SESSION 3

Chairman: R. B. Southworth

14. THE PHYSICAL THEORY OF METEORS

(Survey Paper)

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1. Introduction

I wish to stress during the 20 minutes available to me that a very open-minded approach is required in making assumptions for a physical theory of meteors.

The traditional approach calls for assembling the best estimates of the relevant physical properties of meteoritic stone and iron, and for cometary meteoroids. To this end observations on the dust tails of comets should also be used. The result has always been and still remains that meteors fail by far to penetrate as low in the atmosphere as expected for their masses (using some theory for luminous efficiency with some sort of experimental base, near or remote).

However, as was once written by Jacchia (1963), the relationship between comets and meteors is one between two unknowns. Therefore a wider latitude in the coefficient of luminous efficiency, in the constants of a law of viscosity and in the constants of a vapor-pressure law should be tolerated than heretofore. Also crumbling as an escape from dilemmas should be avoided as much as possible.

2. Oversights in Traditional Theory

I shall now remark upon two oversights in the traditional theory of micrometeorites which affect the lower bound in mass for meteors. The first concerns the emissivity for gray-body radiation by particles whose dimensions are comparable to the wavelengths they are emitting. These emissivities can be much reduced below those of extended surfaces of the same substance. The second is the role of surface tension and the thermal dependence of the viscosity in bringing about effective melting of stone.

I have completed work on a new theory of micrometeorites including these effects, and plan to publish the details in the *Smithsonian Contributions to Astrophysics*. For the present, I shall give a summary.

Kresák and Millman (eds.), Physics and Dynamics of Meteors, 149–160. © *I.A.U.*

3. Micrometeorites

A. PHYSICAL PROPERTIES

1. *Iron*

Öpik (1958) is the source for all properties except for the cross-section for radiation pressure and the emissivity. For estimates of these two quantities the guiding source is Van de Hulst (1957) and particularly useful papers are those by Schalén (1939, 1945) and Schalén and Wernberg (1941). The deduced approximate expression for the emissivity $\bar{\varepsilon}$ as a function of temperature, T, and radius, r, is

$$0 \leqslant r \leqslant r^*, \quad \bar{\varepsilon} = 2(r/r^*)(T/T^*)^p, \tag{1}$$

$$0 \leqslant 1/r \leqslant 1/r^*, \quad \bar{\varepsilon} = 2{\cdot}0 - [2{\cdot}0 - \alpha(T/T^*)^q][1 - (r^*/r)(T^*/T)^p]^2, \tag{2}$$

$$r^* = (2{\cdot}436 \times 10^6)^{-1}\ \mathrm{cm}, \quad T^* = 28\,580\,^\circ\mathrm{K}, \quad p = 1{\cdot}864. \tag{3}$$

For smooth iron we have

$$\alpha = 0{\cdot}791, \quad q = 0{\cdot}1525. \tag{4}$$

For rough iron, assuming unlimited roughness (Öpik, 1958, pp. 52–54) for large particles we have

$$\alpha = 1{\cdot}000, \quad q = 0. \tag{5}$$

For the ratio of the cross-section for radiation pressure from sunlight to the geometric cross-section, $\bar{Q}_{pr}$ we have

$$0 \leqslant r \leqslant 1{\cdot}143 \times 10^{-5}\ \mathrm{cm}, \quad \bar{Q}_{pr} = 2{\cdot}628 \times 10^5 r, \tag{6}$$

$$1{\cdot}143 \times 10^{-5}\ \mathrm{cm} \leqslant r \leqslant \infty, \quad \bar{Q}_{pr} = 1 + 2[1 - (1{\cdot}15 \times 10^{-5}/r)]^2. \tag{7}$$

The ratio of acceleration from radiation pressure to that from the Sun's gravity is given by Southworth (1964) as

$$\gamma = 5{\cdot}9 \times 10^{-5} \bar{Q}_{pr}/(\rho_m r), \tag{8}$$

where ρ_m is the density of the particle.

2. *Cometary Meteoroids*

Öpik (1958) is again the source for all properties as for stone except for radiation pressure and emissivity while the possibility of a reduced thermal diffusivity is allowed.

Southworth (1964, Figure 5, p. 64) plots a curve of

$$\mathrm{d}\log[nmQ_{\mathrm{sca}}\bar{f}(\theta)/0{\cdot}03]/\mathrm{d}\log(\rho_m r/\bar{Q}_{pr})$$

against $\log(\rho_m r/\bar{Q}_{pr})$. Here n is the number of particles per unit of $\log(\rho_m r/\bar{Q}_{pr})$ in each of five tails of Comet Arend-Roland (1957III), m the mass of a particle of radius r, Q_{sca} the ratio of the scattering to the geometric cross-section, and $\bar{f}(\theta)$ the

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mean of the scattering function in the range of scattering angle, θ, from 45° to 135°. These tails were synchrones. It can be shown for a particle of iron that

$$\lim_{r \to 0} (\rho_m r / \bar{Q}_{pr}) = 3{\cdot}0 \times 10^{-5} \text{ gm cm}^{-2}. \tag{9}$$

For a synchrone of iron particles with radii down to about 7×10^{-6} cm it is clear that a singularity would occur at a minimum value of $\log(\rho_m r/\bar{Q}_{pr}) = -4{\cdot}52$. This singularity would appear as a bright spot at the edge of the synchrone. This did not happen in Comet Arend-Roland but one tail exhibited a cut-off at $\log(\rho_m r/\bar{Q}_{pr}) = -4{\cdot}6$ without any peak. There was only a monotonic increase to $\log(\rho_m r/\bar{Q}_{pr}) = -2{\cdot}7$ without data above that value. Another tail exhibits the same cut-off but with a peak at $\log(\rho_m r/\bar{Q}_{pr}) = -4{\cdot}1$. A third tail yielding data only for $-4{\cdot}4 \leqslant \log(\rho_m r/\bar{Q}_{pr}) \leqslant -4{\cdot}0$ is monotonic and coincides nearly with the results for the other two tails. The remaining two tails yielded data only for much larger particles.

These results are suggestive. I have made two assumptions to fit them: (1) The observed cut-off is that appropriate for cometary meteoroids and meteoritic stone:

$$\lim_{r \to 0} \bar{Q}_{pr} = 4 \times 10^{10} \rho_m r. \tag{10}$$

(2) The distribution function vanishes as the cut-off is reached at

$$\rho_m r_{\min} = 7{\cdot}5 \times 10^{-5} \text{ gm cm}^{-2},$$

where the subscript min refers to the radius at cut-off. The adopted behavior for the ratio of cross-sections for larger particles is

$$7{\cdot}5 \times 10^{-5} \text{ gm cm}^{-2} \leqslant r \leqslant \infty, \quad \bar{Q}_{pr} = 3 - 2\left(1 - \frac{7{\cdot}5 \times 10^{-5}}{\rho_m r}\right)^2. \tag{11}$$

For the smallest particles I assume the density of stone (3·4 gm cm^{-3}) so that

$$r_{\min} = 2{\cdot}2 \times 10^{-5} \text{ cm},$$

but allow the density to be lower for larger particles in analogy with the fairy castle structures of Hapke and Van Horn (1963). The larger meteoroids are assumed to be built from particles of radius, $r_{\min}$.

Also in analogy with iron I adopt expressions (1) and (2) for the emissivity with

$$r^* = (3{\cdot}712 \times 10^5)^{-1} \text{ cm}, \quad T^* = 28\,580\,^\circ\text{K}, \quad \alpha = 1{\cdot}000, \quad q = 0, \quad p = 1{\cdot}864. \tag{12}$$

The viscosity of stone may be expressed in the form

$$\mu = \mu_0 \times 10^{T_0/T},$$

which I have fitted to the values of $\log \mu$ vs T^{-1} given by Öpik (1958, p. 160) for various terrestrial stones. The results are

$$\mu_0 = 1{\cdot}7 \times 10^{-8} \text{ gm cm}^{-1}\text{ s}^{-1}, \quad T_0 = 16\,500\,^\circ\text{K}. \tag{13}$$

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This fits the terrestrial stones with a standard deviation in log μ of $\pm 0{\cdot}5$. It fits the Seratov meteorite within 0·2 (Volarovič and Leonteva, 1941).

B. LOWER LIMIT ON SIZES

This is established by requiring elliptical orbits about the Sun, i.e., I arbitrarily exclude the case of passage of the Earth through the tail of a comet. Figure 1 exhibits this limit for iron and solid stone.

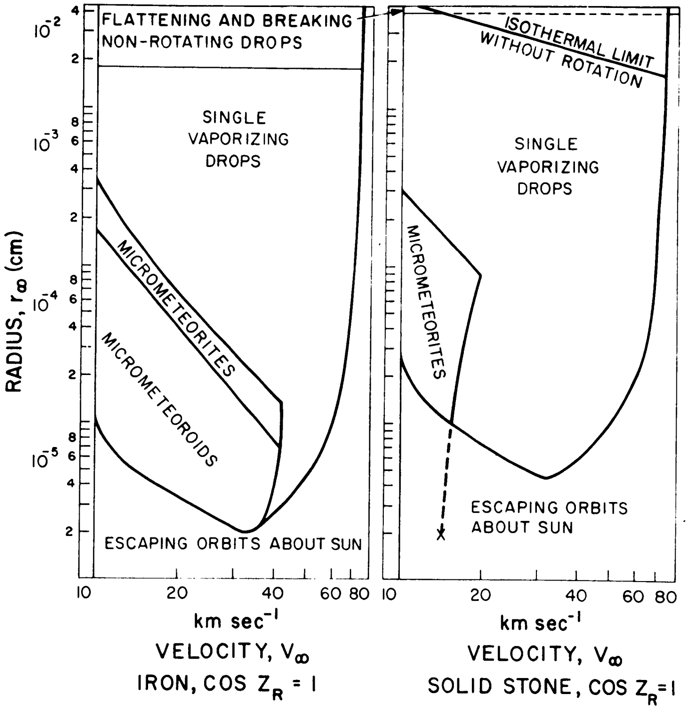

FIG. 1. *Partial charts for modes of ablation.*

C. MICROMETEOROIDS

I wish to introduce the term *micrometeoroid* to describe a solid unmelted particle which has not lost a significant fraction of its mass in passing through the atmosphere from above.

The surfaces of micrometeoroids are assumed to be rough because the reflection properties of Mercury, the moon and the asteroids indicate that they are rough and these micrometeoroids are subject to the same weathering processes. Accordingly, a coefficient of accommodation of unity is adopted. This roughness combined with an

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internal roughness (holes in lattice structures) is also used as an argument for neglect of sputtering.

Free molecular flow and isothermal heating of the meteoroid are assumed.

The analysis involves a grand assembling operation drawing upon work originally done by Gaede (1913), Wegener (1919), Öpik (1937, 1958), Levin (1940) and Whipple (1950). The results are embodied in the figure. Please notice that for iron with the radiant in the zenith, the regime of micrometeoroids is limited by the melting isotherm (1800 °K) for velocities below 40 km sec^{-1} and radii above $7{\cdot}1 \times 10^{-5}$ cm. Below 40 km sec^{-1} and in the range of radius 5·5 to $7{\cdot}1 \times 10^{-5}$ cm the melting isotherm is the limit; the meteoroids radiate according to (1). Below $5{\cdot}5 \times 10^{-5}$ cm the limit is set by the condition that the mass loss be no more than half the original mass computed with the trajectory for constant mass and Öpik's (1958, p. 156) law of vaporization.

For iron with cosine of the zenith distance, $z_{R'}$ of the radiant equal to 0·1 we have an upper limit which follows the melting isotherm to 39 km sec^{-1}, $5{\cdot}5 \times 10^{-4}$ cm and then the sublimation limit for higher velocities. All these meteoroids radiate in accord with (2).

For stone, no micrometeoroids occur for $\cos z_R = 1$; all are melted. For $\cos z_R = 0{\cdot}1$ they can be solid to 32 km sec^{-1}. Melting consists of the deformation by surface tension towards spherical shape overcoming viscosity.

For cometary meteoroids it is melting of the smallest particles $2{\cdot}2 \times 10^{-5}$ cm in radius that is important. The result is an effective melting temperature of about 1016 °K with all vertically descending meteoroids melting but with some sizes remaining solid at velocities up to 29 km sec^{-1} for $\cos z_R = 0{\cdot}1$.

D. MICROMETEORITES

I reserve this term for melted but not significantly ablated meteoroids. The significant changes from micrometeoroids are due to the smooth surfaces of the drops in contrast to the rough surfaces of the micrometeoroids. I adopt from Öpik (1958, pp. 46–52) the accommodation coefficients 0·48 for iron and 0·78 for stone. Öpik's (1958, pp. 56–57) theory of sputtering from smooth surfaces predicts thresholds at 42 km sec^{-1} for iron and 51 km sec^{-1} for stone. These are pre-empted by loss of mass due to vaporization which imposes the upper limit on size throughout for micrometeorites.

Unaccommodated air molecules are assumed to scatter about the direction of specular reflection thus causing the drag coefficient to remain unity (Öpik 1958, pp. 34–37). The ratio of the impact velocity of air molecules to re-evaporation velocities is so large that the heat transfer coefficient will be the same as the accommodation coefficient.

The results appear in the figure. The curves for stone extend down to $2{\cdot}2 \times 10^{-5}$ cm to cover the case of cometary meteoroids which melt and spin apart sufficiently high in the atmosphere. It is evident that melting will usually occur at much lower heights

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than the normal stopping height for such small particles so that they will be heated and vaporized over a very short distance in the much more dense lower environment.

4. Meteors

A. SINGLE SPHERICAL VAPORIZING DROPS

Here the classical theory may be employed as developed by Gaede (1913), Wegener (1919), Öpik (1933), Fisher (1934), Hoppe (1937), and Whipple (1938). The upper limit on this regime is set by deformation of the drop from the aerodynamic pressure due to surface tension. Attention was first drawn to this phenomenon by Öpik (1937). It has been the subject of extensive experimental study for water drops suspended in a vertical air stream. The results are assembled and discussed in the monograph by Mason (1957).

I am currently working on this model and have preliminary results at hand: For iron with $\cos z_R = 1$ the upper limit on radius is $1{\cdot}8 \times 10^{-2}$ cm while for $\cos z_R = 0{\cdot}1$ it is $5{\cdot}5 \times 10^{-2}$ cm. For stone the limits are $2{\cdot}0$ and $6{\cdot}0 \times 10^{-2}$ cm respectively. These tiny stone droplets penetrate to end heights of 70–95 km (higher for greater velocity).

B. FLATTENED OR DIVIDING DROPS

If a meteoroid in the form of a drop passes a point on its trajectory where the aerodynamic pressure on the drop is comparable to the pressure from surface tension, the drop assumes a more and more flattened shape. The dimensionless number (Mason, 1957) appropriate to these circumstances is the Bond number

$$B \equiv \frac{3\Gamma \rho_a V^2 r}{\sigma_T}, \tag{14}$$

where Γ is the drag coefficient, ρ_a the air density, V the velocity, r the radius and σ_T the surface tension. Drops flatten in such a way that for larger and larger Bond number computed using the radius of a sphere of the drop's mass, their deceleration approaches a critical value corresponding to

$$B_c = 5 \tag{15}$$

for a spherical drop. The drops may or may not subdivide into smaller drops. In any case, they behave dynamically as though they were spheres with the above critical Bond number. Therefore once B_c is reached, the drop may be assumed to subdivide into N_D droplets all with radius r_D:

$$r_D = \frac{B_c \sigma_T}{3\Gamma \rho_a V^2}. \tag{16}$$

The number of droplets becomes

$$N_D = \frac{3}{4\pi\rho_m}\left(\frac{3\Gamma}{B_c\sigma_T}\right)^3 m\rho_a^3 V^6, \tag{17}$$

where ρ_m is the density of the meteoroid. The deceleration equation takes the form

$$\frac{dV}{dt} = -\frac{9\Gamma^2}{4B_c\rho_m\sigma_T}\rho_a^2 V^4, \tag{18}$$

and the ablation equation the form

$$\frac{dm}{dt} = -\frac{9}{8}\frac{\Lambda\Gamma}{B_c\rho_m\zeta\sigma_T} m\rho_a^2 V^5. \tag{19}$$

Their solution may be written as

$$\begin{gathered} H_2 \equiv \frac{2}{\rho_a^2}\int_h^\infty \rho_a^2(h')\,dh', \quad y \equiv 1-(V/V_\infty)^2, \quad \sigma \equiv \frac{\Lambda}{2T\zeta}, \\ \frac{9\Gamma^2 V_\infty^2}{4B_c\rho_m\sigma_T}\frac{H_2\rho_a^2}{\cos z_R} = \frac{y}{1-y}, \quad m = m_\infty \exp(-\tfrac{1}{2}\sigma V_\infty^2 y). \end{gathered} \tag{20}$$

This system of equations may be taken to apply from the point at which

$$N_D = \frac{3\rho_m^{1/2}}{4\pi}\left(\frac{\cos z_R}{5\sigma_T M_2}\right)^{3/2} m_\infty V_\infty^3 [y(1-y)]^{3/2} \exp(-\tfrac{1}{2}\sigma V_\infty^2 y) \tag{21}$$

passes unity. Above that point on the trajectory the classical theory applies.

The next point at which discretion is called for is that at which N_D reaches a maximum. At that point classical theory for N_D drops of equal mass can be adopted as one extreme which assumes that all really flat drops have shattered and that no coalescence occurs between drops. The other extreme is an extremely flat unbroken drop which begins to return toward a spherical shape or steady mutual coalescence until one spherical drop is reached, i.e. we only return to classical theory when N_D returns to unity. In the former case, the end height is the same as for the single drop with maximum Bond number equal to the critical value.

This regime is limited by the requirement that the meteoroid be isothermal, which is exhibited in the figure for non-rotating stone meteoroids.

C. NON-ISOTHERMAL METEOROIDS ABLATING BY MELTING AND SPRAYING

I am still working on the limit of this regime. I anticipate that the result will be that all irons in free molecular flow, up to a certain limit on radius and large enough not to be isothermal, will behave in this way while all non-isothermal solid stones and cometary meteoroids which are not rotating will ablate by vaporization and undergo significant shielding by their own vapors, i.e. they will be in a viscous flow of their vapors. These are the results already found by Öpik (1958, pp. 101–106). For iron he finds the limit

$$r_\infty V_\infty \leqslant 1{\cdot}6 \times 10^7 \text{ cm}^2 \text{ s}^{-1}. \tag{22}$$

I expect to find a similar expression for stone with a much smaller number on the right.

Mention should be made that rapid rotation may introduce some spraying by solid stone (Öpik, 1958, pp. 107–108). Such rotation may cause ablation by melting and spraying of cometary meteoroids. Application of the condition that there be no significant shielding of the meteoroid by an incipient air cap yields upper limits above those attained by nearly all Super-Schmidt meteors discussed by Jacchia *et al.* (1967). Thus we may look to this body of data for an observational reconnaissance of our problem.

5. Comparison of Theory and Observations

We may argue as follows: Let us assume that Verniani's (1964) determination of the exponent n in the conventional expression (Hoppe, 1937) for the luminous efficiency,

$$\tau_p = \tau_{0p} V_\infty^n, \tag{23}$$

is correct. Then let us use the experimental determinations of τ_{0p} by McCrosky and Soberman (1963) and by Friichtenicht *et al.* (1968) for iron rescaled for stone by a factor 1/6. The result for stone is

$$\tau_{0p} = 5 \times 10^{-20}\, 0 \text{ mag gm}^{-1} \text{ cm}^{-3} \text{ s}^4.$$

This value is half that recommended by Verniani (1964) and Jacchia *et al.* (1967).

Let us next select those meteors which exhibit at the two or more observed points on the trajectory constant values of

$$\sigma = \frac{I_p/V^3}{\mathcal{M}_p V(-\mathrm{d}V/\mathrm{d}t)}, \quad \mathcal{M}_p \equiv \int_t^\infty (I_p/V^3)\, \mathrm{d}t', \tag{24}$$

and

$$K_m = \frac{\rho_a V^2}{\mathcal{M}_p^{1/3}(-\mathrm{d}V/\mathrm{d}t)}, \tag{25}$$

where I_p is the photographic intensity.

We recall that in the theory of meteors we have

$$\sigma = \frac{\Lambda}{2\Gamma\zeta}, \quad K_m = \frac{\rho_m^{2/3}\Gamma A}{\tau_{0p}^{1/3}}. \tag{26}$$

Verniani (1964) has shown that introduction of a variation of ρ_m with aphelion

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distance in the meteor's orbit significantly improves the observed fit. His least squares solution for n treats this density variation as an absolutely known function and thus leads to rather too small a probable error. It can be said that $n=0$ and 2 are absolutely excluded and that $n=0{\cdot}5$ and $1{\cdot}5$ are rather improbable. The observations do not distinguish between $n=0{\cdot}75$, $1{\cdot}00$ and $1{\cdot}25$.

From this point we follow Jacchia *et al.* (1967) to find a density of $0{\cdot}18$ gm cm^{-3} for the new value of τ_{0p}. Then we begin to compare observations and theory by noting that for ablation by vaporization we expect

$$\log \sigma = -\,11{\cdot}5,$$

and for ablation by melting and spraying

$$\log \sigma = -\,10{\cdot}7.$$

But nearly all meteors observed with the Super-Schmidt cameras lie somewhere in between.

We then look at the correlation of $\log\sigma$ vs. $\log V_\infty$ and $\log m_\infty$. Jacchia *et al.* (1967) suggest the following six surfaces in the three-dimensional space:

$$1{\cdot}12 \times 10^6 \leqslant V_\infty \leqslant 4 \times 10^6 \text{ cm s}^{-1},\ 0{\cdot}02 \leqslant m_\infty \leqslant 0{\cdot}18 \text{ gm},$$
$$\log \sigma = -\,10{\cdot}80 - 0{\cdot}9\,(\log V_\infty - 6),$$

$$1{\cdot}12 \times 10^6 \leqslant V_\infty \leqslant 4 \times 10^6 \text{ cm s}^{-1},\ 0{\cdot}18 \leqslant m_\infty \leqslant 140 \text{ gm},$$
$$\log \sigma = -\,10{\cdot}76 - 0{\cdot}9\,(\log V_\infty - 6) - 0{\cdot}23 \log m_\infty,$$

$$1{\cdot}12 \times 10^6 \leqslant V_\infty \leqslant 4 \times 10^6 \text{ cm s}^{-1},\ 140 \leqslant m_\infty \leqslant 2000 \text{ gm},$$
$$\log \sigma = -\,11{\cdot}24 - 0{\cdot}9\,(\log V_\infty - 6),$$

$$4 \times 10^6 \leqslant V_\infty \leqslant 7{\cdot}43 \times 10^6 \text{ cm s}^{-1},\ 0{\cdot}02 \leqslant m_\infty \leqslant 0{\cdot}18 \text{ gm},$$
$$\log \sigma = -\,11{\cdot}33,$$

$$4 \times 10^6 \leqslant V_\infty \leqslant 7{\cdot}43 \times 10^6 \text{ cm s}^{-1},\ 0{\cdot}18 \leqslant m_\infty \leqslant 140 \text{ gm},$$
$$\log \sigma = -\,11{\cdot}29 - 0{\cdot}23 \log m_\infty,$$

$$4 \times 10^6 \leqslant V_\infty \leqslant 7{\cdot}43 \times 10^6 \text{ cm s}^{-1},\ 140 \leqslant m_\infty \leqslant 2000 \text{ gm},$$
$$\log \sigma = -\,11{\cdot}77.$$

Here the revised luminous efficiency has been taken into account.

Re-examination of the data suggests that nearly as good a fit will be found by suppressing the transition surfaces for $0{\cdot}18 \leqslant m_\infty \leqslant 140$ gm replacing them by a discontinuity at $m_\infty = 10$ gm. Also the horizontal plane surface for the region $4 \times 10^6 \leqslant V_\infty \leqslant 7{\cdot}43 \times 10^6$ cm s^{-1}, $140 \leqslant m_\infty \leqslant 2000$ gm should be suppressed in favor of a continuation of the sloping plane surface for the range $1{\cdot}12 \times 10^6 \leqslant V_\infty \leqslant 4 \times 10^6$ cm s^{-1},

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$140 \leqslant m_\infty \leqslant 2000$ gm. The results are

$$
\begin{aligned}
&0{\cdot}02 \leqslant m_\infty \leqslant 10\,\text{gm},\ 1{\cdot}12 \times 10^6 \leqslant V_\infty \leqslant 4 \times 10^6\,\text{cm s}^{-1},\\
&\qquad\qquad \log\sigma = -10{\cdot}80\text{–}0{\cdot}9(\log V_\infty - 6),\\
&\qquad 4 \times 10^6 \leqslant V_\infty \leqslant 7{\cdot}43 \times 10^6\,\text{cm s}^{-1},\\
&\qquad\qquad \log\sigma = -11{\cdot}33,\\
&10 \leqslant m_\infty \leqslant 2000\,\text{gm},\ 1{\cdot}12 \times 10^6 \leqslant V_\infty \leqslant 7{\cdot}43 \times 10^6\,\text{cm s}^{-1},\\
&\qquad\qquad \log\sigma = -11{\cdot}24 - (\log V_\infty - 6).
\end{aligned}
\tag{27}
$$

The corresponding extreme values of $\log\sigma$ are $-10{\cdot}84$ and $-12{\cdot}02$. This range is in tolerably good agreement with theoretical expectation if we allow some shielding by the meteoroid's own vapors at the massive and high-velocity corner. But we anticipate a transition at a critical value of $r_\infty V_\infty$ or $r_\infty V_\infty^3$ or $m_\infty V_\infty^3$ if melting and spraying occurs in the low-velocity small mass corner and ablation by vaporization applies in the high-velocity large mass corner. We might tentatively invoke this as the cause of the break in the slope of the surface at 4×10^6 cm s^{-1} for $0{\cdot}02 \leqslant m_\infty \leqslant 10$ gm except that over such a range of a factor 500 in mass we anticipate a corresponding range of a factor 8 in velocity. Also no theory predicts the discontinuity at $m_\infty = 10$ gm nor does it predict the velocity dependences indicated by Equations (27).

Also there is the complication described by the fragmentation index, χ. This behavior is a very smooth non-flaring process like the progressive flattening and break-up of droplets. Jacchia *et al.* (1967, Figure 16.2) find a mass dependence which I interpret as two regimes for $\bar{\chi}$:

$$
\begin{aligned}
0{\cdot}02 \leqslant m_\infty \leqslant 10\,\text{gm}, \quad \bar{m}_\infty &= 1{\cdot}18\,\text{gm}, \quad \bar{\chi} = +0{\cdot}25, \quad \sigma_\chi = \pm 0{\cdot}29,\\
10 \leqslant m_\infty \leqslant 4000\,\text{gm}, \quad \bar{m}_\infty &= 273\,\text{gm}, \quad \bar{\chi} = 0{\cdot}00, \quad \sigma_\chi = \pm 0{\cdot}20,
\end{aligned}
$$

where the former contains 346 Super-Schmidt meteors and 12 small-camera meteors and the latter group contains 13 Super-Schmidt meteors and 46 small-camera meteors. The dispersions are standard deviations for individual meteors about the mean fragmentation indices, $\bar{\chi}$. It is at once apparent that these two regimes are very nearly Super-Schmidt meteors alone and small camera meteors alone so that the same skew distribution of χ with a tail running to large values will occur for the small regime as appears for the Super-Schmidt meteors and the same symmetric distribution will occur for large meteors as is observed for small camera meteors.

A striking point is that the mass of 10 grams divides meteors into two classes both for $\log\sigma$ and for χ. The group of larger mass shows $\log\sigma$ depending on V_∞ and hence does not behave in accord with theory. The group of smaller mass shows the same dependence on V_∞ below 40 km s^{-1} and also the faint meteor anomaly since $\bar{\chi}$ is significantly larger than zero.

A third effect is present: The beginning points seem to occur at about constant $\rho_a V_\infty^{3\cdot5}$ which suggests that constant $\rho_a V_\infty^3$ may be assumed and suggests that the

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beginning heights are determined by a change from cooling of the surface or of ablated drops by radiation to cooling by vaporization. The early portions of the trajectories may tell us something about the law of vaporization and the radiative efficiency of the surface.

We have failed to find a behavior matching theory so that we are finally driven to looking only at those meteors which appear to be clearly asteroidal. Only for these might a rational comparison of theory and observation be possible. There are three such meteors: Nos. 1242, 19816 (Cook *et al.*, 1963) and 7946 (Jacchia *et al.*, 1967). All of these appear to have been well beyond free molecular flow so that the simple theory need not apply, especially for the luminous efficiency.

We thus do not have a valid physical theory of meteors but a parameterization without understanding.

6. Conclusion

Our best data come from the photographed meteors. An open-minded effort to explain these is the first priority. After that we can go to larger meteoroids with the added complications of viscous and continuum flow and downward to radar meteors where the accuracy of observation and the interactions of ions and electrons with the environment are the added hazards. You will notice that is a personal statement of feeling about priorities, not a suggestion that work on these other classes of meteors is inappropriate or fruitless. With this remark I introduce a session advertised as one on the physical theory of meteors but which contains only papers on radar meteors.

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DISCUSSION

Bronšten: At the end of his report Dr. Cook has mentioned the problem of larger meteoroids. The theory of their motion through the Earth's atmosphere is much more complicated than any physical theory of meteors, because the shock wave around the body must be examined involving the equations of hypervelocity aerodynamics and even of plasma physics. I would like to point out only two examples. The first is connected with the drag coefficient Γ and the heat-transfer coefficient Λ. In the physical theory of meteors they have been taken as constant parameters. But for large meteoritic bodies we have to assume these coefficients as functions of an unknown parameter of the flight η:

$$\Gamma = \Gamma(\eta); \quad \Lambda = \Lambda(\eta).$$

The sense of η is not clear. It could contain a combination of the air density ρ, of the mass M and velocity v, or of the Mach and Reynolds numbers. Only the experiments can elucidate this question.

The second problem is the mode of ablation of large bodies and their mass loss. Before the frontal part of the body, near the critical point, the temperature of the shock wave is of the order of 10^5°. The evaporation process is the main form of ablation there. But on the side-surface the temperature is much lower ($\sim n \times 10^3$°) and the flow lines are almost tangential to the surface. This means that the main process of ablation on the sides of meteoroids is melting and spraying. The relation between both forms of ablation under different conditions may be determined only by experiments. Such an experiment carried out in the U.S.S.R. shows that the mass loss for meteorites is not so great as for ordinary meteors.