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NOTE

Wake-Induced Dust Cloud Formation Following Impact of Planetary Landers

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Measurements from landers on Venus have indicated dust clouds thrown up at impact. The possibility of similar phenomena occurring on planned Titan and Mars missions is assessed: it is found that the Huygens probe to Titan may observe such a cloud. © 1993 Academic Press, Inc.

Introduction. Landers on planets with significant atmospheres wherever possible use aerodynamic forces to control their descent. Typically at impact they are descending at a terminal velocity, where the aerodynamic drag equals their weight. Thus momentum is continuously being transferred to the atmosphere; this momentum transfer manifests itself as a wake behind the descending craft.

During the landing of the Soviet Venera 9 and 10 spacecraft on Venus, sudden drops in the light intensity measured by up- and down-looking photometers (Moshkin *et al.* 1979) were observed. The light levels subsequently returned to their original preimpact values. These observations have been interpreted (Moshkin *et al.* 1979) as light being blocked by clouds of dust being stirred up by the wake of the landers.

Similarly, the Pioneer Venus Day Probe (Ragent and Blamont 1979) detected a sudden increase in its nephelometer reading at impact (the nephelometer emits light and measures how much is backscattered from cloud droplets or dust in the atmosphere). Again, this measurement decayed afterward to its preimpact level and was interpreted as being due to the lander-induced agitation of surface particulates.

A number of other missions are planned to bodies with atmospheres, and it is appropriate to consider whether a similar phenomenon is likely on these missions. In particular, while most Mars landers plan to use Radioisotope Thermoelectric Generators (RTGs) to provide power (Hubbard *et al.* 1991), the baseline concept for the ESA MARSNET mission (Chicarro *et al.* 1991) is to use a solar array. The deposition of dust on this array could reduce the available power.

Also, the European Space Agency Huygens probe to Titan, while not strictly a lander, may well survive impact and return data from the surface (Lorenz 1991). Further, it carries a Descent Imager/Spectral Radiometer (DISR) (Tomasko *et al.* 1990) which, as well as performing imaging and spectral measurements, also includes photometric channels which could detect a dust cloud raised following impact. Such a dust cloud could degrade surface imaging immediately following touchdown.

Method. First it is necessary to consider the wake velocities required to agitate surface particles. It will be assumed that the terminal velocity of particles is a representative figure for the atmospheric motions required to generate and sustain a dust cloud. Terminal velocities are calculated by equating drag to weight, i.e., for spherical particles

$$4\pi r^3 \rho_P g/3 = \rho_a \pi r^2 C_d V^2/2, \tag{1}$$

with ρ_P being the particle density, r the particle radius, g the local acceleration due to gravity, ρ_a the atmospheric density, C_d the drag coefficient, and V the terminal velocity. These parameters for the various planetary bodies in question are listed in Table I. The drag coefficient is assumed to be that of a smooth sphere, varying with Reynolds number $\mathrm{Re} = (2\rho_a rV/\mu)$, where μ is the viscosity of the atmosphere, with the relation (Massey 1975, p. 311)

$$C_d = (24/\mathrm{Re})(1 + 3\mathrm{Re}/16)^{1/2}. \tag{2}$$

Note that Stokes' Law, used in some studies (e.g., see Ragent and Blamont 1980) is inappropriate for larger particles, which fall at Reynolds numbers too high for Stokes' Law to be valid.

The above system of equations is iterated several times to achieve convergence. (Note that while surface particulates are unlikely to be perfectly smooth spheres, the method gives representative values for the full Reynolds numbers range.) The results are illustrated in Fig. 1. For small particles (low Reynolds numbers), the descent velocities are affected by the particle weight and the gas viscosity: larger particles fall at higher speeds and Reynolds numbers, where viscosity is unimportant, and the velocity is controlled by weight and atmospheric density. The differing parameters for the various bodies for these two different flow regimes lead to the (perhaps unexpected) crossover of the terminal velocity curves for Earth and Mars (and the hint thereof for Venus and Titan). For small sizes (the low Reynolds number Stokes' flow regime) all the descent velocities are within an order of magnitude of each other, whereas for large particles the speeds differ significantly. The low gravity and thick atmosphere of Titan give terminal velocities similar to Venus with its very thick atmosphere. These values contrast with the very thin atmosphere of Mars where particles fall rapidly. Values for Earth are intermediate.

Having considered the flow velocities necessary to levitate a particle, it is now appropriate to consider the flow velocities in the wake of landing spacecraft.

Velocities in the wake of a body in a flow clearly vary from zero (the undisturbed condition at infinity) to the velocity of the body itself (the

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TABLE I
Planetary Parameters for Aeolian Dust Pickup

Body	Venus	Mars	Titan	Earth
Surface atmospheric pressure (bar)	90	7E-3	1.5	1
Surface atmospheric temperature (K)	740	200	95	283
Dominant species	CO_2	CO_2	N_2	N_2
Atmospheric density (kg m^{-3})	64	0.02	5.3	1.23
Atmospheric viscosity (10^{-6} Pa-sec)	35[a]	13	6	17
Surface gravitational acceleration (msec^{-2})	8.9	3.7	1.35	9.8
Particle composition	Rock	Rock	Water ice	Rock
Particle density (kg m^{-3})	2800	2800	1000	2800

[a] Value for CO_2 at 770 K and 1-bar pressure. Higher pressure may substantially increase this value.

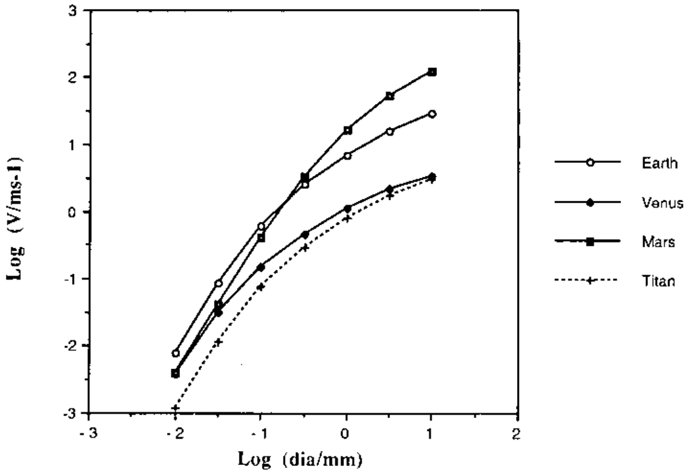

FIG. 1. Terminal descent velocities of particles from submillimeter to centimeter sizes: Large particles fall far slower on Venus and Titan than on Mars or Earth.

"no-slip" condition). Here the method of Moshkin *et al.* (1979) is used to estimate wake dimensions and velocities.

The width of the wake B at a distance x downstream is taken as

$$B \approx (\beta C_x S x)^{1/3}, \tag{3}$$

where the C_x is the drag coefficient of the spacecraft and S is its reference area; dimensionless parameter β is assumed to be 0.2. The wake velocity U compared to the descent velocity U_{dv} is given as

$$U/U_{\mathrm{dv}} = (C_x S/\beta^2 x^2)^{1/3}. \tag{4}$$

For the purpose of this paper, we assume the cloud-generating wake to be that with a velocity of half or more of the descent velocity, i.e., that in the range $0 < x < x_{1/2}$, where

$$x_{1/2} = \sqrt{8 C_x S/\beta^2}. \tag{5}$$

Thus the mass of this wake is given by

$$M_W = (\rho_a \pi/4) \int_0^{x_{1/2}} B^2(x)dx \approx 2.7 \rho_a (C_x S)^{3/2}/\beta. \tag{6}$$

Conservation of momentum dictates that the mass of particular material in any dust cloud formed by the wake must be significantly lower than this.

The relevant parameters and results are listed in Table II. Also listed is the ratio $x_{1/2}/U_{\mathrm{dv}}$, which gives an indication of how quickly the wake reaches the surface. It is seen that the Huygens and Venus probes have broadly similar characteristics, with wakes of 80 kg or more which deposit themselves on the surface over a couple of seconds. On the other hand, Mars landers have much less massive wakes which "splash" onto the surface much more quickly. The descent velocities quoted in the table give an upper limit for wake velocity and can be compared with the terminal velocities in Fig. 1 to derive an upper limit for the size of particle which can be supported by the atmospheric motions induced by the wake.

Conclusions. The terminal descent velocities for particles of surface material for various bodies have been calculated and compared with the wake velocities of various landers. The wake dimensions and a characteristic wake mass have also been evaluated. It is seen that, on Mars, wake masses are so low that minimal disturbance of surface material due to lander wakes is expected, although it should be noted that the high landing velocities may cause some surface material to be (briefly) disturbed as impact ejecta. On the other hand, the wake characteristics for the Huygens probe are similar to those of the Venus landers, and the terminal velocities of particles on Titan are similar to those on Venus, so that should there be fine (or even millimeter-size) particles at the Huygens landing site, an optically thick cloud may be formed for some seconds, as on the Venus missions. The nature of Titan's surface remains a matter of considerable debate at present, but the possibility of fine particulates certainly cannot be eliminated: indeed some models (Raulin *et al.* 1992) suggest "fluffy" organic deposits on

TABLE II
Planetary Landers and Wake Characteristics

Lander	Diameter (m)	Descent velocity U_{dv} (msec^{-1})	Drag area S (m^2)	$C_x S$ (m^2)	Wake length $x_{1/2}$ (m)	Wake mass (kg)	Wake time $x_{1/2}/U_{\mathrm{dv}}$ (sec)
Venera, 9,10	2.1	7	3.5	3.2	25	5000	3.5
Pioneer Venus Day Probe	0.8	9	0.45	0.4	9	220	1
Huygens	1.3	7	1.23	1.1	15	85	2.1
Mesur	1.0	30	0.8	0.7	12	0.16	0.3
Marsnet	0.9	30	0.6	0.6	11	0.12	0.3
Mars 94 Penetrator	0.7	100	0.38	0.35	8	0.05	0.1

Titan's surface which might be susceptible to aeolian pickup. If such particulate deposits exist and are agitated into a cloud by the Huygens probe wake, the cloud may be detectable by the DISR instrument.

The method used in this paper has been approximate. It might be instructive to characterize the wake of spacecraft models by means of simple wake traverse measurements in a wind tunnel, or perhaps by computational fluid dynamics. Drop tests of models onto particle beds might also be interesting, in particular to understand how the wake dumps itself onto the surface and picks up particulates.

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