FALL TIMES OF METEORITIC DUST IN THE UPPER ATMOSPHERE

M. Munir Qureshi
Dawood College of Engineering and Technology, Karachi
AND
J. Maybank
Physics Division, Saskatchewan Research Council, Saskatoon, Canada

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Based on Stokes' law, calculations have been made to determine terminal velocities and fall times from various heights for meteor dust particles of different diameters. While, mean values of 1.8×10^{-4} g./cm. sec. for air viscosity and 5 g./cm3. for the density of meteoritic material have been used in the calculations, Cunningham's correction has been applied to Stokes' law to account for the molecular mean free path variation with height and its influence on fall times. It has been found that micrometeorites take varying times to reach the tropopause from different heights.

Introduction

Despite the critical dependence of the meteor hypothesis on settling rates for the particles presumed to influence rain yield from clouds, very few calculations on this parameter have been carried out. Bowen[1] quoted rough estimates of 30 days for settling times from 30 km. to the earth's surface of material in the 4-10μ size range but did not elaborate on this, even to the extent of giving expected densities. He recognized that under Stokes' law conditions, the terminal velocity dependence on the square of the diameter would result in a wide spectrum but the basis of the theory required only a sharp "front" for the descending particles, this to be composed of the largest sizes. Here a major difficulty arises, for all estimates of meteor influx would limit the number of 8 micron diameter particles to fewer than one per cubic metre for an entire shower, and considerably longer delay times would be involved if the more numerours 2-5μ particles were required by the theory. Alternatively, Bowen used the evidence from noctilucent clouds at 70-90 km. altitude as evidence that meteor dust particles—assumed to be responsible for the water vapour nucleation and cloud formation at this level—were in fact more numerous than otherwise indicated, but this greater height would also result in increased delay times for settling.

In support of Bowen's theory, Rosinski and Pierrard [2] postulated that the vaporization of larger meteors in the 80-110 km. region would produce by coagulation many micron-sized particles per unit volume, and that this process was the source of ice nucleating material. They made no calculations of settling rates, but through comparison of meteor shower and rainfall anomaly dates, arrived at delay times varying from 40 to 65 days.

Buddhue [3] carried out calculations of terminal velocities for meteor particles at different heights up to 100 km. As he assumed Stokes' law behaviour without any consideration of the molecular mean free path variation with height and its influence on settling rates, his data are of little value. Because of the confused nature of the subject, the obtaining of more reasonable estimates of fall times would appear to be important; inasmuch as it is only against those estimates found by assuming the upper atmosphere to be stable, stationary medium, that one can discuss the influence of stratospheric winds and turbulence on this settling.

Basis of the Procedure

Published measurements of the terminal velocity, V, of natural particles were treated as experimental determination for each type of particles of drag coefficient, C, over a range of Reynold's number, Re

$$C = \frac{2mg}{\sigma V^2 A} \quad ; \quad R_e = \frac{D\sigma V}{\eta}$$

where m is the mass, D is the diameter and A is the cross sectional area of the particle; σ is the density of the air; η is the dynamic viscosity of the air and g is the acceleration due to gravity. If ρ is the density of the particle, then

$$V_s = \frac{gD^2 \;(p-\sigma)}{18\eta} \qquad (1)$$

which is Stokes' law. This law is applicable to particles with diameters between approximately 1 and 50μ and generally σ may be neglected.

Equation (1) can be used to determine rough terminal velocities and settling times from various heights for particles of different diameters. A mean value for the gravitational acceleration of 970 cm./sec^2. may be regarded as reasonable as it changes but little with height. Air viscosity is practically independent of pressure over the range considered here and as its variation with temperature is relatively small—about 30 percent for 100°C.—a mean value of 1.8×10^{-4} g./cm. sec. can be used. Density poses a major problem, inasmuch as little is known of the composition of the smaller particles. For iron-nickel materials a value of 7.8 g./cm.^{3} would be appropriate, while the more common silicaceous meteors could be expected to have densities around 2.8 g./cm^3. In view of this confusion an intermediate density of 5 g./cm.^{3} has been assumed in the present work, a value that would be applicable to silicaceous meteors with iron-nickel occlusions as well as to the iron oxides studied by Rosinski and Pierrard.[2] It appears unlikely to be greater than this, but could conceivably be less.

Results and Discussion

The resulting terminal velocities are 0.06 cm./sec. for a 2μ diameter sphere, and 1.0 cm./sec. for one of 8μ. Fall times will depend upon the upper level chosen—the lower one being the tropopause height of about 10 km—but from the 80 km. level of noctilucent clouds would be 1170 and 81 days for the two sizes, respectively. From the 35 km. level those times would be reduced by nearly two thirds, giving a delay time for the larger, but rarer, particles close to that required by Bowen.

A major flaw in the above calculations is that the theory behind Stokes' law presumes the mean free path, for molecules in the medium to be considerably less than the dimensions of the particles. When this condition is not satisfied, and the two are of the same order of magnitude, Cunningham's correction in the form:

$$V_t = V_s \left(1 + k \frac{\lambda}{D}\right) \qquad (2)$$

must be applied to the Stokes' terminal velocity V_s to get the true velocity, V_t. The constant, k, has a value of about 0.9. Now λ varies markedly with atmospheric pressure and temperature. Using the equation:

$$\lambda = \frac{\lambda_0 P_0 T}{P\, T_0}$$

it is possible to get for a particular pressure, P, and temperature, T, from its value of 5.5×10^{-6} cm. at standard conditions ($P_0 = 1013$ mb, $T_0 = 273$°A) and the values so calculated for different heights are plotted in Fig. 1. From this graph it can be concluded that particles in the 2-8μ size range are falling at 10 times their Stokes' law rates at heights of 50 km., 5 times at 40 km. and twice at 35 km. The effect of this "slipping" of particles through the air at low pressures is to bring all material very rapidly down to heights of 50 km. and to narrow considerably the spread in settling times with diameter.

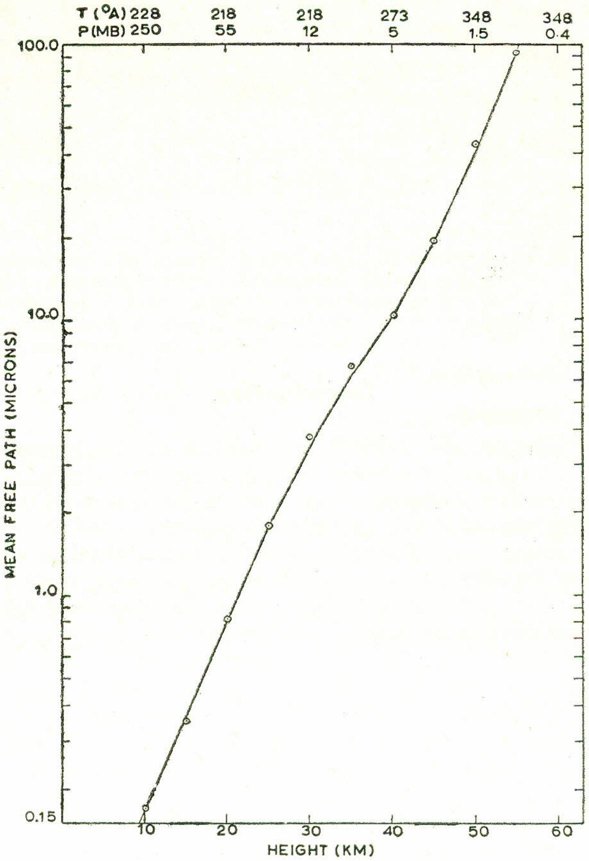

Fig. 1.— Mean free path of air molecules at different altitudes, as calculated from standard atmospheric conditions.

Calculations of terminal velocities based on Stokes' law with Cunningham's correction are given in Table 1, together with fall times to reach successive levels, based on average fall speeds over the interval. It is assumed that these small particles will be rapidly decelerated to these speeds and that negligible time is spent above 50 km.

Thus it is possible for the very largest of the meteoritic particles not likely to be subject to melting or vaporization during transit to reach the tropopause level in a period of 30 days assuming: (1) a density of at least 5 g./cm.^{3} for the material; (2) the validity of Cunningham's correction when the mean free path is considerably greater than the particle diameter; (3) a stationary non-turbulent medium. If meteor material of cometary origin is primarily silicaceous, these times would be increased by a factor of nearly two. Regardless of density, it appears impossible to ascribe any influence on rainfall anomalies 30 days following a meteor shower to the smaller, more numerous particles. Those coagulation products, formed from vaporized meteors and discussed by Rosinski and Pierrard,[2] would not possess sizes greater than two or three microns[4] and so this effect may be ruled out as a possible source of more numerous ice nuclei 30 or even 60 days hence.

Table 1.—Terminal Velocities and Fall Times of Meteoritic Material of 5 g./cm^3 Density in the Atmosphere.

Height h	Terminal velocity at height, h, for different diameters				Time to fall to h from previous height for different diameters			
	2μ	4μ	6μ	8μ	2μ	4μ	6μ	8μ
50 km.	1.25 cm. /sec.	2.6 cm. /sec.	4.2 cm. /sec.	5.8 cm. /sec.	–days	–days	–days	–days
45	0.65	1.3	2.4	3.1	6.1	3.2	1.5	1.3
40	0.35	0.8	1.4	2.1	11.5	5.6	3	2.1
35	0.25	0.62	1.1	1.8	19.5	8	5	2.9
30	0.17	0.44	0.9	1.5	27	10.4	5.5	3.5
25	0.11	0.35	0.75	1.2	40	14	7	4.0
20	0.09	0.30	0.62	1.1	58	17.5	8	4.8
15	0.075	0.27	0.59	1.05	70	20	9.5	5.5
10	0.068	0.26	0.58	1.02	80	22	9.5	5.5
Stokes' law value	0.063	0.25	0.56	1.00				
				Total	312	102	50	30
				Total at V_s	720	184	82	46

Some estimate of the prevalence of air motions and turbulence in the stratosphere should be made, and of their effects on the meteor aerosol. Wind speeds have been measured with fair accuracy up to 30 km. and their mean values are so in excess of the terminal velocities given above as to divert particle motion almost into the horizontal, and to channel it into the paths of the so-called jet streams. More important would be the effect of vertical air currents, the presence of which can be inferred even at 80 km. from the formation of noctilucent clouds. They would cause some decrease in settling time for a few of the already scarce 8μ size particles, but only over certain relatively small regions of the earth's surface, with the result that a precipitation peak dependent on this material could be considerably flattened. Furthermore, the updrafts associated with air movement in the stratosphere would not only retard the fall of some of these relatively dense 8μ particles but would result in remixing of the meteor dust size spectrum, and in the introduction of large amounts of terrestrial materials to further confuse the situation. That this does occur is borne out by the finding of numbers of spores and bacilli at altitudes of 12 to 25 km.[5] as well as by observations of Hodge and Wright[6] that the majority of particles found in the range of 17 to 30 km. are of terrestrial origin.

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