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THE MICROMETEOROID ENVIRONMENT OF PROJECT APOLLO

February 25, 1965

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BELLCOMM, INC.

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PURPOSE AND SCOPE

In order to maintain an up to date assessment of the meteoroid hazard to Project Apollo, continued review of the available information about the meteoroid environment is necessary. This paper is the first report on a systematic effort undertaken for that purpose. We present here a discussion of current knowledge concerning distributions of particles in the mass range of about 10^{-6} grams or smaller.

SUMMARY

A review of the micrometeoroid environment is presented. Information about fluxes of dust particles in the mass range of about 10^{-6} grams or smaller derived from zodiacal light and F-corona studies is discussed and compared with the results of direct measurements obtained by satellites. Near earth measurements obtained by microphone systems define a flux three to five orders of magnitude higher than can be predicted from the astronomical calculations; the discrepancy has been attributed to a hypothetical cloud of captured micrometeoroids around the earth. Data from the deep space microphone measurements by Mariner II are in good agreement with those derived from the zodiacal light and F-corona studies. No explanation consistent with near earth microphone data has been found to account for the close agreement of particle influx rates derived from these studies and those defined by near earth penetration measurements by the Explorer XVI satellite.

THE MICROMETEOROID ENVIRONMENT OF PROJECT APOLLO

I. INTRODUCTION

Space outside the earth's protective atmosphere and beyond contains many small fragments of interplanetary debris. An encounter between such an interplanetary particle and a spacecraft is bound to be violent since the velocity of the two objects relative to each other is many kilometers per second. The type of debris which is sufficiently numerous to justify concern is divided here into two broad categories (as a function of size): meteoroids ranging in mass from a few grams down to about 10^{-5} grams* and the micrometeoroids, ranging from about 10^{-5} grams down to 10^{-15} grams or even less. The discussion in the present paper will be limited to the later type particles; a review of the visual and radar meteoroids is deferred to a future part of this study.

Micrometeoroids or interplanetary dust particles are too small to produce observable traces of light or ionization when entering the atmosphere. Before the day techniques were developed to directly measure particle fluxes by satellites, the only source of information about interplanetary dust came from astronomical studies of the solar F-corona and of the zodiacal light.

It has been conclusively established that these two phenomena are a result of the scattering and diffraction of the sun's light by interplanetary debris (Grotrian, 1934; Van de Hulst, 1947; Allen, 1946). Photometric measurements made it possible to then construct models of the spatial and size distribution of these

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*When entering the atmosphere, these particles become luminous (visual meteoroids) and produce a trail of ionization detectable by radar (radar meteoroids).

interplanetary particles. Approaching the subject in historic order, a review of the information derived from these studies is briefly presented (Section II).

In Section III, we discuss the significance of the information gained from direct measurements by rockets and satellites. Data from these direct measurements are compared with particle distributions inferred from astronomical calculations of the surface brightness of the F-corona and zodiacal cloud. The latter studies predict a particle distribution of about 10^5 times smaller than measured by microphone sensors used in most of the direct measurements. If one postulates that a captured cloud of interplanetary dust orbits the earth, the difficulty arising from this discrepancy is removed but some new problems are thereby created. The situation is not clearly understood.

A review of terrestrial accretion studies of micrometeorites is deferred to the second and future part of this work.

II. THE MICROMETEOROID ENVIRONMENT

A considerable amount of interplanetary debris is dispersed in space, moving in widely different orbits around the sun. Most of these objects are tiny dust particles believed to be fragments given up by periodic comets.

The distribution of these particles is far from uniform and their number density is subject to large erratic fluctuations (Dubin, 1960-I; Dubin, Alexander and Berg, 1962). An unusually large increase in the number of micrometeoroids is called a shower and is suspected to be associated with the orbit of periodic comets. Such "showers" may only last for a few hours. The total number density of these particles in the neighborhood of the earth's orbit but not necessarily in the neighborhood of the earth itself is believed to fluctuate around a mean value of about a few particles per cubic mile. This is sufficiently numerous to give rise to spacecraft hazard as a result of puncture or other damage arising from a mutual collision. Since these particles are moving with a velocity of many kilometers/sec (and so is the spacecraft) relative to the earth, an average particle will have a (relative) kinetic energy of many times its mass in TNT and the consequences of a collision with a spacecraft will be correspondingly serious. During an Apollo type mission, in particular, the CSM will experience a great many such encounters with certainty.

The general problem at hand can be formulated as follows: one has to calculate the probability of encountering a meteoroid of a given kind* during a specified mission and then to define the history of the craft in terms of the particular meteoroid events it is likely to experience. With this information secured, it then becomes possible to design a spacecraft to qualify a given mission within specified tolerances.

The dynamic characteristics of individual meteoroids are sufficiently diverse and our knowledge of their properties sufficiently limited that statistical considerations have to be introduced. The number of times, N_o, that a given event will take place can then be written as

$$N_o = FE \tag{1}$$

where the flux F is the number of meteoroids of a particular kind, for example, having mass m or greater, crossing a randomly oriented area of space per second, expressed in units of m^{-2} sec^{-1} and E is the product of the surface area of the spacecraft by the time of the mission in units of m^2 sec; E is known as the exposure. Clearly if $N_o << 1$, the event is not likely to occur and we may dismiss it from our consideration. If on the other hand a probability for no puncture of, say, 99% is desired, one has to consider all events for which $N_o \geq .01$. One may then define a flux to be "significant" if it reached the threshold value which a designer must consider in order to satisfy reliability requirements.

From the point of view of a manned lunar mission, one may generally distinguish between two types of hazards: hazard to spacecraft and hazard to crew during extravehicular activities. Orrok (1964) discussed this problem and found that the significant flux for an astronaut during an Apollo type mission is about 10^{-8} to 10^{-6} particles/m^2 sec and for the combined CSM it is about 10^{-11} to $10^{-9}/m^2$ sec. This corresponds (see, e.g., Figure 6 of this paper) to the flux of meteoroids with a mass of about 10^{-9} gm to 10^{-6} gm for the astronaut and about 10^{-5} gm to 10^{-3} gm for the CSM. We therefore conclude that the flux of micrometeoroids** is significant for the astronaut but not for the CSM.

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*By "kind" one usually means its size, or its mass or the thickness of aluminum it is able to penetrate. Meteoroids large enough to produce detectable signals when entering the earth's atmosphere are usually classified according to their visual, photographic or radar magnitudes.

**Defined as those particles with mass less than 10^{-5} gms.

III. ASTRONOMICAL INFORMATION ABOUT MICROMETEOROIDS

Zodiacal Light and F-Corona

After twilight and before dawn, a faint glow called the zodiacal light can be seen diminishing in brightness from the horizon toward the zenith in the plane of the ecliptic (i.e., plane of the earth's orbit around the sun or the sun's path in the sky around the earth). This phenomenon is so faint that it can only be seen on clear nights and far away from cities. The light coming from man-made illumination is sufficiently strong to merge the zodiacal light into the background. Grotrian (1934) first suggested, and now it is generally accepted, that a scattering of the sun's rays by interplanetary dust gives rise to the zodiacal light. The Fraunhofer lines are little broadened and the light is partially polarized. Near the antisolar point the brightness of the background sky increases; this faint glow is known as the gegenschein. While different opinions exist in regard to its origin, there are reasons (see, e.g., Elsasser, 1963) to believe that the gegenschein is the result of back scattering of the sun's rays by dielectric dust.

The intensity of the sun's corona can be separated into two spectroscopically distinct components, called K and F (Grotrian, 1934). The K-corona is strongly polarized and is caused by the scattering of light by free electrons near the sun's surface. The F-corona is little polarized (Ohman, 1947) and is attributed to solar photons diffracted by interplanetary particles far away from the sun. At sufficiently high elongations the F-corona merges into the zodiacal light and hence the latter can be considered as a mere extension of the F-corona. Because of data reduction difficulties, accurate observations in the elongation of about 10° to 20° (from the sun) are not available. This is indicated in Figure 1 which is a plot given by Elsasser (1963) of the observed intensity of the sun's corona and that of the zodiacal light. The individual contributions of the F and K components to the surface intensity of the corona are indicated.

Elongation is measured from the sun, $\square^{\circ}$ means square degree and the superscript M means magnitude*.

Details of the observed zodiacal light intensity are better indicated in a semi-logarithmic plot. Figure 2 gives the observed intensity (solid line) and polarization (dashed line) of the zodiacal light as reproduced from Giese (1963). The left vertical scale corresponds to the total intensity (both polarized components) and the right vertical scale gives the % polarization P, definited as

$$P = \frac{I_1 - I_2}{I_1 + I_2} \qquad (2)$$

where I_1 and I_2 are the intensities in each plane of polarization (see Figure 3). The width of the shaded regions represents the uncertainty in the plotted values.

Theoretical Models

Any satisfactory model has to reproduce the brightness of the F-corona and zodiacal light (Figures 1 and 2) as well as the observed polarization (Figure 2). The geometry of the situation is illustrated in Figure 3.

Assuming that the scatterers are spherical particles of radius a, a mathematical statement of the problem can now be given in terms of the scattering function S_k (ϕ, a) for polarization

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*The Magnitude M of a light source is defined as $M = -2.5 \log_{10} L/L_o$ where L is the illuminance of the source at the point of observation; L_o is the illuminance of a source of zero magnitude and is equal to 2×10^{-7} foot candles or 2×10^{-6} lux. The sun has a magnitude of -26.7, the full moon -12.6 and Jupiter -2.5. The limiting magnitude that the naked eye can detect is about +6. From the definition of magnitude, one can see that increasing L by 10x will decrease M by -2.5 etc... In Figure 1, we see that the intensity of the zodiacal light at 90° elongation is 100 stars of $10^M/\square^{\circ}$; in terms of magnitude this then becomes $M = +5/\square^{\circ}$ or barely visible with the naked eye.

K defined by

$$I_k(\phi) = \frac{I_o S_k\ (\phi, a)}{\Delta^2} \qquad K = 1,\ 2 \qquad (3)$$

where $I_k(\phi)$ is the contribution to the scattered light by one scatterer at scattering angle ϕ (see Figure 3), I_o is the incident beam and Δ is the distance from scatterer to the observer. The functions S_1 and S_2 depend on the size of the particle, the wavelength of the incident radiation and the complex dielectric constant of the scatterer. Physically, S_k is the superposition of the processes of reflection, refraction, diffraction and absorption.

To obtain the total intensity scattered into the direction ε, one has to integrate Eq-3 over the particle distribution and along the line of sight. This can be expressed as

$$I_k(\varepsilon) = L \int_o^\infty \frac{I}{R(\Delta)^2} \int_{a_o}^{a_1} N\ (R,a)\ S_k\ (\phi,a)\ da\ d\Delta \qquad (4)$$

where L is the solar constant and $N(R,a)da$ is the number of particles per cm^3 with a radius between a and a+da at a distance R from the sun. a_o and a_1 are the minimum and maximum particle radii, respectively.

This problem has been treated in the literature by a number of authors*. All of these studies are consistent in assuming an interplanetary medium of spherical dust particles with a

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*For a review, see Giese (1963), Elsasser (1963) and Ingham (1963).

radius of the order of a micron or larger (with or without an admixture of free electrons) and with a spatial distribution* of

$$N\ (a,R)\ da = C\ a^{-P}\ R^{-\alpha} da,\ \text{and} \tag{5}$$

$$N\ (a,R)\ da = 0\ \text{when}\ R < .1\ \text{AU} \tag{6}$$

where N(a,R) da is the number of particles with a radius between a and a+da(cm) per cm^3 of space, C, P, and α are constants and R is the distance from the sun in AU**.

Eq-4 is based on the consideration that at .1 AU from the sun the particles will become sufficiently hot to melt and decay***.

A minimum value for the particle radius has theoretically been established. Using classical (ether) theory Poynting (1904) found that small particles, due to the sun's radiation, will gradually lose momentum (to the radiation field) and spiral into the sun. Robertson (1937) treated this relativistic problem using the correct covariant formulation that has since been developed. The net result is that particles with a radius less than

$$a \sim .6/\rho\ \text{microns},\ \rho = \text{specific gravity}, \tag{7}$$

are blown out of the solar system by radiation pressure and particles with a radius somewhat larger than $.6/\rho$ are also unstable in the sense that they quickly spiral in toward the sun where they decompose and are then removed by radiation pressure.

Two important generalizations can be derived from the solution of Eq-4 for a particular model, (1) the F-corona results appear to depend weakly on α in Eq-5 (see, e.g., Allen, 1946) and

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*Elsasser (1955) took N (a,R) = 0 for $R < .4$ AU and constant spatial distribution, i.e., $\alpha = 0$ for $R > .4$ AU.

**AU = distance from the earth to the sun.

***At this distance from the sun a black-body will have a temperature of 870°K. While it is by no means clear just what would happen to a micrometeoroid under these conditions, it is generally (and perhaps arbitrarily) assumed that vaporization and subsequent outgassing of volatile components are likely to "undo" a micrometeoroid at this distance from the sun (cf with subsequent discussion).

(2) the largest contribution to the scattered light at large elongations ε comes from that portion of the dust along the line of sight which is nearest the sun (cf Figure 3).

Result (1) is believed to indicate that the F-corona is caused by dust far away from the sun* and (2) means, evidently, that the zodiacal light data provide information of particles far away from the earth. Because of this, F-corona studies may well be more relevant in providing information about the particle distribution not too far away from the earth than are distributions derived from zodiacal light studies. Those latter studies should then provide information concerning the spatial distribution of dust around the sun, i.e., define the value of the parameter α in Eq-5.

It is not easy to define a unique model which will reproduce the observations. The difficulty lies mainly in the fact that several different models are capable to explain the optical properties of zodiacal light. The scattering property of small spherical particles is different depending on their size and material property; one can generally distinguish between two size ranges (i) with a $>\frac{\lambda}{2\pi}$ and (ii) a $<\frac{\lambda}{2\pi}$ (a = radius and λ = wavelength of light used). In case (i), metallic particles produce positive** polarization but reasonable distributions are unable to give quite enough polarization to fit the observations; nor can they reproduce the proper dependence on elongation given in Figures 1 and 2. Dielectric particles produce very slightly negative polarization or none at all. The contribution to the polarization of large (compared with λ) dielectric particles is therefore negligible. The importance of these particles lies in their ability to back scatter and hence to provide a possible explanation of the phenomenon of gegenschein.

In case (ii), both metallic and dielectric particles can polarize strongly; the reason against relying too strongly on such small particles is provided by Eq-7. According to the

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*Van de Hulst (1947) finds that the assumption of no particles to be distributed in a region of .1 AU from the sun changes his results by 4% only.

**From Eq-2 and Figure 2 we see this is in the right direction.

Poynting-Robertson effect, particles with a radius of $a \leq \frac{\lambda}{2\pi} \simeq .1$ micron should have a limited distribution because their radii reach the borderline of the criterion for stability. In recent experiments by Soberman, et al (1961) with the Venus fly trap submicron sized particles from near earth space have been recovered; this stimulated consideration of the optical properties of dust models including very small particles (Giese, 1963).

Electrons can produce large and positive polarizations and with an assumed spatial density of the order of 500-1000 electrons per cm^3 the correct results are obtained. Unfortunately, this electron density is too high to be consistent with our present information.

In Figure 4 we reproduce the results of three such models as given by Giese (1963). All three can explain the observed optical properties of zodiacal light. Model I contains "large" (i.e., case (i)) dielectric particles and 10^3 electrons/cm^3. Model II is a mixture of large dielectric and large and small metallic particles plus about 300 electrons/cm^3. Model III includes no electrons and is a mixture of large dielectric with large and small metallic particles. Details of each model are given in Table I.

To explain the F-corona, the situation is not complicated by strict polarization requirements. The material particle properties are not therefore crucial as in the case of the zodiacal light studies and simple size distributions are capable of correctly reproducing the observations.

Figure 5 is a plot of various suggested particle density distributions evaluated at earth's orbit, i.e., at 1 AU from the sun. Distributions derived by the various authors spread over three orders of magnitude at particle radii of about 10 microns. Beyond particle radii of about 20 microns the F-corona and zodiacal light calculations begin to lose their sensitivity to the assumed distributions. The increasing spread in the distributions as a increases beyond 2×10^{-3}cm is therefore increasingly irrelevant.

Beard (1959, 1963) proposed a distribution which would lie somewhere between the lines marked maximum and minimum, in Figure 5. It can be seen that approximately all of the distributions lie between those derived by Van de Hulst (1947) and Beard (labeled as minimum). Distributions defined by the three models in Table I are very close to each other and are not plotted separately; they are represented by the heavy line labeled Giese (1963).

It may be noted that the curves giving the smallest number density for particles of a given radius include smaller minimum particle radii than do the others. This is a simple statement of the fact that the F-corona and zodiacal light studies can either be explained in terms of a large number of small particles or a smaller number of large particles.

More information regarding the optical properties of these particles is needed in order to define a distribution within a smaller margin of uncertainty.

IV. DIRECT MEASUREMENTS

Brief Review

Numerous measurements have been taken of the micrometeoroid fluxes by means of satellites and rockets (for a review, see e.g., C. T. D'Aiutolo, 1964, W. M. Alexander, C. W. McCracken, L. Secretan and O. E. Berg, 1962). The majority of these measurements have been collected with microphone* systems. Light flash sensors that measure the light intensity** produced upon impact have also been employed and all these measurements (with some exceptions to be noted later) are consistent with each other in defining a flux in the mass range from 10^{-13} grams to about 10^{-7} grams. Figure 6 gives the earlier results as summarized by W. M. Alexander, et al (1962). The data plotted is

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*These systems record the impact of a dust particle when it collides with the sensor. These sensors have been shown (Dubin, 1960) to be sensitive to the momentum of the micrometeoroid. Assuming an average speed of 25 km/sec relative to the spacecraft, these sensors can detect a mass as small as 10^{-11} to 10^{-10} grams.

**This intensity is proportional to the kinetic energy of the incident particle, from which information enables one to calculate the mass of the impacting particle. These sensors have a mean sensitivity of about 10^{-13} grams but are subject to more uncertainty in the data interpretation than are the microphone systems.

the omnidirectional flux of particles per square meter per second with a mass (in grams) equal to or greater than m. Despite large erratic fluctuations between individual counters, the cumulative results constitute a well defined flux. The uppermost data point in the figure marked "Venus Flytrap" is the result of rocket experiments (Soberman, et al, 1961) where micrometeoroids were collected with exposed plates and subsequently recovered. With the use of electron microscopy it was possible to define a flux for very small particles (fraction of a micron and larger); extreme care was exercised to avoid contamination by terrestrial particles.

The solid line in the figure is a good fit to the experimental data and obeys the empirical formula

$$\log F = -17.0 - 1.70 \log m \qquad (8)$$

where F is the omnidirectional influx of particles per m^2-sec with mass of m grams or larger.

The shaded region in Figure 6 corresponds to the particles approaching the minimum size permitted by radiation pressure; this is reflected by a gradual drop in their distribution as indicated. Nothing is known about the density of these particles and hence, the limiting size from Eq-7 is indicated for three different densities.

All measurements corresponding to particles with a mass of 10^{-13} grams have been taken with light flash sensors. With the exception of the Venus Flytrap data all the other measurements have been taken with microphone systems.

The uncertainties in the data are due mainly to the assumption of (i) a velocity of 25 km/sec relative to the spacecraft (escape velocity is 11 $\frac{km}{sec}$), (ii) uncertainty in the sensitivity of the sensor; there may be an error of an order of magnitude associated with the plot given in Figure 6. Clearly, we have a consistent set of experimental measurements defining a near earth flux of micrometeoroids. The larger deviations from the main curve, such as Pioneer I, indicating a flux about 10^2 or 10^3 times less than Eq-8 would predict, is possibly not significant*

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*The data point for Pioneer I was determined from 17 counts recorded during the 1 1/2 day flight and hence its statistical significance may be subject to reservation.

(Dubin, 1962). The Venus Flytrap experiment indicating a flux about 10^2 times higher than Eq-8 cannot be convincingly explained. Carleton (1962) questioned the reliability of the Venus Flytrap measurements as a result of an analytical comparison with the solar coronographic studies by Volz and Goody (1962). Carleton gave evidence that the Flytrap experiment may overestimate the dust particle density by 10^4.

We may note, without comment, that among the data presented in Figure 6, consistency is observed only for the microphone data among themselves and that a comparison with the data provided by photomultiplier systems (10^{-13}gm) as well as the Venus Flytrap required discussion.

A sharp disagreement with the trend exhibited by the data in Figure 6 becomes evident when we consider the data gathered by Explorer XVI. This satellite, flown near earth in 1962-1963, measured penetrations into metal plates of different thicknesses (one to several mils).

The reduced data (with their respective experimental errors) are indicated in Figure 7, together with a comparison with data from other sources which will be discussed below. It can be seen that Explorer XVI measured a flux 10^4 to 10^5 times less than predicted by Eq-8. Since these measurements are statistically significant, the large deviation cannot be taken lightly. Hawkins (1964) questioned the data reduction process employed and D'Aiutolo (1963) suggested that the micro-meteorites may have a structure that prevents most of them from penetrating thin metallic surfaces. It may be possible that these two suggestions are equivalent; the hypervelocity impact properties of extremely loose porous materials impacting metal sheets has not been explained in the literature (or anywhere else). If that proves to be the case, then the Explorer XVI data may shift considerably to the right of their present location on Figure 7 indicating that they represent measurements of much more massive particles than is presently believed.* The discrepancy under discussion remains, therefore, a question mark.

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*The implications of this possibility is not correspondingly serious from the point of view of the Apollo Program since spacecraft hazard is primarily a function of the probability of penetration. Regardless of the actual level of micrometeoroid fluxes encountered during a space mission, one usually is concerned only with the flux of particles able to penetrate a given thickness of protective material.

Comparison of Eq-8 with distributions derived from zodiacal light and F-corona studies also raises some questions, as can be seen from Figure 7. Particle distributions from these studies are given in terms of number of particles with a given radius per cm^3. This is to be converted into fluxes to make a comparison possible. Such a conversion is not straightforward and is subject to uncertainties; little is known about the velocity of particles in the zodiacal cloud. Near earth orbit they should be moving with a heliocentric velocity of around 30 km/sec, assuming a circular orbit. This assumption can, however, be questioned. Conversion from size distribution to mass distribution is uncertain because nothing is known about the particle densities. In any event, conversion* of these distributions to omnidirectional fluxes may be subject to an uncertainty of about $10^{\pm 1}$.

A further difficulty arises as a result of the gravitational attraction of the earth. Due to this force, particles will be caused to alter their orbits in order to come nearer the earth. This gravitational concentration has been studied by Öpik (1951) and he finds that the probability for a particle to collide with the earth is proportional to the expression

$$\frac{V_e^2 + V_G^2}{V_G} \qquad (9)$$

where V_G is the geocentric velocity** (i.e., the velocity the particle would have relative to the earth if the earth were not present) of the particle and V_e is the escape velocity (= 11 km/sec at earth's surface). Studies by Hale and Wright (1965, I and II)*** indicate that an increase in flux of 50 may be expected for particles traveling with a geocentric velocity of about 3 km/sec.

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*In this paper we have used an average particle speed of 30 km/sec and a density of 1 gm/cm^3.

**Expression (9) is seen to become infinite for a vanishing geocentric velocity. This is a simple statement of the fact that an object, at rest relative to the earth, will fall down (to the earth) with certainty.

*** See also Shelton, et al (1964).

A consideration of this effect has not been included in our conversion of the calculated data in Figure 7, but we may well keep in mind that an additional uncertainty (possibly 1 to 10 X) of unknown magnitude is hereby introduced.

Returning to Figure 7, one can see that Eq-8 describes a flux some 5 orders of magnitude higher than is suggested either by the zodiacal light and F-corona data or by Explorer XVI. It is interesting to note the excellent agreement of the F-corona data with those measured by the satellites Explorer XVI and Mariner II.

Since Mariner II measured, on its flight to Venus, fluxes far from the earth, the agreement of these far earth fluxes with the inferred distribution is satisfying. The situation with Explorer XVI is, however, puzzling. Is it merely fortuitous that this latter satellite measured fluxes in agreement with distributions inferred by astronomers? This writer wants to emphasize the seeming contradictions in our present knowledge of the subject which only future experiments are likely to clarify, without deliberately casting doubt on any particular set of distributions presently available.

Assuming that the near earth flux defined by Eq-8 is representative, one has the task of explaining the large discrepancy between this flux and the one based on zodiacal light and F-corona calculations. Suggestions have been advanced that a cloud of captured dust particles surrounds the earth (Whipple, 1960-1961, Nazarova, 1961, Soberman, and Della Lucca, 1961). Dubin and McCracken have expressed criticism on the ground that all these authors used assumed distribution curves other than Eq-8 which is the only distribution curve (within the limits of error) that can be inferred from the data. Hibbs (1961) analyzed the data from Explorer I and found evidence that the impact rate decreased with altitude. Dubin, however, questioned the statistical significance of Hibb's conclusions (Dubin 1961, Hibbs, 1961).

Another difficulty arises when attempts are made to formulate a mechanism or process that would give rise to a dust cloud of captured particles whose spatial density is about 10^5 times the density of the zodiacal cloud. The suggestions that have so far been advanced are speculative in nature and no generally accepted hypothesis exists which would quantitatively explain how such a capture process is possible. Interpretation of the near earth microphone data is not free from controversy (Dubin and McCracken, 1962). The only definite inference that one can draw is that if a captured cloud exists, the difficulty of reconciling the microphone data with the astronomically inferred distributions would be removed. The Explorer XVI data, however, would still remain to be explained.

V. DISCUSSION AND CONCLUSIONS

Our knowledge of the distribution of micrometeorites in space based on direct measurements and astronomically inferred calculations has been discussed. This review is preliminary to the second and major portion of this study where a more complete review of the meteoroid environment for Project Apollo will be undertaken.

Each of the different types of investigations provide us with a definite and self-consistent set of data from which fluxes of micrometeoroids can be defined. The fluxes derived from the different studies are not consistent with each other and their differences require considerable discussion.

The data derived from direct near earth measurements by microphone systems indicate a flux very much higher than the far earth flux inferred from astronomical calculation. This led to the hypothesis of a near earth flux concentration. No generally accepted explanation for the cause of such a concentration has been advanced, however.

The penetration sensors of Explorer XVI indicate a near earth flux which is in agreement with that derived from F-corona calculations and is in sharp disagreement with the microphone data. The microphone system of Mariner II defines a flux in agreement with F-corona calculations and may constitute a verification of the theory.

The seeming inconsistencies among the currently available data indicate, overwhelmingly, the need for further research and experiment in this field.

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TABLE I

Composition of three dust particle models by Giese (1963) approximating the zodiacal light observations (See Fig. 4)

	Material	Refractive index	Range of particle radii in cm	Particle size distribution = number of particle of radius a per cm^3	Spatial density = particles/cm^3 R = distance from the sun in A.U.
Model I	dielectric	1.33	$9.5x10^{-4}<a<9.5x10^{-3}$	$10^{-20}\ a^{-2.5}$	$n=\frac{10^{-15}}{R^{3.5}}+5x10^{-15}$
	electrons	-	-		$n=\frac{.5}{R^3}+\frac{10^3}{R^{1/2}}$
Model II	dielectric	1.33	$9.5x10^{-4}<a<9.5x10^{-3}$	$4.5x10^{-21}\ a^{-2.5}$	$n=\frac{3x10^{-15}}{R^3}$
	metal	1.27 - 1.37 i	$1.5x10^{-5}<a<9.5x10^{-3}$	$8x10^{-21}\ a^{-2.5}$	$n=1.5x10^{-13}/R^{1/2}$
	electrons	-	-	-	$n=\frac{5}{R^3}+\frac{300}{R^{1/2}}$
Model III	dielectric	1.33	$8x10^{-5}<a<3.2x10^{-4}$	$3x10^{-18}\ a^{-2}$	$n=3x10^{-15}/R^3$
	dielectric	1.33	$8x10^{-6}<a<2x10^{-4}$	$10^{-26}\ a^{-4}$	$n=6x10^{-12}/R^{1/2}$
	metal	1.27 - 1.37 i	$8x10^{-6}<a<2x10^{-4}$	$3\ x10^{-27}\ a^{-4}$	$n=1.8\ x\ 10^{-12}/R^{1/2}$

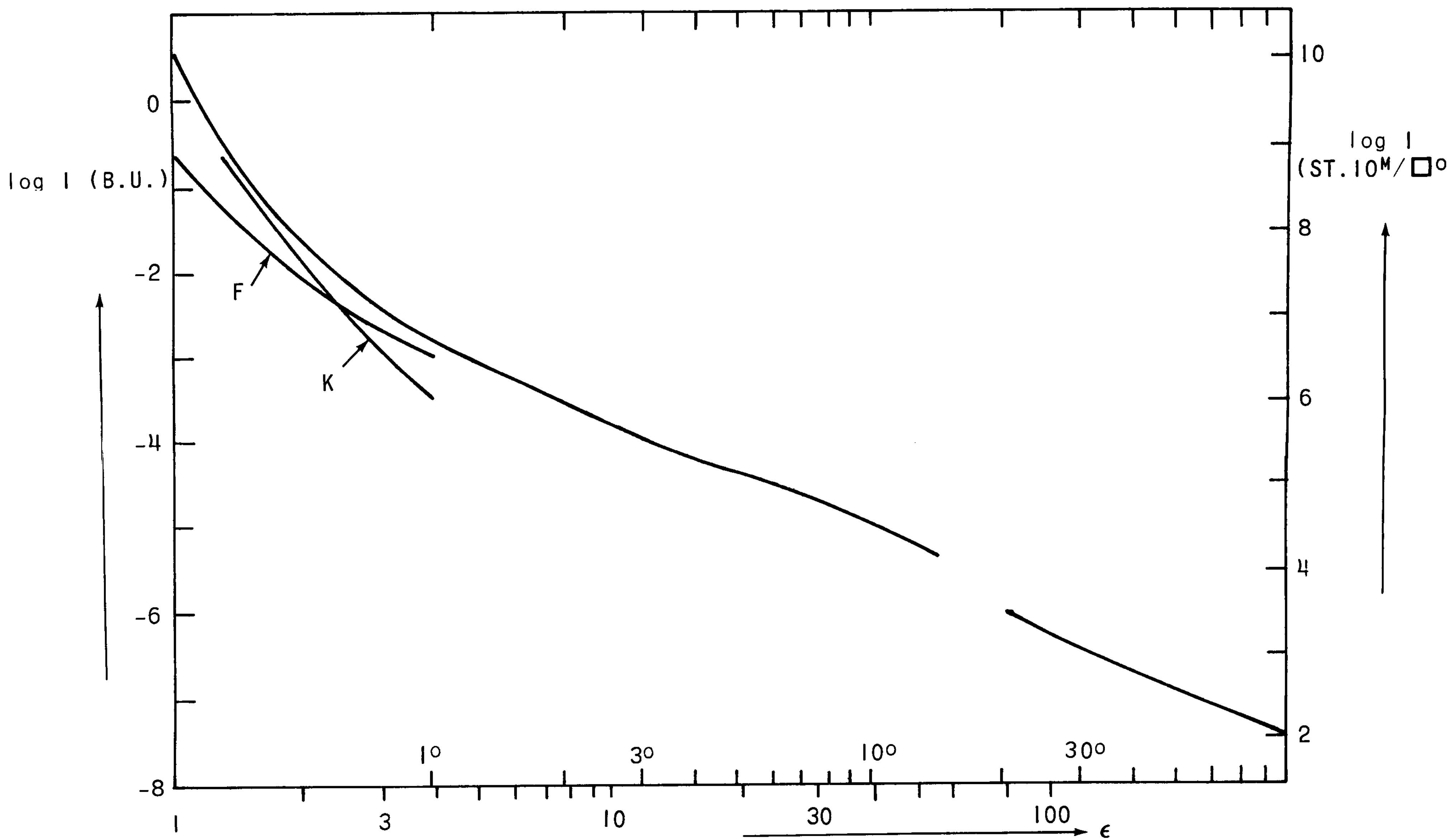

FIGURE I SURFACE BRIGHTNESS OF THE CORONA AND THE ZODIACAL LIGHT. F = FRAUNHOFER-CORONA, K = K-CORONA. Units LEFT: BAUMBACH-UNITS = 10^{-6} TIMES THE SURFACE BRIGHTNESS AT THE CENTER OF THE SUN'S DISK. UNITS RIGHT: STARS 10^{M} PER □° ϵ

ELONGATION MEASURED IN SOLAR RADII.

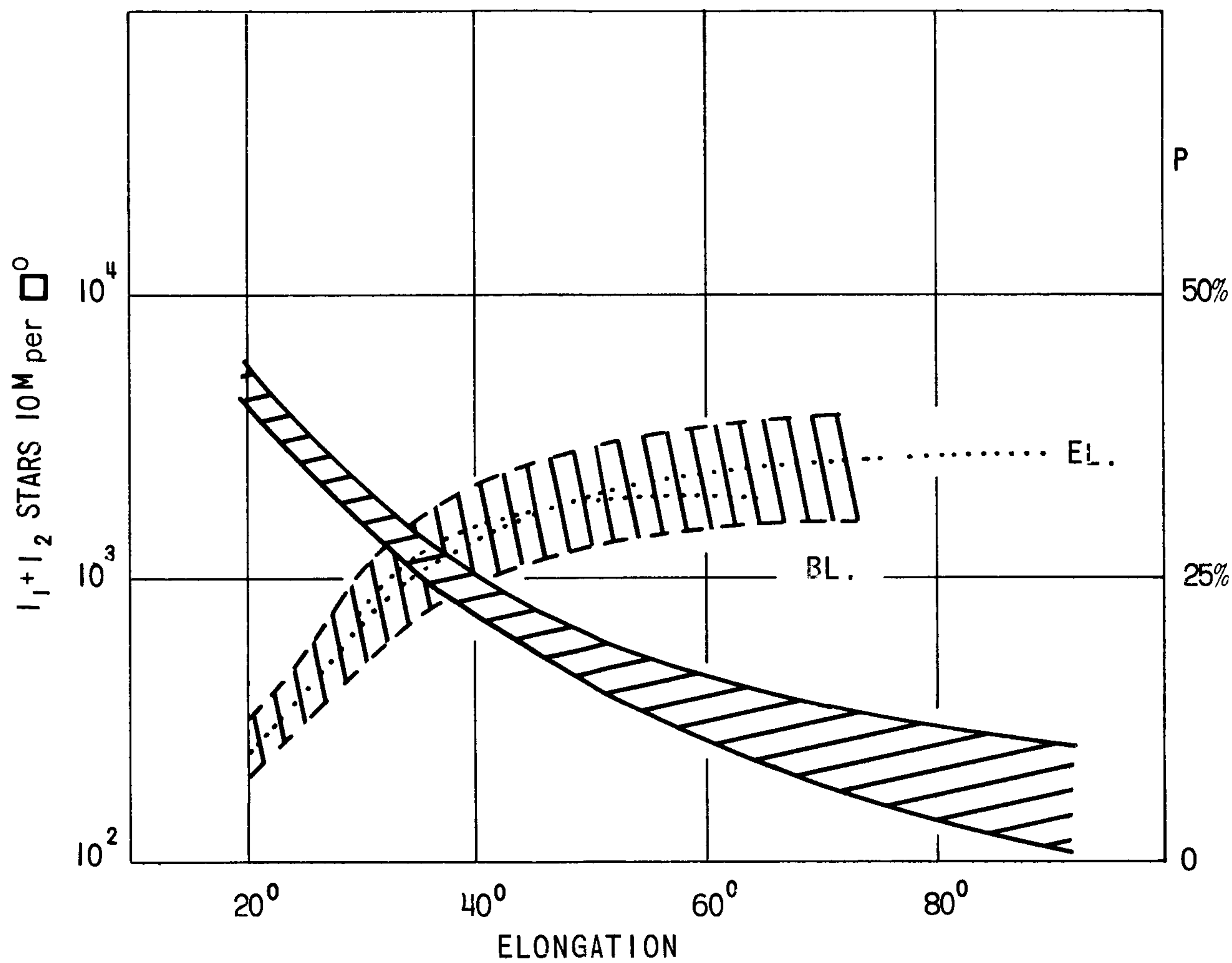

Fig. 2 OBSERVED BRIGHTNESS AND POLARIZATION OF ZODIACAL LIGHT.
EL.. ELSASSER (1958)
BL. BLACKWELL AND INGHAM (1961)
x AXIS, ELONGATION ϵ;
y AXIS, BRIGHTNESS (stars 10^M per. $\square^0$)
AND POLARIZATION (%); RIGHT SCALE.

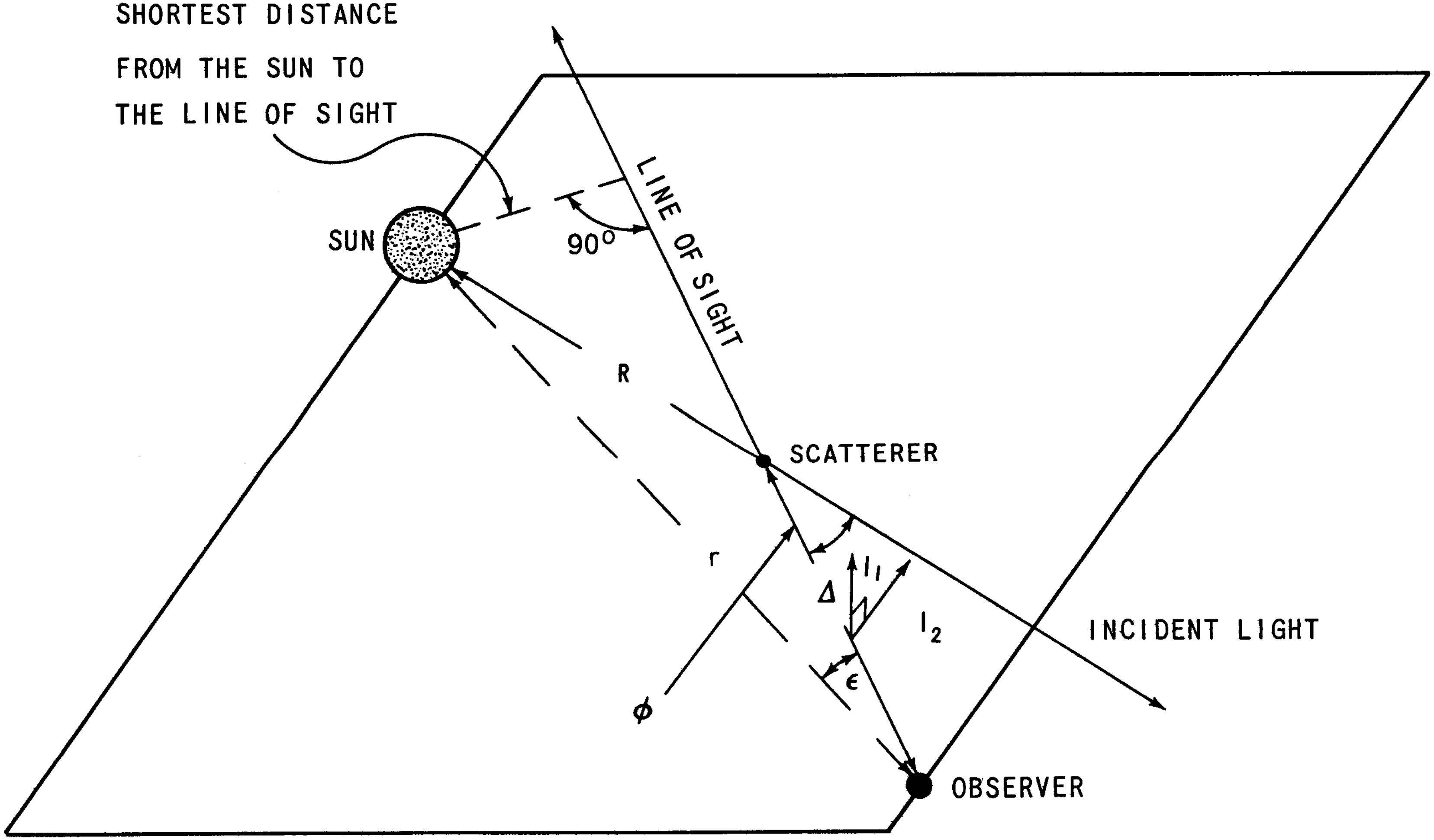

FIGURE 3 SCATTERING GEOMETRY: I_1 AND I_2 ARE THE COMPONENTS OF POLARIZATION PERPENDICULAR AND PARALLEL TO THE SCATTERING PLANE, RESPECTIVELY.

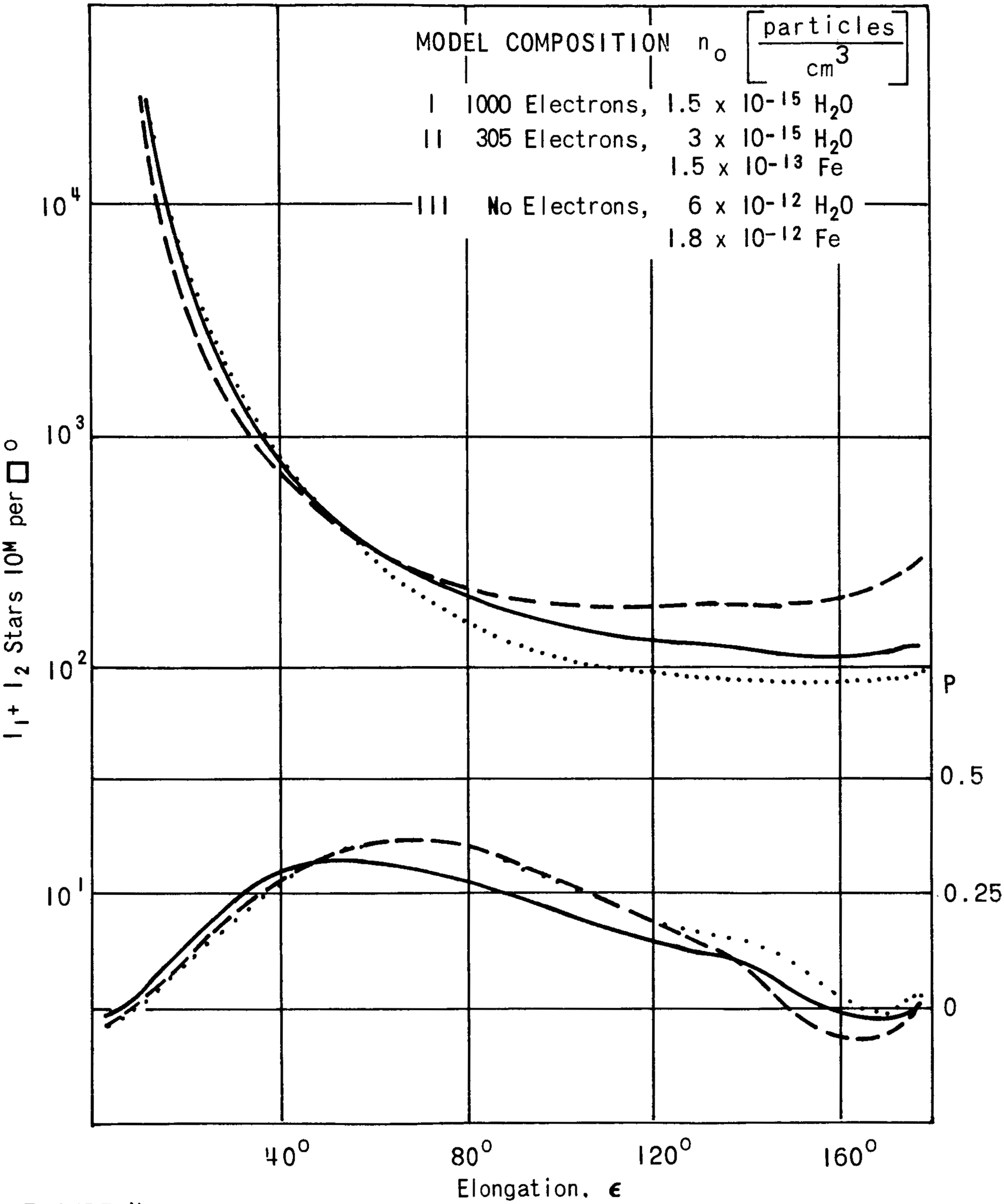

FIGURE 4 BRIGHTNESS AND POLARIZATION RESULTING FROM MODELS APPROXIMATING THE OBSERVATIONS OF ZODIACAL LIGHT. (COMPOSITION, SEE TABLE 1);

- - - - Dielectric Particles and Electrons;

——— Dielectric Particles, Metallic Particles, Electrons;

· · · · · · Small Particle Model.

x Axis, Elongation ε;
y Axis, Brightness I (Stars 10^M per □°) and Polarization (%); Right Scale.

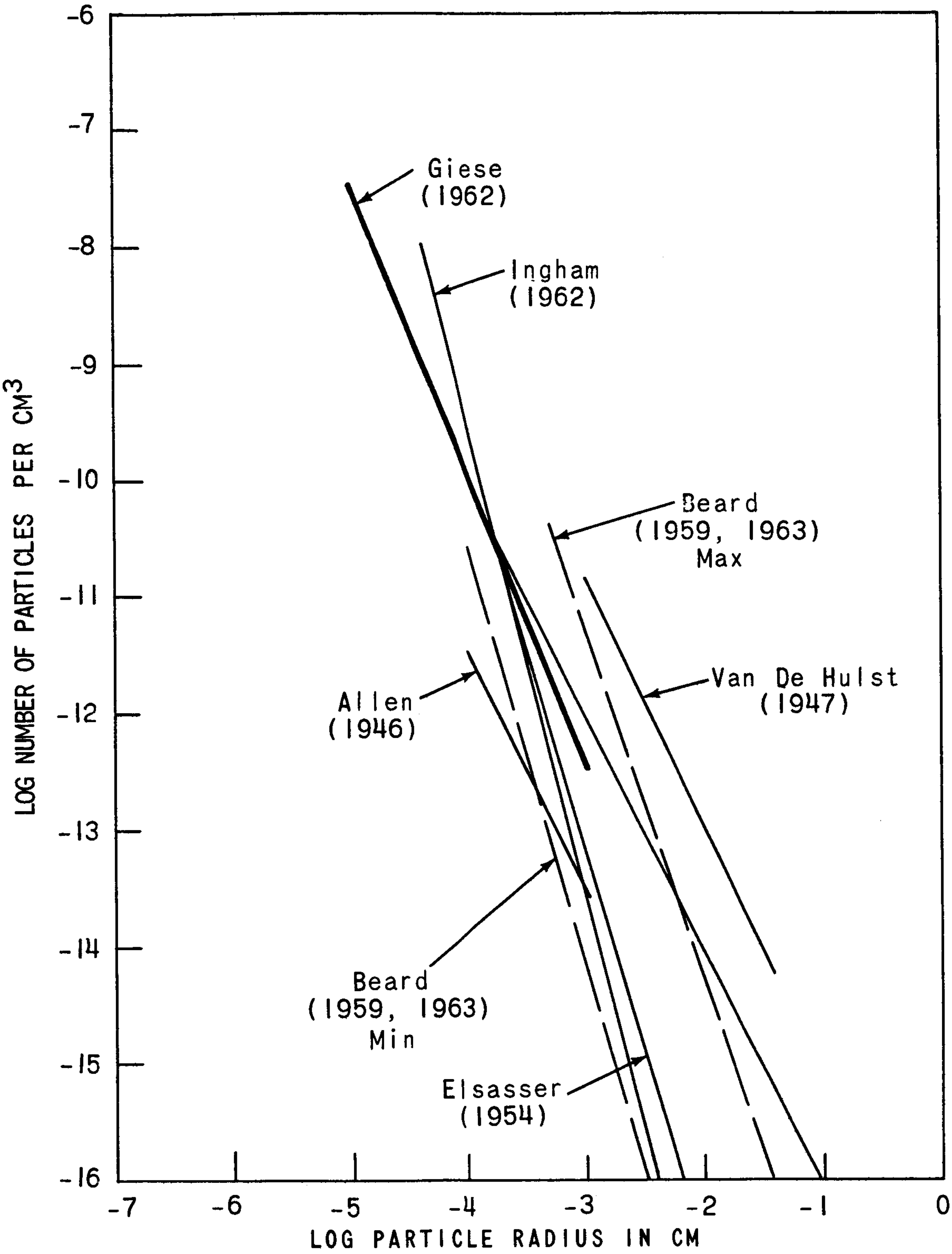

FIGURE 5 PARTICLE DISTRIBUTIONS DERIVED FROM ZODICAL LIGHT AND F-CORONA STUDIES.

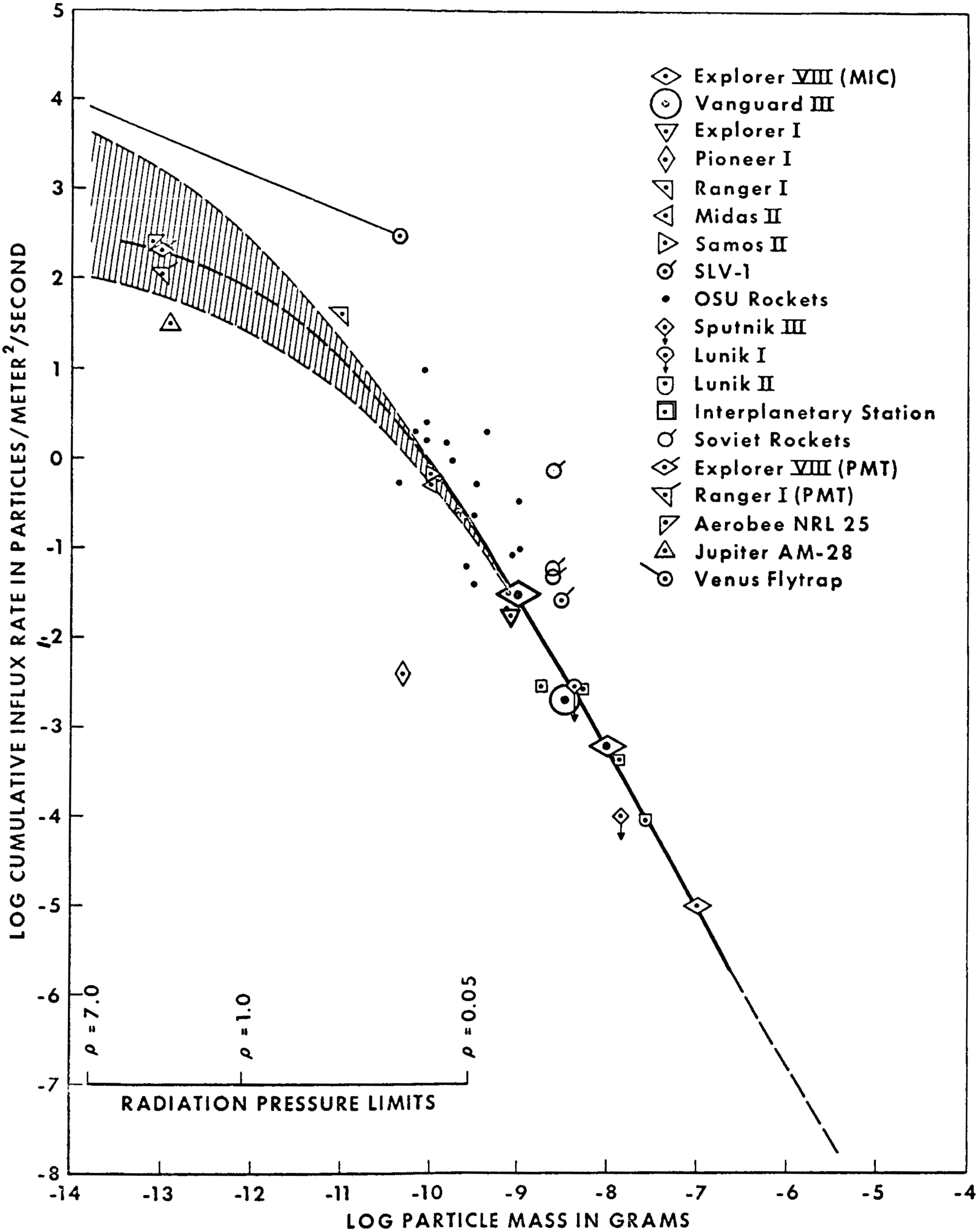

FIGURE 6 AN AVERAGE CUMULATIVE MASS DISTRIBUTION CURVE FOR THE VICINITY OF EARTH DERIVED FROM ALL THE AVAILABLE DIRECT MEASUREMENTS OBTAINED WITH MICROPHONE AND PHOTOMULTIPLIER SYSTEMS.

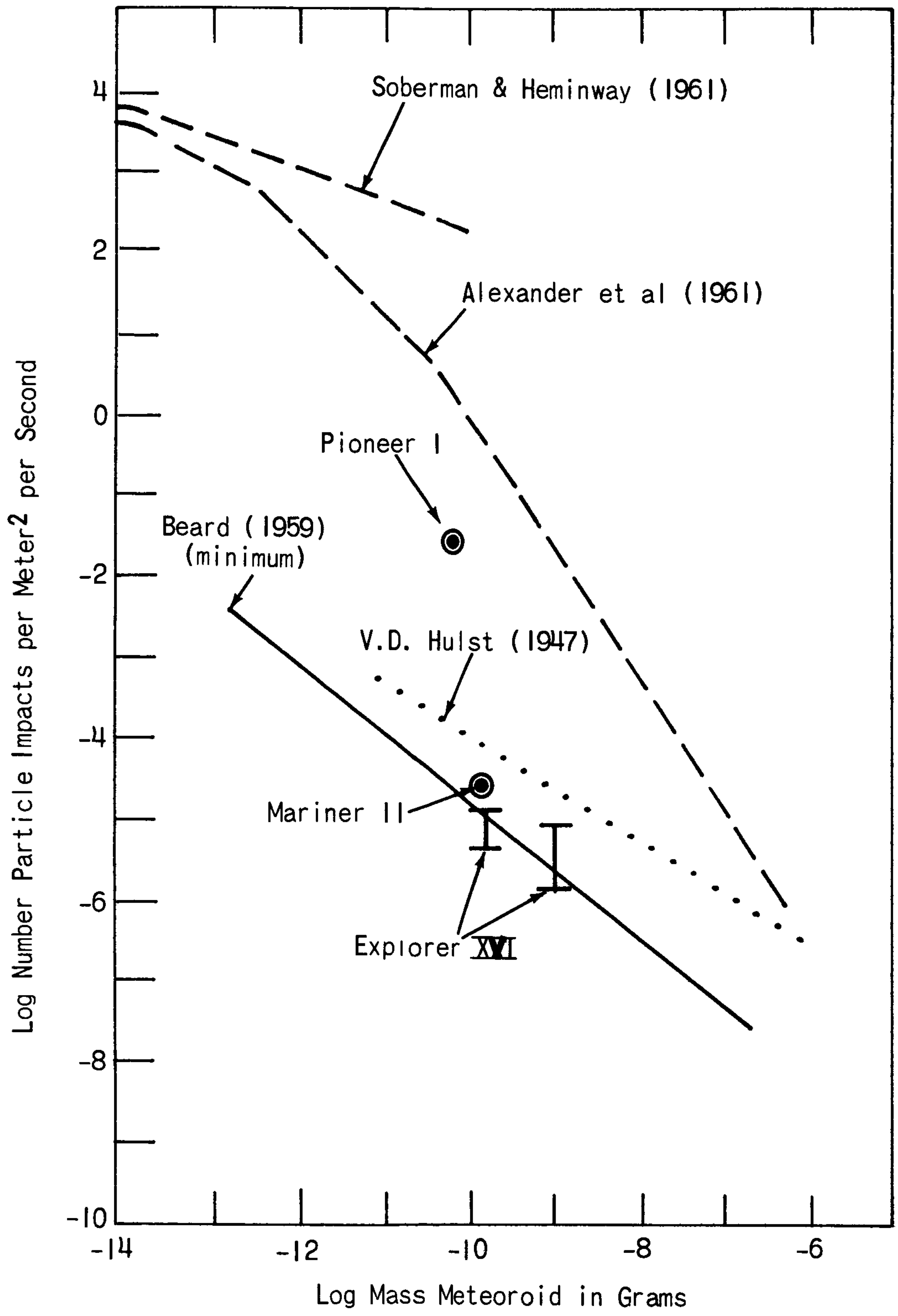

FIGURE 7 COMPARISON OF MICROMETEOROID FLUXES.

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