Dust Devils Throughout the Solar System

Brian Jackson[1] (bjackson@boisestate.edu), Ralph D. Lorenz[2], Jason W. Barnes[3], and Michelle Szurgot[1], [1]Department of Physics, Boise State University, 1910 University Drive, Boise ID 83725-1570 USA; [2]Applied Physics Laboratory, Johns Hopkins University, Laurel MD 20723-6099 USA; [3]Department of Physics, University of Idaho, Moscow ID 83844-0903 USA

Introduction: Dust devils are dry, low-pressure vortices that lift dust and have diameters of a few to hundreds of meters. They may occur wherever dust grains are present and whenever atmospheric conditions support convection. On Earth, dust devils may contribute 30+% to the global dust flux [1], while on Mars, they may dominate the dust budget [2]. Dust devil structures depend on the ambient conditions under which they form, and, as we show, thermodynamic and angular momentum considerations relate these conditions to a dust devil's physical properties. Observations of active dust devils throughout the solar system can refine these relationships. And dust devil observations may soon extend to the Saturnian system: conditions near the surface of Saturn's moon Titan suggest dust devils may stalk Titan's equatorial dune fields. Indeed, Cassini data confirm an active aeolian cycle on Titan [3], and dust devils may significantly contribute to aeolian transport on that world. NASA's Dragonfly mission to Titan will document dust devil activity; however, as we show here, dust devil likely pose no hazard to the mission.

The Relationship between Dust Devil Properties and Atmospheric Conditions: The martian dust cycle is driven, at least in part, by dust devils, but estimates of their contributions range from 10% [4] to more than 70% [2]. Key to resolving this uncertainty is an accurate assessment of the martian dust devil population and its dust-lifting potential, which depend on their wind speed profiles (which determines how effectively they sweep up dust grains) and their sizes (which sets the area over which grains are swept). In spite of decades of lab, field, and numerical experiments [5], the relationships between these properties remain unclear.

Previously developed thermodynamic relationships combined with assumptions about angular momentum conservation provide simple scaling relationships for these parameters, however. To begin with, surface heating results in positive temperature and negative pressure excursions in a dust devil, which both fall off with radial distance. The buoyant air ascends to roughly the top of the planetary boundary layer PBL [6]. Meanwhile, near the surface, surrounding air is drawn in, conserving vorticity and giving a tangential wind field. Dust devils are typically embedded in a non-uniform wind field with a lateral shear along the surface, and the devil's angular momentum likely derives from the difference in velocity from one side of the devil's area of influence to the other. As discussed in [7], combining these assumptions gives the following relationship:

$$R \sim \alpha^{-1} n^{-2} \left(\frac{\gamma R_{\star} \Delta T}{H} \right)^{1/2} h^{1/2}, \qquad (1)$$

In this equation, R is a dust devil's eyewall radius, α the lateral wind shear, n the number of radii R out to which a dust devil draws angular momentum, $R_{\star}$ the gas constant, ΔT the positive pressure perturbation at the devil's center, H the atmospheric scale height, and h the height of the dust devil.

Although Equation 1 provides a relationship between R and h, it involves several parameters that are difficult to measure in practice. For instance, surveys of martian dust devils using space-based imagery can provide heights and radii, given sufficient resolution, but not α or ΔT. However, we may expect that the unmeasured variables exhibit a range of values for any given h. With a sufficiently large population of dust devils, the underlying relationship ought to emerge. To test Equation 1, we analyzed data from the survey of [8], which provides diameters and heights for nearly 200 active devils using the Mars Express High Resolution Stereo Camera. Figure 1 (taken from [7]) shows the resulting fits, first (solid, orange curve) assuming $R \propto h^{\Gamma}$ with Γ allowed to float, and second with fixed $\Gamma = 1/2$.

The scalings here suggest other relationships that can be tested. For instance, a similar scaling relationship applies for the eyewall velocity, $\upsilon \propto h^{1/2}$. Steady state within a dust devil requires that the mass flux of dust must scale with the momentum flux of the wind, which turns out to imply that the dust carried by a devil should also scale with h.

Dust Devils on Titan: Saturn's moon Titan is the only satellite in our solar system with a significant atmosphere, and the Cassini mission observed clear signs of an active aeolian cycle: fields of giant sand dunes girding Titan's equator [9] and equatorial dust storms [3]. The dust storms' appearance not only confirms an active dust cycle but also suggests the possibility of dust devils on Titan.

To assess that possibility, we considered near-surface meteorological measurements returned by the Huygens probe, including the potential temperature and wind profiles, as well as results from terrestrial and martian in-

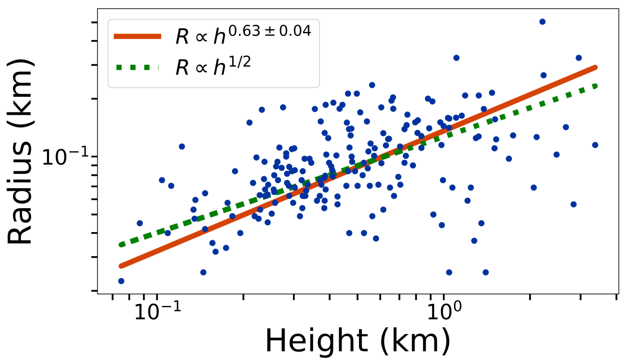

Figure 1: Dust devil heights h and radii R in kilometers reported in [8]. The solid, orange line shows a best-fit $\Gamma = 0.63$, while the dashed, green line fixes $\Gamma = 1/2$.

situ studies of dust devils (Jackson et al. 2020, in review). This analysis suggested a PBL at least $440\,\mathrm{m}$ deep, consistent with previous studies [10, 11]. Theoretical and field studies suggest both that a deeper PBL promotes dust devil occurrence and that vigorous convection requires a minimum positive temperature [cf. 12]. We find that, for temperature perturbations as small as $0.2\,\mathrm{K}$ (much smaller than variations observed across Titan - [13]), Titanian dust devils may exhibit eyewall velocities $\geq 1\,\mathrm{m/s}$ but not greater than $6\,\mathrm{m/s}$, small enough not to pose a hazard to Dragonfly. For a PBL $440\,\mathrm{m}$ deep, theory and observation (Jackson et al. 2020, in review) suggest dust devil diameters of several tens of meters and an areal occurrence rate of a few tens per square kilometer. We estimate that dust devils might loft many orders of magnitude times more dust than is deposited by photochemical haze production [14].

With this size and occurrence rate, we can estimate how often the Dragonfly mission might encounter dust devils. With a flight speed of $10\,\mathrm{m/s}$ [15], we expect two or three encounters an hour. However, Dragonfly will fly in Titan's morning, when dust devils are probably inactive, and so encounters will take place with Dragonfly on the ground. With travel speeds $\sim 1\,\mathrm{m/s}$ [16], one devil may pass over Dragonfly every four hours, with perhaps 15 encounters during each 64-hour mid-day period on Titan. These encounters will resemble those on Mars by landed spacecraft, during which imagery and meteorological data reveal internal structures and dust loads. Thus, if dust devils are active in regions explored by the mission, Dragonfly is likely to encounter them.

References

[1] M. Klose and Y. Shao. A numerical study on dust devils with implications to global dust budget estimates. *Aeolian Research*, 22:47–58, 2016. doi:10.1016/j.aeolia.2016.05.003.

[2] L. Fenton, et al. Orbital Observations of Dust Lofted by Daytime Convective Turbulence. *Space Science Reviews*, 203:89–142, 2016. doi:10.1007/s11214-016-0243-6.

[3] S. Rodriguez, et al. Observational evidence for active dust storms on Titan at equinox. *Nature Geoscience*, 11:727–732, 2018. doi:10.1038/s41561-018-0233-2.

[4] R. Greeley, et al. Active dust devils in Gusev crater, Mars: Observations from the Mars Exploration Rover Spirit. *Journal of Geophysical Research (Planets)*, 111:E12S09, 2006. doi:10.1029/2006JE002743.

[5] Jim Murphy, et al. Field Measurements of Terrestrial and Martian Dust Devils. *Space Science Reviews*, 203(1-4):39–87, 2016. doi:10.1007/s11214-016-0283-y.

[6] L. K. Fenton and R. Lorenz. Dust devil height and spacing with relation to the martian planetary boundary layer thickness. *Icarus*, 260:246–262, 2015. doi:10.1016/j.icarus.2015.07.028.

[7] Brian Jackson. On the relationship between dust devil radii and heights. *Icarus*, 338:113523, 2020. ISSN 0019-1035. doi:https://doi.org/10.1016/j.icarus.2019.113523.

[8] Christina Stanzel, et al. Dust devil speeds, directions of motion and general characteristics observed by the Mars Express High Resolution Stereo Camera. *Icarus*, 197(1):39–51, 2008. doi:10.1016/j.icarus.2008.04.017.

[9] J. Radebaugh, et al. Dunes on Titan observed by Cassini Radar. *Icarus*, 194(2):690–703, 2008. doi:10.1016/j.icarus.2007.10.015.

[10] Tetsuya Tokano, et al. Titan's planetary boundary layer structure at the Huygens landing site. *Journal of Geophysical Research (Planets)*, 111(E8):E08007, 2006. doi:10.1029/2006JE002704.

[11] Ralph D. Lorenz, et al. A 3 km atmospheric boundary layer on Titan indicated by dune spacing and Huygens data. *Icarus*, 205(2):719–721, 2010. doi:10.1016/j.icarus.2009.08.002.

[12] S. Rafkin, et al. Dust Devil Formation. *Space Science Reviews*, 203(1-4):183–207, 2016. doi:10.1007/s11214-016-0307-7.

[13] V. Cottini, et al. Spatial and temporal variations in Titan's surface temperatures from Cassini CIRS observations. *Planetary and Space Science*, 60:62–71, 2012. doi:10.1016/j.pss.2011.03.015.

[14] Erik J. L. Larson, et al. Simulating Titan's aerosols in a three dimensional general circulation model. *Icarus*, 243:400–419, 2014. doi:10.1016/j.icarus.2014.09.003.

[15] R. D. Lorenz, et al. Dragonfly: A Rotorcraft Lander Concept for Scientific Exploration at Titan. *Johns Hopkins APL Technical Digest*, 34:374–387, 2019.

[16] Juan M. Lora, et al. GCM simulations of Titan's middle and lower atmosphere and comparison to observations. *Icarus*, 250:516–528, 2015. doi:10.1016/j.icarus.2014.12.030.