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METEOROID EFFECTS ON SPACE EXPLORATION

by Maurice Dubin
NASA Headquarters

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SUMMARY

Although the meteoroid hazard has not been adequately evaluated for proper design of spacecraft for missions through cislunar and interplanetary space, the extent of meteoroid interactions on space exploration may be estimated. Available information concerning meteoroids and cosmic dust obtained from ground-based observations and satellite measurements is reviewed. These data are presently limited to meteoroids and cosmic dust with heliocentric orbits intersecting the plane of the ecliptic at 1 AU and interacting with the earth-moon system. From such information the expectation of the number of impacts with interplanetary matter as a function of exposed spacecraft surface area, exposure time, and meteoroid mass is presented. An estimate of the hazard has been made using appropriate hypervelocity cratering criteria. Results of other authors are compared with the expectation of meteoroid interaction effects presented herein. The probability of damage to spacecraft is apparently considerably different and a bit less than some earlier estimates.

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INTRODUCTION

Interplanetary space contains debris, in heliocentric orbits, generally known as meteoroids. It is quite evident that the impact of a meteoroid with a space vehicle would be a catastrophic event. The dynamic conditions of such an impact would allow for impacting velocities ranging from a few to about 75 km/sec. The effects of the interactions of meteoroid impacts on space vehicles are of concern in the design of spacecraft for various cislunar and interplanetary missions.

The hazard from meteoroid impacts may be evaluated from (1) knowledge of the distribution of interplanetary matter in the solar system, and (2) knowledge of the characteristics of impact cratering and penetration from meteoroid impacts on spacecraft structures. The distribution of interplanetary matter in the solar system may be described by a mapping function $\Pi = \Sigma_i \pi_i$ where $\pi_i = \pi_i$ $(m, \rho_m, S_m, a, e, i, \Omega, \omega, t)$ and Π is the summation of all small π_i, which is the individual meteoroid structure and position in the solar system at any time. m is the mass, ρ_m the density, and S_m a parameter defining the structural makeup of the meteoroid. The meteoroid orbit is defined by a, e, i, Ω, and ω and its actual position is defined by t, where a is the semi-major axis of the elliptical orbit, e the eccentricity, i the inclination of the orbital with the ecliptic plane, Ω the ascending node and the point where meteoroid crosses the ecliptic traveling north, ω the argument of the perihelion and the angle from Ω to the perihelion measured in the orbital plane of the meteoroid, and t the time.

The magnitude of the velocity of the meteoroid depends on the radial distance r of the meteoroid from the sun:

$$V = \left[G_0\left(\frac{2}{r} - \frac{1}{a}\right)\right]^{1/2},$$

where G_0 is the solar gravitational constant. Thus, if the mapping function were known, the probability of a spacecraft impacting with a meteoroid anywhere in interplanetary space would be known. In fact, if the mapping function Π were known with sufficient accuracy, catastrophic impacts with meteoroids could be avoided.

A great deal is known about the mapping function; for the ascending node, Ω, equal to 1 AU. Π at 1 AU is not known sufficiently well to give discrete predictions of micrometeoroid encounters.

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However, statistical data from encounters of meteoroids with the atmosphere and spacecraft sensors have been sufficient to define a distribution function I(m) which depends mainly on the mass of the meteoroid. I(m) is given in terms of the number of impacts by meteoroids of mass m (and larger) per unit area and time at 1 AU in the plane of the ecliptic and near the earth. Thus, I(m) near the earth may be derived from the mapping parameter II. In practice, II is an unknown function with the exception of about 2000 asteroids in orbits between Mars and Jupiter, several scores of comets, and the meteor showers usually associated with known comets.

The specific gravity or density ρ_m of meteoroids may vary considerably. Meteorites (meteoroids recovered on earth and apparently of asteroidal origin) are solid bodies made of stone or iron. The great majority of meteorites are stones with densities of about 3.5 gm/cm^3, while less than 10 percent are iron or iron nickel with densities of about 8 gm/cm^3. Most of the meteors detected by visual, optical or radio methods have characteristics defining a fragile, and possibly fluffy, structure. The meteor orbits vary considerably from the asteroid orbits. Hence, meteors in general probably have a cometary origin. The densities, ρ_m, of the meteoroids observed in the earth's atmosphere as meteors are probably between 0.3 and 3 gm/cm^3—less than that of meteorites. Although the structure of cometary material has been hypothesized from various models, this structure is practically unknown and difficult to simulate.

To assess the effects of meteoroids on space vehicles at 1 AU, the distribution function I(m) has been derived from available data. I(m) defines the *expectation* of an impact per unit area and time at 1 AU. This function I(m) combined with cratering and penetration conditions defines the meteoroid hazard. The depth of penetration p depends upon the structural parameters m, ρ_m, and S_m of the meteoroid, the target material S_t and density ρ_t, and the relative velocity v and the angle of impact. The penetrating flux may be derived from the combination of the function of penetration depth p and the expectation of impact I(m).

A number of papers have been written on the subject of penetration of spacecraft by meteoroids (References 1 through 6). These and other references are considered in reviewing the expected meteoroid effects, and some parts of References 2-6 will be compared critically below.

RATE OF METEOROID IMPACTS

The rate of meteoroid impacts upon the earth has been obtained from various measurements of meteors and micrometeorites. Reference 7 reviews the derivation of I(m) from data obtained from visual, optical, and radio observations of meteors, from accretion measurements in the atmosphere and on the earth's surface, and from direct satellite measurements.

The cumulative mass distribution I(m) for the omnidirectional flux of dust particles and meteoroids is plotted from Reference 7 (Figure 1). The cumulative influx rate is plotted as a segmented function of the particle mass and in equivalent visual magnitude. The visual magnitude M_v is an astronomical scale for comparing the light intensity of stars and meteor trails; it is a logarithmic scale of brightness, with 5 magnitudes representing a factor of 100. From optical and visual observations the number of meteors as a function of visual magnitude against a star background is almost directly obtained. Radar methods have been used to measure the distribution and number of meteors as a function of the electron density per unit length of the meteor trail. The electron-line density is also related to the visual magnitude and particle mass of the meteor. For ρ_m = 1 gm/cm^3, particles of mass less than 10^{-12} gm would be subjected to a solar radiation pressure force greater than the solar gravitational attraction. The fact that dust particles of mass less than 10^{-12} gm have been detected indicates that the dust particles have densities which are generally greater than 1 gm/cm^3.

The accretion rates represented by the curve A (by Watson) were plotted from Reference 8 as a function of particle mass. The dashed curve B (by Whipple) is plotted as a function of visual magnitude and was obtained from Reference 3. This method of plotting the two distributions serves to illustrate the type of uncertainty involved in displaying the impact rates as a mass distribution. This uncertainty will be discussed later.

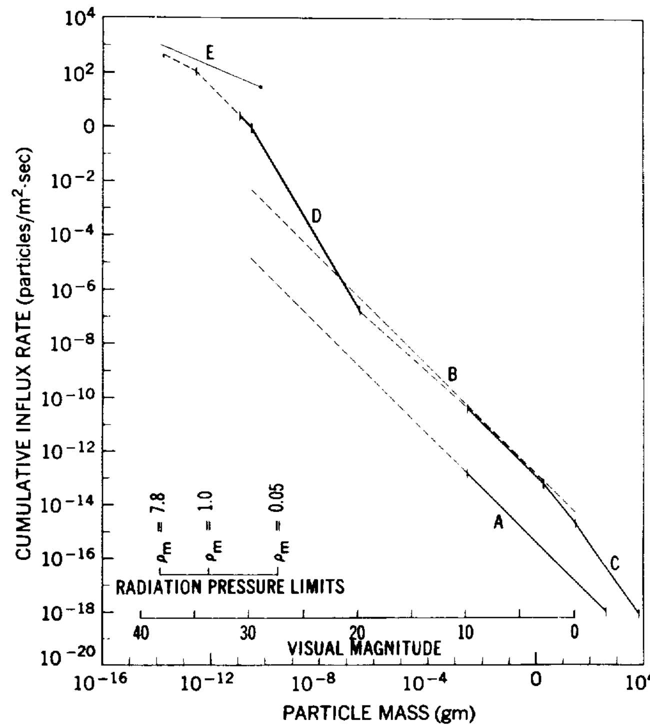

Figure 1—Segmented cumulative mass distribution for omnidirectional influx rates of meteoroids and dust particles. Curves A through E were obtained from References 8, 3, 9, 7, and 12, and 4 respectively.

The curve C, (by Millman and Burland) obtained from Reference 9 is presented in three segments and covers the range from $-10 \lesssim M_v \lesssim 10$. This curve is representative of meteor observations from optical, telescopic, and radar methods. In Reference 10 the cumulative influx rate of photographic meteors in the range of visual magnitude $0 \lesssim M_v \lesssim 5$ was determined using a sample of over 300 meteor photographs. The naked-eye visual meteors and photographic meteors number several tens of thousands. The number of radio meteors observed is greater still by at least another order of magnitude.

In the range of visual magnitudes of $20 \lesssim M_v \lesssim 10$, or particle masses of 10^{-7} gm $\lesssim m \lesssim 10^{-3}$gm, almost no data exist to define a distribution function. This range of particle mass is too small to interact with the earth's atmosphere and form meteors large enough to be detected by ground-based radio techniques and telescopes. A small amount of radar data has been reported out to visual magnitude 14 (Reference 11). This same range of particle mass populates interplanetary space quite sparsely—so much so that the exposure times and areas of sensors on satellites have so far been inadequate to obtain any measurements. This range of mass is of importance in the penetration and damage of spacecraft structures.

On the other hand, particles of mass smaller than 10^{-8} gm are relatively more numerous and have been detected with probes and satellites. The curve D (by McCracken, Alexander, and Dubin) is based on experimental data obtained by direct measurements (References 7 and 12). The curve was obtained with sensors which were calibrated to measure particle mass rather than visual magnitude. This segment of the curve was obtained from experimental rocket probe and satellite data (Figure 2). For the interval of particle mass 10^{-10} gm $\lesssim m \lesssim 10^{-6}$ gm, the cumulative distribution curve of the influx rate of dust particles as a function of particle mass may be described by $\log I = -17.0 - \log m$, where I is in particles/m^2-sec. The function $I(m)$, however, cannot be described correctly by a single first degree equation with logarithmic parameters.

In Figure 1 the two segments for visual magnitude $30 \lesssim M_v \lesssim 40$ were obtained in the analysis of Reference 13, while the curve E (by Soberman and Hemenway) was obtained by collecting dust with an Aerobee rocket trapping device described in Reference 14. The interpolated region between visual magnitudes 10 and 20 represents an important region for spacecraft design, since particles of mass between 10^{-3} gm and 10^{-7} gm may penetrate the surface materials used on spacecraft. The cumulative distribution function in Figure 1 may be analyzed with greater ease if $dI(m)/dm$, the incremental mass distribution as a function of particle mass, or $[dI(m)/dm]\,[dm/dM_v]$, the visual magnitude is plotted. Figure 3 represents the incremental mass distribution curve derived from Figure 1. The rate of accretion by the earth/day in grams/visual magnitude-day (when divided by 1.3×10^{-19}, it becomes the influx in particles/m^2-sec/visual magnitude) is plotted as a function of M_v and particle mass. The curve has been smoothed to remove the effects of using a segmented cumulative mass distribution curve. The uncertainty of spread in mass influx per visual magnitude in the range of visual magnitudes from +10 to 0 is bordered between the curves A and B. The value of 25 gm for a meteoroid of zero visual magnitude and 28 km/sec average velocity (Reference 3) was used in relating visual magnitude to particle mass.

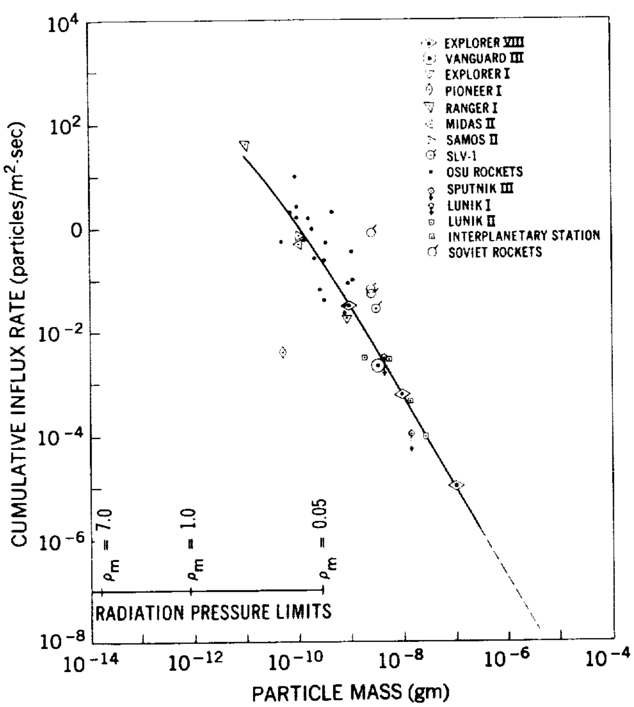

Figure 2—Average cumulative mass distributions of interplanetary dust particles derived from satellite and rocket probe measurements.

In Figure 3 the accretion of interplanetary material on the earth is shown to be dominated by dust particles with masses less than about 10^{-6} gm. The accretion rate of interplanetary dust particles is about 5×10^4 tons/day. A conservative estimate of 10^4 tons/day should probably be used until improved satellite measurements giving particle orbits are obtained. The accretion rate derived from direct measurements is in fair agreement with the estimate (Reference 14) of 4×10^4 tons/day based on mountain top collections and an earlier estimate of 4×10^3 tons/day based on deep sea sediments. Reference 16 gives an influx of 10^{-13} gm/cm^2 sec (5×10^4 tons/day) for particles of radii greater than 1μ based upon observations of the earth's shadow during lunar eclipses.

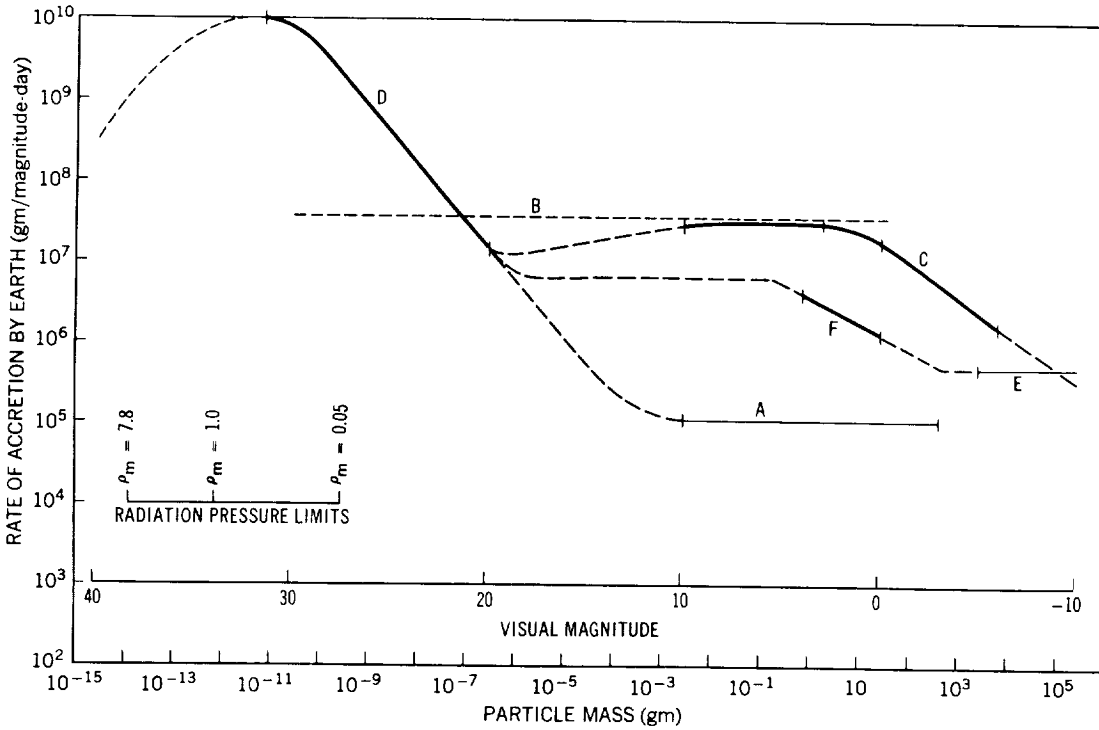

Figure 3—Incremental mass distribution curve for interplanetary material accreted by the earth. Curves A through F were obtained from References 8, 3, 9, 7 and 12, 19, and 10 respectively.

The curves of Figures 1 and 3 are averaged in time. The character of all meteor and interplanetary dust measurements has been defined mostly from ground-based observations. The influx rate of particles usually undergo temporal variations; the major variations are often associated with meteor streams and showers. These showers are well described in the literature (References 9, 17, 18, 19, and 20). During short periods of time—a few hours to several days—the influx rate may increase by one to two orders of magnitude above the average rate. The observations (Reference 11) of very faint radar meteors ($M_v \gtrsim 14$) have shown that a large fraction of meteors occur in streams or sporadic showers. The large fluctuations in the influx rates of faint radar meteors with mass $\approx 10^{-5}$ gm have also been observed from dust particle measurements by probes and satellites (References 7, 21, and 22). The distributions of showers and sporadic showers in interplanetary space are probably very similar to the distribution near the earth. The orbits of showers and sporadic meteors have been described in References 17, 18, 20, and 23. From these and other observations, nearly all the meteoroids observed appear to be of cometary origin and are travelling in direct heliocentric orbits. Althrough it had been apparent that nearly all meteors in the visual and radar range have only small inclination angles with the ecliptic plane, a "toroidal" group discovered at the Jodrell Bank Experimental Station, England, has been confirmed to represent an important fraction of meteors with $M_v \approx 10$ (Reference 23). This toroidal group is represented by short period orbits and inclination angles as high as 60 degrees.

EXPECTATION OF IMPACT BY METEOROIDS AS A FUNCTION OF MASS

The expected impact rate of meteoroids as a function of mass may be obtained from Figures 1 and 3, which are derived from experimental data averaged to smooth effects from large fluctuations and showers. The expectation of impact and penetration of surfaces could be estimated from such a curve. However, the variations appear excessively large in the range of visual magnitudes from $0 \lesssim M_V \lesssim 10$ because of the large spread in the influx rate bounded by curves A and B. Actually, there is *no* discrepancy or spread in the influx rate as a function of visual magnitude. Both photographic and visual data of the numbers of meteors/m^2-sec as a function of visual magnitude give identical results except for a small correction factor of 1.8 visual magnitudes concerned with the photographic process. The major discrepancy shown in Figure 3 results from the estimates of the mass of a meteor resulting in a trail of given visual magnitude. For curve A, a zero visual magnitude meteor, was estimated to have a mass of 0.25 gm and a velocity of 55 km/sec, and the density of the meteor was assumed to be about 3 gm/cm^3. The curve B is based upon the same distribution with a specific gravity of 0.05 and an average velocity of 28 km/sec. In this case, a zero visual magnitude meteor would have an average mass of 25 gm. The discrepancy is dependent upon the luminous efficiency and assumptions relating to the specific gravity of the meteoroid. Recently measurements of luminous efficiency have been made (Reference 25), which would support a higher specific gravity than given in Reference 3. The Reference 3 value of density was recently reconsidered by the same author (Reference 26) as possibly being too low; an average ρ_m of 0.3 gm/cm^3 was given instead of 0.05 gm/cm^3.

From Reference 9 the values given by various authors of the mass of a zero magnitude meteor may be compared as in Table 1, which is based on several references. Except for the change to 0.05 gm/cm by Whipple (References 3 and 17) the mass of a zero magnitude meteor has been estimated between 0.05 and 1.3 gm. This mass range is more than a factor of 20 less than the mass of 25 gm given in Reference 3. The value of 25 gm for a zero magnitude meteor was derived from the assumption that the density of meteors generally had a value of 0.05 gm/cm^3. Although it is well confirmed that the structure of meteoric bodies is weak and fragile, only a single, and hence not significant, measurement of such a low density has been reported. A value of ρ_m close to 1 gm/cm^3 is to be preferred. Thus, the expected impact rate by a meteoroid as a function of mass per unit time and area is really fairly well known.

Table 1

Mass of a Meteoroid of Zero Visual Magnitude.

Mv	Mass (gm)	Velocity (km/sec)	Reference	
			Author	Number
0	0.25	55	Watson	8
0	1.25	40	Whipple	2
0	0.055	40	Levin	28
0	25. (dustball)	28	Whipple	3
0	0.15	30	Whipple and Hawkins	29
0	0.29 1.29 (dustball)	42	Öpik by McKinley	30, 9

Both Figures 1 and 3 should be considered as plots of impact rate as a function of particle mass rather than visual magnitude. Since there is evidence (Reference 27) that penetration depth is a function also of ρ_m (as will be discussed later) the cumulative influx rate as a function of particle mass should be a curve consisting of the curves A and D and with an interpolation between the two distributions of Figure 4. The effective ρ_m to be used should be 1 or 2 gm/cm^3. This is the curve and the specific gravity to be used to determine the *expectation* of impact by a meteoroid.

We may not, in any case, realistically use the curve B with a ρ_m other than $0.05\ gm/cm^3$; for, if the ρ_m for this curve were assumed to be $3\ gm/cm^3$, then the curve would become the curve A. The deceleration as well as visual magnitude of meteors has been accurately measured by photographic methods; such an assumption in the change of area to mass ratio by assuming a ρ_m change without the attendant change of the mass of the meteoroid would be quite inconsistent with observations. The distributions from References 9 and 10 were derived with a similar assumption relating to the mass of a meteoroid as a function of visual magnitude.

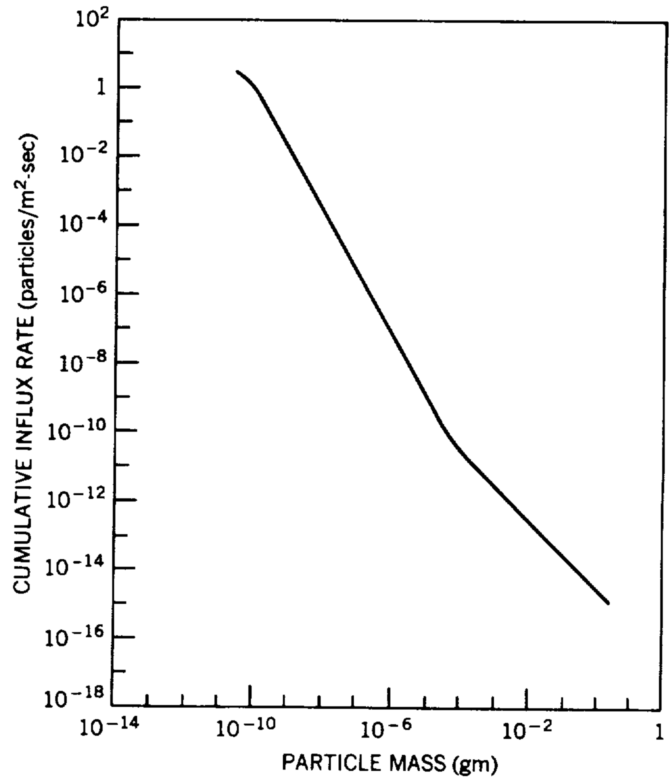

Figure 4—Expected average cumulative distribution of influx rate as a function of meteoroid mass in the vicinity of the earth. Specific gravity of the meteoroids assumed to be approximately 2.

There is some indirect evidence from measurements of the F component of the solar corona and the zodiacal light that the satellite distribution curve may change in interplanetary space. The influx rate might drop by two or three orders of magnitude as discussed in Reference 7. Hence, the expected mass distribution curve might be approximated in interplanetary space by the curve A together with the curve D lowered by two to three orders of magnitude in the range of particle mass from 10^{-10} to 10^{-12} gm.

Thus, in designing spacecraft for journeys in satellite orbits and heliocentric orbits at 1 AU the hazard from meteoroid impacts should be evaluated based on the *expectation* of impact by a meteoroid of a given mass or larger using the available data as described in Figure 4. It is doubtful that this curve is greatly in error. The influx rates (as functions of mass) would probably never be more than an order of magnitude greater than the natural influx rates except during periods of recognizable sporadic showers and several of the known meteor streams.

PENETRATION AND DAMAGE FROM MICROMETEOROID IMPACTS

The mechanism of crater formation is essentially one of cavitation resulting from an intensive plastic deformation wave formed during the impact. The size of the crater and its shape are determined by the properties of the wave and the target material. The initial conditions during the early stages of the impact determine the amplitude and shape of the deformation wave. Eichelberger (Reference 31) further describes the initial stage of the impact or primary penetration as characterized by a very rapid plastic deformation of the target and impacting projectile. If the impact velocity is very high, the surface pressure so far exceeds the yield strength of the material that a hydrodynamic treatment is quite accurate.

The shape of the plastic deformation is determined during a time approximately proportional to

$$\frac{m^{1/3}}{v}\left[1+\left(\frac{\rho_m}{\rho_t}\right)^{1/2}\right]$$

in the initial stage of crater formation. This time defines the width of the deformation wave. The amplitude of the deformation may be estimated from Bernoulli's equation as approximately

$$\frac{1}{2}v^2\rho_m\rho_t\left[(\rho_m)^{1/2}+(\rho_t)^{1/2}\right]^{-2}.$$

The deformation wave propagates into the target, displacing material as it disperses. Hence, the effects in the target depend upon the properties of the target material as described by the material's equation of state. The crater dimensions will be determined by the distance traveled by the deformation wave while its intensity is greater than the strength of the target material. The model described is essentially the same as that used by Bjork (Reference 32) in his theoretical treatment of cratering.

The effect of a meteoroid impact at velocities between 10 km/sec and 75 km/sec may be determined theoretically. Some experimental studies have been made at low velocities—in some cases, up to about 15 km/sec. Bjork has shown that the impacts at meteoroid velocities behave hydrodynamically. Using the equation of state, Bjork solved the impact equations for semi-infinite iron cylinders (References 4 and 32).

Calculations were made for impact velocities of 5.5, 20, and 72 km/sec. Here the impact forces exceed the strength of the materials impacted by a large factor, so that material strength, in addition to viscous effects and heat transfer, was neglected in the calculations. These calculations agreed for craters produced in aluminum at 6.3 km/sec and iron at 6.8 km/sec with experimentally determined crater sizes and shapes.

The penetration depth p, in cm, may be described by the equations:

$$p = 1.09(mv)^{1/3} \text{ for Al on Al,}$$

and

$$p = 0.606\,(mv)^{1/3} \quad \text{for Fe on Fe} ,$$

where m is the meteoroid mass in gm and v the velocity in km/sec. Experimental data for impacts on lead result in a similar equation (Reference 33); $p = 1.3\,(mv)^{1/3}$. The calculated craters were hemispherical with radius p. The craters formed by impacts at oblique incidence were also hemispherical.

Although calculations were made for thick targets, enough information was obtained that if a meteoroid penetrated a depth p in a thick target, it would just penetrate a sheet of the same target material of thickness 1.5 p.

Experimental impact data have been obtained from which the dependence of penetration depth on projectile density was determined (Reference 27). A series of impacts were made on the same target material with a constant projectile mass and a constant impact velocity of about 2 km/sec. A range of projectile densities from 1.5 to 17.2 gm/cm^3 was tested by using different metals. The dependence on ρ_m was described by the equation:

$$p = 2.28\left(\frac{v}{v_s}\right)^{2/3}\left(\frac{\rho_m}{\rho_t}\right)^{2/3} d ,$$

where v_s is the speed of sound in the target, d the diameter of the projectile. The penetration depth probably also depends upon the density ratio between the meteoroid and the target material at the higher impact velocities. For this reason, the cumulative distribution of meteoroids as a function of mass in Reference 3 must be used with consideration for proper dependence of penetration depth on the density of the meteoroid.

The penetration depth to projectile diameter ratio has been plotted as a function of velocity in Figure 5 (Reference 34) to indicate how the theoretical analysis of Bjork compares with extrapolations of experimental results obtained by Summers and Charters (Reference 27), Collins and Kinard, and Atkins. It is noteworthy that such extrapolations lead to very large errors in penetration depth which cannot be correct because of energy and momentum conservation requirements.

Another condition resulting from the deformation wave following the impulsive loading by the meteoroid impact is spallation. The intensive compressive shocks from the impact may rupture and eject material over an extended region around the crater as well as the far surface of the impacted sheet. The diameter of the section spalled is usually several times the sheet thickness, and the spall thickness may be a tenth to a half the thickness of the sheet. In Reference 5, an analytical derivation is used to indicate an energy rather than a momentum dependence for the volume of spalled material. For alloy aluminum a characteristic distance D (in cm) for spalling is given by

$$D = 7.6 \times 10^{-4}\,E^{1/3}$$

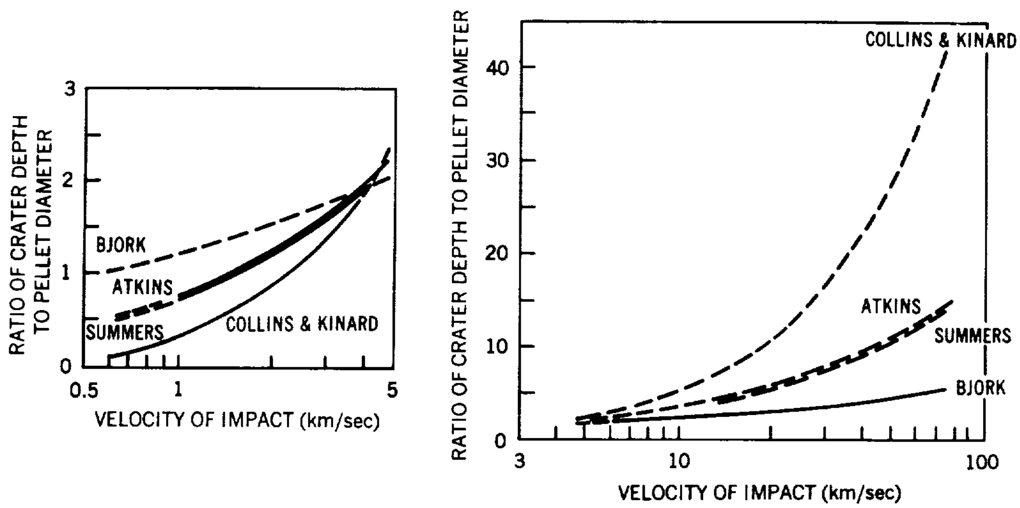

Figure 5—Velocity dependence of the penetration-depth-to-pellet-diameter ratio for aluminum impacting aluminum, based on theory (solid curve) and extrapolated (dashed curve) experimental data.

and, for steel,

$$D = 5 \times 10^{-4} E^{1/3} ,$$

where E is the kinetic energy of the meteoroid in ergs. Spallation can occur in sheet thicknesses two or three times greater than necessary to prevent perforation.

DISCUSSION AND CONCLUSIONS

The estimation of meteoroid effects on space exploration at 1 AU and particularly near the earth depends on the *expectation* of *impact* by meteoroids larger than some critical mass so that penetration of the skin of a spacecraft occurs, and on the understanding of the *extent of damage* resulting from one or more such impacts. The *expectation* of a meteoroid impact per unit area and time may be determined from the cumulative mass distribution curve (Figure 4) consisting of the section derived from satellite measurements, the section derived from ground-based measurements approximately represented by the curve A, and the interpolation between the two curves (Figure 1). The density, which may be used with the distribution for determining penetration rates and spallation effects, ρ_m is 2 gm/cm^3. A nominal velocity for such impacts should be 30 km/sec.

For short exposure times to the space environment, adverse effects may be present during known or sporadic meteor showers. However, for long exposure times this distribution curve should be an effective *expectation* of the impact frequency. The impact rate at 1 AU but away from the neighborhood of the earth may be different, but only for particles of mass less than 10^{-6} gm. In the vicinity of Mars, radial distances from the sun between 1.5 and 5 AU the collision hazard from asteroidal debris may be greater than at 1 AU. For distances less than 1 AU the concentration of meteoroids should increase with a decrease in solar distance. Although most of the meteoroids are moving in direct heliocentric orbits, a retrograde component is known to exist. Radiation pressure forces leading to the Poynting-Robertson effect, the Yarkovski-Radzievski effect (Reference 20). and other effects should decrease the eccentricity of the meteoroid orbits and gradually cause the particles to spiral into the sun. The inclination angles of the orbits, particularly the toroidal orbits, are indicative of a substantial component of the meteoroid population with orbit planes intersecting the plane of the ecliptic at considerable angles. Hence, the meteoroid impact velocities with a spacecraft in interplanetary space should be considered out to 30 km/sec and higher.

A good representation of the penetrating power of meteoroids is given by the theoretical solution of Bjork. So far, from the limited data available from direct experiments on satellites (Reference 13), Bjork's penetration condition with the expected cumulative distribution as a function of mass (Figure 4) has been supported by experiment. Penetration and fracture experiments have been flown on Explorers I, III, XIII, Vanguard III, Midas II, and Samos II (1958 α, 1958 γ, 1961 χ, 1959 η, 1960 ζ, and 1961 $\alpha 1$, respectively).

Comparison of several references (References 3, 4, 5, and 6) which treat the hazard from meteoroid impacts may be made. Whipple (Reference 3) uses a ρ_m of 0.05 gm/cm^3—a value which must be used to determine penetration depth. Whipple's penetration formula is considerably less preferred than Bjork's (Reference 4). Bjork's treatment of the problem is generally good. However, there is not sufficient reason for him to use the Whipple distribution (Reference 3) and at the same time overestimate the meteoroid density. In fact, the correction for the mass of zero magnitude meteoroid, a factor of a hundred, would decrease the required armor thickness by a factor of 5.

Jaffe and Rittenhouse (Reference 5) have used the Bjork penetration condition. However, the selected curves of cumulative mass distribution for low satellite altitudes and far from the earth are not recommended. Davison and Winslow (Reference 6) have considered an upper and lower limit (curves I and II in their Figure 8) in their estimates of rates of penetration of stainless steel. The cumulative distribution curve used in deriving curve II is recommended (their Figure 5). They used Summers' penetration criteria rather than Bjork's with an impact velocity of 15 km/sec and ρ_m of 1 gm/cm^3. In deriving their curve I, they also used the Whipple distribution (Reference 3) but with a ρ_m of 2.7 gm/cm^3. Davison and Winslow concluded that their curve II may be reasonable and that curve I represents a high estimate of the penetration rates of the material investigated.

Thus, there appears to be a preferred approach to the prediction of the rate of penetration of the skins of a spacecraft from meteoroid impacts. It is evident that theory and available experimental data support this singular method of computing the meteoroid hazard. The estimated rates of penetration determined by combining (1) the expected cumulative distribution as a function of mass (Figure 4) and (2) the Bjork penetration criteria together with a ρ_m of 2 gm/cm^3 and an average impact velocity of 30 km/sec is recommended for design purposes. The meteoroid penetration rates computed in this manner represent a consistent estimate based on available knowledge. The conservative designer may incorporate his own safety factors to establish the required reliability. Additional measurements from satellites to confirm the predicted penetration rates are certainly desirable. The extent of the hazard appears to be considerably less than some earlier estimates; hence obtaining experimental data in the space environment will require relatively long exposure times over extended surface areas.

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