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A simple expression for wind erosion threshold friction velocity

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Abstract. Threshold friction velocity u_{*t} is the friction velocity at which wind erosion is initiated. While u_{*t} is affected by a range of surface and soil properties, it is a function of particle size only for idealized soils. In this paper we present a simple expression for u_{*t} for spherical particles loosely spread over a dry and bare surface. In this expression we consider the balance between the driving forces (aerodynamic drag and lift) and the retarding forces (cohesion and gravity) and assume that the cohesive force is proportional to particle size. It is found that u_{*t} can be expressed as $\sqrt{Y_1 d + Y_2 \frac{1}{d}}$, with Y_1 and Y_2 being empirical constants. The new expression is both simple and effective.

1. Introduction

Threshold friction velocity u_{*t} represents the capacity of an aeolian surface to resist wind erosion. Soil particles resting on the surface under the influence of an airstream experience several forces, including the aerodynamic drag F_d, the aerodynamic lift F_l, the gravity force F_g, and the interparticle cohesive force $F_\imath$. The driving forces for the liftoff of sand-sized particles are F_d and F_l, which are related to the wind shear near the surface and hence are functions of the surface friction velocity u_*. Threshold friction velocity is the minimum friction velocity required for wind erosion to occur. At $u_* = u_{*t}$ the aerodynamic forces just overcome the retarding forces (F_g and $F_\imath$) and initialize the movement of soil particles.

In reality, u_{*t} is affected by a range of factors such as soil texture, soil moisture, soil salt content, surface crust, the distribution of vegetation, and roughness elements. Under ideal conditions, u_{*t} can be expressed as a function of only particle size. The $u_{*t}(d)$ relationship for idealized conditions is important, as it defines the lower limit of u_{*t} for a given soil type. Several theories for $u_{*t}(d)$ exist, derived for soils with uniform and spherical particles spread loosely over a dry and bare surface [*Bagnold*, 1941; *Greeley and Iversen*, 1985; *Phillips*, 1980].

Bagnold [1941] derived a simple expression for $u_{*t}(d)$ by considering the balance between the aerodynamic drag and the gravity force and found that $u_{*t} \propto d^{1/2}$. The Bagnold expression describes well the behavior of u_{*t} for particles larger than approximately 100 μm but fails to predict the existence of the minimum of u_{*t} at around $d = 75$ μm and the subsequent increase of u_{*t} with decreasing particle size. *Greeley and Iversen* [1985] have taken into account the cohesive force and aerodynamic lift in addition to the aerodynamic drag and gravity force considered by Bagnold and found that u_{*t} is of the form

$$u_{*t} = A_1 \sqrt{\sigma_p g d} F(Re_{*t}) G(d) \qquad (1)$$

where F is a function of particle Reynolds number at threshold friction velocity, Re_{*t}, G is a function of particle diameter, σ_p is particle to air density ratio, and g is acceleration due to gravity. A_1, F, and G are estimated from wind tunnel measurements [*Greeley and Iversen*, 1985]. This expression overcomes the shortcomings of the Bagnold expression and is effective in describing the behavior of u_{*t} for the entire particle size range. However, the two empirical functions, $G(d)$ and $F(Re_{*t})$, have complex and irrational expressions that are possibly due to a misfit of $G(d)$.

In this paper we describe a new expression for u_{*t} that has a much simpler expression than the Greeley and Iversen one. The new expression also has more rational physical interpretations. When compared with the wind tunnel data, the new expression is equally effective as that of Greeley and Iversen.

2. Review of the Bagnold Expression and the Greeley-Iversen Expression

For a particle of size d, $u_{*t}(d)$ is determined by the balance of F_d, F_l, F_g, and $F_\imath$, as shown in Figure 1. At the instant of particle motion the combined retarding

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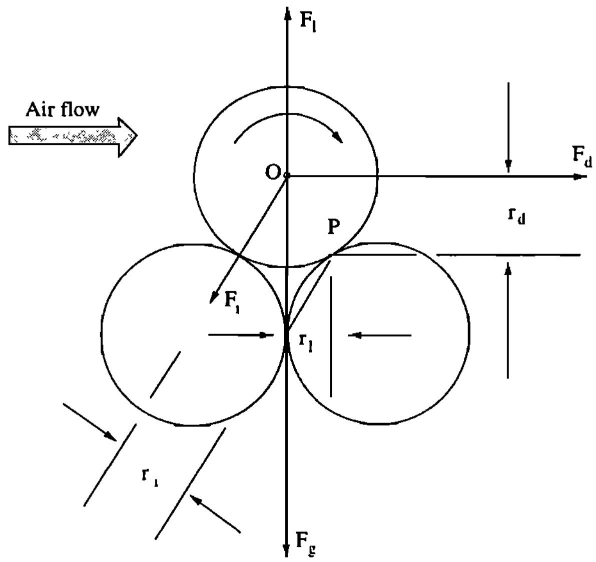

Figure 1. Forces acting on a particle resting on the surface under the influence of an airstream, including the aerodynamic drag F_d, the aerodynamic lift F_l, the gravity force F_g, the moment F_m, and the cohesive force F_i; r_d, r_l, r_m, and r_i are moment arm lengths associated with F_d, F_l and F_g, F_m, and F_i, respectively. O is the center of gravity of the particle, and P is the pivot point for particle entrainment.

effect of F_g and F_i will be overcome by the combined lifting effect of F_d and F_l. The particle will tend to pivot about point P in a downstream direction. The balance of forces at the instant of entrainment can be obtained by the summation of moments about the pivot point P,

$$r_d F_d + r_l(F_l - F_g) + r_m F_m - r_i F_i = 0, \quad (2)$$

where r_d, r_l, r_m, and r_i are moment arm lengths. In general, the moment arm lengths depend on the arrangements of particles and are difficult to determine. However, it is plausible to assume that they are all linearly proportional to the particle size and can be expressed as $r_d = a_d d$, $r_l = a_l d$, $r_m = a_m d$, and $r_i = a_i d$. It follows that

$$a_d F_d + a_l(F_l - F_g) + a_m F_m - a_i F_i = 0. \quad (3)$$

Bagnold [1941] derived a simple theory for $u_{*t}(d)$ by considering the balance between F_d and F_g:

$$a_d F_d - a_l F_g = 0. \quad (4)$$

The drag force on a particle protruding into the airflow can be written as

$$F_d = \frac{1}{2} C_{d,s} \rho A U, \quad (5)$$

where $C_{d,s}$ is the aerodynamic drag coefficient for the particle attached to the surface, ρ is air density, A is the particle cross section perpendicular to the flow, and U is the flow speed at a reference point, say, at the height comparable to the particle diameter. There are difficulties in implementing (5) because $C_{d,s}$ is not well understood and U is not well defined in a flow with a strong shear. A pragmatic approach is to relate F_d to u_* as

$$F_d = K_d \rho d^2 u_*^2, \quad (6)$$

where K_d is a function of the particle friction Reynolds number, defined as

$$Re_* = u_* d/\nu. \quad (7)$$

Assuming $a_d = a_l$ in (4), we obtain

$$u_{*t} = A_B(Re_{*t})\sqrt{\sigma_p g d}, \quad (8)$$

where A_B is a coefficient depending on Re_{*t}, the particle friction Reynolds number at the threshold friction velocity. A_B is called the dimensionless threshold friction velocity, as it can be expressed as

$$A_B = \frac{u_{*t}}{\sqrt{\sigma_p g d}}. \quad (9)$$

A_B has been found to be a constant between 0.1 and 0.2 for $Re_{*t} > 3.5$. Equation (8) implies that $u_{*t}(d)$ is proportional to $d^{1/2}$ for sufficiently large particle Reynolds numbers. Bagnold's prediction is illustrated in Figure 2. For grains larger than approximately 100 μm, the proportionality between u_{*t} and $d^{1/2}$ has been confirmed by experimental data. However, observations have also shown that a minimum u_{*t} exists around 75-100 μm, and for smaller particles, u_{*t} increases rapidly with decreasing d. The early interpretation of this phenomenon is that for $Re_{*t} < 3.5$, the particles lie below the viscous sublayer and are increasingly less susceptible to aerodynamic drag. In this case, the coefficient A_B is no longer a constant but increases rapidly with decreasing particle size, and therefore u_{*t} can no longer be considered to be proportional to $d^{1/2}$.

Iversen et al. [1976] pointed out that the rapid increase of threshold friction velocity with decreasing particle size is due to the interparticle cohesion, rather than the Reynolds number effect. *Iversen et al.* [1976], *Iversen and White* [1982] and *Greeley and Iversen* [1985] considered inter-particle cohesion and aerodynamic lift in addition to aerodynamic drag and gravity force considered by *Bagnold* [1941]. The aerodynamic drag, lift, and moment forces are all expressed as

$$F_d = K_d \rho u_*^2 d^2 \quad (10)$$
$$F_l = K_l \rho u_*^2 d^2 \quad (11)$$
$$F_m = K_m \rho u_*^2 d^2, \quad (12)$$

where K_d, K_l, and K_m, with magnitudes of around 4, 2, and 1, are dimensionless empirical coefficients associated with the aerodynamic drag, aerodynamic lift, and moment, respectively. It follows that

$$a_d F_d + a_l F_l + a_m F_m = (a_d K_d + a_l K_l + a_m K_m)\rho u_*^2 d^2. \quad (13)$$

Table 1. The Functional form of $F(Re_{*t})$ in the Greeley-Iversen Expression

Re_{*t}	A_1	$F(Re_{*t})$
$0.03 \le Re_{*t} \le 0.3$	0.20	$(1 + 2.5Re_{*t})^{-1/2}$
$0.3 \le Re_{*t} \le 10$	0.13	$(1.928Re_{*t}^{0.092} - 1)^{-1/2}$
$Re_{*t} \ge 10$	0.12	$1 - 0.0858\exp[-0.0617(Re_{*t} - 10)]$

As detailed information for the coefficients, such as a_d and K_d, is difficult to obtain, it is sensible to simply denote

$$a_t K_t = a_d K_d + a_l K_l + a_m K_m. \qquad (14)$$

Substituting (13) and (14) into (2) and using (9)-(14), we obtain

$$A_B^2 = \frac{a_l \pi}{6}[1 + \frac{6a_t}{\pi a_l}\frac{F_i}{\rho_p d^3 g}]/a_t K_t. \qquad (15)$$

Greeley and Iversen [1985] hypothesized that A_B is of the form

$$A_B = A_1 F(Re_{*t}) G(d), \qquad (16)$$

where F is a function accounting for the Reynolds number dependence of the aerodynamic drag, and G is a function of particle diameter, accounting for the effects of interparticle cohesive forces. The constant A_1 as well as the functions F and G are determined by fitting (15) to observed data. Measurements obtained in a series of wind tunnel experiments with a range of particle sizes, particle densities, and wind tunnel pressures have been used for the fitting [*Greeley and Iversen*, 1985]. It is found that

$$G(d) = (1 + 0.006/\rho_a g d^{2.5})^{1/2} \qquad (17)$$

and that $F(Re_{*t})$ is as shown in Table 1.

The behavior of (16) is depicted in Figure 2. The minimum of $u_{*t}(d)$ occurs at $d = 75$ μm; for particles larger than this, u_{*t} increases with increasing d (eventually with $d^{1/2}$) due to the increasing dominance of the gravity force. This result is in agreement with the expression of *Bagnold* [1941], as given in (8). For smaller particles, $u_{*t}(d)$ increases rapidly with decreasing d due to interparticle cohesive forces.

Iversen et al. [1987] studied the effect of particle-to-fluid density ratio on u_{*t}. In their study, dimensionless threshold friction velocity A_B was fitted as a function of particle-to-fluid density ratio for particle diameter

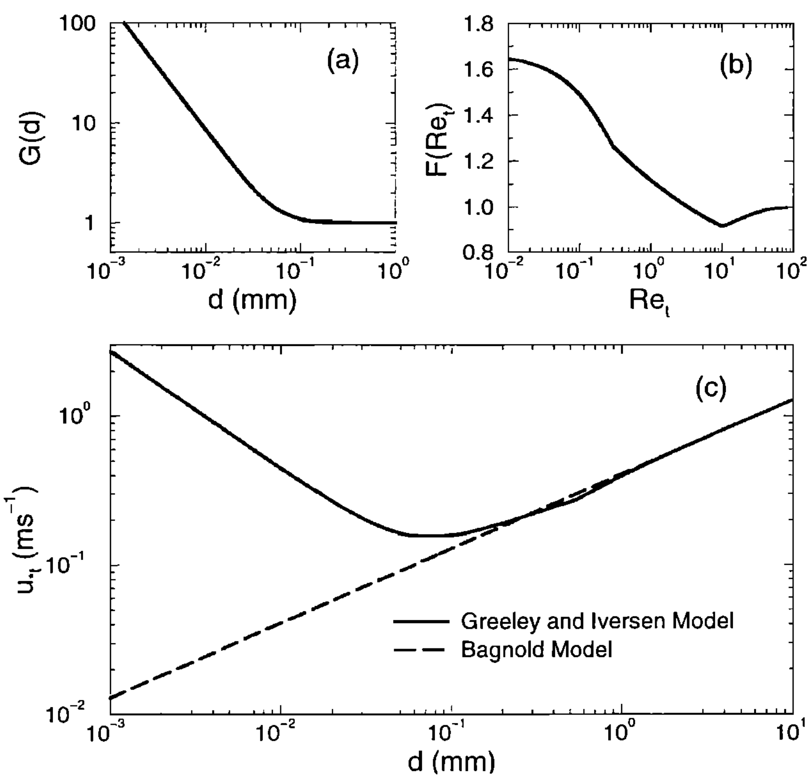

Figure 2. The Bagnold and Greeley-Iversen expressions for the prediction of threshold friction velocity for individual particles.

$d > 200$ μm (or $Re_{*t} > 10$), in which the interparticle force becomes negligible compared with the other forces on the particle at threshold. Using broader data sources including measurements of u_{*t} in liquid, they found that A_B decreases by a factor of 2.5 as Re_{*t} increases from 0.05 to 10 and A_B is almost constant for $Re_{*t} > 10$. The decrease of A_B with increasing Re_{*t} may be a result of the relative decrease of the cohesion forces when compared with the particle weight.

3. The New Expression

While the expression of Greeley and Iversen well describes the wind tunnel observations reported by *Iversen and White* [1982], the two empirical functions in (16), $G(d)$ and $F(Re_{*t})$, have rather complex expressions. A simpler expression for u_{*t} with rational physical interpretations can be derived through an explicit treatment of the cohesive force.

Interparticle cohesion is a combined effect of the van der Waals force, liquid and chemical force, and electrostatic force, all of which are sensitive to soil properties, such as particle shape, particle surface texture, soil mineralogy, packing arrangement, and the presence or absence of bonding agents such as soil moisture and soluble salts. For spherical particles free of the influence of moisture and chemical binding, the cohesion can be attributed mainly to the van der Waals force and the electrostatic force. While an accurate estimate of these cohesive forces is difficult, it is useful to consider their general behavior in theory.

3.1. The van der Waals Forces

The attraction between uncharged micron-sized particles is due to the van der Waals forces. The van der Waals forces are types of a short-range force with the domain of importance under a diameter of a dust particle. Theories originated from colloidal sciences exist for the calculation of the van der Waals forces for idealized situations, notably the Hamaker theory and the Liftshitz theory [*Langbein*, 1974; *Mahanty and Ninham*, 1976]. For a small spherical particle of diameter d with a separation δ from a same sized particle, one approximation for the van der Waals attraction forces between the two particles in vacuum is

$$F_{i,v} = \frac{h_w}{32\pi\delta^2}d, \tag{18}$$

where h_w varies between 10^{-18} and 10^{-21}J, depending on the material. The minimum value of δ is conventionally considered to be 0.4 nm. For regions with separation smaller than 0.4 nm, the interactions between the particles are further complicated, as Verwey and Overbeek repulsion [*Theodoor and Overbeek*, 1985] takes place. The above relationship is considered to be valid for $\delta/d \ll 1$. For $\delta/d > 0.2$ the van der Waals attraction becomes negligible beyond this range, being of the order of thermal (Brownian) forces. If particles are surrounded by air, the van der Waals attraction between the two particles may increase due to the interactions between the gas molecules adsorbed on the particles. In room temperature, van der Waals forces between particles can be increased up to 2 orders of magnitude with increasing pressure [*Xie*, 1997].

3.2. Electrostatic Force

The electrostatic force applicable for dust emission is the electrical double layer force, also called the nonconductor force. For smooth and ideally spherical particles, it can be written as

$$F_{i,e} = \frac{\pi E U^2 d}{2\delta}, \tag{19}$$

where U is the contact potential difference that generally ranges from 0 to about 0.5 V, δ is the separation between the two adhering particles, and E is the permittivity of free space.

The above discussions indicate that despite large uncertainties in the magnitude of the cohesive force, it appears to be linearly proportional to particle size. In the idealized situation that contiguous particles have smooth and clean surfaces, so that electrical charges and capillary forces can be eliminated, the interparticle force is proportional to the particle diameter, namely,

$$F_i = \beta d, \tag{20}$$

where β is a dimensional parameter. For a range of powder particles, *Phillips* [1980] suggested that the order of magnitude of β is approximately 10^{-5} Nm^{-1}. Equation (3) can now be rewritten as

$$a_t K_t \rho u_{*t}^2 d^3 = a_l \frac{\pi}{6}\rho_p g d^4 + a_i \beta d^2, \tag{21}$$

where K_t should be a function of Re_{*t}. It follows that

$$u_{*t}^2 = f(Re_{*t})(\sigma_p g d + \frac{\gamma}{\rho d}), \tag{22}$$

where

$$f(Re_{*t}) = \frac{\pi}{6}\frac{a_l}{a_t}\frac{1}{K_t}$$

$$\gamma = \frac{6}{\pi}\frac{a_i}{a_l}\beta.$$

The function f is inversely proportional to K_t, which in essence is a drag coefficient depending on Re_{*t} and needs to be determined empirically. We assume that $f(Re_{*t})$ can be approximated with a polynomial of Re_{*t} and fit (22) to the experimental data of *Iversen and White* [1982] for the particle size range between 50 and 1800 μm, within which the experimental data are most reliable. It turns out that an excellent fit of the observed data can be achieved using $f(Re_{*t}) = 0.0123$ with values of γ ranging between 1.65×10^{-4} and 5×10^{-4} kg s^{-2}. The new expression for u_{*t} is thus very simple.

Figure 3 shows a comparison of (22) and (16), together with observed data of *Cleaver and Yates* [1973],

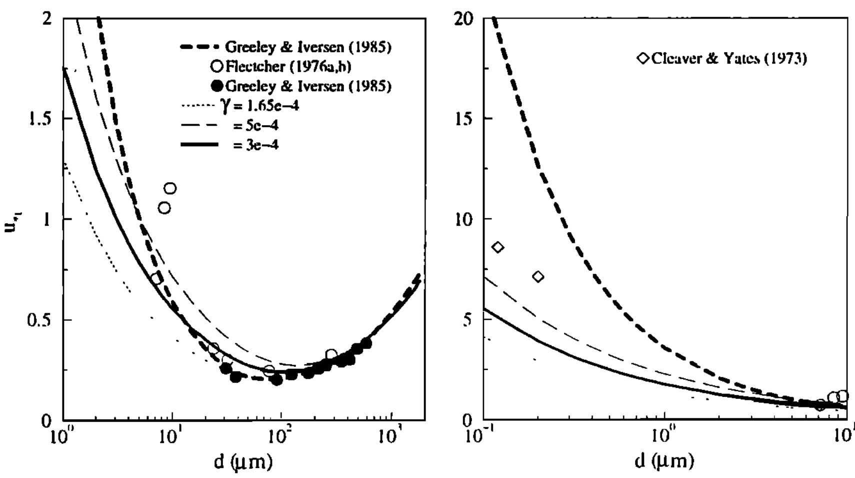

Figure 3. Comparison of the new expression, equation (22) with three different γ values, with the Greeley-Iversen expression, equation (16), together with the observed data of *Fletcher* [1976a, 1976b], *Greeley and Iversen* [1985], and *Cleaver and Yates* [1973].

Fletcher [1976a, 1976b], and *Greeley and Iversen* [1985]. For the particle size range $50 \le d \le 1800$ μm, the predictions using (22) and (16) are in good agreement but differ somewhat for the particle size range $1 \le d \le 50$ μm. For the latter particle size range, there is no reliable experimental data for validation, and therefore it is difficult to judge which one of the two expressions performs better. An obvious advantage of (22) is that it has a much simpler functional form than (16) and the physical interpretation of (22) is tidy.

A further comparison has been made by applying (22) and (16) to different planetary conditions. The six cases considered by *Iversen and White* [1982] are listed in Table 2. The predictions obtained by using (22) and (16) for the cases of Mars and Venus are shown in Figure 4. For all cases, (22) agrees well with (16) for particle sizes larger than 10 μm.

The new expression has several interesting features that deserve further discussion. Equation (22) suggests a new dimensionless threshold friction velocity of the form

$$A_N = \sqrt{f(Re_{*t})} = \frac{u_{*t}}{\sqrt{(\sigma_p g d + \frac{\gamma}{\rho d})}}. \qquad (23)$$

The conventional form of A_B contains effects from both the particle Reynolds number and the interparticle cohesion. *Iversen and White* [1982] and *Iversen et al.* [1987] have determined the specific form of A_B by attempting to isolate one effect from the other. The functional form of A_B in the expression of *Greeley and Iversen* [1985] implies that the cohesive force F_i is proportional to $d^{1/2}$ rather than proportional to d. This leads to a possible underestimation of F_i and an unnecessarily complicated expression, namely, (16). In contrast, A_N explicitly accounts for the effect of interparticle cohesion in the $\gamma/\rho d$ term. Equation (23) implies that if interparticle cohesion is considered, u_{*t} is in general proportional to $\sqrt{Y_1 d + Y_2 \frac{1}{d}}$ rather than to $\sqrt{d}$ as the previous expressions suggest. Hence A_N can be determined by assuming it is only a function of particle Reynolds number $f(Re_{*t})$.

A_N shows a weak dependence upon Re_{*t} and this is certainly the case for the particle size range between 30 and 1300 μm, for which most u_{*t} measurements have been made. From the wind tunnel measurements for the Venus case, *Iversen et al.* [1987] have found (see their Figure 4) that A_B is almost constant for the particle size range between 32 and 311 μm with increased

Table 2. Planetary Conditions Used by *Iversen and White* [1982]

		P, Pa	T, K	ρ, kgm^{-3}	$10^4\nu$, m^{2}s^{-1}	g, ms^{-2}	ρ_p/ρ
Mars	Case 1	500	240	0.011	11.2	3.75	240,000
	Case 2	500	150	0.0177	5.3	3.75	150,000
	Case 3	1,000	240	0.0221	5.6	3.75	120,000
	Case 4	1,000	150	0.0353	2.64	3.75	75,000
Earth		10^5	300	1.227	0.146	9.81	2.160
Venus		–	–	64.6	0.00443	8.77	41

Here P is surface pressure, T is temperature, and ρ_p is set to be 2650 kg m^{-3} for all cases.

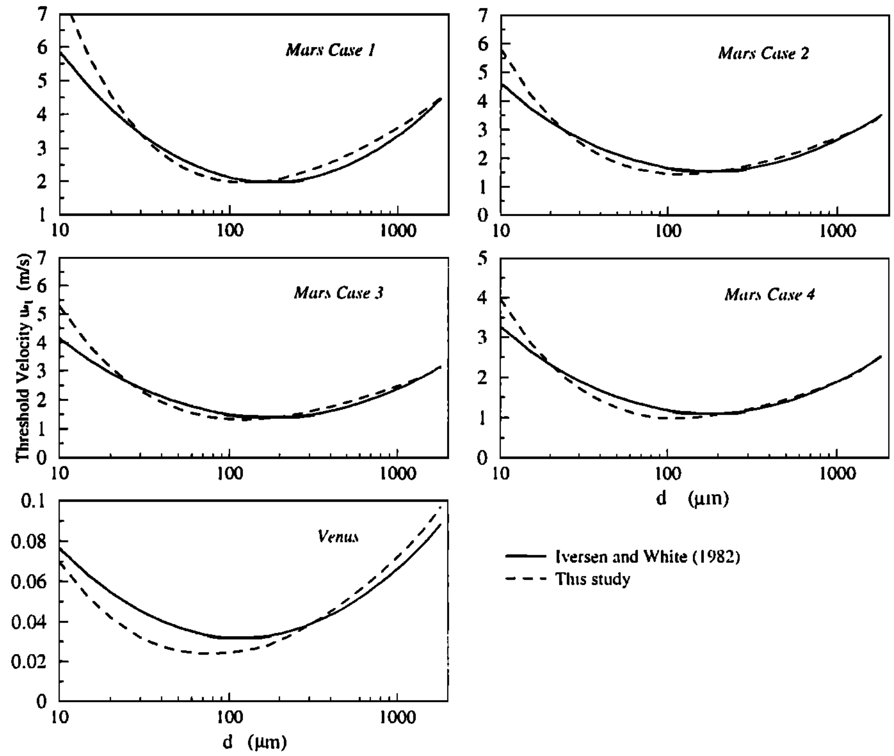

Figure 4. Comparison of equation (22) and (16) for planetary conditions of Mars and Venus listed in Table 2.

Re_{*t}. The wind tunnel data of *Iversen and White* [1982] suggest that for a given particle diameter, A_B decreases by a factor of 1.3 as Re_{*t} increases from 0.05 to 1. We have found that the value of $f(Re_{*t})$ does not vary over a wide range but lies between 0.011 and 0.013, which is consistent with the observations of *Iversen and White* [1982]. For large particles ($d > 200$ μm), equation (22) shows that the asymptotic behavior of the $u_{*t}(d)$ relationship is $u_{*t} \propto d^{1/2}$ and $A_N = A_B \simeq 0.11 - 0.12$. For small particles, the term Y_2/d dominates $Y_1 d$, and thus u_{*t} is determined by the balance between the aerodynamic and cohesive forces. The rapid increase of u_{*t} with decreasing d shows the strong effect of the cohesive force and the diminishing influence of the gravity force. For $d < 50$ μm, the cohesive force is at least 100 times larger than the gravity force. The asymptotic behavior of the $u_{*t}(d)$ relationship for small particles is $u_{*t} \propto d^{-1/2}$ as $d \to 0$.

The values of γ range between 1.65×10^{-4} and 5×10^{-4} kg s^{-2} and imply that the coefficient of interparticle force β is around 10^{-4} with the assumption of $6a_i/\pi a_l$ being of order of 1. This value of β is 1 order smaller than the measured values of 0.0012 (for quartz particles) and 0.0017 (for Pyrex particles) [*Corn*, 1961].

4. Conclusions

In this paper we have derived a new expression for calculating the wind erosion threshold friction velocity u_{*t} for spherical particles loosely spread over a dry and bare surface. This expression takes into account the effect of interparticle cohesion on u_{*t} but retains a simple functional form, namely, (22). The key argument embedded in the new expression is that the interparticle cohesive force should be, in general, proportional to d^{-1}. The new expression compares well with the Greeley-Iversen one for the conditions of Earth, Venus, and Mars. We note that the Greeley-Iversen expression is derived through fitting it to experimental data. We have found that although u_{*t} is a function of Re_{*t}, the dependence of the former on the latter is a weak one. For wind erosion studies on Earth, this dependency can be neglected. On the basis of the wind tunnel measurements presented by *Greeley and Iverson* [1985], the expression we recommend for calculating u_{*t} is

$$u_{*t} = \sqrt{A_N(\sigma_p g d + \frac{\gamma}{\rho d})}, \qquad (24)$$

with A_N being around 0.0123 and γ being around 3×10^{-4} kg s^{-2}.

In this paper, as in many others, we have assumed that the particles under consideration are spherical. Of course, real particles are not ideally spherical, smooth, and nondeformable. Small particles often have the shape of a platelet with considerable surface roughness and often show large deformation in the contact region. Therefore the theoretical predictions (23) and (19) are rarely applicable to yielding accurate estimates for the van der Waals and electrostatic forces. There are other types of interparticle forces, such as the capillary and Coulomb forces, which depend strongly on the moisture and chemical agents between the particles. It virtually impossible to accurately determine the magnitude of the cohesive force acting on small particles. As a consequence, the uncertainty in the prediction of u_{*t} becomes larger as the particle become smaller.

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