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THE MINIMUM FREE-STREAM WIND SPEED FOR INITIATING MOTION OF SURFACE MATERIAL ON MARS

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SUMMARY

Estimates of the minimum free-stream wind speed that is required for initiating the motion of surficial material on Mars have ranged from 30 to about 200 meters per second. Thus the best value for this quantity is not well established. Graphical comparison of much of the pertinent data taken in the laboratory and in the field on Earth provides a minimum value for the "Bagnold coefficient" of 0.08 and this in turn provides a minimum value for the threshold friction velocity of 1.3 m/s for initiating motion of particulate matter on Mars at low elevations where the pressure is 7 mb. The most appropriate value of the ratio of friction velocity to free-stream velocity for putative unstable conditions appears to be 0.026. Thus the minimum free-stream wind speed for initiating motion is obtained as 50 m/s. If the surface material on Mars, however, is less cohesive than that on Earth, the minimum value may be smaller.

INTRODUCTION

The minimum free-stream wind speed required to initiate the motion of sand or dust on the surface of Mars has been estimated in a number of papers, with results that have been interpreted as ranging from 30 to perhaps as high as 200 m/s. Sagan and Pollock (ref. 1) are sometimes quoted as deriving the minimum required free-stream speed as being 80 to 200 m/s for a surface pressure of

5 mb. This result can easily be obtained from their paper, but it would be fairer to quote a different result from that paper. They state that, for a pressure of 10 mb, if the atmosphere is neutrally stable the required speed is in excess of 83 m/s but, since the atmosphere is highly unstable during the day, milder winds than that would be required. But they add that the expected uncertainties are factors of two or three. Golitsyn (ref. 2) estimates the minimum required speed to be about 80 m/s. Hess (ref. 3) obtains, for a surface pressure of 8 mb, a free-stream speed of 60 m/s. Gierasch and Goody (ref. 4) derive the surprisingly low value of 30 m/s whereas Iversen et al. (ref. 5) have the surprisingly high estimate of 120 m/s.

With the information that is available, it appears to be possible to make a better estimate of the value of the minimum required free-stream wind speed than has sometimes been done. It is the purpose of this paper to make this estimate.

SYMBOLS

A	coefficient in Bagnold's equation for u_{*_t}
A,B	quantities in equation for ratio of velocities
C_D	proportionality constant
D	particle diameter
f	Coriolis parameter, $2\omega \sin \phi$
g	acceleration due to gravity
Re_*	particle friction Reynolds number
Ro	surface Rossby number, U/fz_o
U	free-stream wind speed
u_*	friction velocity, $(\tau/\rho)^{1/2}$

u_{*_t}	threshold value of friction velocity
z_0	roughness length
κ	von Karman constant
μ	coefficient of viscosity
ρ	fluid density
σ	particle density
τ	shear stress
ϕ	latitude
ω	angular speed of rotation of planet

THE THRESHOLD VALUE OF FRICTION VELOCITY

The stress τ exerted on a surface by a wind is proportional to the density ρ and to the square of the speed of the wind at the top of the boundary layer,

$$\tau = C_D \rho U^2 .$$

If one defines a speed u_*, which is generally called the "friction velocity," as $C_D^{1/2} U$, then

$$u_*^2 = \tau/\rho$$

It has been shown (e.g., by Bagnold, ref. 6) that the threshold value of the friction velocity, which is the value at which the wind initiates motion of grains of diameter D, can be calculated by the equation

$$u_{*_t} = A\left(\frac{\sigma-\rho}{\rho} gD\right)^{1/2} \tag{1}$$

where, for cohesionless grains, the coefficient A is a function of the "particle friction Reynolds number"

$$Re_* = \frac{\rho u_* D}{\mu} \qquad (2)$$

For a turbulent boundary layer (above the laminar sublayer, if a sublayer exists) A is a very weak function of Re_*. For the laminar case, A is a very rapidly varying function of Re_*. Most of the data on threshold conditions have been presented in the form of plots of threshold value of friction velocity u_{*_t} versus effective diameter of particles. In the extension of terrestrial data to Mars, it has been assumed by others (e.g., Ryan, ref 7, and Gifford, ref. 8) that A is a universal function of Re_*. To facilitate this extension, we have plotted in figure 1 the results of six papers (refs. 5, 9 to 13) in the form u_{*_t} as a function of Re_* for terrestrial conditions (density, gravity, viscosity). We have made the same assumption as others and have converted these results to the form of the Bagnold coefficient A as a function of Re_* in figure 2, for application to Mars.

The smallest values of u_{*_t} shown on figure 1 are 0.14 m/s for Bagnold (ref. 9) and 0.12 and 0.10 for Chepil (refs. 11 and 12). For the first of these the nominal diameter represents a range of diameter for which the ratio of maximum to minimum apparently was 1.8. The second was for soil with 15% clods of up to 25-mm size, and the third was for a range of sizes from fine dust up to the nominal size. Chepil in reference 12 implies that for a mixture of grains "such as a commonly occurring dune material," the coefficient A is reduced by about 15% at the average equivalent diameter of the mixture. Thus, for a mixture that is composed of a narrow range of sizes, we would use 0.14 for u_{*_t}. For a mixture composed of a wide range of sizes, such as dune sand, we feel justified in using a value as small as 0.12, and this is the value that we have chosen. The corresponding value of Re_* is seen to be 0.9. From figure 2 the corresponding value of A is 0.08.

With values for A and Re_*, the two equations (1) and (2) can be solved for the minimum value of u_{*_t} and the corresponding value of D. We use a particle density σ of 2.65×10^3 kg/m^3 and a coefficient of viscosity μ of 1.1×10^{-5} kg/m sec. We use atmospheric densities corresponding to two elevations on Mars: altitude zero with respect to the mean surface level in the equatorial zone, for which the density is 1.2×10^{-2} kg/m^3 and the pressure is 4.8 mb, and altitude 4 km below that level, for which the density is 1.7×10^{-2} kg/m^3 and the pressure is about 7 mb. This latter altitude is approximately the altitude of the proposed Viking landing sites in Chryse and Tritonis Lacus (formerly Nodus Laocoontis). Use of the altitude of these two landing sites is particularly appropriate. They may be the locales of relatively frequent events or changes in appearance that can be attributed to wind-blown sand or dust. Antoniadi's book (ref. 14) states that yellow clouds very frequently obscure Chryse. Slipher's book (ref. 15) states that "The large bright region between Elysium and Syrtis Major has revealed the greatest array of striking changes [between 1907 and 1962] of any part of the desert areas of Mars.... Perhaps the most extraordinary change in this region occurred around Nodus Laocoontis...."

Simultaneous solution of equations (1) and (2) with A = 0.08 and $Re_* = 0.9$ provides the results that for altitude zero the minimum of the threshold value of the friction velocity u_{*_t} is 1.6 m/s and the corresponding value of diameter D is 510 μm; for the lower altitude the minimum value of u_{*_t} is 1.3 m/s and the corresponding value of D is 450 μm.

POSSIBILITY OF REDUCED COHESION

It must be recognized that the process of deriving a minimum value of u_{*_t} for Mars as above on the basis of data taken on Earth may have omitted an effect that could conceivably alter to a considerable extent the values of u_{*_t}. The Bagnold relation, equation (1), was derived without taking account of possible cohesion between adjacent grains of soil. (The word "cohesion" is used herein to mean either or both cohesion and adhesion.) Almost all experiments were done without regard to the constitution of the ambient gas or its moisture content. It is conceivable that the CO_2 atmosphere on Mars may affect the cohesion of the particles of the soil, and it is much more likely that the greatly reduced water vapor content of the Martian atmosphere reduces significantly any forces of cohesion among particles because of reduced quantities of adsorbed water. The only experiments in which the relative humidity of the air was controlled seem to be those reported in Addendum III of reference 16 by Belly. These experiments appear to show that the amount of water vapor in the air can have a large effect on u_{*_t} even for grains as large as those in a mixture having a mean diameter of 440 µm. Thus, we feel constained to point out that our minimum value of u_{*_t} for Mars may in fact be an overestimate of the minimum, and that the true minimum, if one exists, may be considerably smaller. Furthermore, if cohesion does play an important role, then it would appear that the generally-made assumption that the Bagnold coefficient A is a function only of Re_* is not supportable.

THE EFFECT OF FIXED ROUGHNESS ELEMENTS

The presence of immobile, or fixed, roughness elements (usually called non-erodible roughness elements) can have a rather large effect on the value of u_{*_t}. There is not, however, very much quantitative information on the effect. Chepil has stated (ref. 17) that "where the roughness elements...are non-erodible...the value of coefficient A is increased considerably." Iversen et al. have shown (ref. 5) that the value of the coefficient A can be tripled by the presence of fixed roughness elements. Chepil however shows (ref. 11) no or very little effect of fixed roughness near the minimum part of the curve of u_{*_t} vs $\sqrt{D}$. In the present calculations, we assume either an absence of fixed roughness elements or that they do not have significant effect on the minimum value of u_{*_t}.

MINIMUM THRESHOLD VALUE OF THE FREE-STREAM SPEED

We obtain the estimate of the free-stream speed appropriate for our value of u_{*_t} by determining the value of the ratio u_{*_t}/U. This ratio can be considered to be a function of the Rossby number and of the degree of stability or instability. The ratio can be taken to be (Shir, ref. 18)

$$\frac{u_*}{U} = \kappa \left[\left(\ell n \frac{u_*}{U} Ro - A \right)^2 + B^2 \right]^{-1/2}$$

where $A \approx 1.3$, $B \approx 2.8$ for the neutrally stable case. This equation appears to be valid also for the unstable case, but the values of A and B as functions of the degree of stability are not known.

We use 0.40 for κ, which is the value that has been in use for about 30 years (ref. 19). Reference 19, for example, states, however, that for Rossby numbers corresponding to smooth terrain 0.35 is probably a good choice for the value of κ. But in the absence of much supporting evidence for this value, we have used 0.40. If the correct value is less, than U would be correspondingly larger.

We estimate the surface Rossby number U/fz_0 to be about 2×10^9. From the preceding equation or from the plot of $\frac{u_*}{U}$ vs Ro, figure 3 of Shir (ref. 18), we find $u_*/U = 0.024$. If we use figure 4 of Csanady (ref. 20) we obtain 0.021. If we use figure 3 of Monin (ref. 21) we have 0.025. All of these results are for the neutrally stable boundary layer. Csanady's figure 4 does show also results for the stable and the unstable cases, but we believe that these are correct only qualitatively, not quantitatively, because the value of the constant in the first of Csanady's equation (19a) applies only to the neutrally-stable case (Hess and Clarke, ref. 22). For the unstable case the value of the constant should be less. Csanady's figure 4 does show that for the unstable boundary layer the value of u_*/U is greater than for the neutrally-stable case, unless Ro is very large. Monin states that measurements on Earth show that as stratification increases from stable to lapse, u_*/U increases. Pasquill (ref. 23) quotes results of Clarke (ref. 24) as showing that, on the average, for unstable conditions the value of u_*/U is 1.6 times its value for stable conditions. These quantitative results, however, must be for smaller values of Ro than are appropriate for Mars. Therefore, it does not appear to be either unreasonable or unconservative to use a value of at least 0.026 for the ratio for the unstable case on Mars. Thus, for the higher altitude, for which $u_* = 1.6$ m/s, the free-stream wind speed $U = 62$ m/s. For the lower altitude, for which $u_* = 1.3$, $U = 50$ m/s.

We have thus arrived at a minimum value for the required free-stream wind speed for initiating the motion of surface material at the proposed landing sites for the 1975 Viking mission to Mars. Although we used rather different values than Hess did (ref. 3) for most of the quantities that enter the calculation, we obtain a result fairly close to his. This result should allay some of the concern that is generated by estimates that much stronger winds are required.

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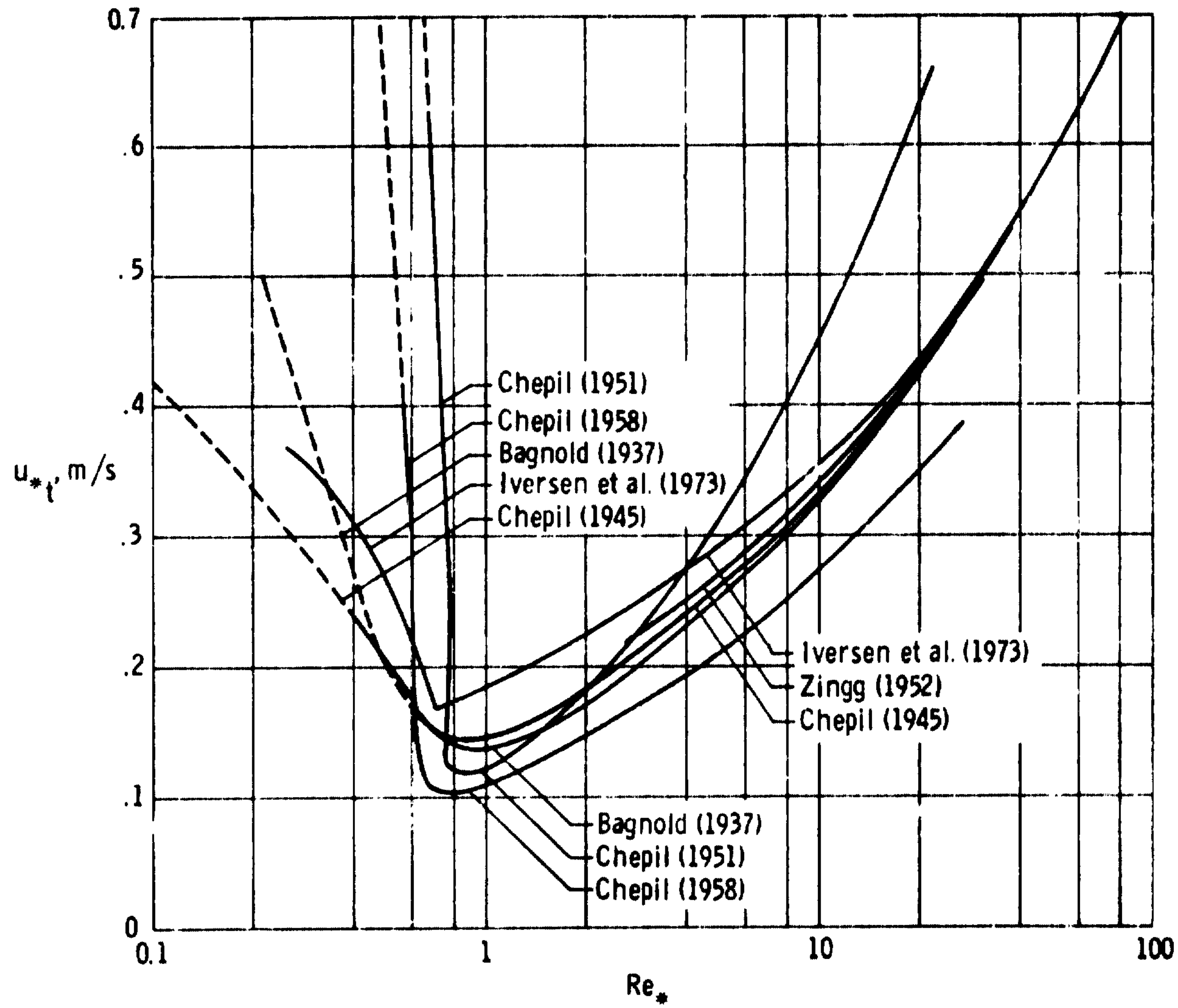

Figure 1. - Threshold friction velocity for Earth's atmosphere as calculated from data of various experimenters.

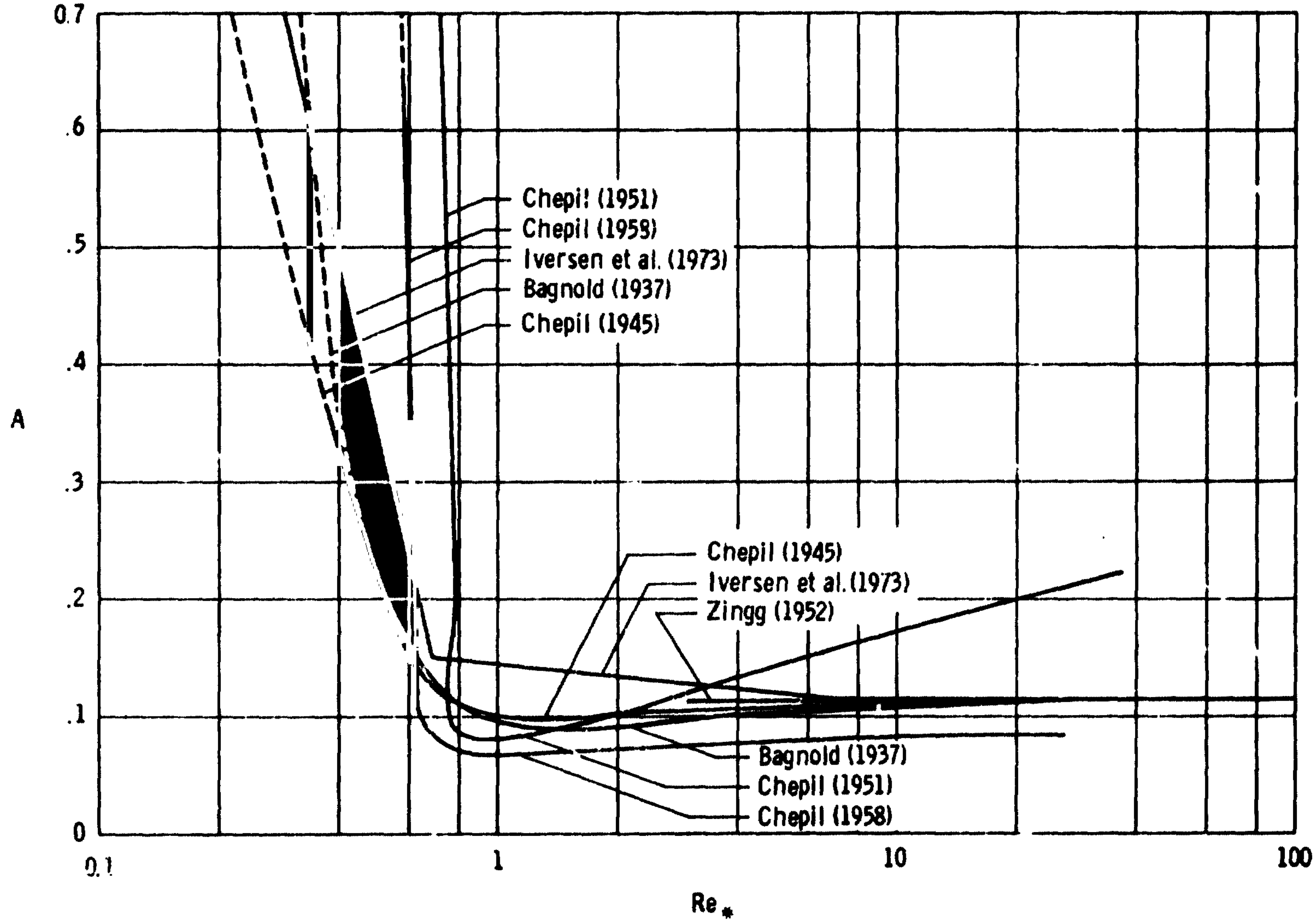

Figure 2. - Coefficient A as calculated from data of various experimenters