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Solar heating of suspended particles and the dynamics of Martian dust devils

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[1] The heat input to Martian dust devils due to solar warming of suspended particles is assessed based on a prior estimate of dust loading and from an analysis of shadows cast by dust devils in images taken from orbit. Estimated values for solar heating range from 0.12 to 0.57 W/m^3 with associated temperature increases of 0.011 to 0.051°C per second. These warming rates are comparable to the adiabatic cooling rate expected for a gas parcel rising on Mars with a vertical velocity of 10 m/s. Solar warming of suspended dust serves to maintain buoyancy in a rising dust plume and may be one cause for the large scale of dust devils observed on Mars. **Citation:** Fuerstenau, S. D. (2006), Solar heating of suspended particles and the dynamics of Martian dust devils, *Geophys. Res. Lett.*, *33*, L19S03, doi:10.1029/2006GL026798.

1. Introduction

[2] Since the discovery of dust devils, rotating columns of unstable air, on Mars [*Ryan and Lucich*, 1983; *Thomas and Gierasch*, 1985] significant effort has been directed at understanding the formation and dynamics of these atmospheric vortices. Of particular interest are explanations for the relatively high numbers of dust devils in certain regions on the Martian surface and the enormous size of some of these dust columns relative to their terrestrial counterparts. The interest in Martian dust devils has lead to recent models of the vortex fluid dynamics [*Renno*, 1998] and the meso-scale environments [*Toigo et al.*, 2003] in which they occur. Scaling arguments based on low-density flow analysis suggest that boundary layers on Mars in general should be larger than comparable flow features on Earth [*Greeley and Iverson*, 1985]. Similarly, the Grashof number used to compare the dynamics of freely convecting systems, indicates that a characteristic dimension for a thermally buoyant plume in the 1% atmospheric density on Mars would be about twenty times that for a plume under the same temperature gradient driving force on Earth [*Traugott and Yamamura*, 1975]. Another aspect of the low density atmosphere on Mars is a greatly reduced heat capacity in comparison to Earth's atmosphere. The following observations suggest that the effect of a low heat capacity on dust devil dynamics can be significant and may provide a possible explanation for the prevalence and large scale of Martian dust devils.

2. Solar Heating of Suspended Dust Particles

[3] The environments in which dust devils occur on Earth and Mars are similar except for the density of the atmosphere. The relevant temperature range on Mars is 225 K–290 K and on Earth, 280–320 K. The solar intensity at the surface during which dust devils can form ranges from 300 to 500 W/m^2 on Mars and roughly 900–1100 W/m^2 on Earth. The gravitational field on Mars is 0.38 g. The density of the Martian atmosphere (0.013 kg/m^3) however, is just 1% of that on Earth (1.22 kg/m^3). Somewhat surprising is the fact that despite its low density, the atmosphere of Mars is just as able to support suspended dust particles as our own atmosphere. This capability to suspend dust is illustrated in Figure 1, a plot of settling velocity vs. particle size for Earth and Mars. As the plot illustrates particles with diameters ranging between 10 μm and 300 μm will fall at the same rate on Mars as they do on Earth. This comparison was previously made by *Murphy et al.* [1990], but it warrants emphasis here because this behavior of particles in low density atmospheres is perhaps not a very intuitive one. Particles smaller than 10 μm will fall faster on Mars due to the larger mean free path of the gas. Similarly, larger bodies (d > 300 μm) on Mars will fall at roughly ten times the velocity that they would on Earth because their profile drag is proportional to ρu^2, where ρ is the gas density and u is the velocity. However, in the intermediate size range the drag experienced by a spherical particle is determined according to the viscous flow, or 'Stokes', regime. In this regime the drag force F resisting that of gravity is given by:

$$F = C_d \rho u^2/2\ A = m_p g \quad (1)$$

$$C_d = 24/Re = 24\mu/\rho u\ D_p \quad (2)$$

where A is the particle cross sectional area, Re is the Reynolds number, μ is the gas viscosity, and D_p and m_p are the particle diameter and mass. When equation 2 is substituted for C_d in equation 1, ρ cancels out, and the expression for the particle drag is independent of gas density. Therefore, in the Stokes regime, the only aspect of the atmosphere influencing particle drag is viscosity, a property that is independent of pressure and that varies in proportion to the square root of the gas temperature. Because the low density atmosphere of Mars exhibits, to first order, the same viscosity as Earth's atmosphere, particles over a wide range of sizes settle at the same rate. The mechanism by which particles become suspended due the action of wind, however, is highly dependent on the atmospheric density for reasons first pointed out by Bagnold over 50 years ago [*Bagnold*, 1941], and much progress has been made in furthering understanding of this mechanism since then [*Greeley et al.*, 1980]. Nevertheless, without stating anything about suspension mechanisms, one can conclude that Martian dust devils have the possibility of

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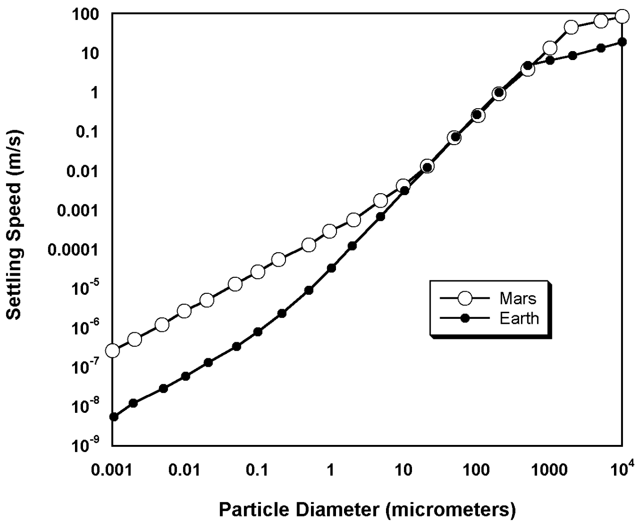

Figure 1. Calculated particle settling velocity (meters/second) as a function of particle diameter (micrometers) on Earth and Mars.

carrying dust loads comparable to their terrestrial counterparts. Preliminary measurements by *Metzger et al.* [1999] have found this indeed to be the case.

[4] When sunlight falls on a cloud of suspended dust, a fraction of that radiant energy is absorbed by particles, which in turn quickly transfer the additional heat to the surrounding gas, warming it. The effect was recently postulated by Lorenz who attempted to observe it in terrestrial dust devils [*Lorenz*, 2004]. In the hypothetical case of two clouds of equal dust concentration with roughly equal levels of sunlight impinging on them, one on Mars and one on Earth, the amount of absorbed energy will be comparable in both cases. In the case of the cloud in the 1% atmosphere of Mars, however, the resulting temperature rise ΔT in the surrounding gas will be 100 times greater than for the same dust cloud on Earth. Therefore, what is a small degree of temperature rise due to solar warming in terrestrial dust clouds could be very substantial on Mars. To state it another way, the heat capacity of the gas contained in a Martian dust devil is a hundred times smaller (due to the 1% density) than that in a terrestrial dust devil, resulting in a relative hundred-fold larger temperature rise for the same heat input.

[5] Solar heating of Mars' thin atmosphere due to suspended dust has been extensively modeled over the past 3 decades starting with the work of *Gierasch and Goody* [1972], and temperature increases of 50°C have been measured for the upper Martian atmosphere during dust storm events on Mars [*Zurek et al.*, 1992]. Such temperature increases in the Martian atmosphere, both in models and observation, take place over time scales of one day. In contrast, the residence time of the gas in a rising dust devil plume is only 1 to 5 minutes; a duration seemingly too short for any appreciable solar warming to take place. However, when one considers that dust loading in a Martian dust devil can be three or four orders of magnitude greater than in the surrounding atmosphere, the possibility of rapid warming from sunlight becomes more plausible. Metzger and coworkers concluded that a 10 meter wide dust devil captured by the Mars Pathfinder camera contained 7×10^{-5} kg of dust per cubic meter while the background atmospheric dust content was estimated to be 9×10^{-9} kg per cubic meter [*Metzger et al.*, 1999].

[6] An estimate of the solar heating in the Martian dust devil described by *Metzger et al.* [1999] can be made with assumptions about the dust particle size and absorption properties. By analyzing images of the sun taken from the surface of Mars, *Tomasko et al.* [1999] estimated that the mean diameter of suspended particles is 3 micrometers. Data from the same study, integrated over the visible solar spectrum, indicates that 11% of the incident energy is absorbed by dust particles, and 89% is scattered. Multiplying the cross sectional area of a 3 micrometer particle (7×10^{-12} m^2) by the number of particles (1.7×10^9) in a cubic meter containing 7×10^{-5} kg of mineral dust (density 3 g/cc) yields an estimated total cross sectional area of 0.012 m^2 per cubic meter. Taking 430 W/m^2 as the irradiance from the afternoon sun on Mars one estimates that 5.2 watts of energy impinges on the dust in that cubic meter. Of this intercepted energy, 11% or 0.57 watts, is absorbed and converted into heat. Warm dust grains quickly transfer excess heat to the surrounding gas maintaining local thermal equilibrium. The heat capacity of CO_2 is 860 J/kg-K and the density of the Martian atmosphere at 7 mBar and 270 K is 0.013 kg/m^3. Using these values one may calculate that warming a cubic meter of Martian atmosphere with 0.57 watts will raise its temperature by 0.051°C per second. If the volume of gas were carried aloft in a dust devil with a vertical speed of 20 m/s it would warm by 2.6°C in the time it would take to reach an altitude of 1 km. If the dust column were rising at 10 m/s, the effective temperature rise at 1 km would be 5.2°C.

3. Analysis of Martian Dust Devil Shadows

[7] A more direct estimate of the solar radiation absorbed within a dust devil plume may be obtained by analyzing the depth of shadows cast by dust devils as observed from orbit. Light levels within the dust devil shadow and non-shadowed regions of such images provide a measure of the sunlight blocked by the dust column. The fraction of sunlight that is 'missing' from the dust devil's shadow provides a good estimate of the energy scattered and absorbed by particles within the column. In addition, the dimensions of the shadow and bright plume provide a rough measure of the height and volume of the column within which the absorbed fraction of the blocked sunlight is converted to heat. The analysis requires consideration of the indirect sunlight, (i.e. light scattered by the surrounding dusty atmosphere) as well as direct sunlight as is illustrated in the following example of this approach.

[8] One of several images of dust devils captured by Mars Orbiter Camera (MOC) aboard MGS is depicted in Figure 2. This particular image (MGS MOC Release No. MOC2-1231, 25 September 2005) is useful because it contains both a shadow of arbitrary magnitude cast by a dust devil, and darker shadows caused by terrain whose depth indicate the intensity of the indirect sunlight. A study of the photograph with image analysis software (Scion Image, Scion Corporation, release 4.0.1) yields the following relative light intensities on a scale from 0 to

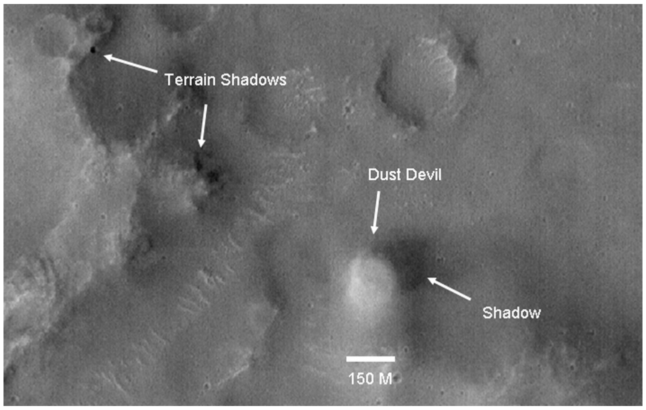

Figure 2. Image of Loire valley dust devil captured by the Mars Global Surveyor orbiter (MGS MOC Release No. MOC2-1231, 25 September 2005, incident sun angle 34.9°) used to determine the intensity of direct and indirect illumination of the plume. Absorbed solar radiation is estimated from the depth of the shadow cast by the dust devil. Image: NASA/JPL/Malin Space Science Systems.

255. Average intensities for deep terrain shadows and sunlit plain are 36 and 113 respectively. These values are consistent with a relatively dust free Martian atmosphere (optical density ~0.5) previously estimated to have a roughly 2 to 1 ratio of direct to indirect illumination [*Landis et al.*, 2004]. Assuming a noon time flux of 440 W/m^2 and correcting by the cosine of the incident angle of the sun at the time the image was taken (34.9°), the flux of direct sunlight to the surface in this image is estimated at 360 W/m^2.

[9] The relative intensity of the light in the dust devil shadow is 66. The indirect component of the illumination can be isolated from the dust devil shadow region and the surrounding plain by subtracting 36, the average intensity measured in terrain shadows, to yield direct illumination components for the shadow and plain region of 30 and 77 respectively. When the direct illumination components are thus compared one may conclude that only 39% (30/77) of the direct sunlight penetrates the dust cloud. In other words 61% of the direct sunlight, an effective 220 W/m^2, is 'missing' from the shadow. The shadow appears to cover 17,400 square meters and hence an estimated 3.8 million J (17,400 m^2 × 360 W/m^2) of energy is intercepted by the suspended dust each second. If we assume that 11% of this energy is absorbed by the particles and converted to heat that is transferred to the gas in the column, then direct sunlight pumps 4.2×10^5 Watts of heat into the dust devil. The 200 meter height of the plume is calculated by dividing the length of the shadow (140 meters) by Tan (34.9°). If the dust devil plume has a width of 150 meters then the volume of the cylindrical plume is estimated to be 3.5×10^6 cubic meters. Thus on average, each cubic meter of this dust devil is warmed by 0.12 Joules of heat per second. Dividing this value by 0.013 kg/m^3 and the gas heat capacity (860 J/kg-K) yields the result that the atmosphere inside the dust column is warmed by 0.011°C per second. If the warming due to indirect sunlight scattered from the particles in the surrounding atmosphere is taken into account, this estimate for the heating rate could increase by an additional 50% or more.

[10] Solar warming of suspended dust works to maintain buoyancy in the rising dust column by reducing, or even reversing, the cooling that occurs through adiabatic expansion. The principle is illustrated in Figure 3 which is a plot of gas temperature as a function of altitude. Because atmospheric pressure decreases with altitude, rising parcels of air undergo expansion and thereby cool. This rate of temperature decrease as a function of altitude is termed the dry adiabatic lapse rate and is a thermodynamic property of the atmosphere determined by composition, density, and gravitational field. On Mars the dry adiabatic lapse rate is 4.5°C/km [http//:pds.atmospheres.nmsu.edu]. The actual temperature variation with altitude, or the true lapse rate, has been determined with measurements from the Mars Global Surveyor orbiter and the Opportunity Mars Exploration Rover from the surface [*Smith et al.*, 2004]. Data representing the temperature profile above the Opportunity rover at 13:30 local time on sol 22 is plotted as curve "A" in Figure 3, while the adiabatic lapse 4.5°C/km rate is indicated as line "B". Without solar warming from suspended particles, gas inside a dust devil will rise until its temperature drops, through adiabatic cooling, to that of the surrounding atmosphere. At this point the gas inside the plume will no longer be buoyant and will cease climbing [*Barcilon*, 1967]. Solar warming of suspended dust will cause the gas inside the column to cool at a slower rate. If a warm gas plume rises at 10 m/s the temperature drop due to adiabatic cooling will be 0.045°C per second. Subtracting from this value the rate of solar warming calculated for the dust loading cases above yields an effective cooling rate for the rising gas inside the dust devils. Case "C" in Figure 3 represents the effective cooling rate (0.045 – 0.011°C/s) calculated from the shadow of the 25 September 2005 dust devil assuming a vertical rise rate of 10 m/s. Cases "D" and "E" are for gas parcels with the 7×10^{-5} kg/m^3 dust loading estimated by Metzger et al. assuming vertical

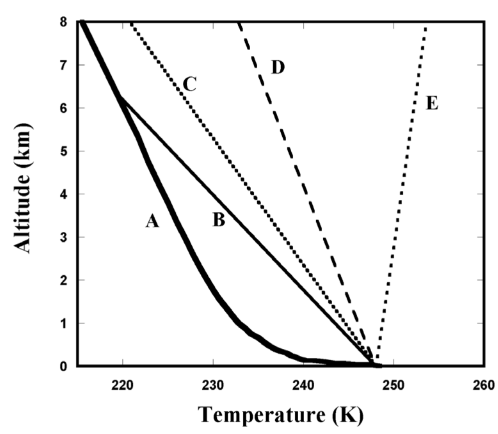

Figure 3. Temperature profiles: (A) measured above Opportunity rover at 13:30 local time on sol 22 by *Smith et al.* [2004], (B) dry adiabatic lapse rate for Mars ~4.5°C/km, (C) calculated for September 25, 2005 dust devil with estimated solar warming of 0.011°C/s, and a gas parcel with 7×10^{-5} kg/m^3 dust loading estimated by Metzger, et al.rising at 20 m/s (D) and 10 m/s (E).

velocities of 20 m/s (0.045–0.026°C/s) and 10 m/s (0.045–0.052°C/s) respectively.

4. Conclusion

[11] The above analysis does not address several aspects of the problem including the fact that the adsorption will not be uniform throughout a dust column if it has a high opacity. In high opacity dust devils solar warming would be expected to occur primarily at the edges of the plume as has been observed for larger dust storms on Mars [*Newman*, 2001]. What the analysis does indicate is that solar warming of suspended particles in Martian dust devils will lead to a heat input of a magnitude that is on the order of cooling from adiabatic expansion. The added buoyancy from this effect may provide one explanation for the large size and prevalence of Martian dust devils. The phenomenon is a major component of the thermodynamics governing dust devils on Mars and should be accounted for in local and meso-scale models.

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