THE METEORITE FLUX AT THE SURFACE OF MARS

ROBERT D. DYCUS

Space Division, North American Rockwell Corporation
Downey, California

Received January 23, 1969; Revised May 26, 1969

Estimates of the average meteorite flux at the Martian surface are presented. These estimates were derived by generating a meteorite flux distribution for the top of the Martian atmosphere, and then adjusting this flux for mass loss and deceleration in the atmosphere. The top-of-the-atmosphere meteorite flux distribution was based on meteorite fall, asteroid, and lunar and Martian crater data. The effects of the Martian atmosphere were evaluated by performing a numerical integration of the mass loss and deceleration equations of the physical theory of meteors through an atmospheric model based on Mariner IV data. Results of this preliminary study indicate the Martian surface is afforded varying degrees of protection from impacting meteorites in the mass range 10 grams to 1 metric ton. Meteorites with masses greater than 1 metric ton are little affected by passage through the atmosphere while meteorites of ~ 10 grams mass and less are completely decelerated by the Martian atmosphere and impact the Martian surface with terminal free-fall velocities.

Introduction

The photographs transmitted by Mariner IV (Leighton, Murray, Sharp, Allen, and Sloan 1965) revealed numerous large craters on Mars. While this finding surprised a majority of the astronomical community, in retrospect one might have anticipated the numerous craters for several reasons: (1) Mars' close proximity to the asteroid belt should result in a relatively high impact rate if meteorites are debris from collisions in the asteroid belt; (2) The tenuous Martian atmosphere, confirmed by the Mariner IV occultation experiment, may be rather ineffective in decelerating impacting meteorites and thereby reducing their cratering; and (3) The tenuous atmosphere may be ineffective in eroding and filling craters by wind erosion. It should be mentioned in passing that Tombaugh (1950) and particularly Opik (1950, 1951) appreciated at least one of the above factors and did predict the highly cratered Martian surface. However, these predictions were generally overlooked.

The observed Martian craters suggest that meteorite impacts have been very important to the surface history and structure of the Martian surface. For this reason, quantitative estimates of the meteorite flux at the surface of Mars are of considerable interest. In addition, flux estimates are also necessary to assess the hazard meteorites pose to structures and operations on the Martian surface. The purpose of this paper is to present quantitative nominal estimates of the meteorite flux at the surface of Mars.

There is difficulty in precisely defining the meteorite flux at earth, and even greater difficulties may be expected in defining the meteorite flux at the remote distance of Mars. Many assumptions must necessarily be made and partial and incomplete data relied upon. The resulting estimate may, therefore, only be considered preliminary, and may be subject to rather large revision as our knowledge becomes more complete.

Basic Assumptions Regarding Meteorite Origin

It is necessary to first define some basic terminology as used in this report. The definition of the International Astronomical Union of a meteoroid (Millman 1962) as a solid object moving in interplanetary space, of a size considerably smaller than an asteroid and considerably larger than an atom or molecule, is adopted. The light phenomenon resulting from entry of a meteoroid into the earth's atmosphere is termed a meteor. In the following, a meteorite is defined as the remains of a meteoroid which reaches any planetary surface after passage through the planetary atmosphere. Further, the term is broadened to refer to the body in space prior to and during atmospheric entry.

It is assumed that all meteorites collected at earth are of asteroidal origin. At one time this was a widely held view and a common assumption. Now, however, there is not complete unanimity on this point. Perhaps the most serious objection to the above assumption is the very short cosmic-ray exposure ages, typically 1-10 million years, found for chondrites. It has been shown by Opik (1966*a*) from first principles and by Arnold (1965) from Monte Carlo computer calculations that collision lifetimes of asteroidal fragments perturbed into earth crossing orbits must be considerably greater than the chondrite exposure ages.

Due in large part to this chondrite "age problem," Urey (1959,

1965) and Arnold (1965) have suggested that chondrites are ejecta produced from lunar surface impacts of asteroid-origin-iron meteorites and comets. However, this suggestion has not been supported by chemical analyses of the lunar surface at three Surveyor sites (Hibbs 1969). These analyses have shown the lunar surface chemical composition is unlike hypersthene chondrites, the most common type of stony meteorite. A possibility still remains, however, that a small group of meteorites such as the basaltic enstatite chondrites may have a lunar origin.

Also, due in large part to the chondrite age problem, Opik (1966*a*, 1968) has suggested that meteorites are derived from comets. While this suggestion may be appealing from the standpoint of explaining the chondrite age problem, other pertinent observational data are in good accord with an asteroidal origin. Among these data one may cite: (1) observed light variations of asteroids indicative of irregular shaped fragments. These shapes are easily explained by collisional processes and agree with the irregular pre-atmospheric entry shapes of meteorites; (2) The few reasonably well determined orbits of meteorites have low incliniations with aphelia in the asteroid belt, in agreement with an asteroidal origin; (3) The color excess of 69 asteroids (the difference between the $(B-V)$ color index of an asteroid and the sun) has been found by Sytinskaya (1965) to be comparable to that of stony meteorites and stony meteorite crust; (4) The clustered distribution of gas retention and cosmic-ray exposure ages of meteorites is consistent with asteroid-collision produced meteorites (Hartmann and Hartmann 1968); (5) the lack of correlation between meteorite falls and known meteor shower maxima (Fisher and Swanson 1968); and, the absence of meteorite falls during periodic comet meteor showers is not inconsistent with an asteroidal meteorite origin.

In addition, the cometary-meteorite theory may meet with some difficulty in reconciling sufficient pressures to explain meteorite compositions while meeting the boundary conditions of comet nuclear masses and low-density conglomerate ices of Whipple's (1955) icy comet model. Although the writer believes the evidence weighs heavily in favor of asteroidal origin, he agrees with Donn (1969) that any proposal to which Opik has given serious thought should be carefully considered.

It now appears that the chondrite age problem is not insurmountable to an asteroid origin theory. Fisher (1966) has suggested that the chondrite exposure ages appear suppressed due to micrometeoroid erosion in space. This suggestion has been examined by Wetherill (1967) in considerable detail. He finds chondrite age suppression by erosion is possible, but requires liberal values of the asteroid mass-distribution slope and the ratio of fragmented to impacting collision mass. Hartmann and Hartmann (1968) have also arrived at the same conclusion, attributing the erosion primarily to "chipping" collisions. These collisions are produced by projectiles with masses less than 1/125th the target mass. In this case the projectile mass is insufficient to break or shatter the target meteorite. Instead, cratering or chipping of the meteorite occurs.

In summary, the asteroid origin explanation of meteorites meets with some difficulties, but in the main they can be overcome by adopting various plausible assumptions. In this regard the theory of Hartmann and Hartmann (1968) of asteroid collision, based on earlier work of Anders (1965), appears very promising. The alternate theories of a lunar or cometary origin of meteorites meet with even greater difficulties.

Meteorite Flux Relations

Meteorites, meteors, and asteroids are observed to follow the cumulative mass distribution

$$N = km^{s} , \qquad (1)$$

where N is the number of objects of mass m and greater. N represents the count, space density or flux of bodies depending on the value assigned the constant k. "S" is the slope of the mass distribution and is usually fairly constant over large ranges of mass.

Equation (1) can be written in logarithmic form applicable to meteorites in solar space

$$\log N = \log k + S \log m + f(r) , \qquad (2)$$

where $f(r)$ represents the meteorite distribution near the ecliptic plane as a function of the distance r from the sun. This distribution is assumed to be independent of celestial longitude and mass for meteorites of 1 gram mass and greater. Meteorites this massive are practically unaffected by Poynting-Robertson effect, and are distributed in space principally by mutual collisions and planetary perturbations.

The Meteorite Flux Model for Solar Space

The mass distribution slope is usually obtained from log-log plots of cumulative count data versus mass using equation (2), i.e.,

$$S = \partial \log N / \partial \log m \quad . \tag{3}$$

Data pertinent to the meteorite mass distribution slope may be obtained from: (1) meteorite fall and find data collected at earth; (2) asteroid count data which applies to immense bodies with masses between approximately 10^{15} and 10^{23} grams; and (3) lunar and Martian crater data. Use of the crater data assumes these craters are produced by meteorite impact or that the impact craters can be distinguished and separated from those of internal origin.

Many analyses of S appropriate to the above data have been made. The meteorite data have been analyzed by Hawkins (1960) and Brown (1960). Asteroid count data have been presented by Kuiper, Fugita, Gehrels, Groeneveld, Kent, Van Biesbroeck, and Van Houten (1958) and by Kiang (1962). Among the numerous workers analyzing crater data are: Opik (1960); Dodd, Salisbury, and Smalley (1963); Baldwin (1964); Hartmann (1966*a,b*); McGillem and Miller (1962); Fielder (1965); Brinkman (1966); Arthur, Pellicori, and Wood (1966); Shoemaker (1966); Leighton, *et al.* (1965); and Chapman, Pollack and Sagan (1968). This listing is only partial with respect to all the workers in the field and with respect to the often large number of publications of the various investigators. To facilitate interpretation of this wealth of data, only those analyses condisidered by the writer to be representative of the best are presented in Table I.

The data indicate that for very large bodies, observed asteroids and large crater-producing asteroids, S appears to be near -0.60, while for both the smaller iron and stone meteorites the magnitude of S appears to be larger, ~ -0.80. Such an increase in the magnitude of S for smaller bodies should be expected for the following reason. Fesenkov (1965) as early as 1947 showed that the collision probability for bodies in the asteroid belt increases with decreasing mass due to the increased surface area. The increased crushing for smaller masses resulting from more collisions increases the magnitude of S as shown by Hawkins' (1960) data for terrestrial rock crushing also presented in Table I. According to Hawkins' data

TABLE I

OBSERVATIONAL DATA PERTAINING TO THE SLOPE OF THE ASTEROIDAL MASS DISTRIBUTION

Population	Data	Data Range	S
Asteroids	Kiang (1962) analysis of asteriod data to 20th magnitude		−0.63
Meteorites	Brown (1960) analysis of stone meteorite falls	$8 \times 10^3 < m < 3 \times 10^5$	−0.77
	Brown (1960) analysis of iron meteorite falls and finds	$3 \times 10^4 < m < 4 \times 10^6$	−0.76
Lunar Craters	Fielder (1965) analysis of 3,877 craters over all of moon	$5 < D < 1300$	−0.54
	Hartmann (1966*a*) analysis of mare craters including ranger data	$4 \times 10^{-3} < D < 100$	−0.60
Martian Craters	Leighton *et al.* (1965) analysis of mariner IV photographs	$4 < D < 120$	−0.60
	Hartmann (1966*b*) analysis of mariner IV photographs		−0.57
Crushed Rock	Hawkins (1960) initial stages of terrestrial rock crushing		−0.67
	Hawkins (1960) well crushed rock		−1.00

m, mass in grams
D, crater diameter in kilometers

meteorites exhibit a moderate degree of crushing while the large asteroids exhibit very little.* For meteorite masses of primary concern to this study, a value of $S = -0.80$ is adopted as most appropriate for both iron and stony meteorites.

Log k may be evaluated from meteorite fall data. Unfortunately, these data consist of only some 1000 falls reported by eye-witnesses, almost all of whom are nonprofessional observers. The resulting dependence of these data on a variety of human and geographical factors is well known (Nininger 1963; Dycus 1968). For this study Brown's (1960) estimate of the one-gram-and-greater meteorite influx on earth (for combined stones and irons corrected for diurnal and seasonal effects) has been adopted with the following corrections applied: (1) Brown's influx rate has been multiplied by a factor of 14 as suggested by Millard (1963) to account for meteorites never recovered or reported; (2) The flux was divided by 2.92 to remove effects of convergence in the earth's gravitational field. The basis of this correction is discussed later; (3) The masses were adjusted for an average meteorite ablation loss of 80 percent. This last correction is in general agreement with Hawkins' (1963) assumption of a 90 percent mass loss for stones and 80 percent for irons. The log of the meteorite flux in nongravitationally disturbed space at 1 a.u. derived in the above discussed manner is -15.42 in units of one gram and greater meteorites incident per square meter per second.

The meteorite flux increase toward the asteroid belt can only be estimated at present. Several independent approaches, however, indicate this increase may amount to about two orders of magnitude at the center of the asteroid belt compared to 1 a.u. First, adopting the earlier assumption that the spatial distribution of meteorites is independent of mass, then Witting, Narin, and Stone's (1965) data on the distribution of asteroid perihelia indicate nearly two orders of magnitude increase of meteorite flux at the center of the asteroid belt. Note, however, that these data are for all cataloged asteroids and, therefore, contain considerable observational selectivity. Second, Anders and Arnold (1965) have performed trajectory

*Hartmann and Hartmann (1968) starting from the physics of a single collision have arrived at similar conclusions. The Hartmanns find asteroid collisions produce fragments with $S = 0.67$ for masses greater than 10^8 gm. At masses less than 10^8 gm the increased grinding due to more collisions and the presence of "chipping collisions" raises the value of S.

analyses of asteroids of three Hirayama families to determine the relative impact rates on Mars and the moon. In their analyses 1000 sample trajectory calculations resulted in from 22 to 33 impacts at 1 a.u. for asteroids of all three families. Again, the number of expected impacts is about two orders of magnitude greater in the asteroid belt compared to 1 a.u. Third, extrapolations of asteroid size-frequency distributions (Dycus 1965) also suggest an increase of two orders of magnitude. However, such extrapolations are very uncertain as observational completeness is assured only for asteroids brighter than $\sim +9$ absolute magnitude (masses $> \sim 10^{21}$ gm).

Adopting the constants discussed above together with the two orders of magnitude flux increase in the asteroid belt, equation (2) becomes

$$\log N = -18.97 + 4.44r - 0.89r^2 - 0.80 \log m \qquad (4)$$

for the meteorite flux near the ecliptic plane. N is the average number of meteorites of mass m grams and greater incident per square meter per second at a heliocentric distance of r astronomical units.

The Meteorite Flux at the Top of the Martian Atmosphere

At Mars' mean distance from the sun, 1.52 a.u., equation (4) reduces to

$$\log N = -14.28 - 0.80 \log m \qquad (5)$$

representing the meteorite flux in space undisturbed by Mars' gravitational field. This flux is increased at the top of the Martian atmosphere by convergence in Mars' gravitational field. To precisely determine this flux increase, the meteorite velocity distribution must be known. Obviously, this distribution is not known; however, a useful estimate of the flux increase can be made in the following manner.

From an analysis of meteorite radiant and diurnal fall distributions, Wood (1961) has estimated the mean velocity of meteorites at 1 a.u., independent of acceleration by the earth's gravitational field, to be approximately 8 km/sec. Adopting a $r^{-1/2}$ dependence of this velocity with distance (Kessler 1967), the mean meteorite velocity at 1.52 a.u. is 6.5 km/sec. It may be shown from the energy integral that the velocity V_∞ at the top of a platetary atmosphere is related to the gravitationally undisturbed planetocentric space velocity V_p by

$$V_\infty = [2GM/R + V_p^2]^{1/2} \quad , \tag{6}$$

where M and R are the mass and effective radius (solid body radius plus height of atmosphere) of the planet, resepectively. "G" is the universal constant of gravitation. From the above expression the mean atmosphere entry velocity of meteorites at the top of the Martian atmosphere is found to be 8.2 km/sec. This estimate also appears well supported by Opik's (1966*b*) calculated impact velocities of selected Mars-orbit-crossing asteroids.

The ratio I of the meteorite flux on a planet with mass M compared to the flux on the same body with no mass is given by the ratio of the capture cross section πb^2 to the geometric cross section of the planet πR^2, i.e.,

$$I = b^2/R^2 \quad . \tag{7}$$

The radius of the capture cross section b may be shown from conservation of angular momentum to be

$$b = R\, V_\infty / V_p \quad . \tag{8}$$

Combining equations (6), (7), and (8) yields

$$I = [2GM/RV_p^2] + 1 \quad . \tag{9}$$

Substituting the appropriate values into the above equation yields $I = 1.60$ for Mars and $I = 2.92$ for earth. The value for earth was applied earlier as a correction to the meteorite fall data. The factor 1.60 applied to equation (5) results in

$$\text{Log}\, N = -14.08 - 0.80 \log m \quad . \tag{10}$$

for the meteorite flux at the top of the Martian atmosphere.

Meteorite Mass Loss and Deceleration in the Martian Atmosphere

The Martian atmosphere acts upon entering meteorites principally in two ways; it reduces their masses through ablation and their velocities through atmospheric deceleration. To estimate this mass loss and deceleration a computer program was written to perform preliminary quantitative analyses. The program was based on the physical theory of meteors developed over the last forty years by a number of writers. Representative contemporary reviews of this work have been given by Whipple and Hawkins (1959), and by McKinley (1961). In view of the large body of literature only the basic equations pertinent to this study are presented. The reader is referred to the above review articles for derivation of the equations from first principles.

According to the physical theory of meteors, the rate of mass loss experienced by a meteorite of mass m and density δ_m entering an atmosphere vertically with velocity V is

$$\frac{dm}{dt} = (-\lambda A/2\xi)(m/\rho_m)^{2/3}\rho_a V^3 \quad , \tag{11}$$

where ρ_a is the atmospheric density. "A" is a dimensionless shape factor defined such that $A\ (m/\rho_m)^{2/3}$ is the effective cross-sectional area of the body. For a sphere, $A = (9\pi/16)^{1/3} = 1.2$. It is customary to assume that irregularly shaped meteorites will rotate and have a mean A near that of a sphere. The heat transfer coefficient, λ, measures the efficiency of the collision process to convert kinetic energy to heat. Estimates of this coefficient range from approximately 0.1 to 0.6. ξ is the heat of ablation of the meteoritic material. Estimates of this quantity vary from about $2\text{–}10 \times 10^{10}$ erg/gm, for silica $\xi = 8 \times 10^{10}$ erg/gm.

As the meteorite is losing mass it is also decelerating by

$$\frac{dV}{dt} = -(\Gamma A/\rho_m^{2/3} m^{1/3})\ \rho_a V^2 \quad , \tag{12}$$

where Γ is the drag coefficient which varies depending upon the instantaneous ratio of the molecular-mean-free path to the dimensions of the meteorite. For supersonic velocities in free-molecular flow Γ is nearly constant and equal to unity. In continuous flow Γ may decrease to about 0.5.

The atmospheric density in equations (11) and (12) may be represented in an isothermal atmosphere under hydrostatic equilibrium by the relation

$$\rho_a = \rho_o e^{-Z/H} \quad , \tag{13}$$

where ρ_o is the surface density and Z the altitude in an atmosphere with scale height H.

The computer program written for this study simultaneously integrated the mass loss equation (11) and the deceleration equation (12) through a 30-layer atmospheric model with equal 5-km layers. A simple Euler-Cauchy integration was performed using values of the various parameters shown in Table II.

TABLE II
PARAMETERS USED IN MASS LOSS AND DECELERATION CALCULATIONS

Symbol	Quantity	Adopted Value	Comments
A	Shape factor	1.2	Value appropriate to sphere
λ	Heat Transfer coefficient	0.4	Assumed nominal constant value
ξ	Heat of ablation	8×10^{10} erg/gm	Value for silica
Γ	Drag coefficient	1.0	Assumed constant which introduces some error
ρ_m	Meteorite density	3.5 gm/cm^3	Approximate mean density of stoney meteorites
ρ_0	Martian atmosphere surface density	1.465×10^{-5} gm/cm^3	Corresponds to surface pressure of 5mb indicated by Mariner IV data; Fjeldbo, Fjeldbo, and Eshleman (1966)
H	Martian atmosphere scale height	9.0 km	Derived from Mariner IV date; Fjeldbo *et al.* (1966)

TABLE III
METEORITE MASS LOSS AND DECELERATION IN THE MARTIAN ATMOSPHERE*

Mass at Top of Atmosphere (gm)	Calculated Mass Reaching Surface (gm)	Calculated Surface Impact Velocity (km/sec)
10^{10}	9.96×10^{9}	8.18
10^{9}	9.91×10^{8}	8.16
10^{8}	9.81×10^{7}	8.10
10^{7}	9.60×10^{6}	8.00
10^{6}	9.19×10^{5}	7.77
10^{5}	8.45×10^{4}	7.28
3.16×10^{4}	2.51×10^{4}	6.87
10^{4}	7.39×10^{3}	6.29
3.16×10^{3}	2.17×10^{3}	5.49
10^{3}	6.44×10^{2}	4.42
3.16×10^{2}	1.97×10^{2}	3.10
10^{2}	6.20×10^{1}	1.66
3.16×10^{1}	1.96×10^{1}	0.43
10^{1}	6.20×10^{0}	**

*Meteorite entering atmosphere vertically at 8.2 km/sec
**Meteorite completely decelerated to impact at free fall terminal velocity

The inadequacy of the physical theory of meteors to completely describe pertinent meteorite phenomena at the earth is well known. The tendency of cometary meteoroids and meteorites to fragment (McCrosky 1955) is a complicating factor, and a physical theory accurately allowing for fragmentation remains to be formulated. The phenomena of frothing and sloughing discussed by Allen and Baldwin (1967) may also apply to meteorites. No allowance for fragmentation, the assumption of numerous nominal values, and the simple integration scheme must result in loss of accuracy. However, in spite of these shortcomings, the results serve a useful purpose as an initial attack upon the problem.

Results of the computer calculations are presented in Table III. These results indicate the Martian atmosphere has very little effect on entering meteorites of masses greater than 10^{10} gram. With little loss of accuracy the flux of these meteorites at the Martian surface is well represented by equation (10). For meteorites in the mass range $1 < m < 10^{10}$ grams, atmospheric mass loss becomes important. To represent the average meteorite flux at the Martian surface in this mass range, a third order polynomial was fitted by the method of least squares to 21 points adjusted for atmospheric mass loss. The resulting relation

$$\text{Log } N = -14.249 - (0.8115)\log m + (9.89 \times 10^{-3})(\log m)^2 - (7.20 \times 10^{-4})(\log m)^3 \tag{14}$$

had a variance of 7.18×10^{-5}. Fits of fourth and fifth degree polynamials reduced the variance, but it was felt the third degree equation represented the calculated points with as much accuracy as warranted by the mass loss calculations.

Deceleration is the most significant effect the Martian atmosphere has on entering meteorites. This deceleration greatly diminishes the kinetic energy of smaller meteorites and, consequently, their resulting impact cratering. Relations between impacting meteorite kinetic energy and the diameter of crater formed are commonly based on underground nuclear explosion data. Shoemaker, Hackman, and Eggleton (1962) have found $D = 74\ W^{0.294}$ for the diameter of a crater in meters produced by a meteorite impact of W kinetic energy expressed in kilotons of TNT (one kiloton TNT equals 4.185×10^{19} ergs). This relation is based on a scaled depth of burst applicable to stony meteorites striking a target of the same density. Although the nuclear explosion data are for craters greater than ~ 1 km in diameter, for illustrative purposes, the cratering equation is extrapolated to smaller diameters. Based on this equation the cratering for a Martian surface with no atmosphere compared to a Martian surface under a 5 mb atmosphere is shown in Figure 1. The figure indicates that the Martian atmosphere provides the surface very little protection against impacting meteorites with masses greater than a metric ton (10^6 grams); varying protection is afforded the surface from impacting meteorites with masses between approximately one metric ton and 10 grams. Meteorites of ~ 10 grams and smaller should be completely decelerated by the atmosphere and impact with terminal free fall velocities.

The writer would like to express his appreciation to Drs. John D. Schopp and C. T. Daub of San Diego State College, for the many valuable comments and suggestions contributed in reviewing preliminary drafts of this paper.

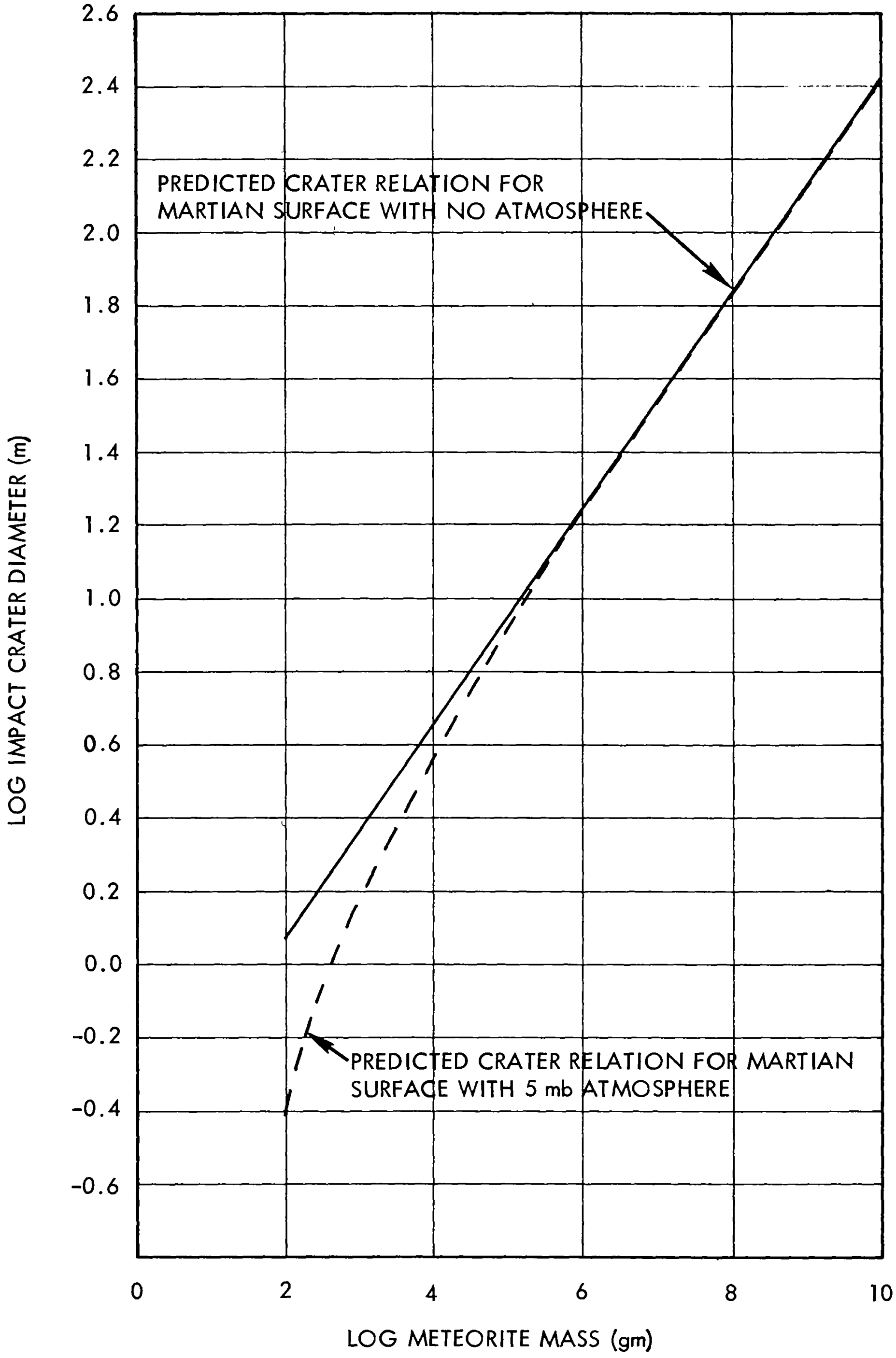

FIG. 1—Predicted crater diameters for meteorites impacting the Martian surface.

REFERENCES

Allen, H. J., and Baldwin, B. S., Jr. 1967, *J.G.R.* **72**, 3483.
Anders, E. 1965, *Icarus* 4, 399.
Anders, E., and Arnold, J. R. 1965, *Science* **149**, 1494.
Arnold, J. R. 1965, *Ap. J.* **141**, 1548.
Arthur, D. W. G., Pellicori, R. H., and Wood, C. A. 1966, *Comm. Lunar Planet. Lab.* **5**, No. 70.
Baldwin, R. B. 1964, *A.J.* **69**, 377.
Brinkmann, R. T. 1966, *J.G.R.* **71**, 340.
Brown, H. 1960, *J.G.R.* **65**, 1679.
Chapman, C. R., Pollack, J. B., and Sagan, C. 1968, *S.A.O. Special Rept.* No. 268.
Dodd, R. T., Salisbury, J. W., and Smalley, V. G. 1963, *Icarus* 2, 466.
Donn, B. 1969, *Sky and Tel.* **37**, 38.
Dycus, R. D. 1965, *North American Rockwell Corp. Space Division Rept.* SD65-1684, p. 99.
— 1968, *Pub. A.S.P.* **80**, 548.
Fesenkov, V. G. 1965, NASA TTF-378.
Fielder, G. 1965, *M.N.R.A.S.* **129**, 351.
Fisher, D. E. 1966, *J.G.R.* **71**, 3251.
Fisher, D. E., and Swanson, M. F. 1968, *J.G.R.* **73**, 6503.
Fjeldbo, G., Fjeldbo, W., and Eshleman, V. R. 1966, *J.G.R.* **11**, 2307.
Hartmann, W. K. 1966*a*, *Icarus* 5, 406.
— 1966*b*, *Icarus* 5, 565.
Hartmann, W. K., and Hartmann, A. C. 1968, *Icarus* 8, 361.
Hawkins, G. S. 1960, *A.J.* **65**, 318.
— 1963, *Nature* **197**, 781.
Hibbs, A. R. 1969, *Astronat. Aeronaut.* 7, 50.
Kessler, D. J. 1967, *Adv. Astronat. Sci.* **24** (in press).
Kiang, T. 1962, *M.N.R.A.S.* **123**, 509.
Kuiper, G. P., Fugita, V., Gehrels, T., Groeneveld, I., Kent, J., Van Biesbroeck, G., and Van Houten, C. J. 1958, *Ap. J. Suppl.* 3, 289.
Leighton, R. B., Murray, B. C., Sharp, R. P., Allen, J. D., and Sloan, R. K. 1965, *Science* **149**, 627.
McCrosky, R. E. 1955, Dissertation, Harvard University.
McGillem, C. D., and Miller, B. P. 1962, *J.G.R.* **67**, 4787.
McKinley, D. W. R. 1961, *Meteor Science and Engineering* (New York: McGraw Hill).
Millard, H. T. 1963, *J.G.R.* **68**, 4297.
Millman, P. M. 1962, *J.R.A.S. Canada* **55**, 265.
Nininger, H. H. 1963, in *The Solar System*, Vol. 4, B. M. Middlehurst and G. P. Kuiper, eds. (Chicago, University of Chicago Press) p. 162.
Opik, E. J. 1950, *Irish A.J.* 1, 22.
— 1951, *Proc Roy. Irish Acad.* **54A**, 165.
— 1960, *M.N.R.A.S.* **120**, 404.
— 1966*a*, *Adv. Astron. Astrophys.* 4, 302.
— 1966*b*, *Science* **153**, 255.
— 1968, *Irish A.J.* 8, 185.
Shoemaker, E. M. 1966, *J.P.L. Tech Rept.* 32-800-2.

Shoemaker, E. M., Hackman, R. J., and Eggleton, R. E. 1962, *Adv. Astronaut. Sci.* **8**, 70.
Sytinskaya, N. N. 1965, *Soviet A.J.* **9**, 100.
Tombaugh, C. W. 1950, *Sky and Tel.* **9**, 272.
Urey, H. D. 1959, *J.G.R.* **64**, 1731.
—— 1965, *Science* **147**, 1262.
Wetherill, G. W. 1967, *J.G.R.* **72**, 2429.
Whipple, F. L. 1955, *Ap. J.* **121**, 750.
Whipple, F. L., and Hawkins, G. S. 1959, *Handbuch der Physik* **52**, 519.
Witting, J., Narin, F., and Stone, C. 1965, *Science* **149**, 1496.
Wood, J. 1961, *M.N.R.A.S.* **122**, 79.