenience in evaluating population-integrated effects, for considering a power law to be a likely distribution for dust devil parameters, as in other fields (e.g. Newman, 2005; Bak, 1996).

### 4. Data requirements for future analysis

Here we outline the terrestrial data required for several different investigations. First, a crude benchmark is to simply acquire a set of data that is comparable with the Mars data: i.e. an inventory of a few hundred datapoints. This would allow at least a different investigations. First, a crude benchmark is to simply acquire a set of data that is comparable with the Mars data: i.e. an inventory of a few hundred datapoints. This would allow at least a future data may allow relationships to be more clearly defined. Specifically, numerical simulations of dust devils (e.g. Toigo et al., 2003) show that the wind field around devils is not purely radial but rather has spiral arms like a galaxy. The maximum windspeed encountered by a single fixed sensor may not be the maximum in the structure as a whole, nor will it spatially coincide with the peak pressure drop. Thus the spatial variability within a single dust devil may degrade the observed correlation of meteorological variables. This difficulty may be ameliorated by array measurements: measurements from a two-dimensional array (or a 1-D array normal to the direction of motion, as intended in Lambeth's experiments in 1959) will allow the instantaneous radial profile of a devil to be estimated (together with the azimuthal variance described above) and even if the core is not resolved directly, the miss-distance can be determined and corrected for.

In that connection, it should be underscored that all the data reported in this paper refer to measured pressure drops, which are not necessarily the peak pressure drop either of the encountered dust devil at that moment, nor of the dust devil throughout its life cycle. Ellehoj et al. (2010) assume a Lorentzian (i.e. ~1/(d²+1)) function to describe the fall-off of pressure perturbation with distance d. Laboratory measurements of horizontal pressure profiles are discussed in Snow et al. (1980), which suggest a rather similar d⁻² fall-off with distance. Cantor et al. (2006) and Balme and Greeley (2006) give useful discussions favored). In all probability, the small number of detected events likely means the actual population maximum pressure drop in dust devils is rare enough not to have been observed, and instrumental sensitivity and/or selection effects in chase measurements mean that the minimum is lower than 0.3 mbar. The actual range might perhaps be from 0.1 mbar to 20 mbar, a factor of 200: see Lorenz (2011) for a related discussion on the comparable span of dust devil diameters observed on Mars. As discussed there, if a single dataset is to simultaneously detect one or a few events in the largest size bin, and to efficiently count the smallest pressure drop in the population (200 times smaller, and thus 20⁰ times more abundant) then a dataset of the order of 10⁴ events is likely to be needed: this is probably unrealistic with present methods (though a combination of fixed stations to measure small drops and pursuit measurements to acquire the largest ones would be feasible).

A remark about the absolute value of pressure drops in dust devils on Mars and Earth is in order. Fundamentally the defining feature of a devil is lofted dust and a vortical motion, such that the wind is organized (i.e. the velocity associated with the coherent structure is markedly greater than the random turbulent fluctuations in the wind field in which the structure is embedded). The pressure drop ΔP in a Rankine vortex model of a dust devil (e.g. Renno et al., 1997, 2000) will be related to the density ρ and velocity V by ΔP = ρV². Taking Mars wind velocities as a factor 2–4 larger, and density a factor of 100 smaller than on Earth (both quantities of course vary with location on Mars and Earth) then the pressure drops in Martian dust devils should be 6–25 times smaller than those seen on Earth. It can be seen in Fig. 1 that the observed populations indeed appear to differ by this amount, i.e. a factor of 10 (Mars dust devils 30–300 mbar, Earth 300–3000 mbar), but it is not clear whether the observed ranges are defined by instrumental sensitivity or by limits in the underlying distributions.

A correlation between meteorological variables in dust devils is present (e.g. see Ryan and Carroll, 1970; Balme and Greeley, 2006 and other papers) but generally there is considerable scatter in the data. Most relations are explored with simple linear regression of single (peak) values. More rigorous statistical analysis could be usefully applied even to existing data, but future data may allow relationships to be more clearly defined. Specifically, numerical simulations of dust devils (e.g. Toigo et al., 2003) show that the wind field around devils is not purely radial but rather has spiral arms like a galaxy. The maximum windspeed encountered by a single fixed sensor may not be the maximum in the structure as a whole, nor will it spatially coincide with the peak pressure drop. Thus the spatial variability within a single dust devil may degrade the observed correlation of meteorological variables. This difficulty may be ameliorated by array measurements: measurements from a two-dimensional array (or a 1-D array normal to the direction of motion, as intended in Lambeth's experiments in 1959) will allow the instantaneous radial profile of a devil to be estimated (together with the azimuthal variance described above) and even if the core is not resolved directly, the miss-distance can be determined and corrected for.

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of dust devil structure. A key factor influencing the details of the profile is whether the flow is a one-cell vortex, wherein the radial flow is exclusively inward and upward, or a two-cell flow wherein there is a central downdraft and an annular convergence and updraft zone, as noted in laboratory experiments by Snow et al. (1980). This distinction, however, may be unimportant in the far field, i.e. in all but the closest encounters ($d < \sim 2\times r$).

5. Approaches for acquiring terrestrial comparison data

Several directions for acquiring fixed-station terrestrial data suitable for population estimation and Mars comparison are suggested here, but any such observation program will require a more sustained effort than has been executed previously for in-situ observations. If Ryan and Carroll’s (1970) statistics of 80 encounters in 30 days (of which days 19 were ‘favorable’) are representative, then acquiring a good dataset for Mars comparison (~100–200 events) from a single station, likely requires 1–2 months of consistent observation at 4 encounters/day. (It may be noted that those workers artificially ‘groomed’ the dust at their site regularly to encourage dust lifting.) There is some support for a several-encounters-per-day expectation: the Phoenix observation gives similar rate of encounters of $>3$/day (the Mars Pathfinder detection frequency was lower by virtue of a higher threshold of detection, missing smaller vortices, and a lower observation duty cycle). While the Lambeth (1996) study yielded only 0.16 dust devils/day, it is likely that a terrestrial study with modern instrumentation and a lower detection threshold might yield much higher counts, more comparable with those at Mars.

A first approach is to simply apply current methods (meteorological stations with conventional dataloggers, which an investigator can ill-afford to lose) in a more sustained way. Daily downloading of the high-cadence measurements is usually required, and attendance of observers is recommended to prevent theft or damage to visible meteorology masts and $>\$1000 dataloggers. The costs associated with dedicated personnel being present for $\sim 2$ months are significant, although if servicing the equipment and/or provision of security can be accomplished by other means (e.g. at a secure facility, and/or enlisting resident personnel to maintain the equipment) a program could be affordable.

New technologies, however, open up new possibilities. Lorenz (2010) suggests some data acquisition methodologies that may permit array measurements, and/or long-duration in-situ surveys, to be acquired affordably. Some key enabling technologies are (1) the availability of small, accurate, robust and inexpensive pressure transducers with adequate sensitivity and response time to study dust devils, (2) flash memory, which offers robust, compact and nonvolatile storage of large datasets, (3) easy to use microcontrollers to supervise sensor interrogation functions and/or to perform intelligent triggering of data acquisition and (4) the convergence of ever-decreasing electrical power requirements of the above and the availability of affordable solar cells that permit long-term field operation without battery replacement. These factors are not all required simultaneously—event-triggered data acquisition can ameliorate memory requirements, for example.

The affordability of sensor systems overall is a key issue. Arrays of many tens of stations are only practicable when individual stations cost a few hundred dollars, although this may entail some compromises e.g. in the fidelity of wind measurements. Similarly, if the hardware costs of stations are inexpensive compared with the costs of deployment, they can be considered ‘expendable’ and several can be installed and left unattended with the expectation that at least some will survive to acquire data. Measures such as camouflaging or installing at more remote and/or secure sites can enhance survival probability. If a large number of stations is available, they can be deployed in a close array, with the intent of measuring the horizontal variation of parameters associated with individual dust devils, or in a wider array, with the intent of acquiring a large number of single-station encounters, or some hybrid of these two end-members.

A final possibility is to exploit existing infrastructure. Conventional meteorology installations – many of whose data can be interrogated via the internet – typically only record data every 15 min or so. This is however a rather arbitrary cadence, imposed via the station software following meteorological tradition. In principle a software adjustment might permit more rapid sampling. There is also at least one class of widespread pressure measurement system with a high measurement cadence and very high resolution. Infrasound monitoring via microbarometers has been introduced at a number of locations worldwide as part of the monitoring effort in support of the Comprehensive Test Ban Treaty on nuclear weapons (pressure waves from nuclear explosions, especially above ground, are a useful adjunct to seismic records in determining detonation conditions, yield and location). These pressure data are often made available online and can be queried on the web. Most stations, of course, are not in locations of interest for dust devils, being in nondesert regions or sites where dust devils are otherwise uncommon but it seems certain that at least some may be. It may be also hoped that the number of stations for which these types of data are recorded may increase, since the existing data acquisition infrastructure for seismic motion detection, data recording and distribution means that the incremental cost of providing microbarometer data (or indeed full meteorology variables such as windspeed and direction) is rather modest.

6. Conclusions and recommendations for future work

This paper has shown that the Mars Pathfinder and Phoenix datasets of pressure drops both appear consistent with power law distributions with differential slopes of about $\sim 2$, a distribution also seen for diameters at Gusev by the Spirit rover. Comparable terrestrial data do not exist, but some avenues by which they might be obtained, and the statistical requirements for determining whether they show the same population as Mars have been described.

In addition to securing and evaluating comparable terrestrial data, it remains in future to reconcile the populations of dust devil diameters observed optically with those estimated from in-situ meteorology data. One possible approach, well beyond the scope of the present work, would be to construct a model wherein dust devils in a test region are simulated with functions that describe their formation, growth, motion and decay, functions for pressure and wind fields, etc. Coupled with simulations of observation processes, such a model could create synthetic datasets that take into account, for example, the effects of miss distance on in-situ data, and size-dependent detection efficiencies, camera fields of view and image acquisition cadence for imaging. To continue the wildlife analogy, a variety of statistical approaches in this vein, often using Bayesian methods to jointly estimate the population and detection efficiencies, have been applied in wildlife observation—a prominent example is the census of Alaskan Bowhead Whales using combined visual observation and hydrophone data (Raftery and Zeh, 1998), this census being used to determine whaling quotas. Such a model could not only reconcile in-situ measurement and imaging perspectives but could also quantitatively connect observations of dust tracks with those of...
the dust devils themselves and thereby constrain the migration and longevity of these fascinating structures.

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