

Fluid Transport on Earth and Aeolian Transport on Mars

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Experimental data on cohesion-free particle transport in fluid beds are applied, via a universal scaling relation, to atmospheric transport of fine grains on Mars. It may be that cohesion due to impact vitrification, vacuum sintering, and adsorbed thin films of water are absent on Mars—in which case the curve of threshold velocity versus grain size may show no turnup to small particle size, and one micron diameter grains may be injected directly by saltation into the Martian atmosphere more readily than 100 micron diameter grains. Curves for threshold and terminal velocities are presented for the full range of Martian pressures and temperatures. Suspension of fine grains is significantly easier at low temperatures and high pressures; late afternoon brightenings of many areas of Mars, and the generation of dust storms in such deep basins as Hellas, may be due to this effect.

The Mariner 9 television observations of Mars, obtained over a year in orbit around that planet, have unveiled a wide range of features, stationary and time-variable, which appear explicable only in terms of aeolian transport of fine-grained material (Sagan *et al.*, 1972, 1973, 1974; Veverka *et al.*, 1974; Sagan and Veverka, 1975). The great Martian dust storms of 1971 and previous years provide quite independent evidence that substantial aeolian transport occurs at least episodically on Mars. All discussions of transport physics (Ryan, 1964; Sagan and Pollack, 1967, 1969; Hess, 1973; Greeley *et al.*, 1973; Sagan and Veverka, 1975) have been based on the book by Bagnold (1941), the relevant experiments for which were performed in the late 1930's. Recently, and in the Mars context, there has been further effort to perform wind tunnel experiments on threshold velocities (Greeley *et al.*, 1973). The present paper is an attempt to use experiments on the aqueous transport of fine grains on Earth to scale the problem of atmospheric transport of fine particles on Mars.

The upper curve of Fig. 1 is an averaged version of White's (1970) summary of the experimental data on cohesion-free transport of grains in water and oil. Ten sets of experiments are included. The ordinate in Fig. 1 is the threshold value, θ_0 , of the dimensionless entrainment function, which is a measure of the ratio of the mean fluid shear stress to the gravity stress on the topmost layer of grains. It is given by

$$\theta_0 = A^2 = \rho u_{*0}^2 / Dg(\rho_p - \rho), \quad (1)$$

where u_{*0} is the threshold frictional velocity to initiate grain motion, D is the grain diameter, g is the local acceleration due to gravity, ρ is the atmospheric density, and ρ_p is the density of the solid grain particles. θ_0 is the same as A^2 in Bagnold (1941). The abscissa in Fig. 1 is the frictional Reynolds number,

$$\text{Re} = Du_{*0}/\nu, \quad (2)$$

where ν is the kinematic viscosity of the fluid. θ_0 is a function of Re only for cohesionless flow (see, e.g., Raudkivi, 1967).

The experimental data on the threshold of grain movement are generally obtained

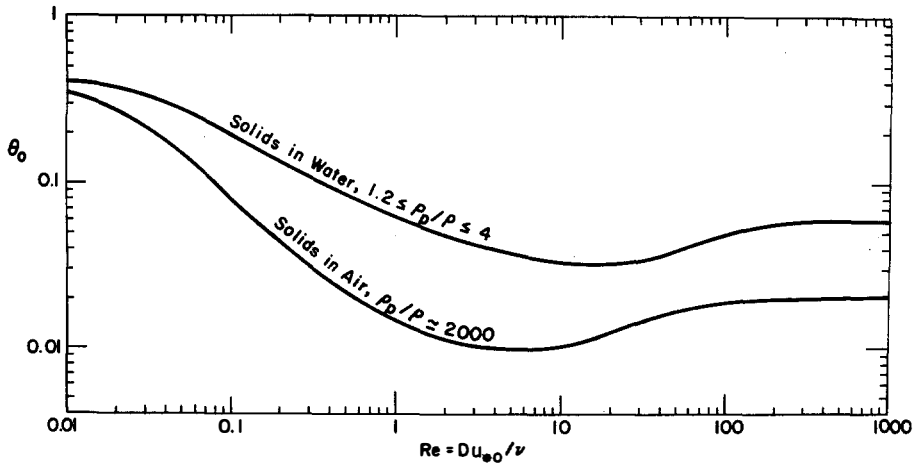


FIG. 1. Dependence of the threshold dimensionless entrainment function, θ_0 , on the frictional Reynolds number for two ratios of grain to fluid density. The upper curve is an averaged version of the experimental data, summarized by White (1970).

by gradually increasing the flow velocity over a grain bed whose surface is made as uniformly flat as possible. The observer notes the value of u_* at which grain motion seems, in his personal judgement, to have started. There being no precise definition of "first motion", this value, u_{*0} , may vary appreciably from one observer to another, not only subjectively but also with the observer's particular method of preparing the surface of the test bed. When, as with water or oil, the grain density ρ_p is but a small multiple of ρ the initial movement of the least securely lodged grain may cease when that grain has found a more secure lodgement. The visual impression of movement strengthens progressively as u_* is increased.

The lower curve of Fig. 1, also for cohesionless grains, is a modification of the upper curve necessitated for windblown sands by the 1000-fold increase in the density ratio. The first, now relatively very massive, grain to be moved impacts so violently with the sand surface at the end of its saltation as to eject more grains into the air stream and to form a small crater. It thus not only triggers an immediately observable chain reaction but also creates a number of insecurely lodged grains. As a result, the minimum value of θ_0 is reduced from 0.03 for solids in water to 0.01 for solids in a gas of air density. The values in

this lower curve of Fig. 1 are extrapolated from experimental data confined largely to the range $1 < Re < 10$. The minimum value of $\theta_0 = 0.01$ corresponds to the generally employed value $A = 0.1$. This minimum is reached at a Reynolds number of about 3.0. Since the atmospheric density on Mars is 10^{-2} that on Earth, and since the threshold frictional velocities there are an order of magnitude more than on Earth (see below), the appropriate dependence of θ_0 on Re for Mars should be a curve slightly below the lower curve in Fig. 1.

Since ν/u_{*0} is a measure of the thickness δ of the laminar boundary sublayer, Re is proportional to D/δ , and defines the degree to which the exposed surface grains project above or are submerged within the laminar layer. The flattish minimum of θ_0 occurs at a value of Re such that D projects above into the flow region of maximum turbulent intensity. The general shape of the $\theta_0 - Re$ curve together with the constant limiting values of θ_0 in water, 0.06 and 0.4, are in fact deducible from the known behavior of turbulent boundary flow (Raudkivi, 1967; Bagnold, 1956). Thus the quantitative relationships exhibited in Fig. 1 should be applicable generally, provided no other physical agency intervenes. White (1970) noted that no sign exists of any dependence of the upper curve of Fig. 1 on geometry, sorting, or angle of repose.

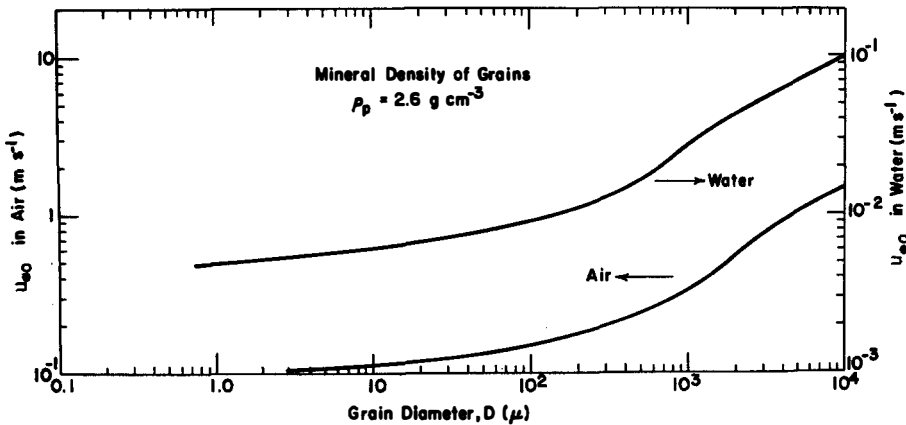


FIG. 2. Dependence of the threshold frictional velocity in air and in water on grain diameter (derived from Fig. 1).

Equations (1) and (2) can be rewritten to give expressions for u_{*0} and D :

$$u_{*0} = [\theta_0 g \nu (\rho_p - \rho) \text{Re} / \rho]^{1/3} \quad (3)$$

and

$$D = \{\rho \nu^2 (\text{Re})^2 / [\theta_0 g (\rho_p - \rho)]\}^{1/3}. \quad (4)$$

In Fig. 2 we see the dependence of the threshold frictional velocity on grain diameter for water and for air in terrestrial conditions with $\rho_p = 2.6 \text{ g cm}^{-3}$. Figure 2 is remarkable because it shows no small grain size turnup in u_{*0} . Such a turnup has been reported in a variety of experiments, both in air (Bagnold, 1941; Greeley *et al.*, 1973) and in water (Bagnold, 1941). Indeed, Bagnold (1941) concluded "that the refusal of fine surface particles to be moved by a wind is not entirely due to cohesion caused by adsorbed moisture but is a true phenomenon of fluid dynamics as proved by the corresponding behavior of sand in water." However, Bagnold then goes on to stress the difficulty of such measurements. We now believe that the early experimental data of Hjølstrom [quoted in Bagnold (1941, p. 90)] is in error; careful recent work in water by Mantz (1973) shows, between 16 and $76 \mu\text{m}$, no sign of a turnup. The upper curve in Fig. 1 is believed to be more reliable than the sparse and uncertain data which led to the preceding conclusion, and we now conclude that the small grain turnup in the threshold velocity curve is not chiefly a fluid dynamics effect.

It can, however, be readily understood in terms of cohesion—due, e.g., to a thin film of adsorbed moisture or to electrostatic effects. In either case, since the cohesion force varies as the grain area while the gravitational braking forces vary as the volume, the smaller grains (which have the larger ratio of area to volume) should preferentially cohere. Cohesion serves to increase the effective grain weight and in this case the turnup to small grain sizes has the same explanation as the turnup to large grain sizes—the fact that drag is an area force and gravity a volume force.

The Martian atmosphere is much drier than the driest desert regions on the Earth, and adsorbed moisture may play a negligible role in grain physics there. [But diffusion limitation on loss of liquid water from grain interstices has been proposed at least at certain times and places on Mars (Sagan *et al.*, 1968; Farmer, 1975), and adsorbed water may still play some role on Mars.] However, the clumping and aggregation of lunar fine grains smaller than a few tens of microns in diameter is well established (see, e.g., Quaide and Wrigley, 1972; McCay *et al.*, 1972; Görz *et al.*, 1972; King *et al.*, 1971); and that the lunar grains are completely dry is an extremely secure conclusion. The greater cohesion in lunar as compared to terrestrial grains has been noted repeatedly (e.g., Mitchell *et al.*, 1972). The clumping of small lunar grains is partly an effect of impact

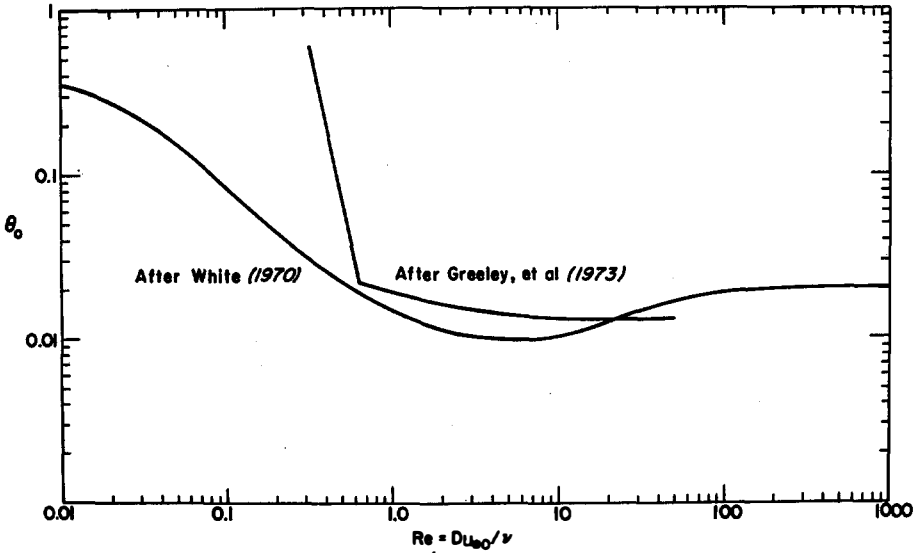


FIG. 3. A comparison of the functional dependence of the threshold entrainment function on the frictional Reynolds number for mineral grains in air. The experimental results of Greeley *et al.* (1973) are compared with the calculations of Fig. 1, lower curve.

vittrification and partly a vacuum sintering effect. Both effects become essentially negligible when a significant atmosphere is present.

Nevertheless, the character of the small

grain turnup is likely to be different for different clumping mechanisms, and it seems to be of some interest to carry the cohesion-free curves of Fig. 1 into the Martian context. Figure 3 shows a compari-

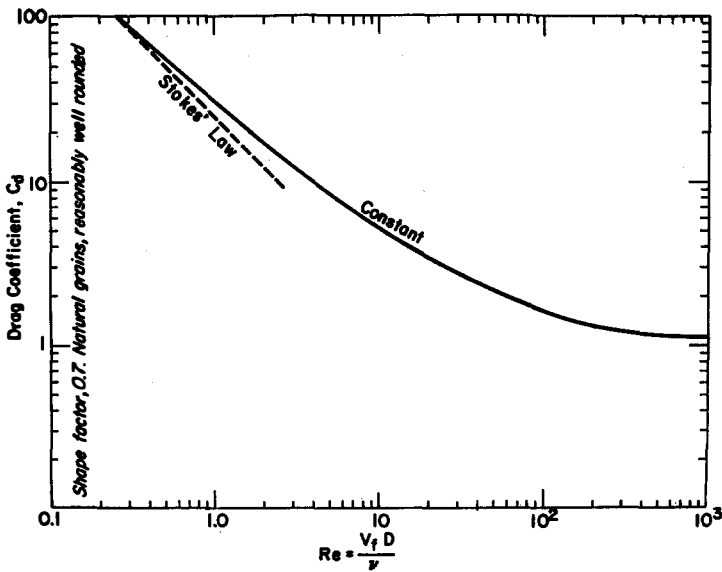


FIG. 4. The functional dependence of the drag coefficient for natural grains on the Reynolds number for the fall velocity. This relationship is expected to apply in all planetary atmospheres. Also shown is the Stokes' law approximation which holds for small Reynolds numbers.

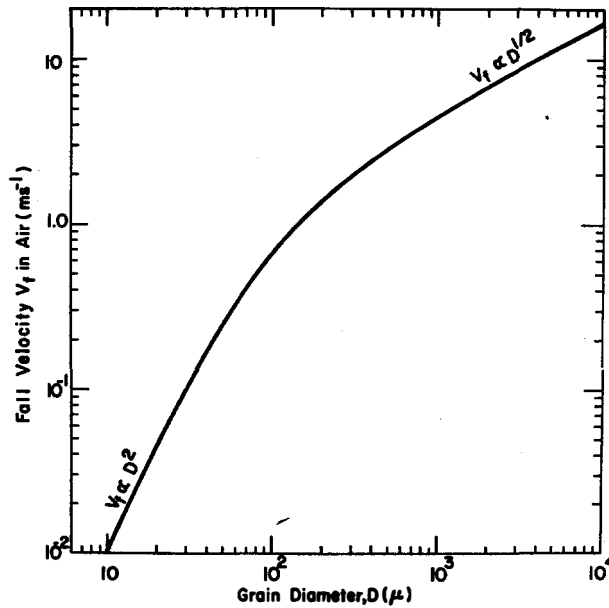


FIG. 5. Dependence of fall velocity on grain diameter for grains of density 2.6 g cm^{-3} falling in the Earth's atmosphere.

son of the $\theta_0 - \text{Re}$ curve of Fig. 1 with the same curve derived by Greeley *et al.* (1973) for a wide variety of materials of different density in a wind tunnel. The agreement is

only fair. The abruptness of the discontinuity near $\text{Re} = 0.7$ in the curve of Greeley *et al.* (1973) needs explanation.

It has recently been confirmed experi-

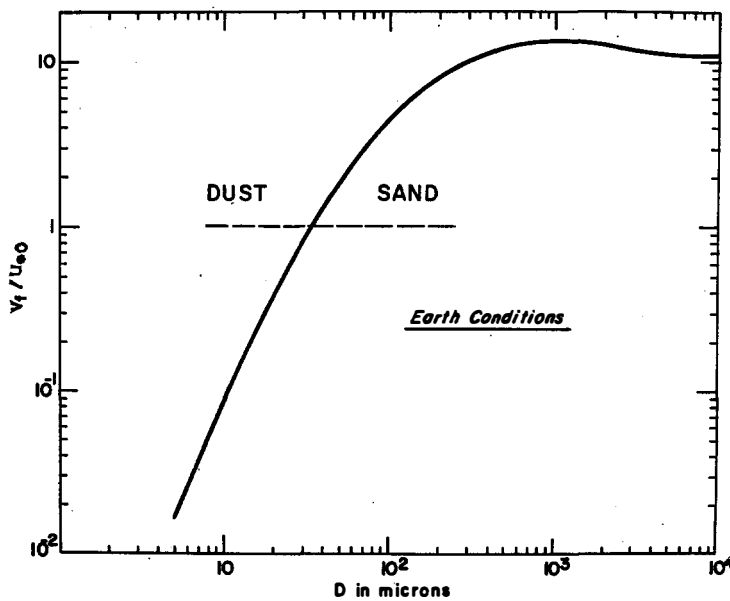


FIG. 6. The functional dependence of the ratio of fall velocity to threshold velocity on grain diameter for the Earth's atmosphere. The ordinate is unity at grain diameters of about $35 \mu\text{m}$, which is a convenient definition of the distinction between dust and sand.

mentally (Francis, 1973) that no appreciable suspension of small particles by upward turbulent eddies occurs until the mean normal eddy velocity component exceeds the fall velocity V_f of a grain through the fluid; that is, until u_* exceeds $0.8 V_f$. Thus, in general, there is a range of values of u_*/u_{*0} between 1 and V_f/u_{*0} within which grains are transported wholly in saltation rather than in suspension. Now

$$V_f/u_{*0} = [4/(3C_d \theta_0)]^{1/3},$$

which is a constant of the grains (Bagnold, 1973). Here C_d is the drag coefficient. Since both C_d and θ_0 increase with decreases in their respective Reynolds numbers, the range of the suspension-free saltation stage decreases progressively with decreasing grain size, until a certain small diameter is reached at which $V_f/u_{*0} \approx 1$; then the grains become suspended at the very threshold of movement.

In Fig. 4 we show the universal relation between the drag coefficient for the fall velocity and the fall velocity Reynolds number; while Fig. 5 exhibits fall velocity versus particle size for the conditions of the Earth's atmosphere. Values of $\rho_p = 2.6$

g cm^{-3} and $\nu = 0.14 \text{ cm}^2 \text{ sec}^{-1}$ are assumed. The resulting functional relation for the ratio of fall velocity to threshold frictional velocity as a function of particle diameter is given in Fig. 6. The two velocities are equal at grain diameters between 30 and 40 μm .

Now dune formation is confined to the saltation mechanism. Thus material having a dominant diameter less than 30 or 40 μm does not collect to build dunes, but is dispersed into the atmosphere (the smaller particles being carried to higher altitudes), is carried to great distances, and eventually settles out as a thin featureless deposit of dust. Terrestrial dune sand is rarely observed to have a dominant diameter less than 100 μm and the most common diameter lies between 250 and 300 μm . The finer material, the abundance of which declines rapidly with decreasing diameter in dune sand, has been carried away in suspension by strong winds.

Figures 7–10 each show curves for u_{*0} and V_f as a function of grain diameter for Mars, for four ambient temperatures: 150K, 200K, 250K, and 300K, and for six surface pressures between 1 and 15 mb. The temperature enters through the perfect gas law and through the assumed temperature

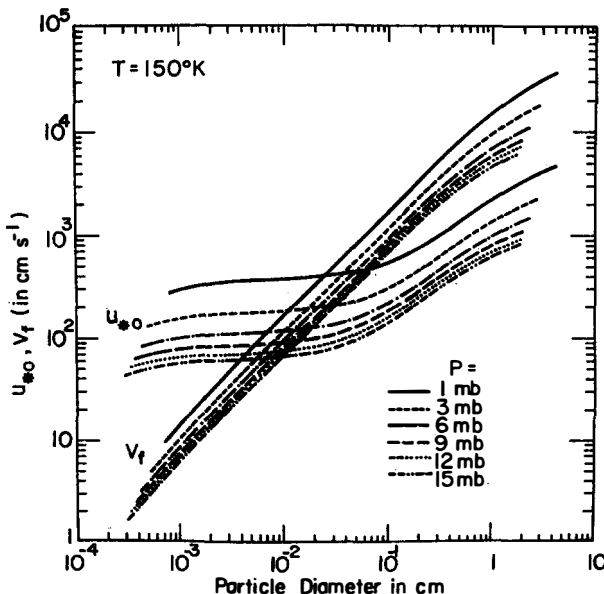


FIG. 7. The values of the threshold velocity and the fall velocity as a function of grain diameter for the Martian atmosphere. A temperature of 150 K is assumed.

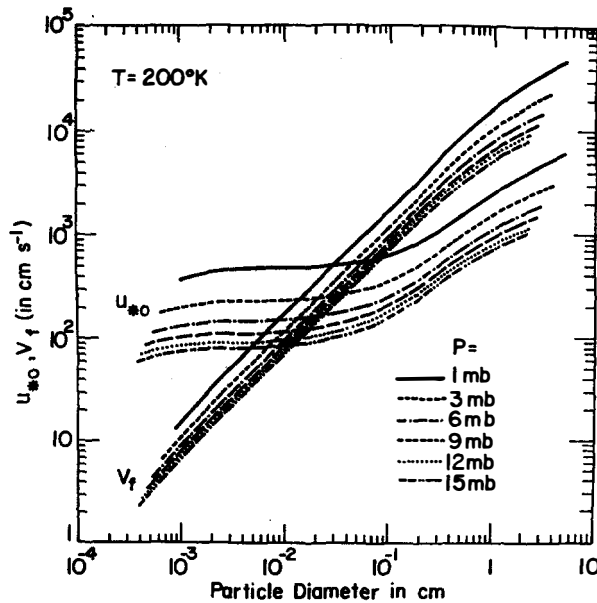


FIG. 8. The values of the threshold velocity and the fall velocity as a function of grain diameter for the Martian atmosphere. A temperature of 200 K is assumed.

dependence of the kinematic viscosity of the Martian CO_2 atmosphere:

$$\nu = [(1.46 \times 10^{-4})/\rho] (T/300)^{0.95} \text{ cm}^2 \text{ sec}^{-1}. \quad (6)$$

For a given pressure and temperature the intersection of the appropriate fall velocity curve and the threshold frictional velocity curve defines a vertical line which separates Martian sand from Martian dust. For

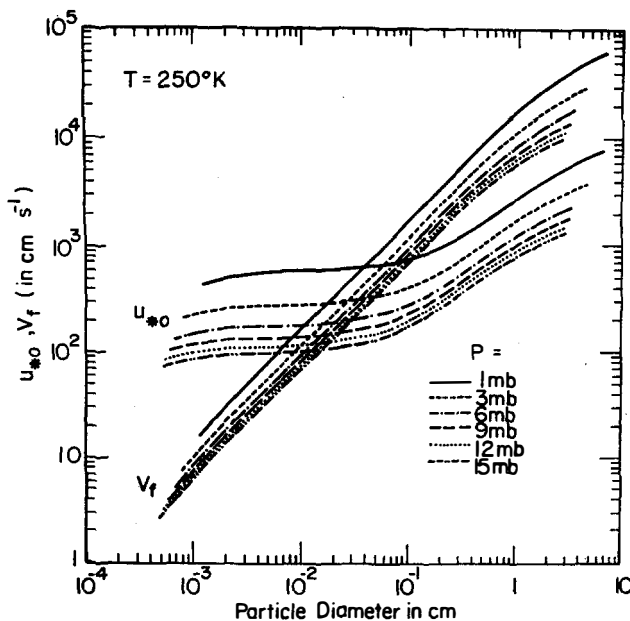


FIG. 9. The values of the threshold velocity and the fall velocity as a function of grain diameter for the Martian atmosphere. A temperature of 250 K is assumed.

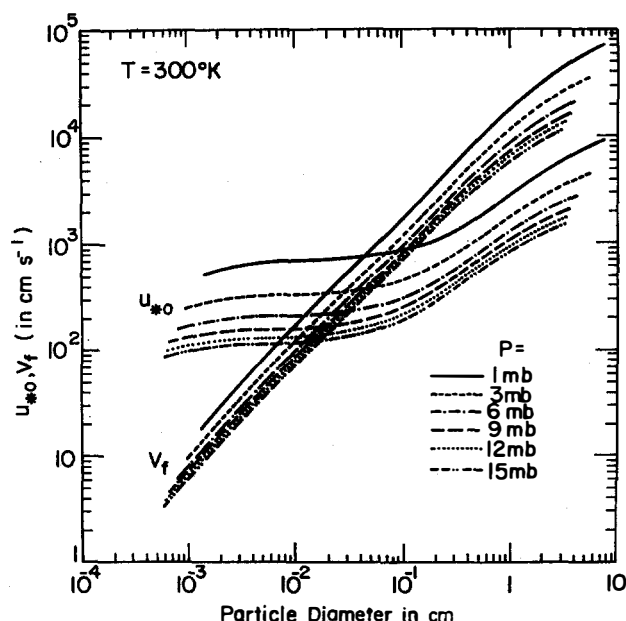


FIG. 10. The values of the threshold velocity and the fall velocity as a function of grain diameter for the Martian atmosphere. A temperature of 300 K is assumed.

example, for $T = 250\text{ K}$ and 6 mb pressure, the boundary between sand and dust occurs at about $200\mu\text{m}$ diameter, a few times larger than the comparable critical grain diameter for the Earth. Both from the very existence of dust storms and from a range of other data, it seems clear that saltation indeed occurs on Mars (Sagan and Pollack, 1969; Sagan *et al.*, 1972, 1973; Conrath *et al.*, 1973; Woiceshyn, 1975; Mass and Sagan, 1975). Thus larger grains can be put into suspension in the Martian than in the terrestrial atmosphere and dunes on Mars should be composed of larger particles than dunes on Earth.

Because they were derived from a scaling law based on aqueous transport, the curves for u_{*0} in Figs. 7–10 do not show a small grain turnup. The long shallow region of these curves, generally below $200\mu\text{m}$ diameter, corresponds to the minimum in curves which allow for cohesion. For $T = 250\text{ K}$ the flat part of u_{*0} corresponds approximately to 2 msec^{-1} for 5 mb pressure, in good agreement, considering the absence of a small grain turnup, with the result of 2.6 msec^{-1} derived by various authors who include the effects of cohesion

(see Sagan and Veverka, 1975). At the same temperature, 1 mb pressure corresponds to 6 msec^{-1} for the flat part of the curve. If a curve slightly below the lower curve in Fig. 1 had been employed the agreement would have been even better.

It seems possible that vacuum sintering of grains, and impact vitrification as on the Moon, does not occur on Mars because of the 5 mb pressure; and that cohesion by adsorbed films of liquid water also does not occur, because of the dryness of the Martian atmosphere. In this case the curves of, e.g., Fig. 9 may apply to the real Mars. Grains of a few μm diameter would then be more easily lifted than grains of a few hundred μm . Observations of the middle to late stages of the great 1971 dust storm clearly show a pronounced preponderance of particles a few μm in diameter (Conrath *et al.*, 1973; Pang and Hord, 1973; Moroz and Ksanfomaliti, 1972; Hartmann and Price, 1974; Toon *et al.*, 1975). This could be understood by the Stokes-Cunningham equation in which the smallest grains fall out last and are carried to the highest altitudes. On the other hand, the storm is generally understood as having a self-

sustaining aspect (Golitsyn, 1973; Gierasch and Goody, 1973; Hess, 1973), and limb photography by Mariner 9 is suggestive of many successive dust injection events (Sagan, 1972). If there is no small grain turnup of the threshold velocity on Mars, grains of a few microns diameter will be raised directly, by primary saltation events, as long as the threshold velocity is exceeded. The dust storm observations are consistent with, although not uniquely indicative of, such a picture.

Let us compare Figs. 7 and 10 for the case of a 6 mb surface pressure. We see that the curves for u_{*0} and V_f intersect at approximately 1.3 m sec^{-1} for $T = 150 \text{ K}$; and at $\approx 2.3 \text{ m sec}^{-1}$ for $T = 300 \text{ K}$. It is significantly easier to place fine dust in suspension on Mars at polar or nighttime temperatures than at equatorial or daytime temperatures. The results suggest that the major dust injection events may occur just before sunrise and in the polar winter, when direct optical frequency observations cannot be made (although infrared detection might be possible). It is just possible that the "dawn haze" on Mars—usually attributed to water condensation—has such an origin. Likewise, the raising of dust in the late afternoon should be easier than at midday; and some cases of late afternoon brightening on Mars, which has been observed for many decades, may be due to the greater ease of suspending dust grains in the thin Martian atmosphere at lower temperatures.

Likewise, suspension is significantly easier in higher pressures; for example, at $T = 250 \text{ K}$ and $p = 1 \text{ mb}$, a threshold frictional velocity as high as 6 m sec^{-1} is required. There is some observational evidence that such threshold velocities are occasionally achieved even at these pressures on Mars (Sagan *et al.*, 1974). At $T = 250 \text{ K}$ a threshold frictional velocity of only 1 m sec^{-1} is required at 15 mb pressure. In the deepest regions of Mars, such as the great Hellas basin, ambient pressures probably range as high as 9–12 mb. We see from Fig. 7 that at temperatures of 150 K the corresponding threshold frictional velocity is only about 0.7 m sec^{-1} for $u_{*0} = V_f$. Thus, even were there no higher wind velocities

in Hellas, it would be a priori the most likely place to raise dust on Mars. Since in addition, Hellas appears to have the highest vertical velocity components (relative to the ground) on the entire planet (Mass and Sagan, 1975) this provides a strong case for Hellas as a source of the major Martian dust storms. The dependence of u_{*0} on atmospheric density implicit in the above discussion is close to the $-\frac{2}{3}$ power, as expected directly from theory (Sagan and Pollack, 1967).

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