Space-Debris Hazards of Interplanetary Exploration

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An evaluation of the hazard of the particulate matter in space is given in the light of existing scientific experimental data and theoretical analyses. It is disclosed that, when one includes all matter down to that of electron size, scientific observation indicates definite spatial variation due to the proximity of a planet. Space-density calculations for the regions in the proximity of the moon and Mars demonstrate no radical concentrations and lead one to conclude that hazards exist only in perturbations from the "normal" environment due to clouds and/or streams. A hazard probability from a Poisson statistical standpoint should possibly be based on two or more impacts.

Nomenclature

A_s = projected surface area
b = average geocentric altitude of vehicle
C = concentration; see Eq. (A3)
G = Newton's gravitational constant
H = time
I = (impact rate), relative rate of accretion $= 100\ N_T(y)/N_T(y = 0)$
k_{pe} = flux variation parameter; see Eq. (8)
k_s = stream factor; see Eq. (13)
k_v = relative activity factor; see Eq. (11)
k_{vi} = relative activity (monthly)
M = grams mass
M' = planet mass
n = impacts or number of particles
N = (aggregate) total number of particles
N_T = (particulate flux), aggregate particles m^{-2} sec^{-1}
$N_T'(y)$ = relative flux at y; see Eq. (A9)
$p_{(n)}$ = probability of n impacts or n particles passing through area A_s in time H
p_n = probability of at least n impacts or at least n particles passing through area A_s in time H
r = radial distance from planet or satellite
r_p = effective radius of particles
R = radius of planet or satellite ($R_{\text{earth}} = 6400$ km, $R_{\text{Mars}} = 3332$ km)
R_0 = effective radius of the earth
S = $p_{(0)}$, probability of "survival"
S_{se} = shielding factor (Ref. 17), 1– (sector radians shielded/2π) averaged over a complete cycle (for circular orbiting vehicles)
u = (lunicentric/geocentric) velocity of particle at $r = \infty$
u_1 = u/v
v = $v(r)$, particle velocity at r
v_∞ = escape velocity; for earth, 11.2 km/sec; for moon, 2.37 km/sec; for Mars, 5.1 km/sec)
$V.L.$ = view loss factor; see Eq. (14)
V_m = mean velocity of particles relative to earth (km/sec)
y = R/r
θ = $\sin^{-1}[R_0/(R_0 + b)]$
π = 3.1416
$\rho(y)$ = space density at y
ρ_∞ = space density of particles where planetary influence is not felt

Introduction

THE debris-laden space through which man must travel comprises particle sizes ranging from fundamental (electron, proton, etc.) to that of a large comet head (many miles in diameter). Particle velocities may reach close to that of light. The statistical significance of the particulate type and distribution, as well as the damage potential, must be taken into account before one can assess the hazard.

A recent revision of the photographic and visual picture as a result of the Trailblazer I experiment[1] has been made by F. L. Whipple.[2] His reduction of debris estimate near the earth by three orders of magnitude brings it more in line with the satellite and space-probe observations.[3] However, much uncertainty still remains as to the validity of his arguments. The almost yearly drastic revision of conclusions is indicative of a poor confidence level of results. Therefore design must remain conservative. One must use the latest impact theory combined with satisfactory statistics to assess the environmental hazard. An approach by F. B. Shaffer[4] assumes that the hazard criteria is penetration. He suggests that a normal statistical approach might be better than the usual Poisson technique but that this cannot be resolved without more thorough analysis.

Herein we will use the Poisson statistical approach and state that the hazard criteria cannot be considered as a hypervelocity penetration. In fact, a below-sonic-velocity impact may be more dangerous than a hypervelocity impact, depending upon the surface construction.[5] Moreover, spalling cannot be underestimated, since its probability of occurrence is greater than that of penetration. It thus appears that each design must be evaluated separately. Note the recent work on self sealing.[6]

However, we are concerned with evaluating the hazard. We can say from observation that no tangible evidence exists to prove that any failure of a space vehicle can be attributed to this environment. In fact, no penetration of over 0.002-in.-thick beryllium copper had occurred on the Explorer XVI satellite despite its 10 month traverse through the normal recurrent meteor showers and the earth's dust belt in its near circular orbit of 750 km.[7] Have the scientists overestimated this hazard?

Let us first examine the meteoroid environment. One is confronted with the interpretations of many scientists of non-too-exacting experimental data coupled with theoretical predictions based upon limited premises.[8,9] Here it will suffice to present an acceptable conservative mean design environment and to demonstrate how to assess deviations from this mean. The method used in establishing the lunar and Martian environment components is presented. No knowledge is currently available to allow an understanding of how realistic this description is, but it is believed to be quite conservative.

Knowledge of particle distribution and behavior in space stems from earthbound visual, photographic, and radar observations, as well as limited experimental data relayed to earth from satellites or space probes. The distribution and behavior may also be analyzed, at least for simplified boundary conditions on a theoretical basis. One may thus antici-

Presented at the AIAA Meeting on Engineering Problems of Manned Interplanetary Explorations, Palo Alto, Calif., September 30–October 1, 1963 (no preprint number; published in bound volume of preprints of the meeting); revision received March 12, 1964.

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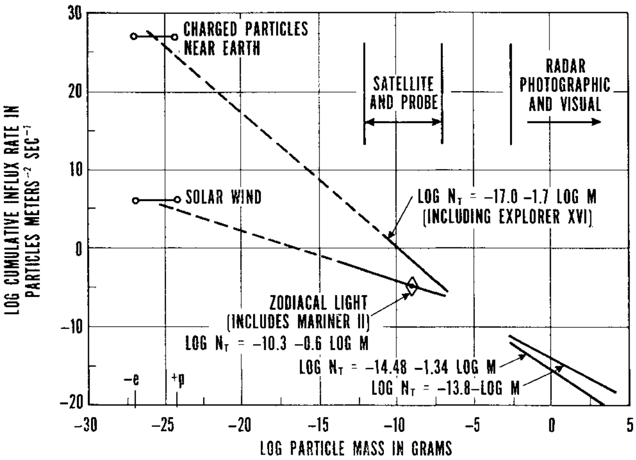

Fig. 1 Latest particulate mean environment of space; "cumulative" indicates all particles of mass M or greater.

pate a wide variation in attempting to ascertain a debris environment, since various authors treat the subject matter differently. Nevertheless the origin of the particles is fairly well agreed upon, especially those of prime concern to the near-earth space voyager. Particles may be of cosmic, solar, planetary, asteroidal, or cometary origin, all of which must be taken into account in defining the over-all particulate matter in space. However, the particulate matter of prime interest for space vehicle structural design is predominantly of cometary origin[2] (90–99%) following known (or unknown) comet paths with less than 1–10% of asteroidal origin. Such debris therefore follow heliocentric orbits lying predominantly in (or near) the ecliptic plane and follow direct orbital paths (that is, in the same direction as the major planets' motion about the sun). Approximately 50% travel in planes inclined not over 15° from the ecliptic.[10] Only a small percentage travel in retrograde orbits, and a few percent follow very narrow eccentric orbits. Thus the predominant velocity range with respect to the earth is 15–28 km/sec. (Narrow eccentric orbit particles have velocities of 45–55 km/sec, and retrograde particles have velocities of 55–76 km/sec, with respect to the earth.[11]) In the vicinity of Mars, particulate velocities, instead of ranging from 15–76 km/sec, as in the case of the near earth, would range from approximately 7–64 km/sec (since Mars' escape velocity is less than half that of earth and maximum circular orbital velocity at Mars' distance from the sun is approximately 64 km/sec).

The Mean Environment

The model mean environment is characterized by an aggregate flux N_T vs mass M relationship where N_T is the number of particles of mass M or greater passing a unit of area per unit of time at a given position in space relative to the earth-sun system. This environment is based on a conservative design picture gleaned from the experimental and theoretical information available to date.[2, 3, 7, 9]

For direct orbiting particles at altitudes (from earth) of 6×10^5 statute miles and above (where the moon's influence is not felt),

$$\log_{10} N_T = -10.3 - 0.6 \log_{10} M \tag{1}$$

where N_T = aggregate particles m^{-2} sec^{-1}, and M = grams mass. For altitudes of 200 statute miles down to the earth's atmosphere (approximately 45 miles),

$$\log_{10} N_T = -17 - 1.7 \log_{10} M \tag{2}$$

(Note that this conforms with the latest NASA investigations.[3, 7]) A linear variation of $\log_{10} N_T$ vs $\log_{10}$ altitude is to be used between the altitudes of Eqs. (1) and (2).

Using the theory of S. F. Singer[12] modified to conform with the altitude variation proposed by Whipple[13] [which agrees with the foregoing mathematical model of (1) and (2)] and applied to the lunar environment, a characteristic maximum flux, which occurs approximately 6000 statute miles from the moon which is 20% higher than at the moon's surface, is expressed by (see Appendix):

$$\log_{10} N_T = -14.5 - 1.28 \log_{10} M \tag{3}$$

Assuming that Eq. (1) also prevails at 6×10^5 statute miles from the moon where the earth's influence is not felt and assuming a linear log flux/log altitude relationship between indicated altitudes, one can obtain a complete mean direct orbit particle flux of space debris for the earth-moon system where the influence of other planets is not felt.

The mean velocity of the particles relative to the earth is expressed as[9]

$$V_m = (4500 + 56M^{-0.41})/(160 + 3.74M^{-0.41}) \tag{4}$$

A retrograde orbiting component of mean velocity 65 km/sec (with respect to the earth) may be added to the picture as described by Jaffe and Rittenhouse.[14] This retrograde component for altitudes for which Eq. (1) is valid is 10% of N_T above $\log_{10} M = -1.4$, increasing linearly to 14% (heliocentric) below $\log_{10} M = -6.6$ (40% geocentric), M in grams mass. For altitudes for which Eq. (2) is valid, the retrograde component comprises 10% of N_T above $\log_{10} M = -1.4$ falling linearly to 0% at $\log_{10} M = -6.6$. This current mean environment is shown in Fig. 1. Data were taken from Refs. 2, 3, and 9.

Deviations from the Mean Environment

Deviations from the mean environment occur with time and position in space. They are caused by the sporadic and streaming nature of the debris, combined with the interaction effects of the moving matter with that of moving charged particles and with planetary action. It is to be noted, for instance, that the intense stream (or shower, as it is often called) of the Giacobini-Zinner Comet debris called the Giacobinid Shower of October 10, 1959 has not recurred, calculations showing that particle orbits have been changed by the gravitational pull of the planet Jupiter. It is to be noted that deviations from the mean environment to be encountered in a specific space flight cannot be currently predicted. Results of a recent Soviet flight indicate the ship's passage through two showers, only one of which was identified as one of the yearly recurrent showers impinging on the earth.[15] Extremely intense shower activity is possible. This is recorded for the Leonid shower of November 12, 1799 before its perturbation by other planets.[16] The intensity maximum was estimated at near 30,000/hr, more than two orders of magnitude greater than the maximum hourly rate of any other normally recurrent earth-impinging stream. This stream's earth-impingement maximum intensity seems to have been gradually increasing during recent years indicating a possible spectacular display for 1965 or 1966.

General Variations and Probability

The probability of a particle passing through a unit area per unit time (and thus impacting on unit surface if placed

Table 1 Relative monthly activity of meteoroids[17, 18]

Month	Relative activity, k_{vi}	Month	Relative activity, k_{vi}
January	0.6	July	1.8
February	0.4	August	1.6
March	0.5	September	1.1
April	0.6	October	1.1
May	1.1	November	0.9
June	1.6	December	0.7

in this environment) is a nonstationary statistical process (one whose statistical properties change with time). Such a complex process does not lend itself to practical analysis. A stationary Poisson distribution of spatial flux, however, is an adequate approximation[10] and is given by the probability $p_{(n)}$ of n impacts or n particles passing through area A_s in time H:

$$p_{(n)} = N^n e^{-N}/n! \tag{5}$$

where $N = N_T A_s H$ is the total number of particles of possible concern for the flight. The probability of no impacts is thus

$$p_{(0)} = e^{-N} \tag{6}$$

The probability of at least one impact (one or more particles passing area A_s in time H) is

$$p_1 = 1 - p_{(0)} = 1 - e^{-N} = 1 - [1 - N + (N^2/2) - \ldots]$$

And, since generally $N < 0.1$,

$$p_1 \cong N = N_T A_s H \tag{7}$$

Pereira has called $p_{(0)}$ the probability of survival[17] and uses the symbol S. Adopting this nomenclature yields his probability of penetration:

$$p_1 = 1 - S = 1 - p_{(0)} = N_T k_{pe} \tag{8}$$

where k_{pe} is a factor to account for variations of flux.

The probability of the vehicle's receiving one impact (and only one) is

$$p_{(1)} = Ne^{-N} \cong N(1 - N) \tag{9}$$

so that if two or more impacts were allowed,

$$p_2 = 1 - (p_{(0)} + p_{(1)}) \cong 1 - (1 - N + N - N^2) = N^2 \tag{10}$$

Table 2 Annually recurring meteor stream[a]

(1) Shower	(2) Date of maximum	(3) Duration, days	(4) Mean velocity with respect to earth km/sec	(5) Max. hourly radar echo rate	(6) (3) × (5)
Quadrantids	Jan. 3	4	42.7	95	380
Aurigids	Feb. 9	5	. . .	5	25
Virginids	March 13	16	30.8	1	16
Lyrids	April 21	3	48.4	11	33
η Aquarids	May 4	5	64	15	75
Arietids	June 8	21	39	66	1386
ζ Percids	June 9	16	29	42	672
β Tourids	June 30	13	32	27	351
δ Aquarids	July 29	30	42.7	34	1020
α Capricomids	Aug. 1	35	25.5	10	350
Perseids	Aug. 12	20	60.4	49	980
Orionids	Oct. 22	9	66.5	18	162
Southern Tourids	Nov. 1	91	30.2	5	455
Northern Tourids	Nov. 1	47	31.3	10	470
Leonids	Nov. 17	7	72.0	10-1957 54-1961	70
Puppids/ Velids	Dec. 6	9	. . .	50	450
Geminids	Dec. 14	9	36.5	80	720
Ursids	Dec. 22	8	35.2	13	104
Giacobinids[b]	Oct. 10	(1)[b] 0.16+	23.1	(10,000)[b] 2185	354
					8073

[a] Compiled from Northern and Southern Hemisphere studies (Refs. 11, 19–21) and considered typical for the entire Earth.
[b] Average recurrence 6.5 years (maximum rate adjusted accordingly).

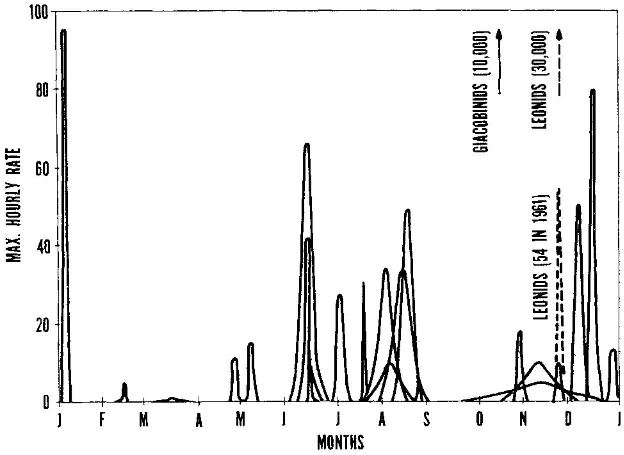

Fig. 2 Major meteoroid shower rates impinging on earth; approximate yearly recurrent.

It is thus seen that if $N = 0.1$, as noted as a high value in deriving Eq. (7), then $p_2 = 0.01$, signifying a very low probability of two or more impacts. Such a criteria as p_2 would allow an order of magnitude reduction in hazard of space debris. That is, if two or more impacts were to be allowed, then only a long time period, i.e., large H or large surface area A_s would be required for a hazard to exist.

The probability p_1 must be modified for short-duration flights to take into account what appears to be a seasonal variation. The relative monthly activity was presented by Pereira[17] from a compilation of Ref. 18 and is repeated in Table 1 for completeness.

The multiplying factor [part of the coefficient k_{pe} of Eq. (8)] for the probability of penetration, $1 - S$, is given by

$$k_v = \frac{\Sigma \text{ relative activities } k_{vi} \text{ (Table 1)}}{\text{number of months}} \tag{11}$$

Thus, if a three-month period of exposure were to take place starting in July, k_v would equal 1.5.

Streams

Streams are debris from known comet paths and thus roughly resemble orbital rings (ellipses) of dust in space moving with mean velocities, as dictated by the orbital position, particulate mass, mass attraction, and radiation drag (Poynting-Robertson effect). If the earth intersects the orbit, a meteor shower occurs. Thus, annual showers prevai lfor recurring orbital intersection. It must be recognized that the meteoroid material is not spread evenly about the orbit and that intersecting orbits prevail, such that a space vehicle can intersect many streams simultaneously and be showered upon by a flux that is orders of magnitude higher than the sporadic background.

A list of the meteoroid streams that give rise to meteor showers is given in Table 2 (compiled from Refs. 11, 19, 20, and 21) and presented graphically in Fig. 2. One should note that many other streams the orbits of which do not intersect the earth's orbit can be expected in space, so that a large uncertainty remains as to the hazard potential. Nevertheless one may conjecture that the description of earth-stream intersection will be typical for the space vehicle. The average stream hourly rate can be estimated as the sum of the products of columns (3) and (5) of Table 2 divided by 365 (days in a year) and multiplied by the ratio of the area under a 3σ normal distribution to that of a constant (rectangular) distribution of the same width. Such a procedure assumes that stream flux at 3σ normal distance from the maximum intensity is practically nonexistent, building to maximum intensity according to a Gaussian characteristic, and is not constant over the duration of observation.

Thus, the estimated average hourly rate is (8073/365) × (0.997/2.4) = 9. Since the average sporadic hourly rate is 10 (Ref. 22), one notes that for long-duration trips (at least one year) the combined average sporadic and stream effect yields at most 19/hr. Thus a stream factor [part of the coefficient k_{pe} of Eq. (9)], can be defined as

$$k_s = \frac{\text{over-all average hourly rate}}{\text{average sporadic hourly rate}} = \frac{19}{10} = 1.9 \qquad (13)$$

for long-duration (over one year) average stream exposure.

Short-period exposure to intense streams such as the Giacobinids could yield $k_s = 10{,}000/(2.4 \times 10) = 420$ or over two orders of magnitude increase over the sporadic background. (Note that here it is supposed that one travels across a stream and does not travel constantly in the maximum flux region of superimposed streams. Such an intense maximum, however, would yield at most $k_2 = 1050$ or a three orders of magnitude increase over the sporadic background.)

Streams are generally extremely wide, as can be ascertained from their duration as shown in Table 2. Thus a stream of near 300,000 statute miles in width would be obtained for the Giacobinid shower of one day's duration on the assumption that the earth crosses the stream at, say, near 11.5° (estimated from orbital diagrams) with stream (since the earth travels at near 2.6×10^6 km/day = 1.6×10^6 statute miles/day). This narrow stream is thus larger than the mean distance of the earth to the moon.

Altitude Effects (Shielding)

The effect of planetary (or lunar) capture through gravitational attraction has been taken into account in our previous description of the mean environment and will be further noted, assessing the lunar environment, in the Appendix. Planets and their moons, however, have an additional effect of shielding a spacecraft that is in their vicinity from the directionally moving debris. This effect is small in comparison with the orders-of-magnitude effects of flux increase from factors mentioned previously and in comparison with the uncertainty that still exists in the description of the mean environment. Many authors and analysts thus ignore this effect. Nevertheless, the environment and its major deviations will eventually be defined such that shadow shielding will become a more significant factor. The shielding effect is complicated in that retrograde as well as direct orbiting particles are present. Deviations of debris orbital paths from the ecliptic plane also affect shielding, as do stream effects.

A simplified version of shielding is given by the viewing loss ($V.L.$) equation of Davidson and Winslow,[10]

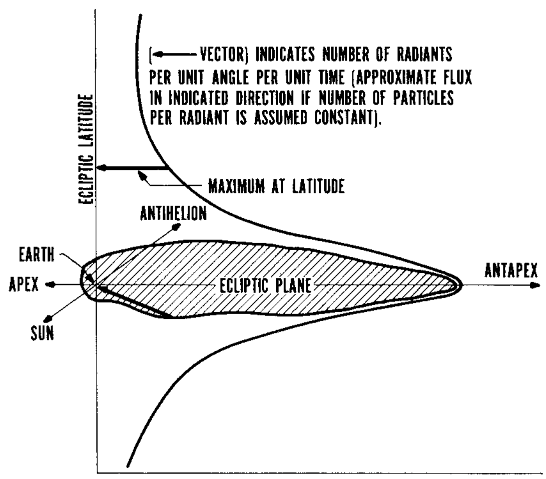

Fig. 3 Relative distribution of meteor radiants with respect to the sun.

$$V.L. = (1 - \cos\theta)/2 \qquad (14)$$

where

$\theta = \sin^{-1}[R_0/(R_0 + b)]$
R_0 = effective radius of the earth
b = average geocentric altitude of vehicle

A value of shielding for cislunar orbiting vehicles to a higher order of accuracy can be obtained from the work of Pereira[17] which assumes random motion of meteoroids parallel to the ecliptic plane and an "effective radius" of earth = 44010 miles. (This includes a 53-mile layer of atmosphere.) His factor is $S_{23} = 1 -$ (sector radians shielded/2π), averaged over a complete cycle (for circular orbiting vehicles). At most, shielding decreases the flux by 0.5.

Particle Dispersion Processes

An excellent discussion of the phenomenon of particle dispersion processes is given by Lovell.[23] He concludes:

> The Poynting-Robertson effect introduces a selective drag which, in the course of time, will separate out the particles in a shower according to their size, eventually causing all to fall into the sun—the small ones faster than the large ones . . . .
> The possibility of other dispersive influences has been mentioned by Whipple in Ref. (24). Meteors must carry a positive charge as a result of photoelectric effects due to the sun's radiation, and if the sun has a magnetic field a motion of the line apsides must result greater for smaller meteors than for larger ones. Simple electrostatic effects might also tend to disrupt the originally compact stream.

Directionality

It is difficult to form any conclusion of directionality except for the earth-moon system, that is, in the vicinity of the earth's orbital path. A polar plot showing particle directionality (in reality, numbers of meteor radiants per unit angle, per unit time, becoming number of particles under the assumption of a constant number of particles per radiant) has been presented in Ref. 25 and is illustrated in Fig. 3. The vectors drawn to the center marked earth represent flux magnitude and direction in the earth's orbital path with respect to the sun. (The ecliptic latitude variation is from Ref. 23.)

Probability of Encounter

Having defined a mean design environment and noted the deviations possible, it is now necessary to assess the probability of encounter of debris with a specific space vehicle in the fulfillment of its mission. It has already been noted that the probability of encounter is modified by a factor k_{pe} to account for variations in flux (Eq. (8). Major variations are caused by:

1) Flight time H at a location in space where the projected exposed area normal to the plane of the ecliptic is A_s
2) The area A_s
3) A factor to account for stream activity k_s as just explained, where k_s = 1.0 for short (stream-free) flights, 2.0 for long (average yearly) flights, and ~1000 for maximum concentrated stream effective flights. (This last value may be greater, as indicated by past meteor-shower history)
4) The seasonal variation factor k_v (note: k_v has maximum value of 1.8 for July)
5) A shadow-shielding factor S_{se} as previously explained: $0.5 \leqslant S_{se} \leqslant 1.0$

Thus k_{pe} can be numerically evaluated as

$$k_{pe} = HA_sS_{se}k_vk_s$$

and the probability of encounter p_1 obtained from Eq. (8), if p_1 is to be used as a design criteria, or p_2 from Eq. (10).

Personnel in space suits outside the space vehicle are partially shielded by the proximity of their parent craft and expose a relatively small area A_s (planform area) for relatively short periods of time H. Thus k_{pe} would be quite small. The hazard is thus conceivably negligible in the normal mean space environment.

It is well known that shaped charges have greater penetration characteristics. Thus, the nature of the impinging particle is all important in assessing the hazard. The near-earth particles appear to be predominantly of the loose aggregate, fluffy nature, indicating a possible minimum hazard (low penetration or spalling possibility on impact). The percentage of particulate matter that is hazardous from a shape/density point of view has yet to be evaluated. It is important to note, however, that, considering the past history of space vehicles, this factor must reduce the space-debris hazard by orders of magnitude. It is once again tantamount to allowing at least one impact, that is, to using p_2 of Eq. (10), in the hazard evaluation.

Recommendations for Acquiring Additional Data

It is still necessary to define more accurately the mean environment, especially the mean flux with respect to planet and satellite location in space. It is also necessary to establish to greater accuracy the deviations from the mean environment—stream effects, dust storms, clouds, variation in particle shape and density, shielding, velocity variations, and the effect of solar storms. This requires better and more reliable sensors on space probes and satellite vehicles to yield information on particle velocity, mass, impact frequency, major chemical composition, and structural shape and charge potential without the current major shortcomings of spurious indication and difficult calibration.

Effects of shape and density of debris on penetration and spalling need to be established. Indeed, the very nature of what comprises a hazard must be clarified, because use of special skin design could almost eliminate this environment from further consideration.[6]

In addition, a better interpretation of past meteorite data is needed, especially in clarifying particle mass/visual and photographic magnitude relationships from existing observations. Current efforts along this line have used man-made meteoretic particles of aluminum and iron.[1, 26] Further interpretation of recent results are needed, along with additional similar experiments using particles of alloy composition better approximating meteoroidal material.

Zodiacal clouds, Gegenschein, and corona should be studied with a view toward clarifying the effects of physical particulate characteristics on observational interpretations. The results of particle capture experiments should be factored into a laboratory study of light reflectivity, scatter, polarization, and absorption, so that new interpretations (more exacting) of past observations can be made. Thus, a great deal must yet be accomplished before man can say that he possesses a reasonable knowledge of the nature of the space-debris hazard.

Appendix

The problem of accretion of interplanetary dust by the earth through gravitational force is treated in Ref. 12. This theory is presented herein and modified to estimate the environment in the proximity of the moon and Mars.

Space Density Calculations

If R = radius of planet or satellite and r = radial distance from planet or satellite c.g., then we can define

$$y = R/r \tag{A1}$$

The escape velocity is given by

$$V = (2GM'/R)^{1/2} \tag{A2}$$

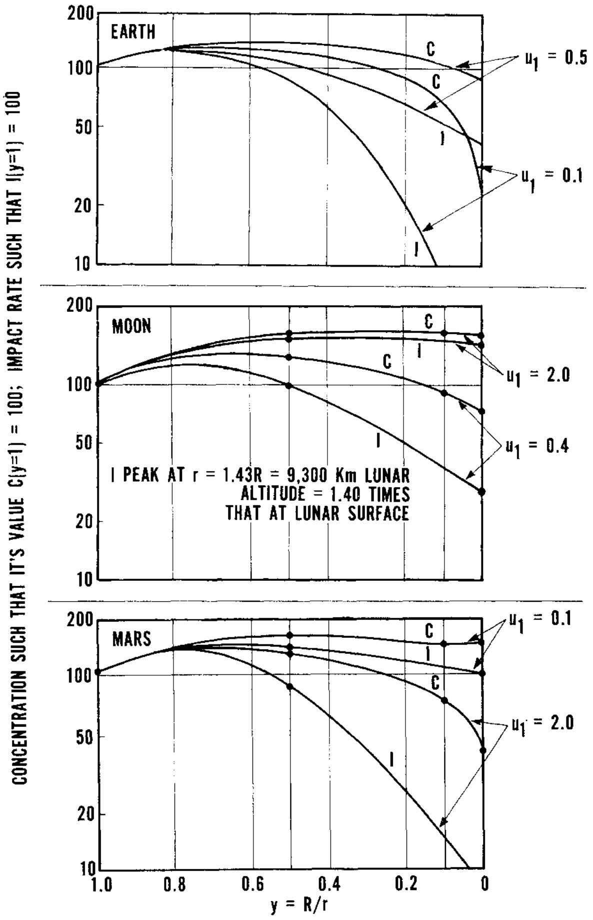

Fig. 4 Concentration of dust and impact rate observed by an instrument approximately at rest with respect to the planet as functions of radial distance from planet, in fractions of planet radius.

The relative space concentration is

$$C = 100\rho(y)/\rho(R) \tag{A3}$$

The particle velocity is given by

$$v^2 = u^2 + v^2 y \tag{A4}$$

The space density at r is given by

$$\frac{\rho(y)}{\rho_\infty} = \left(\frac{u_1^2 + y}{4u_1^2}\right)^{1/2} \left\{1 + \left[1 - y^2\left(\frac{u_1^2+1}{u_1^2+y}\right)\right]^{1/2}\right\} \tag{A5}$$

where $u_1 = u/v_\infty$ and u = (lunicentric/geocentric) particle velocity at $r = \infty$, and $\rho_\infty = 2 \times 10^{-23}$ to 5×10^{-21} gm/cm³. Since u = 1–5 km/sec, for the earth, $u_1 \cong 0.1$–0.5; for the moon, $u_1 \cong 0.4$–2.0; and for Mars, $u_1 \cong 0.2$–1.0.

The relative space concentration, Eq. (A3), can now be found for various values of y using Eq. (A5). Results are plotted in Fig. 4 as C curves.

Rate of Accretion Calculation

The rate accreted by a body of small motion relative to particles in space (approximately stationary particles) is

$$\frac{1}{A_s}\frac{dM}{dH} = \rho(y)v(y) \tag{A6}$$

With Eq. (A4), this yields

$$\frac{1}{A_s}\frac{dM}{dH} = 0.5 \times 10^4 \rho_\infty v_\infty \frac{(u_1^2 + y)}{u_1} \times \left\{1 + \left[1 - y^2\left(\frac{u_1^2+1}{u_1^2+y}\right)\right]^{1/2}\right\} \tag{A7}$$

For the earth, y equals 1, and

$$\frac{dM}{dH} = \rho_\infty(\pi R^2)u\left(1 + \frac{v_\infty^2}{u^2}\right)$$

It is now necessary to ascertain a relation[27] between M and the number of particles N_T of mass M or greater prevalent in the space environment:

$$N = 1.8 \times 10^{-6}M^{-1} \quad \text{(A8)}$$

Since M is proportional to the cube of the radius of the particle, one would obtain $N = 1.43 \times 10^{-6}\, r_p^{-3}$, where the radius is in cm for particles of density 0.3 gm/cm³. (Singer[12] uses $N \sim r_p^{-2.8}$.)

The particle flux is thus

$$N_T = (N/AM)(dM/dH) \quad \text{(A9)}$$

which with Eqs. (A7) and (A8) can be written

$$N_T'(y) = \frac{N_T M^2}{0.9 \times 10^{-2}\rho_\infty v_\infty} = (u_1^2 + y)x\left\{1 + \left[1 - y^2\left(\frac{u_1^2+1}{u_1^2+y}\right)\right]^{1/2}\right\} \quad \text{(A10)}$$

which can be solved for various values of y. The relative rate of accretion $100\, N\delta(y)/N\delta(y = 1)$ is plotted for $u_1 = 0.1$ and $\varphi_1 = 0.5$ in Fig. 4. The values for $\varphi_1 = 0.1$ agree reasonably well with Singer's,[12] but those for $\varphi_1 = 0.5$ are higher, probably due to the higher exponent on r_p in (A8).

For the moon, $v_\infty = 2.372$ km/sec, reducing the flux to 0.212 of the value at the earth. The variation of accretion (flux) with lunar altitude is obtained by examining a plot of u_1 vs y for $u_1 = 0.4$ to $u_1 = 2.0$, as shown in the center part of Fig. 4. Peak flux at 6000 statute miles is thus $1.4 \times 0.212 \cong 0.30$ of that of earth's atmosphere at extreme altitude (approximately 75 statute miles). At most, one order-of-magnitude increase is present here from ($y = 0$) to the moon ($y = 1$) as compared with two orders-of-magnitude increase for ∞ to earth. (Whipple shows a four order-of-magnitude increase for earth.[13] He recently reduced this by three orders of magnitude, bringing the values more in line.[2]) For Mars, since $v_\infty = 5.1$ km/sec, the flux accretion is 0.455 that of the earth. This indicates that peak flux at Mars atmosphere extreme is about half that of earth's atmosphere extreme. The characteristics for Mars are shown in the bottom part of Fig. 4.

Taking the Zodiacal characteristic as prevailing at 6×10^5 statute miles from the moon and a characteristic mass of 10^{-9} g or greater yields (see Eq. (1)

$$\log_{10} N_T \cong -5$$

Also assuming that the moon peaks at an impact one order of magnitude less than that of the earth (in variation from ∞), since for earth [see Eq. (2)], $\log_{10} N_T \cong -2$, the moon peak would be at $\log_{10} N_T = -3$. Thus considering the point of common N_T and mass of Eqs. (1) and (2) to prevail for the moon, namely, $\log N_T = -6.7$ and $\log M = -6.1$, one obtains, by solving Eqs. (1) and (2) simultaneously, two sets as characteristic of the lunar environment, which result in the equation

$$\log_{10} N_T = -14.5 - 1.28 \log_{10} M$$

as the near-lunar flux-mass characteristic. This is also Eq. (3).

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