5 DYNAMICS AND EVOLUTION

5.1 SOURCES OF INTERPLANETARY DUST

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ABSTRACT

Attention is centered on cosmic dust measures made by sensors on Pioneers 8 and 9 in Earth-like orbits. The conclusion follows Zook and Berg that the particles are largely "β-meteoroids," interplanetary impact debris expelled by solar radiation pressure. An analysis of periodic comet orbits and comets observed during the missions failed to yield correlations, except possibly for debris from Comet Encke. A treatment of β-meteoroids from this stream is presented.

The solar-centered maximum impact rate is considered and indicates that formation of the observed β-meteoroids occurs more at solar distances greater than 0.5 AU rather than less.

The interesting variation of observed pulse heights with impact direction is analyzed and qualitatively explained in terms of a narrow distribution function of particle masses among the β-meteoroids with a maximum $\Delta \log N/\Delta \log m$ near or below 10^{-13} gm, in general agreement with lunar microcratering data. The mean pulse-height appears to increase when the mass sampling veers towards a minimum in the normal distribution at greater masses.

The observations appear consistent with the author's early conclusion that the interplanetary particles are largely of cometary origin, collision being the major destructive process.

INTRODUCTION

Investigations by Dohnanyi (1970, 1972, 1973) confirm the author's conclusion (Whipple, 1955, 1967) that meteoroids in the interplanetary complex (IPC) derive primarily from cometary debris and are mostly destroyed by mutual collisions. During the subsequent several years remarkable progress has been made in measuring the occurrence of smaller dust particles in the IPC by means of space probes and studies of microcraters on lunar material. Solids of small masses in the range 10^{-14}-10^{-12} grams produced by collisions move in unstable orbits because of their high surface-to-area ratio and consequent acceleration away from the Sun by radiation pressure. Thus their lifetimes in the solar system are extremely short compared to 10^4-10^5 years for the larger average particles in the IPC.

In this paper I concentrate on the cosmic dust measures made by the sensors on Pioneers 8 and 9 in Earth-like orbits about the Sun reported on by Berg and Grün (1973) (BG, hereafter) and McDonnell, Berg and Richardson (1975) (MBR, hereafter). They give data on 319 front-film-grid cosmic dust impacts over a period of seven years, combined for Pioneers 8 and 9. These sensors turn rapidly in the plane of the ecliptic and show a preponderance of impact events originating from particles in orbits with apparent radiants in the solar direction (see Fig. 1). In careful analyses based on both observational and theoretical material, BG and also Grün, Berg and Dohnanyi (1973) show that these events are not noise and are not caused by solar activity but measure true impacts of cosmic dust. The limiting impact function of mass, m, and velocity, v, of impact is determined by ground calibration to be $mv^{2.6} = 1.1 \times 10^4$ (cgs) (BG Fig. 5). The pulse height is logarithmically compressed in data transmission to $\log mv^{2.6}$.

The event rate in Fig. 1 increases rapidly from the antapex ($\phi = 180°$) direction of the space probe motion with respect to the Sun until a maximum is reached just past the solar direction at $\phi = 90°$. The rate decreases monotonically through the apex ($\phi = 0°$) to the antisun ($\phi = 270°$) direction and remains very low around to the antapex. Zook and Berg (1975) (ZB, hereafter) present a thorough analysis of this event frequency distribution as a function of spacecraft orientation, on the basis that the small particles are produced by collisions within the Earth's orbit among the IPC particles, and move outward in hyperbolic orbits at relatively high acceleration by solar radiation pressure. Since the masses required by the calibrations of BG at reasonable interplanetary velocities are consistent with particles in unstable orbits, the arguments by ZB appear to be entirely satisfactory in principle. Were the bodies in stable Earth-crossing orbits the numbers and velocities impacting from the general anti-solar direction should be about equal to those from the solar direction. The observations vehemently deny this expectation and support their premise. ZB call these particles beta-meteoroids because they are produced by the outward acceleration of solar radiation at sizeable values of beta, the ratio of solar light pressure to solar gravity, a quantity which is constant for a given particle as a function of solar distance because of the inverse square laws involved.

In the following sections I shall deal with four aspects of these observations (1) an effort to find direct correlations with comets or cometary streams of debris, (2) possible correlations with Comet Encke debris, (3) problems of the direction of impact, and (4) a discussion of the intriguing variation of pulse height with impact direction (see Fig. 1).

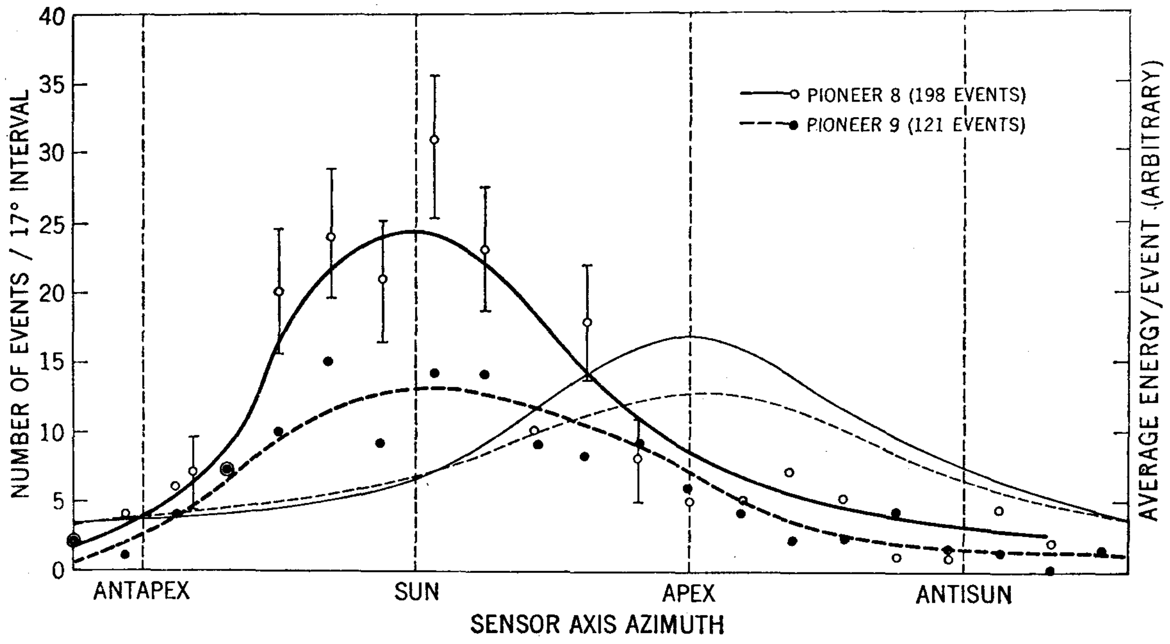

Fig. 1. The Azimuthal Distributions of 319 Front Film-Grid Events (coincidence) during 7 yrs. of Observation from Pioneers 8 and 9 (from Zook and Berg, 1975).

MBR find (Fig. 2) that the overall frequency of events for Pioneers 8 and 9, over seven years, peak sharply at heliocentric longitude λ = 9° (~Oct. 1 in Earth position) with a deep minimum near λ = 90°, (~Dec. 20) a broad maximum near λ = 190° (~Apr. 1) and another minimum near λ = 280° (~July 1). It seemed worthwile to search among the periodic comets and among comets observed concurrently with the space experiments, for orbital characteristics in which the interaction of the associated meteoric streams with interplanetary debris might produce systematic collision areas that could lead to beta-meteoroids observed by Pioneers 8 and 9.

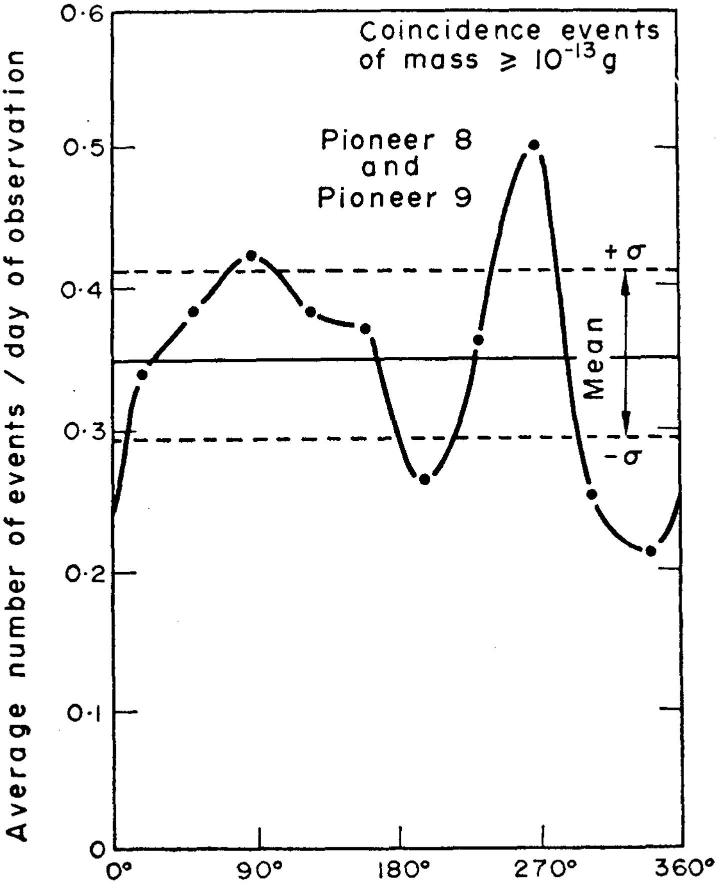

Fig. 2. FFG Events from Pioneers 8 and 9 as a Function of Heliocentric Position, 0° Occurring Jan. 1, 1968 (from McDonnell, Berg and Richardson, 1975).

I studied the orbits of 24 periodic comets with perihelion distance, q < 1.1 AU, plotting the positions of the orbital intersections with the plane of the ecliptic as well as the general motions. I calibrated the expected collisional effects in terms of the absolute magnitudes of the comets and their velocities near the plane of the ecliptic and at perihelion. No direct correlation appeared except for the case of Comet Encke, which will be discussed below. I made similar studies of the ten comets with perihelion distance less than 1 AU observed in the interval from late 1968 to the middle of 1972, comparing the actual positions of Pioneers 8 and 9 in their orbits about the Sun with those of the cometary orbits. Again no correlations of predictable event frequencies with actual concurrent comets appeared except for P/Encke.

DEBRIS FROM PERIODIC COMET ENCKE (TAURID METEORS)

There is strong evidence that P/Encke has been a major contributor to the IPC over several thousands of years (Whipple, 1940, 1955). An elliptical torus of meteoroids, with $q \sim 0.34$ AU and aphelion distance, Q, ~ 4 ($+0.5$–2.0) AU, is produced by the differential rate of nodal regression produced by Jupiter perturbations on P/Encke debris in orbits of different Qs. The lines of orbital apsides move slowly: Near perihelion the particles happen to have their maximum inclination to the ecliptic because of the nature of the perturbations. The inclination, i, varies cyclically from ~4° to ~16°. Thus collisions among the P/Encke meteoroids and with other debris of the IPC should occur most frequently near perihelion to produce β-meteoroids. Perihelion occurs over a considerable range from $\lambda \sim 110°$ to ~160°, centering at $\lambda \sim 130°$. The latter is the zero point (vertical) in Fig. 3, the orbit of P/Encke being the lower ellipse section plotted.

The several curves plotted in Fig. 3 represent the motions of β-meteoroids after their production by collision near perihelion and their subsequent ejection by radiation pressure at values of β from zero (P/Encke orbit) to 100, as indicated by the numbers indicated in the diagram. Values of β above 5 must certainly be infrequent, but the plot of such motions adds to the esthetics of Fig. 3. The relative velocities of impact with the Earth and approximately with Pioneers 8 and 9 are indicated just within the Earth's orbit in Fig. 3, the unit of velocity being the Earth's orbital velocity 29.76 km/sec (see also Table 1). Actual impact velocities would generally be slightly smaller than calculated because I have not included an uncertain term varying ~ cos i, representing reduction in velocity by collisions among the particles near perihelion.

Because the nodes of the P/Encke particles are not far from q at large values of i, the mutual collisions might lead to a fair fraction of particles with low i, which could intercept the Earth's orbit.

Of particular interest is the direction of impact, ϕ, on Pioneers 8 and 9 as a function of β for P/Encke β-meteoroids produced at perihelion. From Table I it appears that β-meteoroids produced by P/Encke would generally impact at $\phi < 90°$ (Sun direction towards apex) by a moderate angle. Particles produced at a solar radial distance r > 0.34 AU would impact with still smaller values of ϕ and with lower velocities.

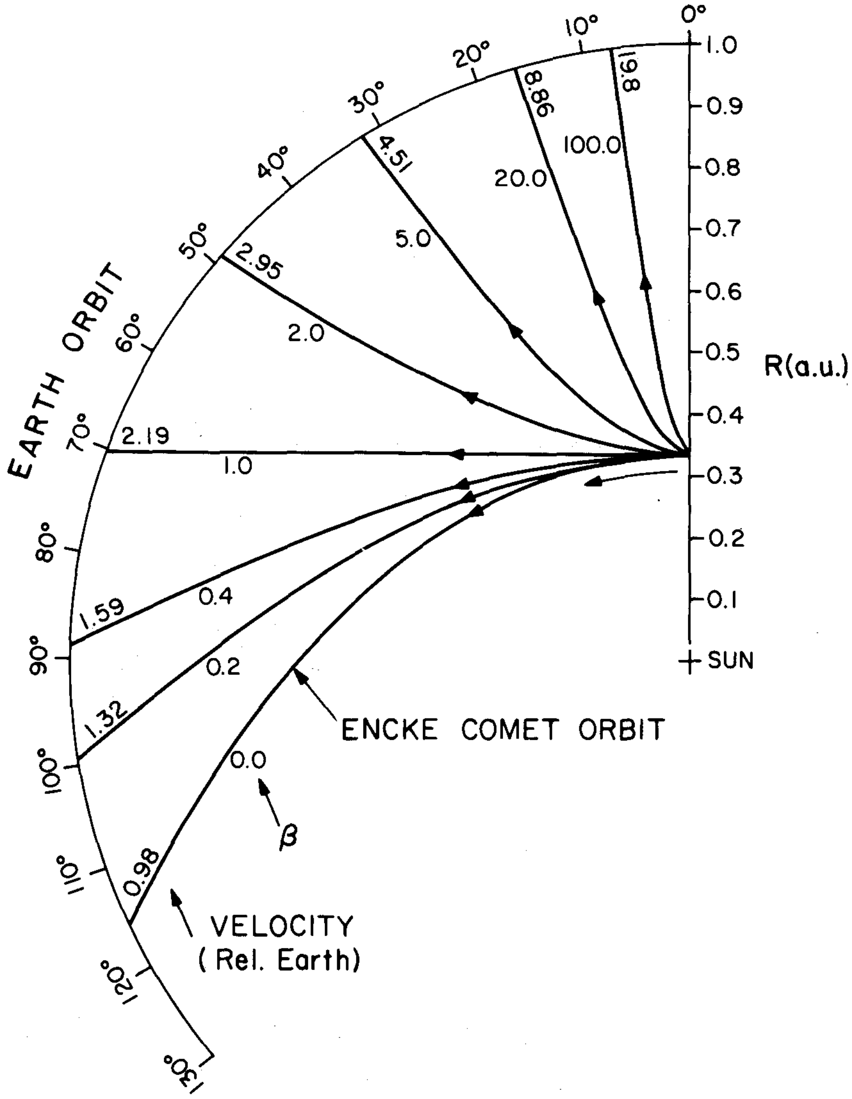

Fig. 3. Calculated Orbits of Particles Released from Periodic Comet Encke at Perihelion (on vertical line) with various Values of β (light-pressure/gravity) and Intercepting the Earth's Orbit with Relative Velocities as indicated (unit 29.76 km/sec).

Impacts with Pioneers 8 and 9 would occur at λ = 110° (±20°) + 90° (±30°) for P/Encke β-meteoroids. This would center near the broad peak occurring about Apr. 1 in Earth orbit (90° in Fig. 2).

Table I

Impact Directions and Velocities
for P/Encke β-meteoroids

β	0.0	0.2	0.4	1.0	2.0	5.0
ϕ (deg)	78	81	82	85	86	87
v (km/sec)	29	39	47	65	88	134

Otherwise I find that most comet-stream produced β-meteoroids would tend to occur near the broad minimum in Fig. 2 (positions 270° to 30°). I conclude that most comets do not provide much collisional activity in the IPC, and must represent minor fluctuations of particle density. Perhaps this is not surprising in view of the long time constant of 10^4-10^5 years for average collisional destruction in the IPC and the low space density in cometary meteoroid streams. Sekanina (1975) has identified and studied 275 streams among 19,698 radio-meteor orbits observed by the Radio Meteor Project at Havana, Illinois, Dec. 2, 1968 to Dec. 4, 1969. The masses involved are the order of magnitude of 10^{-4} to 10^{-3} g. (Cook et al., 1972) not much larger than the maximum of the logarithmic mass distribution function (Whipple, 1967), and therefore of a size to contribute significantly to collisions in the IPC. For only 10 of the 275 streams does Sekanina find the space density equal to or greater than the sporadic space density, and this for the very center of the streams, the most concentrated volumes. For only the Geminids and the Scorpiids-Sagittariids does the central space density exceed 10 times the sporadic space density. Two observed Comet Encke streams (Taurids and Southern Arietids) show central space densities twice that of the sporadic. Near perihelion their space densities must be many times greater. Considering the expected large volume of the Encke Comet stream and its expected higher concentration near perihelion, collisions there might well lead to a significant number of β-meteoroids observable from Earth's orbit.

PROBLEMS OF THE DIRECTION OF IMPACT

Zook and Berg have carried out a most thorough and careful study of the β-meteoroids and the Pioneer 8 and 9 impacts. I wish only to add a few details in this and the following section. The fact that the directions of impact center so strongly in the solar direction ($\phi = 90°$) imposes constraints on the heliocentric distances at which the collisions occur, as ZB point out. I wish to amplify their point, holding to the constraint that $\phi = 90°$ and considering typical original orbits.

For a body moving about the Sun, subject only to the radial force of gravity the angular momentum, h, is a constant given by

$$r^2 \frac{d\theta}{dt} = h = [GM\, q(1+e)]^{1/2} \quad , \tag{1}$$

where θ is the true anomaly in the orbit, G the constant of gravitation, M the mass of the Sun, q the perihelion distance, and e the orbital eccentricity.

For a β-meteoroid released at zero velocity, the value of h remains constant, which means that the velocity perpendicular to the radius vector, $r d\theta/dt$, remains equal to h/r, regardless of β. For such a β-meteoroid to impact the spacecraft in Earth orbit at $\phi = 90$, the original value of h_0 must equal that of the Earth, h_e, given by

$$h_0/1\ \mathrm{AU} = (GM/1\ \mathrm{AU})^{1/2} = h_e/1\ \mathrm{AU} \quad , \tag{2}$$

the Earth's velocity in circular orbit. If we start with orbits of varying q and Q (aphelion distance) with $i = 0$ and release β-meteoroids with zero velocity at q, then $1 + e = 2Q/(q+Q)$ and the constraint on q and Q of Eq. 1 and 2 becomes

$$q = Q/(2Q - 1) \quad . \tag{3}$$

The curve in Fig. 4 represents this relation between q and Q for β-meteoroids released at q and impacting a sensor in Earth-orbit from the direction of the Sun at $\phi = 90°$. Even for a parabolic initial orbit the minimum q is 0.5 AU. It is easily shown that release at solar distances above the curve in Fig. 1 will require larger values of q for the initial orbit, while a correction for finite inclination to the ecliptic will also increase the constrained q above the curve. The values of h for Pioneers 8 and 9 are $1.02\ h_e$ and $0.93\ h_e$, respectively. Thus the higher e and smaller q of Pioneer 9 does not much affect these arguments, nor the observations in Figs. 1 and 2 as compared to those of Pioneer 8.

Now it is true that the angle of acceptance of the Pioneer sensors extends to ±60° with reduced probability with angle (Grün, Berg and Dohnanyi, 1973), but the near symmetry around $\phi = 90°$ in Fig. 1, indicates a preponderance of impact directions very close to $\phi = 90°$ and the necessity of a significant fraction towards the antapex, where ϕ is considerably greater than 90°. It is easy to show that the latter impacts must come from bodies in orbits of high e, low i, and q more nearly 1 AU.

Thus I conclude that the β-meteoroids in large measure are produced in orbits with $q > 0.5$ AU, rather than from orbits with much smaller q, as proposed by ZB. Without access to the original detailed data, the further development of this argument here seems fruitless.

Note that Fig. 4 presents the velocities of impact for $\beta = 0.99$ in terms of the Earth's orbital velocity. For $\phi \geqq 90°$, the velocities of impact are not high, and will continue to decrease to less than 15 km/sec as ϕ increases from 90° to 180° at the antapex.

The inclusion of interstellar meteoroids could, of course, redirect this argument if they preponderately occur at $90° < \phi < 180°$.

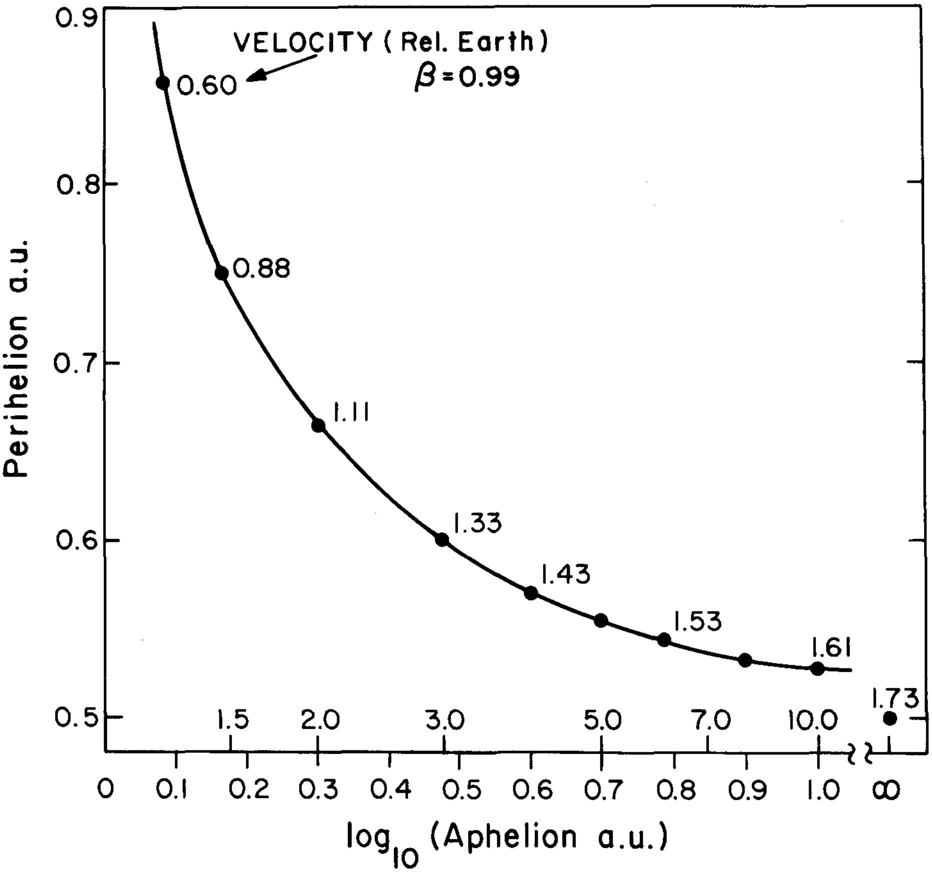

Fig. 4. The Relationship between Perihelion and Aphelion of Orbits such that β-meteoroids Released at Perihelion would Encounter the Earth Apparently from the Solar Direction ($\phi = 90°$). The Unit of Velocity is 29.76 km/sec, for $\beta = 0.99$.

Hemenway (Hemenway et al., 1972) particles of high β and high velocity radially from the Sun would impact with φ's somewhat less than 90°.

THE VARIATION OF THE MEAN PULSE HEIGHT

A most significant observation of the Pioneer 8 and 9 FFG events by BG (Fig. 1), is the variation of the mean pulse height with the direction of impact. The mean pulse height, H, approximately proportional to energy ($mv^{2.6}$), increases steadily from the antapex to a maximum at the apex, being nearly symmetrical about the apex direction of impact. Note that the system averages the logarithm of H, not the linear quantity. For a uniform distribution of particle masses in the particle source, $\langle \log H \rangle$ should be little dependent on the particle mass.

Suppose the cumulative number, N, of particle masses follows an inverse mass, m, power law over a considerable range in m:

$$N = a/m^b \quad , \tag{4}$$

where a is a constant and $b > 0$.

The measured pulse height, H, for a velocity, v, of impact is given by

$$H = H_0 \, m v^{2.6} \quad , \tag{5}$$

where $H_0^{-1} = 1.1 \times 10^4$ cgs (BG, Fig. 5).

Unit pulse height, the limit registered by Pioneers 8 and 9, will occur at a given velocity v_1, and mass m_1, given by $m_1 = 1.1 \times 10^4 / v_1^{2.6}$ cgs. Thus at the given velocity for particles of mass, m,

$$H = m/m_1 \quad , \tag{6}$$

and

$$\langle \ln H \rangle = \int_{m_m}^{m_1} \ln H \frac{dN}{dm} \, dm \Bigg/ \int_{m_m}^{m_1} \frac{dN}{dm} \, dm \tag{7}$$

where m_m is the maximum mass of the distribution function.

From equations 4, 6, and 7, setting $x_i = \ln m_i$ and $\epsilon = m_1/m_m$, we find

$$\langle \ln H \rangle = -\ln m_1 - b m_1^b \, (1 - \epsilon^b)^{-1} \int_{x_m}^{x_1} x e^{-bx} \, dx \quad , \tag{8}$$

and, finally, after integration and substitution of m_i in the limits

$$\langle \ln H \rangle = \frac{1}{b} - \epsilon^b \ln \epsilon \, (1 - \epsilon^b)^{-1} \quad . \tag{9}$$

In the case of a considerable range in the mass distribution function $\epsilon \ll 1$, the second term in Eq. 6 becomes negligible, and $\langle \ln H \rangle \rightarrow 1/b$. Varying v changes m_1 inversely as $v^{2.6}$ but does not change $\langle \ln H \rangle$, unless v is so small that $m_1/m_m = \epsilon$ becomes appreciable.

In view of these considerations the large variation in $\langle \log H \rangle$ observed by BG demands a special distribution function of mass. The variation cannot be accounted for by a changing velocity in a uniform distribution function over a large range in m. As we shall see, this is a powerful additional argument for the "β-meteoroid" theory of ZB, following BG.

Let us now look to the studies of the mass distribution of particles in the 10^{-12} gm range as measured from lunar micro-cratering and beautifully summarized by Hörz et al. (1975). This notable consortium of scientists find strong evidence for a deep minimum in the Δ log N/Δ log m slope of the mass distribution function near 10^{-8} gm, and a relatively sharp maximum in the neighborhood of 10^{-11}-10^{-13} gm (their Fig. 15).

To illustrate the effect on $\langle \log H \rangle$ of such a concentration of particle sizes in a narrow mass range, I have adopted an extreme artificial distribution of mass in the mathematical form

$$\frac{\Delta \log N}{\Delta \log m} = - \frac{1.1}{1 + 10 \log (m/m_0)} \quad , \tag{10}$$

where $\log m_0 = -13$.

Numerical integrations then lead to various functions on a $\log_{10}$ scale in terms of log m as shown in Fig. 5. The Δ log N/Δ log m curve is Eq. 10 from which the log N curve is derived, beginning with N = 1 at log m = -11.5. Other log N curves beginning at log m = -12.0 and -12.5 are not shown to avoid confusion, but would be displaced vertically below the log N curve shown. The three $\langle \log H \rangle$ curves of the log (pulse height) assume the distribution function gives N = 1 at the three masses, log m = -11.5, -12.0 and -12.5. The quantity $\langle \log H \rangle$ applies to a chosen value of m_1 on the abscissa.

The $\langle \log H \rangle$ curves of Fig. 5 show how the pulse height, averaged logarithmically, can vary with the critical value of m_1 for unit pulse height. A shift from a starting velocity v to a higher velocity will shift m_1 to a lower value and hence to the left in Fig. 5. Such a shift might either increase or decrease $\langle \log H \rangle$, depending upon the value of m_1 compared to m_0, and upon the starting value of m for log N. Usually, however, for a more physically acceptable mass distribution function the change should not be so marked.

To explain the pulse heights observed by BG (Fig. 1), I suggest that the growth in the pulse height from antapex to apex arises from β-meteoroids of increasing impact velocity, representing a decrease in mass following some $\langle \log H \rangle$ curve less steep than those of Fig. 5, but suggesting particles more massive than the peak of the Δ log N/Δ log m curve. As the velocity increases beyond $\phi = 90°$, the Sun impact direction, $\langle \log H \rangle$ continues its increase. The rapid rise in $\langle \log H \rangle$ and rapid decrease in N near $\phi = 60°$, some 30° towards the apex from the Sun direction, must then arise from the superposition of another mass distribution function, not necessarily with a velocity increase, possibly a decrease, as suggested by the HEOS velocities by Hoffmann et al. (1974, 1975). Probably this is the tail end of the ordinary meteoroid distribution with a small value of b as indicated by the dip in the Δ log N/Δ log m curve of Hörz et al. Towards the antisun direction, ϕ decreasing through 270°, the velocities are again lower, the masses higher and most of the material comes from the normal meteoroid mass distribution, β-meteoroids not making a significant contribution.

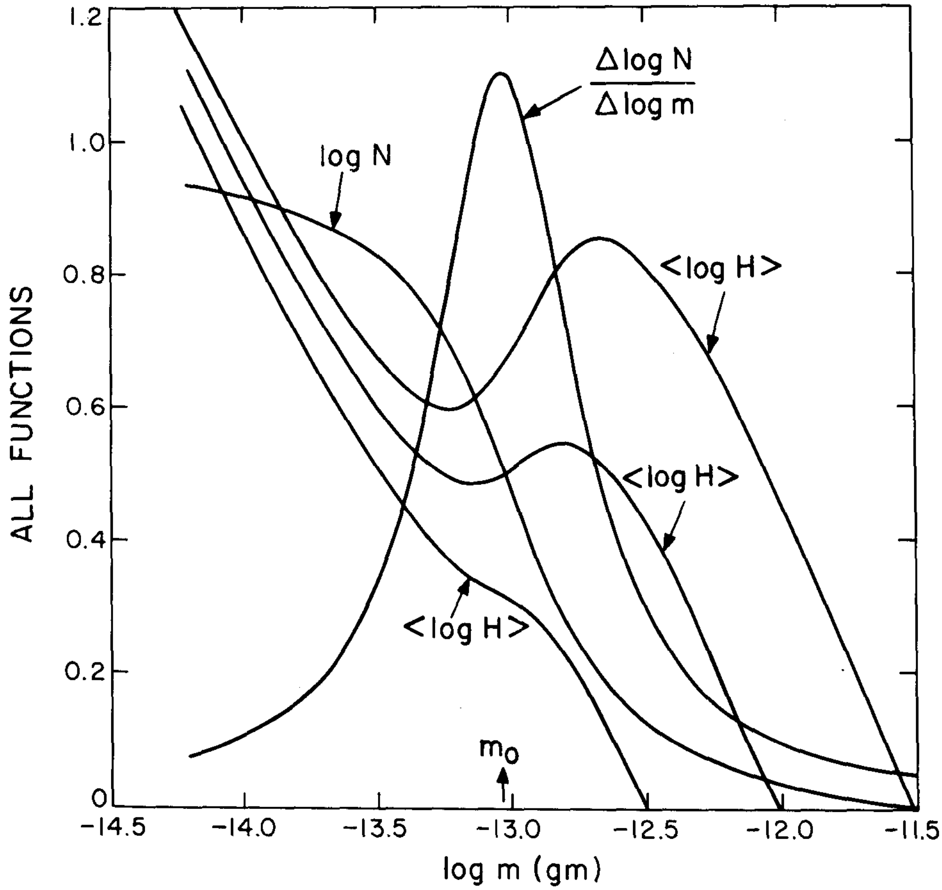

Fig. 5. log N (Cumulative) and Mean log H (Pulse Height)
Developed from $\frac{\Delta \log N}{\Delta \log m} = \frac{-1.1}{1 + 10 \log (m/m_0)}$
⟨log H⟩ Curves begin at log m (gm) = -11.5, -12.0 and -12.5.

This qualitative explanation falls short of a detailed explanation of the ⟨log H⟩ variation with direction, but strongly supports the β-meteoroid explanation by demanding a narrow special mass-distribution function for these particles, as would be expected from the limited range in mass for particles that can be greatly accelerated by solar radiation pressure.

From the Pioneer 8 and 9 FFG measures Rhee, Berg and Richardson (1974) find no significant change in particle concentrations with heliocentric distance between 0.76 and 1.08 AU and no concentration at 1 AU. From the same data Zook (1975) finds the spatial concentration of the parent bodies increasing with heliocentric distance. He develops a theory for the production rate and radial distance from the source of β-meteoroids.

The definitive treatment of the Pioneer 8 and 9 data should include not only the frequency of impact with heliocentric distance and possibly longitude, but also include the important data of impact direction and pulse height. Possibly meteor streams may also play a role in these distribution functions. Note that for β-meteoroids the velocity will probably increase with decreasing mass within the mass-distribution function. The ⟨log H⟩ curves in Fig. 5 were derived on the assumption that for a given m_1 at H = 1, the velocity of the whole mass-distribution function is given by the value applicable to m_1. Thus among actual β-meteoroids a more complicated relationship will be found among ⟨log H⟩, m_1 and the mass-distribution function. The value of ⟨log H⟩ will undoubtedly not increase so rapidly with decreasing m_1 and increasing velocity as indicated in Fig. 5. Note also that the actual meteoroids will possess a velocity-distribution function at each mass, further complicating the theoretical analysis.

REFERENCES

Berg, O. E. and Grün, E., 1973, Space Research XIII, Akademie-Verlag, Berlin, 1047-1055.

Cook, A. F., Williams, J. T. and Shao, C.-Y., 1972, IN Meteor Research Program, pp. 83-89. Final Report Contract NSR 09-015-33, NASA CR-2109.

Dohnanyi, J. S., 1970, J. Geophys. Res., 75, 3468-3493.

Dohnanyi, J. S., 1972, Icarus, 17, 1-48.

Dohnanyi, J. S., 1973, Evolutionary and Physical Properties of Meteoroids. ed. Hemenway, Millman and Cooks, Wash. DC, NASA, Sp. Rep. 319, 363-374.

Grün, E., Berg, O. E., and Dohnanyi, J. S., 1973, Space Research XIII, Akademie-Verlag, Berlin, 1056-1062.

Hemenway, C. L., Hallgren, D. S. and Schmalberger, D. C., 1972, Nature, 238, 256.

Hoffmann, H. J., Fechtig, H., Grün, E. and Kissel, J., 1974, XVII COSPAR at Sao Paulo, Brazil.

Hoffmann, H. J., Fechtig, H., Grün, E. and Kissel, J., 1975, Planet. and Spac. Sci., 23, 215-224.

Hörz, F., Brownlee, D. E., Fechtig, H., Hartung, J., Morrison, D. A., Neukum, G., Schneider, E., Vedder, J. F., and Gault, D. E., 1975, Planet. and Spac. Sci., 151-172.

McDonnell, J. A. M., Berg, O. E., and Richardson, F. F., 1975, Planet. and Spac. Sci., 23, 205-214.

Rhee, J. W., Berg, O. E. and Richardson, F. F., 1974, Geophys. Res. Let., 1, No. 8, 345-346.

Sekanina, Z., 1975, CFA Preprint 313.

Whipple, F. L., 1940, Proc. Amer. Phil. Soc., 83, 711-745.

Whipple, F. L., 1955, Ap. J., 121, 750-770.

Whipple, F. L., 1967, "The Zodiacal Light and the Interplanetary Medium," NASA Sp. Rep. 150, Wash. DC, 409-426.

Zook, H. A., 1975, Private Communication.

Zook, H. A., and Berg, O. E., 1975, Planet. and Spac. Sci., 23, 183-203.