THE PHYSICAL THEORY OF METEORS. II. ASTROBALLISTIC HEAT TRANSFER*

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Received July 10, 1951

ABSTRACT

Previous difficulty in formulating a quantitative physical theory of meteors has in large part originated from the wide gap between terrestrial experiments and meteor observations. The physical theory of meteors falls into three aspects: air resistance, heat transfer, and radiation. This paper summarizes an attempt to analyze the heat-transfer aspect from the standpoint of the available meteor data and of some recent laboratory experiments. The section that relates to the laboratory experiments represents the first published attempt to measure heat transfer to bodies in free flight when the velocity is so high that ablation occurs—thus defining the astroballistic region. The free-flight heat transfer in the astroballistic region appears from these experiments to vary with velocity and air density according to the meteor formula rather than according to the conventional aerodynamic formulae established at lower velocities. The heat-transfer efficiency, expressed in terms of that to a Newtonian putty ball, is about 1 per cent in the region near 1–2 km/sec. The meteor results show considerable scatter in values of the heat-transfer efficiency, with no obvious dependence upon velocity or air density and with a favored estimate lying near 5 per cent. A possible interpretation of the scatter of meteor values lies in the fragmenting and flaring of meteors; and the great importance of further study on this point is emphasized. Some considerations on the maximum-sized meteorite capable of surviving intact lead to an independent gross estimate of the heat-transfer efficiency. An attempt is made to interpret the deep pitting observed in some meteorites in terms of enhanced ablation on an initially irregular surface, in accordance with some additional free-flight experiments.

I. INTRODUCTION

Early reports[1] by one of the authors and by L. G. Jacchia contain a presentation of the theory underlying the translation of meteor observations into data on the interaction of meteoroid and atmosphere. As was indicated in these reports, the theory definitely needs improvement, but attempts to improve it have been severely handicapped by the small advance in our fundamental knowledge of the physical processes involved—from either experimental or theoretical work—since the summary[2] presented by one of us at the beginning of the Harvard meteor studies prior to the war. A recent, more comprehensive investigation[3] by one of us into the air-resistance aspect contained only a few results that could not have been predicted on the basis of our state of knowledge at the time of the earlier report.

Stimuli from at least four sources, however, have prompted us to enter afresh into an investigation of the meteor theory. First, several recent results from the Harvard meteor program have indicated small departures from the functional relations of the earlier theory. Second, the laboratory production and investigation of particles of higher velocity is just now reaching the point of quantitative, experimental study in the region of velocity and air density relevant to the meteor problem. Third, some recent work[4] by one of us, in conjunction with M. A. Cook and H. Eyring, of the University of Utah, has pre-

* An investigation partially carried out under NOrd Contract No. 10449 of the U.S. Naval Bureau of Ordnance.

1 F. L. Whipple, *Proc. Amer. Phil. Soc.*, **79**, 499, 1938; L. G. Jacchia, *Harvard Repr. Ser.*, II-26 (Tech. Rept. No. 2 [1948]), *ibid.*, II-31 (Tech. Rept. No. 3 [1949]), and *ibid.*, II-32 (Tech. Rept. No. 4 [1949]).

2 F. L. Whipple, *Rev. Mod. Phys.*, **15**, 246, 1943.

3 R. N. Thomas, *Harvard Repr. Ser.* II-34 (Tech. Rept. No. 5 [1950]).

4 M. A. Cook, H. Eyring, and R. N. Thomas, *Ap. J.*, **113**, 475, 1951.

sented a theoretical approach to the surface temperature of the meteor on the basis of the generalized reaction-rate theory. Fourth, the Aeroballistics Division of the U.S. Naval Ordnance Laboratory, under the direction of R. J. Seeger, has made available to us the facilities of its controlled-pressure ballistics free-flight range for a study of heat transfer in the conventional ballistic-velocity region.

The meteor theory falls rather naturally into three parts: the problem of air resistance; the problem of heat transfer to the meteoroid; and the problem of radiation from the meteoroid. In the air-resistance summary cited, it was indicated that the effect of heat transfer on drag was the least understood aspect of the drag problem. Theoretical work on the radiation aspect—a problem in classical quantum mechanics—is almost nonexistent.[5] In order to define the amount of radiating material, any experimental approach to the radiation aspect must be based upon a complete, quantitative understanding of the heat-transfer problem. Consequently, we have commenced our reanalysis of the meteor theory with an investigation of the heat-transfer problem.

a) METEOR HEAT-TRANSFER THEORY

The spread in velocity and air density encountered in the meteor problem far exceeds that readily accessible in the laboratory. The velocity range is from about 8 to 73 km/sec; and the air density varies from the sea-level value of 10^{-3} to 10^{-10} gm/cm^3 at the 120-km level. We note that the lowest meteor velocity observed is still high enough that vigorous melting or vaporization of the meteor surface occurs (necessarily, of course, if we are to see the meteor!). Thus we consider that loss of mass by melting or vaporization defines the fundamental characteristic of the range of physical conditions under which we wish to study heat transfer in meteors. We have adopted the term "astroballistic" to designate this region.[6]

We wish, then, an approach to heat transfer in the astroballistic region—and a satisfactory approach must clearly be general enough to cover the whole region. At present there exists no satisfactory theoretical approach to the problem in any part of the relevant range of density or velocity. The hydrodynamic theories of heat transfer do not include the case of mass loss from the body. There is no satisfactory theoretical treatment of the accommodation coefficient for discrete molecules, in the case either of melting or of nonmelting. In the present investigation we proceed empirically, trying first to obtain an over-all estimate of the heat-transfer efficiency across the relevant region. We study the variation of the heat-transfer coefficient, defined—by analogy with the drag coefficient—as a measure of the efficiency of heat transfer in the actual case relative to that in the Newtonian putty-ball case. That is, for the air resistance, we have

$$\text{Drag} = -\Gamma \rho v^2 \mathfrak{A} \tag{1}$$

and, for the heat transfer,

$$\text{Heat transfer} = -\Lambda \frac{\rho v^3}{2} \mathfrak{A} , \tag{2}$$

where ρ, v, and $\mathfrak{A}$ are air density, velocity, and cross-sectional area of the moving object,

[5] One theoretical paper exists—E. Öpik, "Atomic Collisions and Radiation of Meteors," *Harvard Reprints*, No. 100, 1933. This calculation is a rough approximation, failing in several theoretical details.

[6] In a recent discussion over the precise meaning of the terms "hyperballistic" and "hypervelocity" between one of us and J. S. Rinehart, of the Naval Ordance Test Station, particularly in reference to shaped-charge phenomena, Rinehart suggested that the term "hyperballistic" be given precise meaning by applying it to the range to which we have applied the term "astroballistic." "Hyperballistic" and "hypervelocity" seem, however, to have been adopted to designate the region above Mach 10. Since the Mach number is hardly the basic similarity parameter relevant to heat-transfer problems—particularly those involving melting and vaporization—we feel that our introduction of the term "astroballistics" should be useful.

respectively. For the meteor analysis, the further assumption,

$$\mathfrak{A} = m^{2/3} A \ , \tag{3}$$

is introduced, where A is a constant.

b) THE OBSERVATIONAL MATERIAL AVAILABLE

We have four sources of empirical data on Λ, if we exclude data on the accommodation coefficient.

1. From the meteor observations themselves it is possible to infer values of the quantity

$$\sigma = \frac{\Lambda}{2\Gamma\zeta}, \tag{4}$$

where ζ is the energy necessary to separate 1 gm of material from the solid meteoroid. The observed acceleration measures Γ; but the mass and dimensions of the meteoroid are unknown. The observed luminosity measures Λ, under the assumption that the luminosity measures the mass loss from the meteoroid; and the mass loss, in turn, measures the heat transfer. The uncertainty as to mass and dimension—and air density, if one assumes this quantity unknown—then restricts the direct observational data to values of the quantity σ.

2. Values of Γ and Λ may be obtained independently from photographic studies of bodies in free flight. Since the mass and dimensions of the bodies are known, the measured decelerations give Γ directly. Heat-transfer values are inferred from observations of the mass loss from the body; hence the experimental conditions mimic the meteor case closely.

3. A limited amount of wind-tunnel data on a carbon dioxide sphere provides a comparison with the free-flight results. Again, the data on heat transfer are derived from an observation of the mass loss, so the experiment is closely related to the meteor case.

4. Some indirect evidence on the details of the heat-transfer process is obtained from phenomena in meteorites and from some free-flight measures on magnesium projectiles. Long, narrow holes have been found in several meteorites. The question arises as to how such holes or "pits" could be produced. An observation that offers a possible explanation results from a study of ignition as a function of surface contour on the flat front of a magnesium projectile.

c) CONVENTIONAL AERODYNAMIC HEAT-TRANSFER THEORY

In the foregoing, we have expressed the heat transfer in terms of that to be expected for the Newtonian "putty-ball" model, in which the incident air molecules are absorbed by the surface. The laboratory experiments with which this paper deals have, however, been performed in the hydrodynamic-flow region, for which a certain amount of theory exists. The unique feature of the present experiments is the melting of the surface. The conventional aerodynamic theory of heat transfer deals with bodies that do not melt. The physical point of interest is the alteration in the rate of heat transfer to the body when melting occurs.

We note that the conventional aerodynamic theory of heat transfer does not involve any physical characteristic of the body except its surface temperature. That is, the theory specifies the existence of a thermal boundary layer, across which the temperature changes from the free-stream value to that of the body surface. Because of this temperature gradient, there is a heat flow from air to body, given by

$$q = h\,(t_s - t_b)\ , \tag{5}$$

where q is the heat flow; t_b the body surface temperature; t_s the gas temperature outside the thermal boundary layer; and h the heat-transfer coefficient. An expression for h results from solving the steady-state heat-flow equation. For a flat plate, the solution[7] is expressed in the form (for the laminar-flow region)

$$N_u = 0.331 P_r^{1/3} R_e^{1/2} , \tag{6}$$

where

$$N_u = \frac{h\chi}{k} , \qquad P_r = \frac{\nu}{\alpha} = \frac{\mu\, c_p}{k} , \qquad R_e = \frac{u_s \chi}{\nu} , \tag{7}$$

and k is the thermal conductivity, c_p the specific heat at constant pressure, μ the viscosity, ν the kinematic viscosity, and α the thermal diffusivity of the gas, u_s the flow velocity at the edge of the boundary layer, and χ the length of the plate. The quantities N_u, P_r, and R_e are the Nusselt, Prandtl, and Reynolds numbers of the flow. Thus we see that the heat flow should be the same and independent of the composition of the body, so long as t_b remains the same.

Furthermore, in the case where the temperature of the body is held fixed, the theory gives no difference in the heat flow to a solid and to a liquid, so long as the liquid has zero velocity with respect to the solid surface. If the liquid flows over the surface, the hydrodynamics of this liquid motion must be included in the analysis. The problem does not appear to have been treated. Thus it seems difficult to estimate the direction of the correction (to eq. [6]) that would make the solution applicable to situations where melting occurs.

We might, however, inquire whether a formula of type (6) or one of type (2) might be expected to represent the general behavior of the heat transfer, and hence the melting rate. That is, we have two parameters to vary—air density and air speed. Air-speed variation corresponds to a variation of the air temperature near the body. With the exception of a possible—and unknown—dependence of Λ on ρ and v, equation (2) shows that heat transfer varies as ρv^3. On the other hand, equations (5) and (6) lead to a velocity variation through the velocity-temperature dependence of the product

$$k\,(t_s - t_b)\sqrt{\frac{u_s}{\nu}} , \tag{8}$$

since P_r is essentially temperature-independent in the temperature range of astroballistic interest. The density dependence enters only through the term ν, which varies inversely as ρ. Thus, while the quantitative difference in velocity-temperature dependence between equations (2) and (6) is not immediately obvious, the contrast in density dependence is apparent. The meteor expression (2) varies as ρ, while equation (6) varies as $\rho^{1/2}$. Since a characteristic feature of the free-flight tests reported in a later section is an air-density variation, some discrimination between equations (2) and (6) should be possible. The same discriminating criterion should, of course, hold for the meteor moving in the lower atmosphere where the conditions for the hydrodynamic-flow region should hold. The experiments reported in Section III involve this density discrimination.

We note that the Reynolds number corresponding to the meteor observations is about 10^4 or less for both fast and slow meteors (since the fast meteors occur higher in the atmosphere). Hence we have quoted the laminar heat-transfer result in equation (6). For turbulent flow, we have[7] a smaller numerical coefficient in equation (6) and the exponent of R_e becomes 0.8. The experiments reported in Section III were conducted in the normal ballistic regime, at velocities of $2000 < v < 6000$ feet/sec, and at a range of air densities from $\frac{1}{10}$ to 2 standard atmospheres. Thus the free-stream values of R_e lie near and above the transition region of about 5×10^5 for R_e. We note, however, that for these heat-transfer computations we are interested in R_e computed behind the shock wave near the sur-

[7] E. R. G. Eckert, *Introduction to the Transfer of Heat and Mass* (New York: McGraw-Hill Book Co., Inc., 1950).

face. With the blunt bodies we have used, the relevant R_e then falls below the critical value, and we would expect to be in the laminar-flow region.

d) SUMMARY OF INFORMATION ON Γ

As already mentioned, the meteor data appear as a combination of Γ and Λ. To estimate Λ, we require an estimate of Γ. A summary of the problem outside the specific astroballistic effects has been presented elsewhere.[3] The summary indicates that Γ approaches a constant asymptotic value as velocity increases, so long as the rise in velocity does not activate additional degrees of freedom of the atmosphere and meteor. Such activation obviously causes a decrease in the asymptotic value. Consequently, if we commence our analysis with a highly rarefied gas moving at relatively low velocity and progress both to higher gas densities and to higher velocities, the asymptotic value of Γ decreases. The situation is illustrated in regions *I*, *II*, and *III* of Figure 1, where we have indicated

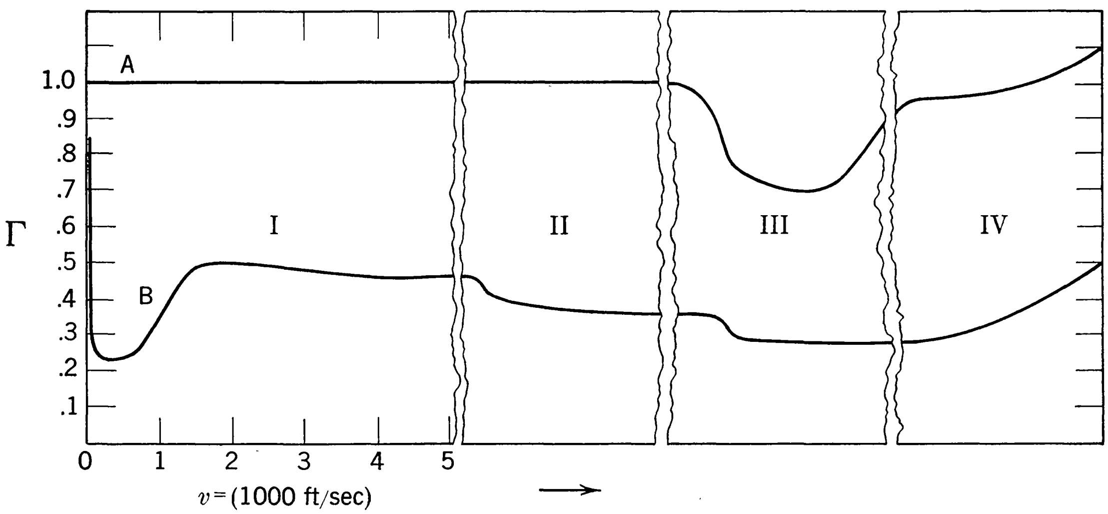

FIG. 1.—The drag coefficient Γ

semiquantitatively the value of Γ for a sphere. Curve *A* represents the situation for a highly rarefied gas; curve *B*, for the hydrodynamic case.[8] The decrease in curve *A* in region *III* results from the onset of inelastic collisions between gas and solid, but the reflection is still specular. The rise of Γ to 1 corresponds to the complete absorption of the incident atoms and re-emission with zero velocity. That Γ before and after the drop has the same value is, of course, peculiar to the sphere, for which $\overline{\sin^2 \theta} = \frac{1}{2}$ over the surface. Region *I* of curve *B* is quantitative, taken from some work by one of us and A. C. Charters.[9] The decrease of Γ in regions *II* and *III* reflects, respectively, the activation of additional degrees of freedom of the gas and of the solid; the numerical values are schematic. On this basis, we see that Γ for a sphere lies between about $\frac{1}{4}$ and 1, with the former value applying to (hydrodynamic regime) all degrees of freedom of gas and solid activated, and the latter applying to no degrees of freedom excited other than the original unidirectional translation of the gas. Since, at the highest meteor velocities and lowest air densities, we expect most of the air molecules to be absorbed by the meteor surface, a value of Γ between $\frac{1}{2}$ and 1 would seem the most reasonable.

[8] H. S. Tsien, *J. Aer. Sci.*, **13**, 653, 1946, has presented a more refined treatment of the very low air-density region, obtaining the velocity dependence of our curve *A*. For our schematic interest, however, curve *A* is sufficient, particularly since a really quantitative discussion requires a knowledge of accommodation coefficient and per cent specular reflection, which are unknown.

[9] A. C. Charters and R. N. Thomas, *J. Aer. Sci.*, **12**, 468, 1945.

We note the possibility of an overdrag term in the astroballistic regime.[4] For a low rate of heat transfer to the meteor—i.e., for the meteor just entering the atmosphere or for a low-velocity object at sea-level—the body dissipates the heat by conduction inward and radiation outward. For a high rate of heat transfer, however, the outer, heated layers are shed faster than conduction can carry the heat inward. After the body reaches a surface temperature much over 2000° K, the energy dissipation by radiation is trivial compared with that by melting and vaporization.[4] For air densities such that the free path of the vaporized meteor atoms exceeds the meteor dimension, the momentum transfer to the solid from the vaporizing material is readily calculated.[4] One obtains a Γ varying with s as $(1 + 0.16s)$, where s is the meteor velocity in units of 10 km/sec. Thus the fastest meteoroids (probably invisible), in the high upper atmosphere, might double their Γ value from this effect. At greater air densities, more refined calculations are needed to establish whether the effect is nontrivial. At present, we can only acknowledge the possibility of this overdrag term and include it as an uncertainty in Γ. Region *IV* of Figure 1 exhibits the effect schematically.

In summary, for a spherically shaped meteor, we expect Γ to be about $\frac{1}{2}$, with an uncertainty factor of about 2, depending on air density and speed. We might also expect some decrease in Γ as we go from the faster meteors in the upper atmosphere to the slower meteors in the lower.

Finally, we should comment on the uncertainty in Γ because of the meteor shape. Most meteors are probably highly irregular in shape, and possibly they are rotating, although this point is uncertain. So long as the meteor simply serves as a "trap"[2] for the incident air molecules—i.e., so long as incident air molecules penetrate the meteor surface—this shape factor is not critical. And it would seem that this picture is the most likely one. At worst, in the purely hydrodynamic regime, Γ cannot have a value more than twice that for the sphere, but it may have a value considerably less than that for a sphere in the case of elongated bodies (the values are roughly in the ratio $[\frac{1}{2}] : \overline{\sin^2 \theta}$, where θ is the inclination of the surface to the direction of motion). As mentioned, however, this shape factor should be of significance only at the very lowest velocities; so we favor the value $\Gamma = (\frac{1}{2}) \pm$ a factor of 2.

II. METEOR DATA—DISCUSSION AND RESULTS

a) PHOTOGRAPHIC OBSERVATIONS OF METEORS

A theory of the luminosity and deceleration of photographic meteors as developed by one of the authors[10] has operated with good success in the determination of upper-atmospheric densities. The various observed data for the photographic meteors led independently to various methods of determining upper-atmospheric density, pressure, and temperature. The comparison of these various methods showed, however, that only one quantity of astroballistic interest could be obtained: $\sigma = \Lambda/(2\Gamma\zeta)$. From all the doubly photographed meteor data available from the Harvard Meteor Program, Jacchia evaluated this quantity for each meteor and, in some cases, at several points along the trail of a single meteor[11] from the following equation (in which I is the observed luminous intensity of the meteor and t is the time measured along the meteor trail and the subscript e denotes the end of the trail):

$$\sigma = \frac{I}{v^3}\left[\int_t^{t_e} \frac{I}{v^3}\, dt\right]^{-1} \left(v\, \frac{d\,v}{dt}\right)^{-1} . \tag{9}$$

Thus σ is determined by the relative mass loss divided by the velocity times the deceleration—or, essentially, from the relative persistence of the meteor divided by its decelera-

[10] F. L. Whipple, "Photographic Meteor Studies. I," *Proc. Amer. Phil. Soc.*, **79**, 499, 1938. Cf. also n. 2.

[11] L. G. Jacchia, *Harvard Repr. Ser.* II-31 (Tech. Rept. No. 3 [1949]).

tion in the atmosphere. Three assumptions specifically enter the analysis: the intensity is proportional to the rate of mass loss; the proportionality factor varies as some power of the velocity; and the drag coefficient remains constant. However, a considerable variation in these assumptions will not greatly affect the derived values of σ. From data on thirty-six meteors, whose velocities exceed 20 km/sec and which provide 55 independent determinations of σ, Jacchia finds a mean value of $\log_{10} \sigma = -11.75$.

A considerable search for correlations of individual values of σ with velocity, atmospheric height, atmospheric density, or residuals from the mean of the density determinations has proved unsuccessful. Figure 2 exhibits plots of log σ against log v and log ρ. As seen from the figures, there is a considerable range in the observed values, nearly one order of magnitude in σ. On the other hand, the range for a single meteor, where more than one determination of deceleration and hence of σ is possible, amounts to very much

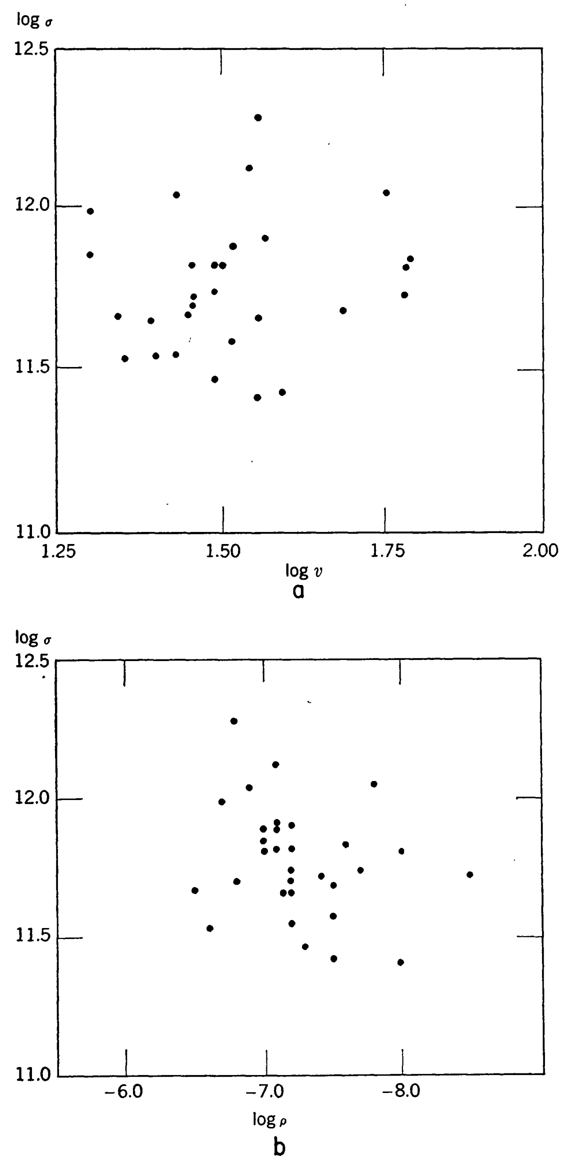

FIG. 2.—a, correlation of σ with v; b, correlation of σ with ρ

less than this quantity. The maximum range is approximately 0.4 in the logarithm but is usually very much smaller.

There seems to be no escape from the conclusion that the value of σ is a near-constant characteristic for a single meteor but varies widely from one meteor to another. In addition, among the meteors with velocities greater than 20 km/sec, there appears to be no systematic variation of σ along the path for a single meteor.

For ten slower meteors (seven included in the above general average) with velocities ranging from initial velocity about 30 km/sec to end-velocities as low as 8 km/sec, Jacchia finds a mean value of $\log_{10} \sigma = -11.61$, with a median value of -11.53. There is some suggestion of an increase in the value of σ with decreasing velocity at the low-velocity range. Jacchia, from unpublished data, has found additional evidence for this effect among single meteors of low velocity, although it is not clearly marked among the faster meteors.

The quantity σ is of great interest with regard to the passage of meteorites through the atmosphere, particularly in reference to the loss of matter. The theory of Hoppe,[12] as used by one of the present writers,[2, 10] leads immediately to a relationship between the mass of the meteor at any time, its velocity v, and its original velocity v_∞ before entering the earth's atmosphere. The relation is

$$m = m_\infty \exp\left[\sigma \frac{v^2 - v_\infty^2}{2}\right]. \tag{10}$$

If the mean observed value $\log \sigma = -11.75$ is adopted, we find that, for initial velocities of 12, 20, and 70 km/sec, the ratios of the final to initial masses are, respectively, 0.3, 0.03, and 1.2×10^{-19}. Hence one should not expect appreciable residual particles remaining from any but the slowest meteors. These results are of the greatest importance in evaluating the initial masses of meteorites found on the surface of the earth.

The interpretation of σ in terms of the heat-transfer coefficient demands a knowledge of the drag coefficient Γ and the heat of fusion or vaporization. In Section I*d* we found that there does not seem to be too great a leeway for the choice of a value for Γ; hence we have adopted the value $\Gamma = \frac{1}{2}$.

There is a greater uncertainty in the quantity ζ and its interpretation. The heat of fusion from 20° C. for common metals found in meteors is of the order of 10^{10} erg/gm; and the heat of vaporization is of the order of 10^{11} erg/gm. The values suitable for stone are not greatly different. Hence we see that much depends on whether the meteoric material is assumed to be immediately fused or immediately vaporized. If fusion is the principal process, we see that the value of Λ is of the order of 0.016; while if vaporization is the principal process, the value becomes 0.16. E. Öpik[13] concludes that solid metallic meteorites, because of their high conductivity and low viscosity just above the melting point, should generally spray material in droplets—so that the heat of fusion should be applicable for such bodies. On the other hand, he concludes that, for stones or silicate-type meteoroids, the low heat conductivity and the high viscosity just above the melting point makes spraying unlikely—so that the heat of vaporization should be used in the equations. We have no certain knowledge as to the physical structure or precise chemical composition of the observed photographic meteors. One of the writers has amassed some evidence to indicate that they are of a rather fragile character, probably consisting of a poorly sintered mass of typical material from interstellar space.[14] If such is the case and we are dealing with an inappreciable percentage of meteoritic irons or their equivalent,

[12] J. Hoppe, *A.N.*, **262**, 169, 1937.

[13] "Researches on the Physical Theory of Meteor Phenomena. III. Basis of the Physical Theory of Meteor Phenomena," *Tartu Obs. Pub.*, Vol. **29**, 1937.

[14] F. L. Whipple, *Ap. J.*, **111**, 375, 1950.

as is suggested by the cometary character of the orbits under consideration,[15] then the heat conductivity of the material should be very small and a considerable amount of silicates should probably be present in the complicated conglomerate. Spectroscopic data as yet do not distinguish among these hypotheses. In any case, it is probably better to assume that the heat required in the ordinary photographic meteor process is the heat of vaporization. Hence we are led to a value $\Lambda \cong 0.1$.

It is necessary, however, to account in some rational fashion for the large intrinsic variation of σ and hence of Λ or ζ among the individual meteors. We must attribute the major source of the variation to ζ or else to unconsidered factors in the problem. One such factor is fragmentation. Jacchia has shown[11] that flares among the photographic meteors must almost certainly arise from fragmentation. It is not at all impossible that fragmentation of a minor character occurs fairly regularly.[4] In terms of the equation for σ, the process of fragmentation would be equivalent to the introduction of a smaller value of ζ, leading to a value of σ greater than one would expect, were fragmentation absent. In turn, our derived value of Λ would be correspondingly increased. If we assume that for the faster meteors the minimum observed value of σ ($\log \sigma = -12.3$) corresponds to the case of zero fragmentation and that ζ corresponds to the heat of vaporization, approximately 10^{11} erg/gm, the value of Λ is 0.05.

The possible, but not definitely proved, increase of σ for very low meteoric velocities does not fit well with the above discussion of fragmentation, since flaring is most frequent among the high-velocity meteors. It is conceivable that in the slower meteors we are dealing with bodies that are like the meteorites rather than the conglomerate[14] of cometary origin. Orbital considerations in four examples support such a view.[16] If so, we might expect that the fragmentation factor would become negligible but that the heat of fusion, instead of the heat of vaporization, would become more applicable because of the increased percentage of metallic material; but we are probably not justified in pressing these interpretations.

b) CONSIDERATIONS BASED ON THE MAXIMUM-SIZE METEORITE CAPABLE OF SURVIVING IMPACT

1. *Basic assumptions and calculations.*—It is evident a priori that there must be a limit to the maximum size of a meteorite falling as a single body. Factors determining the limiting size must include the drag coefficient, the density distribution in the atmosphere, the heat-transfer coefficient, the nature and shape of the meteoritic mass, the gravitational attraction of the earth, the velocity of the body at great distances from the earth, and the detailed circumstances of fall. The largest known meteorite probably represents an optimum or nearly optimum situation with regard to these various factors. Since either precise or optimum conditions are known or can be assumed for all the foregoing factors except the heat-transfer coefficient, it seemed likely that some knowledge of this quantity should be acquired by a careful study of the problem of the maximum meteorite size.

The largest known single body certainly identified as a meteorite is the Hoba-West meteorite found near Grootfontein, Southwest Africa.[17] According to L. J. Spencer and M. H. Hey,[18] the present mass weighs about 6×10^7 gm and is a nickel-rich ataxite of specific density 7.96, composed of iron 83 per cent, nickel 16 per cent, and other substances about 1 per cent. "The metal is comparatively soft and quite malleable," an important characteristic in preventing fracture on landing.[19] An estimate by C. C. Wylie[20] places the original terminal mass at approximately 1.5×10^8 gm.

[15] F. L. Whipple, *A. J.*, **54,** 53, 1948.

[16] Current work in progress on the Harvard Meteor Project.

[17] The Ahnighito of the Cape York meteorites is probably a very close second.

[18] *Mineral. Mag.*, **23,** 1, 1932.

[19] See, e.g., a discussion of terminal ballistics in solids by J. S. Rinehart, *Pop. Astr.*, **58,** 458, 1950.

[20] *Sky and Tel.*, **10,** 3, 1950.

In order to determine the resistance of the atmosphere to such a body entering under the optimum geometrical conditions, we found it necessary to integrate the equations of motion for several sets of geometrical circumstances. These integrations were carried out numerically

If the earth is assumed to be spherically symmetrical throughout, the change in radial distance, r, from the center can be neglected through the relatively thin atmosphere, as can the variation in the acceleration of gravity, g. We choose time, t, as the independent variable and introduce v, the total velocity, and v_h, the radial or vertical velocity.

From the meteor theory[1] the initial mass of the meteorite, m_∞, and the final mass, m_f, are related to the mass m at velocity v by the equations

$$m = m_\infty \exp\left(\sigma \frac{v^2 - v_\infty^2}{2}\right) = m_f \exp\left(\sigma \frac{v^2}{2}\right). \tag{11}$$

We may define an auxiliary quantity, $f(m)$, given by

$$f(m) = \Gamma A m^{-1/3} = \Gamma A m_f^{-1/3} \exp\left(-\sigma \frac{v^2}{6}\right). \tag{12}$$

The equations of motion, as used, then take the forms

$$\frac{dv}{dt} = -g\frac{v_h}{v} - f(m)\,\rho v^2 \tag{13}$$

and

$$\frac{dv_h}{dt} = \frac{v^2 - v_h^2}{r} - g - f(m)\,\rho v v_h\,, \tag{14}$$

where the air density, ρ, is determined by the height, h, above sea-level.

Numerical values of ρ were smoothed from the N.A.C.A. Tentative Atmosphere[21] in the range above $h = 22$ km and from the mean values given in the *Handbook of Chemistry and Physics*[22] below this height.

Starting values of v_0, v_{h0}, and h_0 were adopted at a point in the trajectory where the velocity had been reduced by 1 per cent. The loss of mass above this height was neglected. Above this point the orbit was assumed to deviate negligibly from the conic section (parabola or hyperbola) determined by the velocity, v_g, at very great distances from the earth and by the height, h_p, of the perigee point to which the body would come, were there no atmosphere.

The eccentricity, e, of an orbit with perigee at $r = r_p$ is given by

$$e = \frac{r_p v_g^2}{GM} + 1\,, \tag{15}$$

where G is the constant of gravity and M the mass of the earth.

Near perigee, the projected distance, l, along the earth's surface from the projected perigee point closely approximates the actual orbital arc length. If this approximation is made, the change in height, Δh, above perigee is given closely by

$$\Delta h = r - r_p = e l^2 [2(1+e)\,r_p]^{-1}\,. \tag{16}$$

If, in addition, the variation of ρ with height is assumed to be of the form

$$\rho = \rho_p \exp(-b\Delta h)\,, \tag{17}$$

[21] C. A. Warfield, Nat. Adv. Comm. for Aer., Tech. Rept. No. 1200, 1947.

[22] (31st ed.; Cleveland: Chemical Rubber Pub. Co., 1949), p. 2678.

the deceleration equation (13) at and before the initial point of the numerical integrations becomes (since $v_h \ll v \cong v_\infty$)

$$\frac{dv}{v} = -\Gamma A\, m_\infty^{-1/3} \rho_p \exp\left[-\frac{b e l^2}{2(1+e) r_p}\right] dl. \tag{18}$$

This equation integrates, for a small decrease in v to $v(1-\epsilon)$, to the form

$$I(y) = 1 - \epsilon \left\{ \frac{\pi^{1/2}}{2} \Gamma A\, m_\infty^{-1/3} \rho_p \left[\frac{2(1+e) r_p}{b e}\right]^{1/2} \right\}^{-1}, \tag{19}$$

where $I(y)$ is the probability integral of y and $\Delta h = y^2/b$.

To determine initial values of v_0, v_{h0}, and h_0 for the numerical integration of an orbit determined by h_p or r_p and v_g, the value of e is given by equation (15), $h_0 = h_p + \Delta h$ by equation (19),

$$v_0 = (1-\epsilon)\left(v_g^2 + \frac{2GM}{r_p}\right)^{1/2},$$

$$v_{h0} = -v_0 e l_0 [r_p(1+e)]^{-1}, \tag{20}$$

and

$$l_0^2 = 2\Delta h\, r_p \frac{1+e}{e}.$$

In the actual calculations the values $\epsilon = 0.01$ and $b = 10^{-6}$ cm^{-1} were adopted.

The fundamental data for six numerical integrations are given in section *a* of Table 1

TABLE 1

HOBA-WEST INTEGRATIONS

	a) Assumed and Starting Data					
Trial number	1	2	3	4	5	6
Geocentric vel., v_g(km/sec)	0	0	0	0	12	12
Height of perigee, h_p(km)	13.5	18.1	22.2	33.7	13.3	17.8
$\rho(0)/\rho(h_p)$	5	10	20	100	5	10
ΓA(gm$^{-2/3}$cm^2)	0.225	0.225	0.225	0.225	0.225	0.225
$\log_{10}\sigma$ (cm^{-2}sec^2)	−11.75	−11.75	−11.75	−11.75	−11.28	−11.28
m_∞ (gm$\times 10^{-8}$)	4.58	4.58	4.58	4.58	1240	1240
h_0 (km)	59.1	57.6	55.2	52.8	38.9	37.5
v_0 (km sec^{-1})	11.10	11.10	11.10	11.10	15.82	15.82
v_{h0} (km sec^{-1})	−0.926	−0.871	−0.797	−0.606	−1.230	−1.078
	b) Results of Integrations					
Total time (sec.)	141.3	148.8	162.5	265.*	112.8	155.6
h of max., v_h(km)	11.1	15.5	19.9	40.4	11.6	17
Max. v_h(km sec^{-1})	−0.235	−0.230	−0.198	+0.130	−0.108	+0.028
$\int \rho v dt$ (gm cm$^{-2}\times 10^{-3}$)	7.5	7.5	7.4	1.2	13.2	13.1
$\int v dt$ (km)	876	916	1002	2330	753	1025
v at h=0 (km sec^{-1})	0.63	0.67	0.61	7.59*	0.59	0.62
v_h at h=0 (km sec^{-1})	−0.28	−0.28	−0.29	+0.07*	−0.27	−0.29
Zenith A of fall	64°	66°	62°	....	63°	62°
h of max. pressure (km)	19.6	20.5	22.3	32.7	15.1	18.0
Max. pressure (atm.)	24	22	18	6	153	111

* At the end of the calculation, t = 265 sec., h = 52.1 km.

and the numerical results in section *b*. The first four integrations were carried out for parabolic orbits ($v_g = 0$) representing the minimum velocity of fall; the height of perigee (h_p, if no atmospheric resistance) was varied to determine the range of the earth's effective target area for an ideally tangential approach.

The important numerical product, $\Gamma A = 0.225 \text{ gm}^{-2/3} \text{ cm}^2$, was adopted from $\Gamma = 0.5$ and $A = 0.45 \text{ gm}^{-2/3} \text{ cm}^2$. The "shape-density" factor, A, takes the value 0.306 for a steel sphere and $0.385 \text{ gm}^{-2/3} \text{ cm}^2$ for a steel cube, following the observational result by J. S. Rinehart and G. E. Hanshe[23] that, ballistically, the effective cross-sectional area of steel cubes is $1.50\ d^2$, where d is the length of an edge.

Table 1, section *a*, also lists the adopted values of σ, the initial mass m_∞ of the meteorite, the starting height h_0, total velocity v_0, and vertical velocity v_{h0}, for the six integrations.

2. *Results of the integrations.*—The first four integrations of parabolic orbits were carried out under nearly "ideal" conditions of meteorite fall. The value $\log \sigma = -11.75$ ($\text{cm}^{-2} \text{ sec}^2$) as adopted is the mean value observed for meteors and leads to a total mass loss by ablation of 67 per cent for the parabolic case.

An inspection of Table 1, section *b*, shows that in the fourth trial (the greatest perigee distance) the body fails to strike the earth. In the first three trials the vertical velocity reaches a maximum algebraically (second line) a short distance below the nonatmospheric height of perigee with a small negative velocity (third line). The total amount of air encountered is nearly constant (fourth line) for the first three trials (a surprising result), roughly eight times the amount for vertical fall, while the body traverses about 1000 km (fifth line) of horizontal motion. In addition, the final velocity at impact (sixth line) is nearly constant, at only about 2000 feet/sec, while the vertical component (seventh line) and consequent zenith angle of impact (eighth line) are also nearly constant.

If we limit ourselves to theoretical impacts in which v_h always remains negative, the results of the first four integrations indicate that a parabolic fall for a meteorite like Hoba-West is fairly likely. The target area for such an encounter (measured by the height of perigee) corresponds to more than 30 km of the peripheral radius of the earth. The velocity of impact is not excessive, possibly leading to breakage under adverse circumstances but not providing energy for appreciable melting. It is clear that the limiting conditions might be much more extreme than those postulated, i.e., greater final masses, greater initial velocities, or greater percentages of mass loss (σ).

Trials 5 and 6 were therefore integrated to study the effects of increasing the velocity and percentage mass loss. A study of the asteroids with perihelion distance less than 1 A.U. showed that the minimum velocity of encounter with the earth would be slightly over 12 km/sec (2 cases out of 7), corresponding to a perigee velocity, v_∞, slightly greater than 16 km/sec. Hence v_∞ was adopted as 16 km/sec for trials 5 and 6. At the same time, a maximum value of σ was adopted from the meteor data, $\log_{10} \sigma = -11.28$. The resultant mass loss becomes m (final)/m (original) = 1/826.

An inspection of Table 1, section *b*, shows that the much more extreme conditions of trials 5 and 6 do not greatly alter the calculated conditions of air flight or impact from those for trials 1, 2, and 3. The ***minimum*** value of the assumed (nonatmospheric) perigee distance which will provide enough atmospheric retardation to reduce the velocity below 1 km/sec can be based roughly on the hyperbolic path alone if we require that $\int \rho dl \cong 1.5 \times 10^4 \text{ gm cm}^{-2}$. We find that $h_p = -10$ km appears to give a reasonable lower limit. Thus the Hoba-West meteorite might have landed with a velocity less than 1 km/sec within a perigee range of $-10 \text{ km} < h_p < 20$ km.

The probability, then, that a given meteorite of $v_\infty = 16$ km/sec struck the earth in the range $-10 \text{ km} < h_p < 20$ km can be calculated to be about 0.007, allowing for the increased target area of the earth, produced by gravity. Since the statistics of the space frequencies of such large bodies are practically unknown, it is difficult to interpret the

[23] *Pop. Astr.*, **58**, 467, 1950.

probability of 0.007 in terms of time intervals, geological deterioration, and probability of discovery.

Thus we find that the calculations of trajectories for the maximum-sized meteorites give us only a crude suggestion of an upper limit on the value of σ, perhaps 10^{-11} gm erg^{-1}. On the other hand, the integrations lead us to predict that *very much larger meteorites* than the Hoba-West or the Ahnighito *could* reach the surface of the earth with terminal velocities below 1 km/sec. The questions as to whether they have done so, have survived burial and weathering, and will be found are not easily answered.

Eventually, other observational and theoretical approaches to the value of σ for meteorites should become useful. Particularly, more direct methods of determining actual surface losses by ablation should be developed. Perhaps a detailed theory of pitting (see Sec. V) will throw light on this question. Also the suggestions and calculations by C. A. Bauer[24] of cosmic-ray activity in meteorites based on *He* content bear directly on our problem. His results indicate that the ratio m (final)/m (initial) is probably not less than $\frac{1}{10}$ *if* we accept his interpretation of the observed *He* content in meteorites. Otherwise, the penetration of cosmic rays into the meteorites would be too small to support his proposed mechanism of *He* production.

III. FREE-FLIGHT MEASURES ON WOODS-METAL PROJECTILES

a) EXPERIMENTAL DETAILS

The Naval Ordnance Laboratory made available to us the facilities of their controlled-pressure free-flight range. The equipment is the standard spark-photographic instrumentation[25] that provides a shadow photograph of the moving body in each of two orthogonal aspects transverse to the direction of motion and thus hydrodynamic flow pattern and time-distance records of the motion.

The various low-melting-point alloys provide good material for this study of melting phenomena[26] at velocities that are easily reached. We have used Woods metal (*Bi*, 0.50; *Pb*, 0.25; *Sn*, 0.125; *Cd*, 0.125). Figure 3 shows a sketch of the model. The highest muzzle velocities reached some 6000 feet/sec. The first photograph was taken some 15 feet from the muzzle, and the observations were continued over the next 122-foot base line. Experiments were conducted at velocities of approximately 5000, 4300, 3700, and 2500 feet/sec and at pressures ranging from $\frac{1}{10}$ to 2 atm.

b) EXPERIMENTAL RESULTS

Melting is clearly visible at all the experimental velocities except the lowest, 2500 feet/sec. By comparing measures of the body on the first and last photographs, we could estimate the mass melted. The nose does not lose material symmetrically but tends to change from cylindrical toward hemispherical shape. Presumably, this change of shape results from the greater air velocity at the corners, the melted material being more easily removed there.[27]

Table 2 contains the experimental data relating to the heat transfer. The accuracy in measurement of length changes depends on the pressure, as the optical distortion by the shock wave is the chief limiting factor. Thus the sixth entry in the table shows the results of two sets of measures under poorest conditions. The other cases are much better, and it would appear that $\pm 0\rlap{.}''01$ is about the limit of measuring accuracy. This value is rather poor, in view of the small melting over the observed base line.

[24] "On the Age and Origin of Meteorites" (doctoral diss., Harvard, 1949); *Phys. Rev.*, **74**, 225, 1948.

[25] For a description of similar apparatus, see n. 9.

[26] One of us (cf. n. 3) had carried out experiments with paraffin projectiles that demonstrated the feasibility of such studies.

[27] The question of the equilibrium shape under such melting is an interesting one. The present experiments do not contain sufficient material to solve the problem.

The last column of Table 2 contains Λ, computed from equation (2) with 0.47×10^9 erg/gm as the energy to melt Woods metal from an initial temperature of 75° F.[28] The cross-sectional area of the Woods-metal cylinder is used for the area factor. The Λ values do not show too great a scatter, in view of the measuring accuracy, and we conclude that Λ is about $1\times10^{-2}\pm 50$ per cent uncertainty.

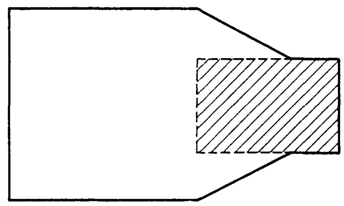

FIG. 3.—Sketch of projectile

TABLE 2

FREE-FLIGHT RESULTS

Rd.	$\bar{v}$ (Feet/Sec)	$\bar{M}$	Air-Density Ratio in Range (to 1.19 $\times10^{-3}$ Gm/Cm³)	Pressure in Range (Atm.)	Reynolds No. *behind* Shock	$-\Delta l$ (Cm)	$\Lambda\times10^2$
95	4540	4.00	0.093	0.10	4.7×10^3	− 0.013	....
101	4300	3.79	0.94	1.0	5.1×10^4	+ .101	1.3
102	4460	3.93	0.45	0.49	2.4×10^4	+ .030	0.74
104	3725	3.28	0.93	1.0	6.2×10^4	+ .089	1.5
105	3605	3.18	1.91	2.1	1.3×10^5	+ (.076) + (.152)	(1.1) (2.1)
106	4025	3.54	0.46	0.50	2.9×10^4	0.053	1.5
109	2215	1.95	....	2.0	....	0	....
110	2555	2.25	....	0.50	....	0	....

c) DISCUSSION OF RESULTS

We have three items of interest in the present data. First, we inquire whether the results cast any light on the discussion in Section I*c* on the variation of heat transfer with air density. Second, we ask about the numerical value of the heat transfer relative to the value obtained from the meteor results. Finally, we note the value of Λ itself, simply as a measure of the fraction of the energy actually going into heating the moving body. We can offer no comment on the last point other than that the 1 per cent heat transfer at these velocities is indeed quite small. We then consider the first two points of interest.

The physical problem here differs considerably from the flat plate lying parallel to the air stream that was considered in Section I*c*. Indeed, the Woods-metal nose more closely resembles a flat plate held perpendicular to the stream. We can, however, ask whether the general form of the heat-transfer dependence on air density follows the direct or the square-root relation.

1. *The variation of heat transfer with air density.*—The second, third, and fourth entries in Table 1 correspond essentially to the same velocity and the same time of flight and

[28] The melting point of Woods metal is 65°.5 C. The heat of fusion is taken to be 0.4×10^9 erg/gm; and the specific heat to be 0.15×10^7 erg/° C gm.

cover a density range of a factor of 10. While the considerable uncertainty in the experimental values has already been remarked, it seems that the data are sufficiently good to cast doubt on $\sqrt{\rho}$ rather than ρ dependence. The first and second entries differ by a factor of 10 in ρ; if the $\sqrt{\rho}$ dependence were correct, one should have a reduction only by a factor of 3 in the melting from the second entry. No appreciable melting can be detected in the first entry because the measured negative length change reflects the measuring accuracy. The sixth entry does not differ a great deal in velocity; and the third and sixth entries together indicate about a factor of 2, rather than $\sqrt{2}$, reduction at $\frac{1}{2}$ atm. pressure. One cannot, of course, conclude positively on the basis of these rather uncertain results that the heat transfer varies exactly as ρ, but the variation seems to follow ρ more closely than it does $\sqrt{\rho}$.

We note that heat-transfer problems in various engineering applications[7, 29] are often approached in the more general form

$$\frac{h\chi}{K} = \text{Constant}\, P_r^{\alpha} R_e^{\beta} . \tag{21}$$

As we have already noted, $\beta = 0.5$ for laminar and 0.8 for turbulent flow on the basis of calculations for a flat plate ($\alpha = \frac{1}{3}$). A least-squares solution for β from our results, involving the shock-wave relations to obtain $(t_b - t_s)$, gives $\beta = 1.06 \pm 0.15$ (m.e.). This result only emphasizes the need for more experiments in the *air-velocity* range here considered (i.e., free-flight rather than wind-tunnel experiments).

2. *Comparison of the results with meteoric values.*—As has been discussed, the meteor observations give values of

$$\sigma = \frac{\Lambda}{2\Gamma\zeta} .$$

The free-flight observations give directly Λ/ζ and Γ. We note, however, that the measured Γ value applies to the body as a whole, and not just to the Woods-metal nose. Thus, to make the comparison with the meteor results valid, we must use the Γ which the cylindrical Woods-metal nose would have, were it the whole projectile. Some experiments have been performed on the drag of cylindrical-headed projectiles, but the complete variation of Γ with Mach number is not so completely known as that for spheres, for example. From the material on hand, however, we estimate Γ for cylinders to be about 0.60 for the average value applying to the present experiments. We do not expect the value to be in error by as much as 10 per cent. From the data of Table 2 we see that Λ/ζ ranges in value from 1.5×10^{-11} to 4.2×10^{-11}, with no obvious dependence on velocity or air density. Thus, from the present experiments, we have the range in σ values:

$$1.25 \times 10^{-11} < \sigma < 3.6 \times 10^{-11} .$$

From the meteor results discussed in Section II, we have the following range in σ:

$$5 \times 10^{-13} < \sigma < 4 \times 10^{-12} .$$

Again, as we have stated, there appears to be no obvious dependence on velocity or air density of the σ values.

We note that there probably is not much difference between the Γ value for an average meteor and that for the cylinder considered in the present experiments. On the other hand, the meteoric material most probably vaporizes, rather than melts, from the surface; and the material—either stone or iron—has a higher value for ζ for either melting or vaporizing than does the Woods metal. For vaporization, ζ has been taken as 9×10^{10} in the earlier meteor work; and, for melting, ζ becomes 1.2×10^{10}. Thus we should expect

[29] Cf. H. W. McAdams, *Heat Transmission* (2d ed.; New York: McGraw-Hill Book Co., Inc., 1942).

σ to decrease in the meteor results, as compared with the Woods-metal results, by a factor of 200 for vaporization or a factor of 30 for melting, from the ζ factor alone. If the meteoric material does indeed vaporize, then we must conclude that Λ rises by a factor of 10 or greater in the meteor range of velocity and density over the value inferred from the Woods-metal experiments. If, on the other hand, the meteoric material melts, the necessity of concluding that Λ rises probably remains, but the rise is small. Certainly some kind of rise in efficiency of heating is to be expected; for the accommodation coefficient certainly exceeds 0.01 in the meteor velocity range. Probably the best estimate is a rise in Λ by a factor of 5 from these experiments to meteor results.

It would be extremely worth while to extend the present work to higher velocities. We can predict, on the basis of the present results and the knowledge that the value of Λ will rise at the higher velocities, that we should be able to observe melting phenomena in iron projectiles for a factor of 50 increase in v^3. Melting in Woods metal began in the range 2500–3500 feet/sec under normal atmospheric pressure. Hence, at a velocity of somewhere between 9000 and 13,000 feet/sec, we should be able to observe significant melting in iron projectiles. These velocity values are *upper limits*, since Λ is expected to increase.

IV. WIND-TUNNEL RESULTS

Our results in this section come through the kindness of the Naval Ordnance Laboratory group under Dr. H. H. Kurzweg. We are particularly indebted to Mr. J. M. Kendall.

TABLE 3

WIND-TUNNEL EXPERIMENTS ON SOLID CO_2

Mach No.	Velocity (m Sec^{-1})	Air Density (Gm Cm^{-3})	Mass Loss (Gm Sec^{-1}Cm^{-2})	Λ
1.87	483	3.28×10^{-4}	4.3×10^{-2}	1.35×10^{-2}
4.25	673	2.66×10^{-5}	1.0×10^{-2}	1.42×10^{-2}

One of us suggested the possibility of rate-of-mass-loss measures on a dry-ice model in the Naval Ordnance Laboratory supersonic wind tunnels (because of the low air speed in such tunnels, one is forced to use very low-boiling-point substances). Table 3 contains the data from these experiments.

We see that the results on Λ are in excellent agreement with those from the free-flight experiments on Woods metal and that they further support the linear dependence of heat transfer upon air density. The wind-tunnel experiments are, of course, inherently limited with respect to the free-flight experiments if we wish to test any great range of materials.

V. PITTING ON METEORS AND THE IGNITION POINT OF MAGNESIUM

a) PITTING ON METEORS

A glance at a few of the larger museum meteorite specimens shows that their surfaces are covered to a great extent by depressions, pits, and holes, with diameters of the order of inches. An unpublished study of the Goose Lake meteorite by E. P. Henderson and S. H. Perry indicates almost conclusively in this case that weathering could not have been responsible for the pitting in this large iron meteorite weighing 2573 pounds. The striking characteristic of many of the pits in the Goose Lake meteorite is the fact that the internal cross-section is larger than the cross-section near the surface of the body.

Because of ablation, we believe that the major portions of the pits on such a meteorite could not directly represent holes that were already present when the meteor struck the atmosphere. On the other hand, there is every reason to believe that meteoroids in space are frequently struck by smaller meteoroids, which would produce a large array of ordinary-shaped crater pits, ranging in size from microscopic dimensions to dimensions comparable with the meteoroid. One would not expect these "crater" pits to penetrate so deeply into the meteor as the "worm-hole" pits on which we seek to comment. We need, then, a mechanism to extend such crater pits deeply into the meteor. Some additional experiments performed by us with the facilities of the Naval Ordnance Laboratory cast a suggestive light on such a mechanism.

b) THE IGNITION POINT OF MAGNESIUM

In the course of the Woods-metal experiments it became evident that melting does not occur below Mach numbers somewhat higher than those at which the stagnation temperature reaches the melting point. We have already seen, however, that the whole phenomenon of heat transfer in this astroballistic region may possibly be better approached by ignoring the concept of temperature difference between gas and solid and by considering heat-transfer efficiency *as though* the gas atoms collided individually with the solid (even though such a naïve picture is certainly incorrect in its details). Then the value of Λ may be regarded as measuring a combination of this degree of inelasticity of collision between one gas atom and the surface and the likelihood of collision with the surface rather than with other atoms alone. Hence one way to raise the effective Λ value is to alter the geometry of the surface to increase these preceding two processes. We note here, of course, that the same idea may be presented from the thermal viewpoint. We recognize that stagnation temperature in the gas occurs only in a limited region at the very center of the cylindrical head. Thus, in order to raise a significant fraction of the surface to the melting point, one must either go to higher Mach numbers or alter the geometry of the surface in some such way that stagnation temperature holds over a greater area.

A straightforward method of increasing the "contact" area, or area over which stagnation conditions hold, is simply to make the front surface of the cylinder concave. Drag measures on such a body show a considerable increase as compared with such measures on a body with a flat face. One might also ask whether the results cannot be accomplished by roughening the front surface. We have studied such a method briefly. As a more sensitive indicator than the melting phenomenon, the flare point of magnesium was used. The flare point occurs at some 750° C, corresponding to stagnation conditions at Mach 3.7 and standard atmospheric temperature, or about 4200 feet/sec. The projectiles used in the study had a muzzle velocity of about 6000 feet/sec. Those projectiles whose flat front surface was nicely polished before firing did not flare. The same negative result occurred when the front of the surface was defaced, no indentation being much more than 1 mm or so in depth. However, when a circular "moat" was cut into a front surface (which was otherwise highly polished), flaring occurred. The phenomenon is reproducible. The distance of travel before flaring appears to vary with the diameter of the "moat," but, owing to lack of time allowed for the use of the experimental facilities, no detailed measures were made.

We interpret the results in the same manner as those for the drag on a body with a concave front. Stagnation conditions hold in the concavity, and the flare point occurs there (spreading out, of course). Now, if the flow pattern were such as to empty the cavity of molten material continuously, we should expect the cavity to propagate into the body at a more rapid rate than the outer surface melts. Thus we suggest the likelihood that the deep holes in meteorites may well represent the enlargement of initial, shallow "crater" pits according to the same mechanism as our magnesium flaring results.

The suggestion is difficult to check experimentally unless some method can be devised to recover the projectiles without damaging their front surfaces or to photograph them end-on in flight. One should probably prefer experiments with iron projectiles. Thus again we point out the desirability of carrying out experiments at velocities above 10^4 feet/sec if the proper launching device can be made available.

VI. SUMMARY

The results on the heat-transfer coefficient, Λ, from the various sources have been discussed in detail in the separate sections. In summary, we conclude that a value of Λ (see eq. [2] for definition) between 1×10^{-2} and 1.5×10^{-2} seems a reasonable estimate for velocities between 0.5 and 1.5 km/sec and in a range of air densities from 3×10^{-5} to 4×10^{-3} gm cm^{-3}. Moreover, the use of the formula

$$\text{Heat transfer} = \Lambda \frac{\rho v^3}{2}$$

seems to give a fair representation of the results over a factor of 200 range in ρ and of 3 in v. When we reach the meteor range of ρ and v—lying between 10^{-6} and 10^{-9} gm cm^{-3} and 8–65 km/sec, respectively—the value of Λ is not so well settled. On the basis of the present meteor observations, we can find no conspicuous correlation of Λ with ρ or v over the meteoric range. We can, however, conclude definitely that Λ increases by at least a factor of 3 when we pass from the ballistic region to the meteoric, since probably the best estimate we can make on the basis of our meteor data gives $\Lambda \sim 5\times10^{-2}$ in the meteor range. We must leave largely unexplained a variation by a factor of nearly 10 in the quantity $\sigma = \Lambda/(2\Gamma\zeta)$ for meteors, although we have presented several quasi-interpretations of the variation. We believe that further laboratory experimental investigation must be carried out in the velocity range 1.5–10 km/sec, at a variety of air densities. With these results and the meteor data now on hand and currently being obtained, the question of heat transfer in the astroballistic regime may be finally settled. We see no fundamental difficulty in the path of such a program.

We call attention to the great simplification in the computations of the heat transfer to rapidly moving bodies in the ballistic and aerodynamic regions that the above work implies. Use of the meteor formula,

$$\text{Heat transfer} = \frac{\Lambda}{2} \rho v^3 ,$$

rather than of the aerodynamic-ballistic formula,

$$\text{Heat transfer} = h (t_s - t_b) ,$$

eliminates the need of knowing the body temperature, t_b, or the stagnation temperature, t_s. We need know only air speed and air density, the two quantities that are always available. The implication of the result for aerodynamic and ballistic research is obvious.

We are deeply indebted to a number of people who have contributed to our thinking and aided in obtaining the results here presented. From the meteor standpoint we are indebted to L. Jacchia for his analysis of the extensive meteor data, and to E. Öpik for extended discussion over the physical theory of meteors. From the same sense, extended to the more general case of the general high-speed reaction between solid and medium, we are especially indebted to M. A. Cook, H. Eyring, and J. S. Rinehart. We are extremely grateful for the use of the Naval Ordnance Laboratory facilities, made possible by R. J. Seeger, and the co-operation in the research there of H. H. Kurzweg, H. Polachek, J. M. Kendall, D. Shanks, G. R. Eber, B. M. Shepard, C. E. Patton, and W. T. Whelen. In our early work in high-velocity ballistics we have been particularly aided by A. C. Charters and members of the Aerodynamics Free-Flight group at Aberdeen. E. P. Henderson has shown great consideration in providing us with the results of his extensive investigations and unpublished manuscripts on meteor pitting.