Smithsonian

Contributions to Astrophysics

VOLUME 5, NUMBER 4

OBSERVATIONS OF SIMULATED METEORS

by RICHARD E. McCROSKY

SMITHSONIAN INSTITUTION

Washington, D.C.

1961

Publications of the Astrophysical Observatory

This series, *Smithsonian Contributions to Astrophysics*, was inaugurated in 1956 to provide a proper communication for the results of research conducted at the Astrophysical Observatory of the Smithsonian Institution. Its purpose is the "increase and diffusion of knowledge" in the field of astrophysics, with particular emphasis on problems of the sun, the earth, and the solar system. Its pages are open to a limited number of papers by other investigators with whom we have common interests.

Another series is *Annals of the Astrophysical Observatory*. It was started in 1900 by the Observatory's first director, Samuel P. Langley, and has been published about every 10 years since that date. These quarto volumes, some of which are still available, record the history of the Observatory's researches and activities.

Many technical papers and volumes emanating from the Astrophysical Observatory have appeared in the *Smithsonian Miscellaneous Collections*. Among these are *Smithsonian Physical Tables*, *Smithsonian Meteorological Tables*, and *World Weather Records*.

Additional information concerning these publications may be secured from the Editorial and Publications Division, Smithsonian Institution, Washington, D.C.

FRED L. WHIPPLE, *Director*,
Astrophysical Observatory,
Smithsonian Institution.

Cambridge, Mass.

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington 25, D.C. - Price 15 cents

Observations of Simulated Meteors

By Richard E. McCrosky[1]

On October 16, 1957, three shaped-charges were fired simultaneously from an Aerobee Rocket at an altitude of 80 kilometers over the New Mexico range in an attempt to simulate meteor phenomena. The charges were mounted in such a way that there would be no ambiguity in the angle between the axes of trajectory of any two simulated meteors, or "meteoroids." Hence, if all three charges were successfully fired and observed, each meteoroid could be related to the specific shaped-charge that ejected it. Absolute aspect information could not be predicted since the rocket and the ejected nose cone, containing the charges, are subject to spin and tumbling.

Shaped-charges are explosive devices designed to focus the detonation front in such a way that a cylindrical or conical metal liner, inserted in the explosive, will collapse on itself and be ejected along the axis of the charge. The tangential forces, which collapse the liner, are symmetrical about the axis and cause no acceleration normal to the liner axis. Three different types of liners were used in this experiment.

Charge A was constructed at the Poulter Laboratories of Stanford Research Institute. The liner was a cylinder of aluminum, closed at the bottom end, 3 inches long and 0.5 inch in diameter. The thickness of the wall, from which the high-speed particles originate, was 0.028 inch and the total liner mass was approximately 5.5 grams. Firings of similar charges at the Poulter Laboratory show that the maximum particle velocity obtainable, for other than an extremely small amount of essentially gaseous material, is 14 km/sec. The particles ejected at this velocity are estimated to be less than 5 microns in diameter. Larger particles are produced but are ejected at lower velocities. At most, only 2 percent of the liner is expelled at velocities greater than 10 km/sec.

Charge B, also made at Poulter Laboratories, was constructed with a conical aluminum liner, 0.375 inch thick, with an apex angle of 120°. Similar charges have attained velocities of 5 to 7 km/sec. These charges eject a limited number of large particles.

Charge C, with a coruscative liner, was constructed by Dr. Fritz Zwicky, of the California Institute of Technology. It produces luminosity through self-contained chemical energy. Velocities in excess of 10 km/sec are thought to be obtainable.

Ground-based optical and radar equipment was employed to observe the luminosity and ionization produced by the ejected material. This paper analyzes the optical observations of two of the charges.

Observations

Five stations on or near the firing range were equipped to make optical observations. Each of the Harvard Meteor Stations—at Sacramento Peak and at Organ Pass—has two Super-Schmidt meteor cameras. One at each station had the usual rotating focal-plane shutter which introduces a time scale on the meteor trail. At Sacramento Peak, an f/0.8, 5-inch aperture Schmidt with a transmission grating yielding 1250 A/mm was also used. The three other stations, which were manned by observers from the Physical Science Laboratories of the New Mexico State University, used ballistic tracking cameras (without rotating shutters) with f/2.5, 3-inch lenses.

Each of these ballistic cameras obtained good photographs of the brilliant explosion and two meteors emanating from it. The Organ Pass station failed to secure observations because clouds obscured the region for the few minutes surrounding the explosion time. The Sacra-

[1] Harvard College Observatory and Smithsonian Astrophysical Observatory.

mento Peak Schmidts obtained successful photographs, although the films show only one meteor. Subsequent analysis has shown that the two meteors and the Sacramento Peak station lay almost precisely in the same plane. Also, the meteor motion was essentially in the direction of dispersion of the grating camera. The meteor spectrum was completely overridden by the spectrum of the explosion, as well as smeared by its own motion.

Geometrical Reductions

Measurements of the ballistic camera plates and of the Super-Schmidt films have permitted a determination of the trajectory of both meteors (see table 1). The ballistic cameras are designated as B18, B50, and B55. The letter *s* or *l* denotes the short or the long meteor trails visible on each plate. The poles of the apparent great circle motions of the *s*-trails lie approximately on the same great circle, and therefore the trails are due to the same meteor. This is also true for the *l*-trails. Because of the unfortunate geometric configuration relating the Sacramento Peak Station and the meteor trails, either great circle passing through the poles of the trails fits the Super-Schmidt pole equally well. However, a preliminary radiant for each meteor, determined from two pairs of the ballistic camera photographs, indicated that the *l*-trail as seen from Sacramento Peak was nearly perpendicular to the line of sight (84°), whereas the *s*-trail departed from the line of sight by only 23°.

One may roughly estimate the length of the *s*-trail, as it would have appeared on the Super-Schmidt film, by comparing the length of the *l*-trails on the photographs from the Super-Schmidt and the ballistic cameras. The end of the *s*-trail will probably not extend beyond the first quarter of the Super-Schmidt meteor and certainly most of the light of the *s*-trail will fall within the explosion image. I have therefore included the Super-Schmidt data in a least-squares solution for the *l*-trail radiant. This result, and a similar solution for the *s*-trails, are represented in table 1. The rms deviations given in the table are derived from the minimum distance between the great circle of meteor motion and the least-squares radiant.

The probable error for a radiant determined from two photographs is given (Hawkins, 1957) by the equation,

$$\delta R = \operatorname{cosec} Q_{12}\,(\sin E_1\,\delta b_1)^2 + (\sin E_2\,\delta b_2)^2, \qquad (1)$$

where Q is the angle of intersection of the trails at the radiant, E is the distance from the radiant to the trail, and δb is the error in the angle of the trail. The subscripts distinguish between the quantities at each of two stations. Q and E are known from the measures but δb must be estimated. In extreme cases, such as the 1-to-2-millimeter trails produced by the simulated meteors, δb is given by the expression $\delta y/x$ where x is the length of the trail and δy is the probable error of measurement perpendicular to the trail. A value of 10 microns is certainly a generous estimate for δy. Probable errors not exceeding 0.7° could be expected for radiants determined from most pairs of the present trails, and radiants determined from

TABLE 1.—*Data for trajectories of two artificial meteors*

Meteor	Film	Trail	Radiant position		rms error	Zenith angle of radiant
			t	δ		
I	B18	*s*	153.°3 E	−66.°2	±0.°01	143.°9
	B50	*s*				
	B55	*s*				
II	SS		40.°4 W	−66.°2	±0.°43	103.°0
	B18	*l*				
	B50	*l*				
	B55	*l*				

four trails should yield rms errors of the same order as given for the *l*-meteor in table 1. The small rms error given for the *s*-meteor is certainly fictitious.

The weight to be given a single meteor in determining the radiant is proportional to the length of the visible trail, and inversely proportional to the angular distance of the trail from the radiant. Weights tend to be equalized because the meteor trail appears to be longer when it is at a greater distance from the radiant. Weighting factors for the ballistic camera trails vary from one another by only 20 percent. The weight of the Super-Schmidt trail was one and a half times that of the ballistic camera trails. The Super-Schmidt trail was not given the extra weight, however, because a possibility existed that some asymmetry of the trail could have been caused by a blending of the two meteors at a point just outside the explosion image. The small difference in weights among the various ballistic camera trails was also ignored and a weight of unity was used throughout the radiant calculations. The angle between the two meteors as derived from these measures is $52\overset{\circ}{.}2$, with an estimated probable error of less than 1°.

The Super-Schmidt trail, lasting about 0.07 second, exhibits four shutter breaks. This trail, in conjunction with the B18 *l*-trail, was analyzed for velocities, ranges and heights by the standard meteor reduction methods (Whipple and Jacchia, 1957). The wide separation between the stations, 52.0 kilometers, is more than sufficient for the determination of accurate distances. The length, from the center of the explosion to the end, is 0.95 kilometer with the midpoint occurring at an altitude of 79.2 kilometers above sea level. The velocity, as determined from the spatial distances between the three adjacent pairs of shutter breaks, shows a marked, although not exceptionally well-determined, deceleration. These velocities are plotted in figure 1 as a function of time. If the deceleration was constant, the meteoroid had an initial velocity of 14.4 km/sec at a point in the center of the explosive burst.

Measurements of the angle between the charge axes were made by Dr. Milton C. Kells of Poulter Laboratories after the charges were mounted in the rocket. A comparison of these angles with the observed angle, corrected for the aberration introduced by the moving rocket, can supply the only reliable method of determining which pair of charges was observed. The correction for aberration requires a knowledge of the vector velocities of both meteors and the rocket. The present measures provide the necessary data for the *l*-meteor. The vertical component of the rocket velocity (0.81 km/sec) is accurately determined by the observed maximum altitude. The horizontal components may be estimated from the launching position, the rocket position at the time of the explosion as determined from the photographs, and the time elapsed between launching and explosion. This simplified technique assumes a constant horizontal velocity, a condition not met before rocket burn-out. However, this component is in reality small enough (0.078 km/sec) to neglect entirely. The direction of motion of the *s*-meteor is well-determined.

Thus, of the nine quantities needed to correct for the angular aberration, only the speed of the second meteor is unknown. A one-parameter solution has been made to determine the angular separation of the two meteors with respect to the rocket as a function of the unknown space velocity of the *s*-meteor. Figure 2 shows the results. Table 2 gives the actual separation angles along with the velocity that must pertain to the *s*-meteor for each of the three separation angles as read from figure 2. The last column of this table summarizes the arguments, given below, for rejecting or accepting each of the six possible associations.

All three shaped-charges were expected to eject their liners with velocities of 5 km/sec or more. Such a velocity would seem to eliminate pairs B–C and A–C but since there may be some chance of a substandard ejection, these possibilities are included.

If the B–C pair produced the two meteoroids, and charge B produced the *s*-meteor (first row of table 1), the luminosity must have been produced by aluminum particles travelling at a velocity comparable to that of the rocket itself. Certainly no meteoric luminosity can be expected at such low velocities; indeed, this is demonstrated by the absence of ablation from the rocket. If charge C (coruscative) were

TABLE 2.—*Separation angles and velocities for s-meteors*

Charge Pairs	Separation angle in rocket ($\pm 1°$)	If *s*-trail is produced by charge:	Velocity of *s*-meteor must be:	Then: intensity (I) or velocity (V) of meteor is:
B–C	36°	B	1 km/sec	I_B: too small
		C		V_B: too large
A–C	48°	A	2 km/sec	I_A: too small
		C		possible, but V_C substandard
A–B	53. 5°	A	5–9 km/sec	V_B: too large
		B		Consistent with expected values of velocity

substandard but produced luminosity by burning, then charge B must have had a velocity of 14 km/sec, twice its expected value. The possibility of a superstandard charge is too remote for consideration.

The same arguments apply to the hypothetical pair A–C; luminosity cannot be produced by the meteoric process at 2 km/sec. The velocity of the *l*-meteor is perfectly consistent with results obtained in ground tests of charge A. It is therefore at least a possibility that the two meteors were produced by a successful charge A and a substandard coruscative charge with a velocity of about 2 km/sec.

For a separation angle of 53°.5, the *s*-meteor must have attained a velocity between 5 and 9 km/sec. The velocity with respect to the rocket, for this range of spatial velocities, is approximately 0.65 km/sec less, and is consistent with that expected for charge B; the

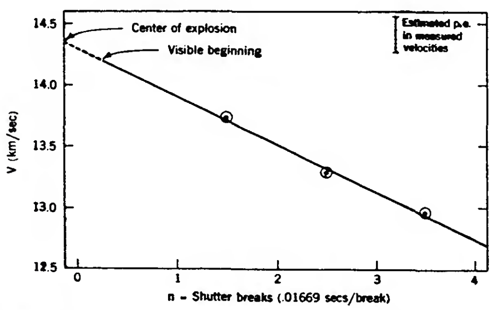

FIGURE 1.—Velocity-time plot of *l*-meteor determined from Super-Schmidt photograph.

l-meteor is consistent with charge A. The reverse identity is not acceptable because of the excessive velocity that must be attributed to charge B.

To summarize, then, it appears almost certain that charges A and B produced the l and s meteors, respectively. There remains a possibility that A and C produced l and s, respectively. In either case, the *l*-meteor, for which a velocity is known, must have resulted from a successful ejection of the liner of charge A.

It is interesting to compare the characteristics of charge A, as determined from laboratory tests, with the meteor it produced.

Velocity.—If the rocket velocities are subtracted from the observed meteor velocity, one finds that the meteor velocity, extrapolated to the center of the explosion, was 14.2 km/sec. The agreement with the laboratory measures of maximum velocity is excellent.

Deceleration.—A second comparison between the observations and the ejected particles can be made by determining a characteristic particle size from the deceleration. The drag equation is given as

$$\dot{V} = -\frac{\Gamma A \rho V^2}{m}, \qquad (2)$$

where Γ=drag coefficient, A=cross-sectional area, m=mass, ρ=atmospheric density, and V=velocity. With the deceleration as determined approximately from figure 1, a drag coefficient of 1.0, a spherical aluminum body,

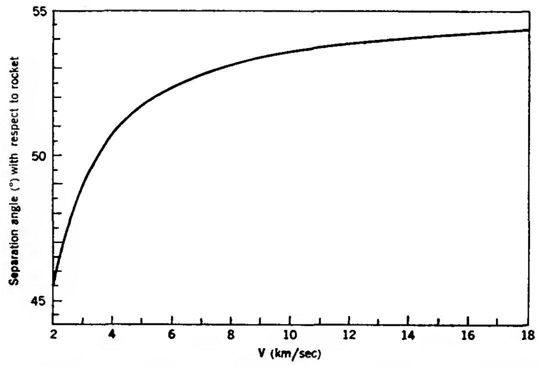

FIGURE 2.—Space velocity of *s*-meteor as function of angle between trajectory axes with respect to rocket.

and atmospheric density as given by the ARDC Atmosphere of 1956 (Minzner and Ripley, 1956), computation yields a particle radius of 30 microns. Too much emphasis should not be placed on this number since the deceleration is not well determined, and the larger particles, which are capable of lasting until the end of the meteor, are probably ejected from the charge with lower velocities. However, the computation indicates that the general size range is comparable to the expected particle size.

Light curve.—Another estimate of a characteristic particle size may be determined by the lifetime of the meteor or, more exactly, by the shape of the light curve. Although the quantity of light produced by a given body cannot yet be specified, the form of the equations predicting meteor luminosity are undoubtedly valid over a far greater range of velocities and atmospheric densities than that experienced by this particular meteor.

The observed light curve is given in figure 3. It is not possible to reproduce this light curve with a cluster of particles of the same size, but a characteristic size can be chosen which will approximate the slope of the curve.[2] The instantaneous intensity of a meteor is given by an equation of the form:

$$I=-\frac{\tau_0}{2}\dot{m}V^n \tag{3}$$

where $\dot{m}$ is the rate of mass loss by vaporization. The luminosity coefficient, specified by the factor τ_0, is assumed to be constant. The velocity exponent, n, is found to lie between 2 and 3. Since the present discussion attempts to determine only the shape of the light curve, the precise values of τ_0 and n are of little importance.

The production rate of vaporized material is given by the expression,

$$\dot{m}=-\frac{\Lambda A\rho V^3}{2\zeta}. \tag{4}$$

For aluminum the heat of vaporization, ζ, is $1\cdot10^{11}$ ergs/gram. The heat transfer coefficient, λ, measures the efficiency with which the colliding air particles transfer energy to the meteoroid. For small bodies this is probably of the order of unity. The derived particle size will vary approximately directly with the value of Λ. Then for $\Lambda=1$ (used here), one obtains a maximum size. If the particles are assumed to be spherical and of density 2.7, one can replace the cross-sectional area by 0.624 $m^{2/3}$. The instantaneous intensity is then given by the expression,

$$I\approx3.2\cdot10^{-12}\rho V^{3+n}m^{2/3}. \tag{5}$$

The time variations of I may be stated explicitly if the trajectory and atmospheric parameters are known. A considerable simplification results when the velocity and atmospheric density remain constant throughout the trajectory, as essentially occurs here.

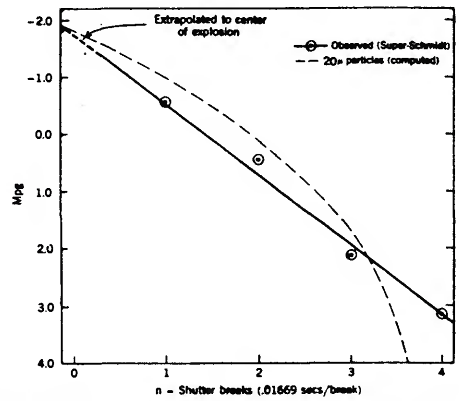

FIGURE 3.—Light curve of *l*-meteor determined from Super-Schmidt photograph.

[2] The shape of the curve, exponential in intensity with time, strikingly resembles the light curves observed in abrupt meteors for which a catastrophic disruption is believed to take place at or near the point of beginning (McCrosky, 1955). One is tempted to presume that the disruption by explosion produced the same distribution of particle sizes as in the pressure-fractured meteoroids.

A spherical particle of radius 20 microns, with trajectory and velocity determined for the *l*-meteor, would produce a light curve of the shape shown by the dotted curve in figure 3. The ordinate has been adjusted to permit an easy comparison with the observed curve. The agreement between the particle size and the upper limit expected from charge A is excellent. However, as with the deceleration analysis, this size should be interpreted as representing only an order-of-magnitude measure of the pertinent particles.

A determination of the number-size-velocity distribution of the ejected particles is an extensive laboratory problem that has not been attempted for charges of this design. Were these data available, one could predict the wake—the luminosity that occurs in the shutter breaks—or the elongation of the dash images resulting from the velocity dispersion of the particles. In fact these two effects are small, indicating (a) that the velocity dispersion of the luminous particles is small (≈ 2 km/sec), or (b) that the velocity-size relationship is such that much of the light in any one dash is produced by particles of similar characteristics; or (c) that the meteor was not produced by charge A but rather by charges B or C, either of which may produce a very limited number of larger particles. However, the reproduction of the observed separation angle, velocity, deceleration and light curve by another charge seems most improbable. One is forced to accept explanation (a), or (b), or a combination of both. The conditions in (b) are not as artificial as they may first appear. The smaller particles are known to attain higher velocities. Their lifetime would be short, but spectacular. A smaller number of larger particles, at lower velocities, would contribute relatively little to the initial luminosity but would persist to the end and become the major light producers.

Luminous efficiency

An integration of equation (3) gives the equation

$$\tau_0=\frac{2}{m}\int_0^\infty \frac{I}{V^n}\,dt. \qquad (6)$$

The luminosity coefficient, τ_0, is determinable if the total mass, velocity, and integrated intensity are known. The integrated intensity of a meteor is independent of the distribution of the particle size, except as the velocity varies with size either through differential deceleration or a distribution of initial velocities.

Of the two present estimates of τ_0, one results from a theoretical investigation of this difficult problem by Öpik (1933, 1955). The other is a semi-empirical result by Cook and Whipple (Cook, 1955) in which the observed forward momentum of a meteor train was related to the mass of the meteor and this, in turn, through the observed luminosity, was related to the luminosity coefficient. Cook and Whipple found a value 220 ($\pm$150) times smaller than that of Öpik.

The experiment described here offers the first example of a measure of meteoric luminosity produced by a known material. For a lower limit on the luminosity coefficient, I have assumed that 2 percent (0.11 grams) of the mass was ejected at the observed velocity. I have also assumed that $n=3$ in equation (6). The luminous efficiency, or the effectiveness with which the kinetic energy is transformed to visible radiation, is then

$$\tau=\tau_0 V.$$

The spectral distribution of the light required to determine the relationship between the intensity (in ergs/sec) and the photographic image is generally unknown. In meteor investigations one commonly adopts Öpik's (1937) expression,

$$M_{vis}=24.6-2.5\log I\ \text{(ergs/sec)}, \qquad (7)$$

and applies a "color index" correction derived from visual and photographic observations of the same meteors (Jacchia, 1957). For bright meteors of $M_{pg}<-1.0$, this color index is -1.8 magnitudes.

From these relationships and the integrated photographic intensity, one finds the luminosity coefficient of aluminum in the meteoric process to be $\tau_{0(Al)}=9\times10^{-10}$ sec/cm, and for a velocity of 14.4 km/sec $\tau_{Al}=0.0013$. Öpik's (1933) value[3] for natural meteoric material may be

[3] This value and the $n=3$ velocity exponent have been used extensively by the Harvard Meteor Project and elsewhere to determine masses. Maintaining a universal, although avowedly relative, mass scale has obvious merit in the present situation. For this reason the comparisons have not been made with Öpik's (1955) more recent value which is 60 percent of the earlier estimate.

expressed (Whipple, 1943) as $\tau_0=8.5\times10^{-10}$ sec/cm. However, aluminum is not a major constituent of meteors and these two values can not be compared directly. Corrections are required for the difference in composition between natural and simulated meteoroids and for any extraneous luminosity produced by oxidation of the aluminum. Neither correction can be reliably computed, but upper limits for these effects can be estimated and may be useful in the design for future experiments of this nature.

Correction for oxidation. The oxidation of aluminum provides a particularly efficient visual light source (White, Rinehart, and Allen, 1952). Photoflash lamps yield about 7×10^5 lumen-sec/gram aluminum in the conversion of the metal to Al_2O_3 (Forsythe and Easley, 1931). If we assume a constant energy per unit wavelength from 3800 to 6000 angstroms, the total luminous energy of the flash lamps is 3×10^{10} ergs/gram. The blue-sensitive emulsions used for meteor photography would be sensitive to perhaps one-half of this. The luminous efficiency for oxidation alone could then be as high as

$$\tau_{AlO}=3.0\cdot10^{10}/V^2=0.015,$$

or more than an order of magnitude larger than the minimum value of τ_{Al} derived from the observations. Oxidation, then, can conceivably be an overwhelming factor and must be considered. However, the conditions under which oxidation takes place in the flash bulb differ substantially from those in the meteor. Appreciable differences in the luminous efficiency of the two processes would not be unexpected.

To set an upper limit on the luminous efficiency of the aluminum molecule in the meteoric process, I will utilize evidence derived from spectra of natural meteors. The band radiation has never been observed in these spectra. This is certainly due to the low abundance of aluminum in meteors and does not imply a zero luminous efficiency of oxidation in the meteoric process. But nevertheless, the mere absence of sensible band radiation is sufficient to specify a significant limit on the efficiency. To determine this limit, suppose the total instantaneous intensity of a meteor is derived from two sources:

$$I=I_0+I_{AlO} \tag{8}$$

where I_0 is the usual line radiation observed in meteors and I_{AlO} is the molecular band radiation. It is reasonable to assume that the oxidation is proportional only to the mass of the aluminum and, unlike the atomic radiation, is not a direct function of the meteor velocity. Collisional energies exceed the dissociation energy of AlO for even the slowest meteors, and some deceleration of the aluminum atoms is always required before appreciable oxidation will occur. An increase in velocity will, at most, delay the oxidation. (An inverse velocity dependence may exist because of the increased oxygen-aluminum ratio for slow—and therefore low altitude—meteors. The form of this function is unknown and will be neglected; the upper limit obtained (below) for the luminous efficiency of oxidation is thus increased.) Then,

$$I_{AlO}=E\,A_{Al}\,\dot{m} \tag{9}$$

where A_{Al} is the abundance of aluminum by weight, taken to be 1.5 percent for natural meteoroids (Öpik, 1955) and E is the luminous efficiency of the oxidation process expressed as luminous energy/gram.

The absence of AlO radiation in any meteor spectra can, in principle, be used to set a limit on the ratio, $k=I_{AlO}/I_0$. Certainly $k=0.5$ is a conservative upper limit. We have then,

$$E=\frac{kI_0}{A_{Al}\dot{m}}, \tag{10}$$

and, from equation (3),

$$E=\frac{k\tau_0V^3}{2A_{Al}}. \tag{11}$$

Note that since the last term of equation (8) is independent of the velocity, one cannot rigorously apply an intensity law of the form of equation (3), to both I and I_0. Although the final results are not significantly affected if I, rather than I_0, is used in equation (3) a choice must be made, and the one made here reflects the writer's opinion that oxidation is negligible in the natural meteor phenomena and that the actual value of k is very much less than 0.5.

The lowest velocity for which a meteor spectrum has been obtained is 8 km/sec. As in all other cases, no AlO radiation was detected (Millman and Cook, 1959); E, then, cannot exceed $8.5\cdot 10^{18}\tau_0$.

Assuming this efficiency applies also to the simulated meteor, for which $A_{\mathrm{Al}}=1$, we obtain from equations (8) and (9)

$$I=I_0+8.5\cdot 10^{18}\tau_0\dot{m} \tag{12}$$

or, dividing by $\frac{\dot{m}V^3}{2}$, we obtain

$$\frac{2I}{\dot{m}V^3}=\tau_0+\frac{1.7\cdot 10^{19}}{V^3}\tau_0. \tag{13}$$

But the left-hand side is equivalent to the apparent value of the luminosity coefficient $\tau_{0(\mathrm{Al})}$, determined from the observations. The maximum correction to be applied for oxidation is then

$$\tau_0=0.17\tau_{0(\mathrm{Al})}. \tag{14}$$

Correction for composition.—Estimates for the corrections necessary because of the difference in composition between natural meteors and the simulated meteoroid can also be based on observations of meteor spectra. The strong aluminum pair at λ3944/3962 ($^2P^0-^2S$) is sometimes visible in meteor spectra. In low dispersion spectra the pair cannot be resolved from the H and K lines of Ca^+. Although the Ca and Al abundances are comparable in stony meteorites (and presumably also in photographic meteoroids), the Al lines are weak compared to H and K. Even in low-velocity meteors, where H and K are not observed and where it might be expected that conditions would favor the excitation of the neutral aluminum, such aluminum is generally absent in the spectra.

The luminosity of low-velocity meteors observed on blue-sensitive emulsion results almost entirely from the iron line emission, particularly from the $^5D-^5D^0$ and $^5D-^5F^0$ multiplets; and a determination of the efficiency of iron is tantamount to determination of the efficiency for natural meteors. Both the Fe and Al lines have upper levels of about 3 volts. The number abundance of Fe in stony meteorites is about 10 times that of Al, but since luminosity arising from the latter is concentrated in two lines, one would expect to observe these lines if the rate of population of the upper levels were comparable for the Fe and Al. Apparently then, the luminous efficiency of aluminum is less than that of iron in the meteoric process. Therefore a lower limit for the luminous efficiency of natural meteors is obtained by assuming equal efficiencies, per atom, of iron and aluminum. For the number of iron atoms in a natural meteoroid to equal the number of aluminum atoms in the simulated meteor, the mass of the former must be $\mu_{\mathrm{Fe}}/\mu_{\mathrm{Al}}A_{\mathrm{Fe}}=13.8$ times the latter where μ is the atomic weight and A_{Fe} is the abundance by mass of iron, taken to be 15 percent (Öpik 1958).

Applying the corrections for both oxidation and composition to the observed luminous efficiency for the simulated meteor, one finds a lower limit to the luminous efficiency of natural meteors,

$$\tau_0=\frac{.15\tau_{0(\mathrm{Al})}}{13.8}=1\cdot 10^{-11}\ \mathrm{sec/cm},$$

or about 3 times larger than the mean value given by Cook and Whipple, but within their probable error.

The value given here is thought to be an extreme lower limit. An equally safe upper limit cannot be obtained from the available data, and a value for as much as 100 times as large has not been precluded by this experiment.

Acknowledgment

The experiment to simulate meteor phenomena was designed and executed by Dr. Maurice A. Dubin of Air Force Cambridge Research Center, Dr. Milton C. Kells of Poulter Laboratories, Dr. John S. Rinehart of Colorado School of Mines, and Dr. Fritz Zwicky of California Institute of Technology.

The analysis was supported by Contract AF19(604)-5196 with the Geophysics Research Directorate of the Air Force Cambridge Research Center.

References

Cook, A. F.
1955. On the constants of the physical theory of meteors. Astron. Journ., vol. 60, pp. 156–157 (abstract).

Forsythe, W. E., and Easley, M. A.
1931. Characteristics of the General Electric photoflash lamp. Journ. Opt. Soc. Amer., vol. 21, pp. 685–689.

Hawkins, G. S.
1957. The method of reduction of short-trail meteors. Smithsonian Contr. Astrophys. vol. 1, pp. 207–214.

Jacchia, L. G.
1957. On the "color index" of meteors. Astron. Journ., vol. 62, pp. 358–362.

McCrosky, R. E.
1955. Fragmentation of faint meteors. Astron. Journ., vol. 60, p. 170 (abstract).

Millman, P. M., and Cook, A. F.
1959. Photometric analysis of a spectrogram of a very slow meteor. Astrophys. Journ., vol. 130, pp. 648–662.

Minzner, R. A., and Ripley, W. S.
1956. The ARDC model atmosphere, 1956. Geophys. Res. Directorate, AFCRC TN-56-204, ASTIA Document 110233.

Öpik, E. J.
1933. Atomic collisions and radiation of meteors. Acta et Commentationes Universitatis Taruensis (Dorpatensis), A 26, No. 2, 39 pp.
1937. Researches on the physical theory of meteor phenomena. III. Basis of the physical theory of meteor phenomena. Publ. Obs. Astron. L'Université Tartu, vol. 29, No. 5, 68 pp.
1955. Meteor radiation, ionization and atomic luminous efficiency. Proc. Roy. Soc. London, A 230, pp. 463–501.
1958. Physics of meteor flight in the atmosphere. 174 pp.

Whipple, F. L.
1943. Meteors and the earth's upper atmosphere. Rev. Mod. Phys., vol. 15, pp. 246–264.

Whipple, F. L., and Jacchia, L. G.
1957. Reduction methods for photographic meteor trails. Smithsonian Contr. Astrophys., vol. 1, pp. 183–206.

White, W. C.; Rinehart, J. S.; and Allen, W. A.
1952. Phenomena associated with the flight of ultra-speed pellets. Pt. 2. Spectral character of luminosity. Journ. Appl. Phys.,vol.23, pp. 198–201.

Abstract

An attempt has been made to simulate meteor phenomena by the high-speed ejection of shaped-charge liners at an altitude of 80 kilometers. Photographs of two of the three charges flown in an Aerobee rocket have supplied sufficient information to specify, with a high degree of probability, which charges were responsible for the observed meteors.

Laboratory tests of one charge give an upper limit to the mass ejected at significant velocities. This limit, together with the observed velocity and integrated intensity, is used to compute a lower limit on the luminous efficiency of aluminum in the meteoric process. The relative efficiencies of aluminum and natural meteoric materials are estimated and a lower limit is derived for the luminous efficiency of this latter material, assumed to have the composition of stony meteorites. This lower limit is comparable to an upper limit determined by Cook and Whipple from meteor train data. An upper limit on the luminous efficiency has not been well defined by this experiment, and a value 10^2 times larger, as has been suggested by Öpik, cannot be excluded.

U.S. GOVERNMENT PRINTING OFFICE: 1961