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REEXAMINATION OF DATA FROM THE ASTEROID/METEOROID DETECTOR

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FINAL REPORT

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EXECUTIVE SUMMARY

A reexamination of the results of the Pioneer 10 and 11 Asteroid Meteoroid Detector, or *Sisyphus* as it was popularly known, has been carried out in the light of a recently derived theory characterizing interplanetary matter and the zodiacal light (ZL). Sisyphus measured individual meteoroids from reflected sunlight and ZL between meteoroid "events". The results were questioned because meteoroid orbits could not be calculated as intended and the ZL as computed from individual meteoroids did not agree with values determined from the ZL mode and from the other ZL sensor on the spacecraft. It is first shown that, independent of any explanation, the measurements are, with high probably, valid and strongly correlated with the ZL. The model which explains the strange behavior of the Sisyphus instrument also resolves the enigma of why the three dust experiments on the Pioneer 10 and 11 spacecraft produced extremely disparate results for the distribution and orbits of meteoric particles and the ZL. The theory based primarily on these measurements requires a population in the inner solar system of cold meteoroid material composed mainly of volatile molecules. These meteoroids in orbits of high eccentricity are called *cosmoids.* They are impulsively disrupted from solar heating, resulting in order of magnitude increases in optical cross section. The dispersed particles, predominantly micron sized, scatter most of the ZL and supply the polarization. The sublimation time in sunlight for micron sized particles of volatile composition opposes the gravitational flux increase expected in approaching the sun. The other two Pioneer 10/11 dust experiments were: the Imaging Photopolarimeter (IPP) for the ZL, and the Meteoroid Detection Experiment (MDE) that measured penetrations of 25 μm (Pioneer 10) and 50 μm (Pioneer 11) thick walls of pressurized gas cells. No two investigations agreed on the dust distribution and only the IPP could be fitted to the prevailing model of dust spiraling inward from the asteroid belt. MDE data showed a nearly constant flux from 1 to 18 AU! The IPP showed the ZL decreasing between an inverse square and cube rate from 1 to 3.3 AU where it was no longer detectable. The prevailing model has the ZL decrease one power faster than the dust. Sisyphus showed small radial variations from 1 to 3.5 AU where measurements ceased abruptly with the instrument still operating. The data show that this population, which is believed to be composed primarily of water, dominates the dust distribution beyond one AU. Once the prevailing short period dust model is discounted, the three instruments, measuring cosmoids, are shown to agree. The subsequent measurements from Helios also show evidence of "fluffy" particles with eccentric orbits. This cosmoid population is expected to be gravitationally attracted and interact with the outer planets, contributing to ring formation, radial spokes and the generation of impulsive radio signatures. In a related effort, proposing an experiment for the Cassini Saturn mission , it was realized that the cosmoid flux would likely pose a threat to the Gallileo and Cassini orbiters. That and several other predictions to test the cosmoid theory are presented. Should the predictions be verified, then those who decided to fund this, despite ambivalent reviewer's comments, should feel pride in their good judgement.

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1. INTRODUCTION AND OVERVIEW

Effort under the subject grant has produced a number of major revelations about the nature of the meteoroid complex in the solar system and some of its effects. While the focus of the effort was on the reexamination of the data from the Pioneer 10 and 11 Asteroid Meteoroid Experiment or *Sisyphus* as it became known, as will be described below, that led to the examination of a number of related experiments and wide ranging conclusions that may impact current and future NASA missions. If our hypothesis and conclusions prove to be correct, then those who decided to fund this effort, in the face of ambivalent reviewer's comments, should feel pride in their judgement.

As the Sisyphus results were, in large measure, responsible for the origin of the hypothesis that a previously unrecognized population of meteoroids were measured, and since those results form the basis for what we believe about this population, this report starts by reviewing the instrument and its measurements. It is shown statistically that the Sisyphus measurements were valid and related to the zodiacal complex. This previously unrecognized population which we call *cosmoids* in near hyperbolic orbit consist largely of weakly bound volatile material. Solar heating causes them to *jet* or disrupt in the inner solar system expelling micrometer (micron) sized particles that increase the solar scattering cross section by orders of magnitude. These particles sublimate with a time constant of tens of hours.

Concurrent with the debate over the Sisyphus results, a dilemma was posed by the results of the other two *dust* experiments carried by the Pioneer 10/11 spacecraft. These did not agree and also disagreed with Sisyphus. As is shown the hypothesized cosmoid population also explains the apparent discrepancy. With the recognition that cosmoids dominate the meteoroid complex beyond 1 astronomical unit (AU) and that the three experiments were measuring mostly, if not entirely, cosmoids rather than non-volatile dust in short period orbit, it is shown that the three sets of measurements agree down to the level of some interesting details the causes of which remain to be explored.

The data from the Dust Analyzers on the Helios spacecraft are discussed and it is shown that those experiments also likely detected cosmoids in their sunward journey. Recent reports of Earth based telescopic observations are shown to be consistent with the Sisyphus data. To explain the ultraviolet photometric measurements from the Dynamics Explorer 1 satellite, cosmoids can substitute for the hypothesized "miniature comets" with a four to five order of magnitude reduction in mass of the bodies.

During this effort the opportunity arose to propose for the Cassini mission to Saturn. In the course of writing that proposal, using the association of Sisyphus with the Pioneer 10/11 Meteoroid Detection Experiment (MDE), we extrapolated the Sisyphus measurements to the Jovian and Saturnian environs. We conclude that the Galileo and Cassini orbiters will likely suffer impacts with kilojoule energy transfers during their several years of orbital life. Voyager measurements believed to be cosmoid related are also briefly discussed.

2. PIONEER 10/11 ASTEROID/METEOROID DETECTOR (SISYPHUS)

As the Sisyphus experiment led to the discovery of cosmoids, and as the results of that investigation provide much of the known information on the flux and characteristics of these meteoroids, a description of the instrument with its original results and enigmas is first presented. The Sisyphus instrument consisted of four optical telescopes with photomultiplier tubes. Each had a 7.5° field of view (FOV). The fields of view (FsOV) overlapped to allow parallax measurements. The optical axes were approximately parallel and pointed at an angle of 135° to the Earth directed spacecraft spin axis. Thus, they were crudely antisolar pointed for most of the trip to Jupiter. Designed to gather data in two modes, Sisyphus could measure individual meteoroids or asteroids as they passed through the FsOV if they reflected sufficient sunlight to be detected above the sky background and yield their orbits; further, between the individual particle measurements or "events", Sisyphus performed photometric mapping in white light of the sky to determine the radial dependence of the zodiacal light (ZL). Of the 283 events recorded in over 3 years, not one yielded an orbit (Soberman et al., 1977). Entry and exit of the FsOV, recorded with microsecond accuracy, were inconsistent with any physically possible trajectory. For 200 events, the entry time in two or more FsOV was the same or nearly so. Simultaneous entry in all four FsOV occurred in 40 cases; impossible unless the object brightens above threshold after it is in view. Testing and simulation showed that this behavior was not due to the instrument (Soberman et al., 1974). Adding to the enigma, the magnitude of the ZL computed from the individual events was more than an order of magnitude too large when compared with the values obtained from the same instrument operating in the background mode (Zook and Soberman, 1974) and those of the Imaging Photopolarimeter (Hanner et al., 1976) on the same spacecraft, although the radial dependence was similar (Soberman et al., 1976).

As the spacecraft rotated, the Sisyphus telescopes viewed an annular region that gradually moved across the celestial sphere during the course of the Earth-Jupiter trajectory. From the photometric maps accumulated during the times between events, threshold and noise levels were determined. Analysis of these maps also provided the radial dependence of the ZL (Zook and Soberman, 1974). The use of four telescopes also provided a tool for noise rejection, since overlapping readings were required for a meteoroid transiting the FsOV to be recorded. Analysis of the data collected during more than three years of observation provided 283 individual meteoroid events that passed a rigorous noise screening (Neste, 1975). An event required at least three telescope thresholds to be exceeded (most exceeded four) with a minimum overlap of 3.2 μs. In addition to entry and exit times, peak intensity in each telescope was recorded for every event. Noise sources inherent in the background such as bright stars and regions where the light level increased rapidly during a scan were rejected by recurrence at the same point in the spacecraft rotation cycle. Electronic noise in the common high voltage power supply, absent in all of the ground and flight tests until the Jovian radiation belts, would have been rejected by its coincident appearance in all four telescope channels. The operating levels of the telescopes were background limited, consequently dark current and other noise inherent in the photomultiplier tubes was negligible. Noise sensitivity tests included operating a flight instrument in the laboratory continuously for one week with cycling light levels similar to those encountered in flight; no spurious events occurred. Worst case calculations predicted a false event rate of less than one per month. Nonetheless, as stated above, of the 283 recorded, *not a single event* yielded an orbit in the original data reduction process despite months of analysis and simulation. Precise entry and exit recordings did not permit a solution to the trajectory equations, while numerous measured transits of Rigil Kentaurus and Jupiter confirmed proper instrument operation. A hypothesis of rotating glinting particles, offered to explain the multiple onsets, inability to calculate trajectories, and the ZL discrepancy, was criticized as being uncharacteristic of asteroid or meteorite material and for providing too small an increase in brightness to account for the discrepancy in the computed ZL values (Auer, 1974, 1976).

3. THE SISYPHUS EVENT MEASUREMENTS

Although the multiple telescope overlapping detection and the rigorous screening of the data was designed to eliminate even a small number of the "events" from being caused by optical or electronic noise, the criticism of the original publications (Auer, 1974, 1976) had left many skeptical of the results and others expressing uncertainty as to the relationship with the existing model of the meteoroid distribution (McDonnell, 1978). Consequently showing that Sisyphus had measured signals resulting from sunlight scattered by meteoroids was the first concern.

We plotted the cumulative number of events as a function of the heliocentric distance (Fig. 1). This plot shows a near constant event rate with an abrupt cutoff at 3.5 AU. The lower event rate for the Pioneer 11 instrument was a consequence of a malfunction in one of the photomultiplier tubes that occurred at 1.1 AU and was attributed to a crack in the envelope. More stringent noise elimination requirements were imposed on the data with a consequent reduction in the number of events accepted. Nonetheless the data mimic the behavior and add credence to the Pioneer 10 Sisyphus results. Several important points come to light as a consequence of this rather simple plot. The constant event rate with increasing solar distance was also independently reported for the Pioneer 10/11 MDE penetration detectors, albeit with continuation beyond 3.5 AU (Humes, 1980). Such a radial distribution is not in keeping with any existing meteoroid distribution model and to date no hypothesis has been offered in explanation. The transition in event rate that occurs at about 1.3 AU in Fig. 1 brings to mind that the MDE penetration detectors also behaved anomalously between 1.2 and 1.4 AU (Stanley et al., 1979).

That the Sisyphus results behave in a manner that is improbable for noise, can be readily shown from the plot in Fig. 1. After a long period during which there is a nearly constant number of events per unit radial distance from the sun, the event rate drops abruptly to zero for both instruments at 3.5 AU. Many recorded passages of Jupiter, stars and sky background data gave ample evidence that the instruments continued to function until arrival at Jupiter. At about 3.5 AU is where inbound comets begin to jet (Whipple, 1985) and this has been hypothesized to result from the energy released in the transition from amorphous to crystalline water ice that occurs at 140 K, the expected surface temperature at that solar distance (Patashnick et al., 1974). This is also the same radial distance at which the ZL dropped below the sensitivity of both Sisyphus in its background

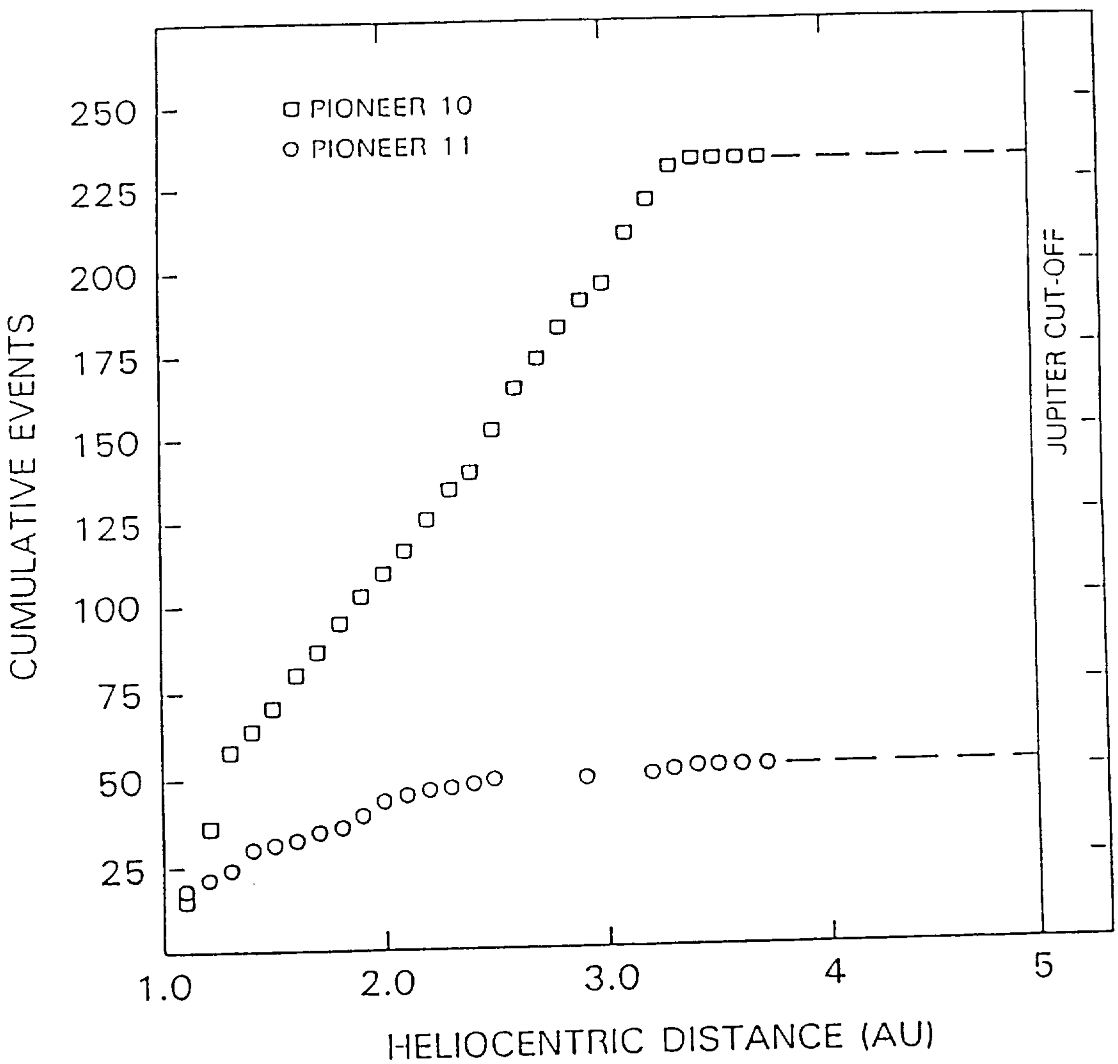

FIGURE 1. CUMULATIVE EVENTS MEASURED BY PIONEER 10 AND 11 SISYPHUS VERSUS SOLAR DISTANCE.

measurement mode (Zook and Soberman, 1974) and the Imaging Photopolarimeter in its ZL measurement mode (Hanner et al., 1974).

Assuming a Poisson distribution, we have calculated the probability of such an abrupt cessation of events resulting from random occurrences. From Fig. 1, the mean event rate for the Pioneer 10 Sisyphus instrument between 1.0 and 3.5 AU is 9.3 per 0.1 AU interval. The Poisson probability of k occurrences with a mean value of b is:

$$P(k) = \frac{b^k e^{-b}}{k!} \tag{3.1}$$

Thus the probability of no events in a 0.1 AU interval is:

$$P(0) = e^{-b} \tag{3.2}$$

which for the Pioneer 10 Sisyphus instrument equals $9.1(10)^{-5}$. The probability of no events occurring from 3.5 to 5.2 AU is:

$$P(0)_{3.5-5.2} = [9.1(10)^{-5}]^{17} = 2(10)^{-69} \tag{3.3}$$

As stated earlier, that the instrument was still functioning was demonstrated by its response to Jupiter which was growing in the annular sweep of the sky made by the FsOV of the telescopes. The star exclusion circuitry allowed the instrument to ignore the affected sectors until very close to the planet where the charged particle flux darkened the photomultiplier envelopes (as had been predicted in the instrument design) and terminated the investigation. The Pioneer 11 Sisyphus instrument degraded after passing 1.1 AU as was stated earlier. Nonetheless it confirms the performance of the Pioneer 10 instrument. From Fig. 1, the event rate from 1.1 to 3.3 AU is 1.5 per 0.1 AU. At 3.3 AU we recorded the last event that passed the stringent noise elimination criteria. From 1.1 to 3.3 AU there were six 0.1 AU intervals in which no events were measured that passed the screening tests. The Poisson probability for a single null interval $P(0) = 0.22$. It can be seen that the six null intervals are consistent with that result. The likelihood of 19 null intervals extending from 3.3 to 5.2 AU based on the earlier behavior of the instrument is $3(10)^{-13}$.

4. SISYPHUS AND THE ZODIACAL LIGHT

To establish that Sisyphus in the individual meteoroid measurement mode had indeed measured the radial variation of the ZL, and that the discrepancy in the original analysis was a consequence of trying to fit a model that assumed dust in short period orbits, we performed a simple calculation. The instrument was reduced to its simplest form; a four fold coincident photometer that measures the incident light in the FsOV in its wavelength pass band with microsecond time resolution. Viewed this way, we can readily transform the event data into brightness levels that would be measured by a conventional photometer viewing the same region of the sky.

The brightness observed by Sisyphus can be written:

$$B_S = \int \frac{L\, dV}{4\,\pi\, r^2} \tag{4.1}$$

where L is the luminosity of point sources per unit volume, r is the distance from the source to the instrument, and dV is the volume element, which can be written:

$$dV = \Omega_S\, r^2\, dr \tag{4.2}$$

where Ω_S is the solid angle subtended by the FOV equal to 0.135 steradians. Substituting into Eq. (4.2) we obtain:

$$B_S = \frac{L\,\Omega_S}{4\,\pi} \int_{r_{min}}^{r_{max}} dr \tag{4.3}$$

Since the minimum range of the instrument is very much less than the maximum, we can neglect it and write:

$$B_S = \frac{L\,\Omega_S\, r_{max}}{4\,\pi} \tag{4.4}$$

If we perform the same calculation for a conventional photometer looking at the same region of the sky, we obtain:

$$B_O = \frac{L\,\Omega_O\,(D_{max} - D_{min})}{4\,\pi} \tag{4.5}$$

where D designates range for the conventional photometer. Taking the ratio of the two brightness values, we obtain:

$$B_O = \frac{\Omega_O}{\Omega_S}\,\frac{(D_{max} - D_{min})}{r_{max}} \tag{4.6}$$

ZL levels are generally presented in units of $S_{10}(V)$, which are equivalent tenth visual magnitude stars per square degree. Thus we can take the FOV, Ω_O of the conventional photometer as one square degree while the FOV of Sisyphus Ω_S in these units is 44.2 square degrees. Detailed photometric analysis showed that the Sisyphus instrument threshold for individual events could be represented as a zero magnitude source in the FOV (Neste, 1975). The threshold adjusted to the background brightness with a 47 ms time constant, so the sensitivity or threshold is for light above background level. The threshold for an event is thus 10,000 equivalent tenth magnitude stars (i.e. the luminosity of a zero magnitude source compared to a tenth magnitude source). The brightness level must then be averaged for the fraction of the time that events were being measured. This indicates that the Gegenschein brightness (i.e. the ZL in the antisolar direction) in $S_{10}(V)$ units should be:

$$B_O = 226\,\frac{(D_{max} - D_{min})}{r_{max}}\,\frac{\tau}{T} \tag{4.7}$$

where τ is the time events were being measured, and T is the total time the instrument was observing. Equation (4.7) leaves us with a parameter that we must specify, the maximum range at which the instrument observed events. While the reanalysis of the Sisyphus results has, as a major objective, the calculation of orbits from the data, and that calculation includes the determination of the range, it is unlikely to determine the maximum range because the baseline of the instrument ($\approx 25\ cm$) was too small for triangulation at large distances (>100 m) from the instrument. Thus (r_{max}) remains an assumption, subject to a constraint discussed below. By choosing the proper value, we can obtain any single Gegenschein value we wish. However, since (r_{max}) must remain constant, it can be looked upon as a boundary condition that allows us to normalize the heliocentric radial distribution, not change its form. The values of ($D_{max} - D_{min}$) are the distances traversed by the conventional photometer in the same units as (r_{max}), that is, the radial distance covered by the Pioneer 10/11 spacecraft.

We have performed the integration for the Pioneer 10 and 11 Sisyphus data. For the Pioneer 10 instrument we used a maximum instrument range of 10 km, which yields a Gegenschein brightness of 105 $S_{10}(V)$ at 1 AU. The longest event measured by the instrument on that mission lasted approximately 38 ms. At a relative encounter velocity of 30 km/s, a body would travel about 1.1 km during that time. At a range of 10 km the diameter of the FOV is 1.3 km, so the assumed maximum range is consistent with the data. In the case of the Pioneer 11 instrument, as we stated earlier, one of the four telescopes degraded as a consequence of what was diagnosed as a thermally induced crack in the envelope of its photomultiplier that damaged the photocathode. This occurred at about 1.1 AU. Additional criteria were introduced to insure noise rejection, resulting in a lower event rate when compared to the Pioneer 10 instrument data, but consistent with those data. For the interval from 1.0 to 1.1 AU, where the instrument appeared to function normally, we used a maximum range of 16.5 km, since one event lasted 63 ms. A maximum range of 2.5 km was used for the integration between 1.1 and 3.5 AU; the longest lasting event measured approximately 9.7 ms during that portion of the mission. The results of these integrations are shown in Figure 2. Also shown, for comparison, in this figure are the results of the Imaging Photopolarimeter (IPP) which was also on the Pioneer 10 and 11 spacecraft (Hanner et al., 1976). As mentioned above, the Sisyphus instrument also measured the ZL when not recording events. From that data a value of 90 $S_{10}(V)$ was obtained for the Gegenschein observed at 1 AU, and a decrease with heliocentric distance consistent with an inverse square relationship was reported (Zook and Soberman, 1974). Of note in Fig. 2 is the rapid (compared to an inverse second or third power) decrease beyond 2.5 AU and that the ZL was not measurable beyond 3.5 AU; as noted by the IPP investigators (Hanner et al., 1974).

It is noteworthy that in both of the foregoing analyses, event probability and ZL radial dependence, we have avoided any interpretation of the events; specifically no reference was made to cosmoids. What is established is that Sisyphus recorded external events that are strongly correlated with the ZL. The cosmoid hypothesis explains not only the Sisyphus data, but also why the three Pioneer 10/11 meteoroid experiments appeared to disagree and allows us to uncover much about this meteoroid population that is still in those results. An example of this occurred during the writing of this final report. As discussed in subsequent sections, the Gegenschein near a planet is different from values at the same solar distance

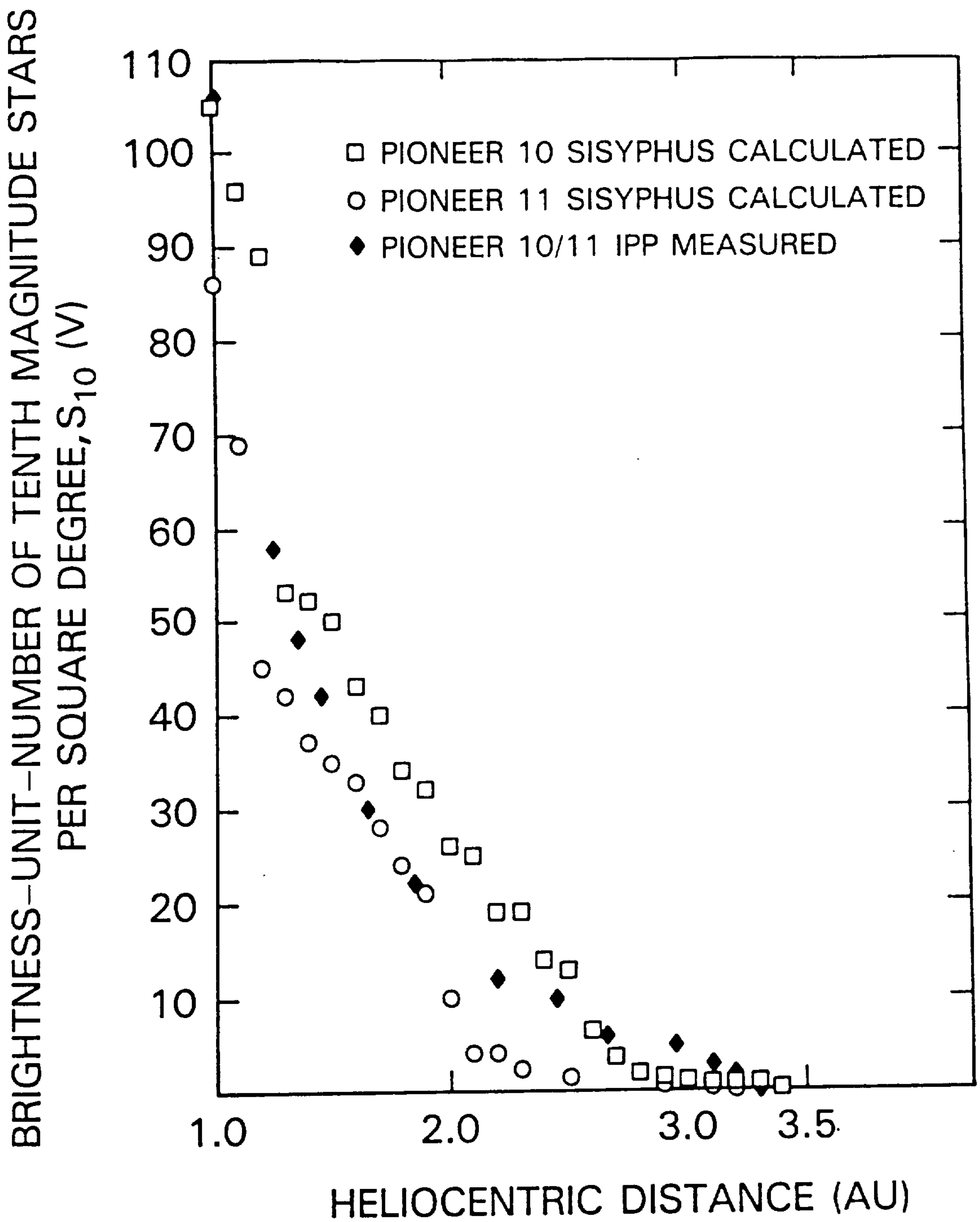

FIGURE 2. THE ZODIACAL LIGHT - GEGENSCHEIN VERSUS SOLAR DISTANCE AS CALCULATED FROM PIONEER 10 AND 11 EVENTS AND AS DETERMINED BY THE IMAGING PHOTOPOLARIMETER (IPP).

in interplanetary space. In calculating the Pioneer 10 and 11 Sisyphus Gegenschein values, emphasis was placed on the 1 AU measurements because the maximum event range must be specified and the longest duration events occurred near the Earth. This is a region where the ZL values change rapidly with flight time and look angle. Given the cosmoid explanation, Gegenschein values measured by the Pioneer 10/11 instruments (Sisyphus and IPP) near the Earth should not be fitted to the interplanetary space distribution. Examination of Fig. 2 shows that the ZL solar distance variation calculated from the two Sisyphus instruments and the IPP measurements would agree even better if the near Earth (<1.2 AU) values were excluded. Further, if these values (when the spacecraft were in the geotail) are excluded, the ZL data of all the Pioneer 10/11 instruments appear to best fit an inverse square distribution.

5. SISYPHUS DIFFERENTIAL ENTRY AND EXIT TIMES

To show graphically the anomalous differential entry times, referred to earlier, that thwarted the early orbit calculations and lead to the conclusion that cosmoid jetting occurs in a time scale of microseconds, we plotted the graphs shown in Figure 3. The top histogram is the time in microseconds between the first two telescopes to reach detection threshold. Note that for 200 of the 283 events, the thresholds of the first two telescopes were exceeded within 4.8 μs. In the instrument mode where most of the data were recorded, the timing counter had a spacing of 1.6 μs per data bit. Thus, these events started in two or less timing bits. The average separation distance, as stated above, was about 25 cm, thus the speed of baseline crossing is unrealistic even for the two bit events. In 40 of the 200 cases, the near simultaneous entry occurred in all four telescopes, which is geometrically impossible; unless the particle brightens above threshold after it is already in the FsOV. This explosive brightening, which we conclude to result from impulsive dispersion or jetting, appears to be characteristic of the Sisyphus events. In contrast, most of the events appear to exit the FsOV in a manner what was anticipated for sunlight reflected from a solid meteoroid. The lower histogram of Fig. 3 shows the differential exit times for the same two telescopes that recorded the first entries. This is the type of distribution that was expected for entries and exits. For example, the small peak at about 200 μs would represent a transverse speed of $\approx 1\ km/s$. From the lower histogram it appears that a few events terminated while the meteoroid was still in the FsOV. With this understanding of the behavior, we are attempting to compute the orbits for at least a portion of the measured events.

6. COSMOIDS

A hypothesis formulated by one of us (Dubin, 1986) explains the Sisyphus measurements as the jetting of gas and volatile fine grains from long period meteoroids or "cosmoids". Like comet nuclei, they have very low albedo (Greenberg, 1986) and are detected only after they jet, forming a cloud of particles that cause a large increase in the scattered sunlight. Jetting is characteristically observed in comets (Sekanina and Larson, 1986) and scales for the smaller cosmoids, usually completely dispersing them. The rapid onset of the

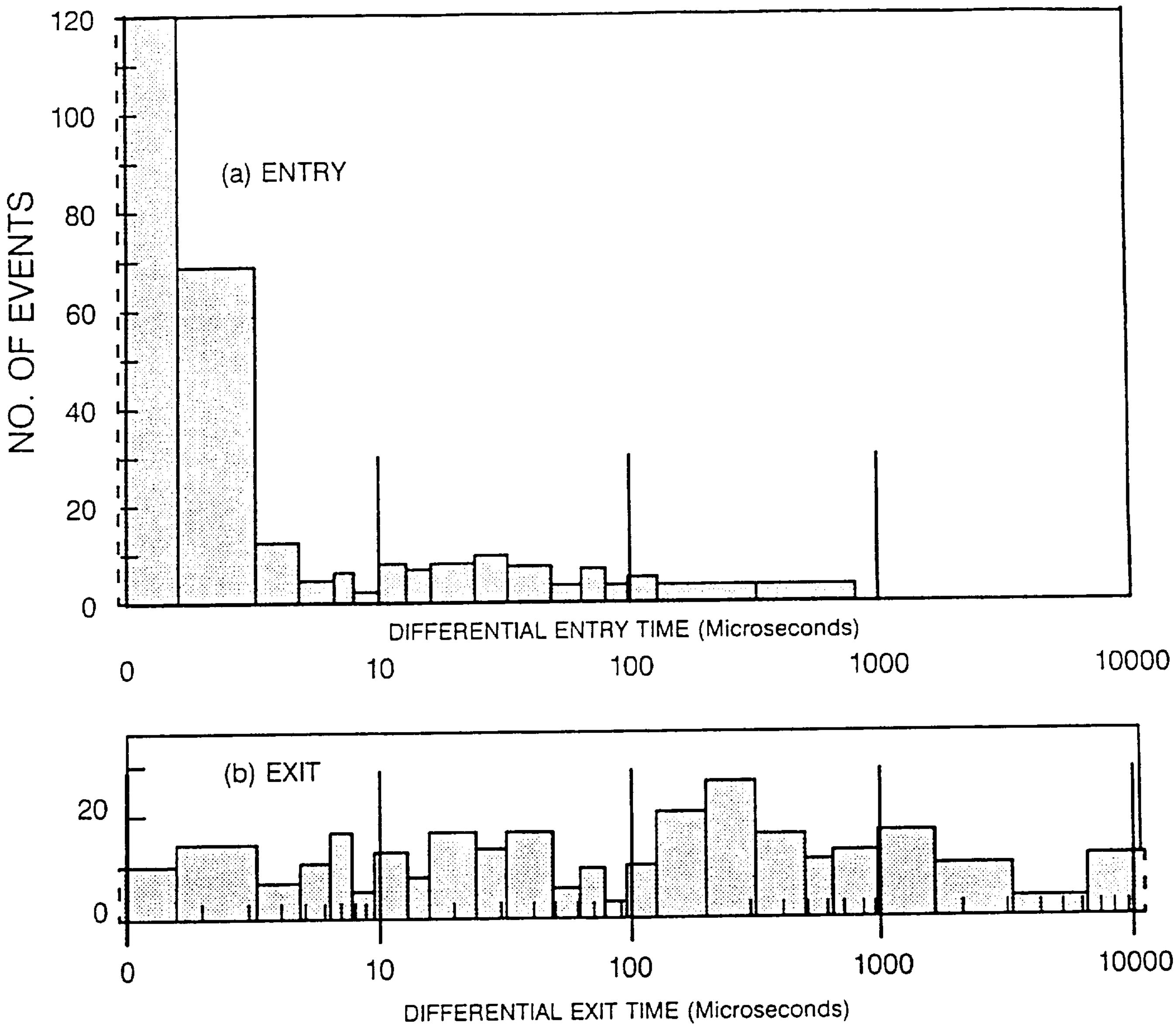

FIGURE 3. ELAPSED TIME BETWEEN THE FIRST TWO SISYPHUS TELESCOPES TO RECORD THE ENTRY OF AN EVENT (UPPER HISTOGRAM) AND THE ELAPSED TIME RECORDED BY THE SAME TWO TELESCOPES SHOWING EXIT OF THE FIELDS OF VIEW (LOWER HISTOGRAM).

jet explains the Sisyphus coincident FsOV entry while the order of magnitude increase in the scattering cross section resulted in an anomalous brightness when derived by classical analysis of the data. The polarization of the ZL can result from scattering sunlight off submicrometer grains, from the "fluffy" structure of larger (> 10 μm) jetted particles as suggested by Giese (1977), or a combination of the two.

Because of the small mass of the cosmoids, they rarely survive perihelion passage. The combination of cosmoid influx and solar heated jetting shows why the radial dependence of the zodiacal light (Weinberg and Sparrow, 1978) does not follow either the large (Soberman et al., 1977) or small particle (Humes, 1980) heliocentric variation. The predominantly micron and submicron sized grains that are expelled in the jetting action are volatile, decreasing in size and consequently, in the amount of sunlight scattered with a time scale of tens of hours. Sisyphus exit times occurred when the cloud left the FsOV and occasionally from dispersion while still in the FsOV.

7. THE PIONEER 10/11 METEOROID ENIGMA

Launched in 1972 and 1973 to flyby Jupiter and ultimately escape the solar system, Pioneer 10 and 11 were the first spacecraft to traverse the asteroid belt. In 1979, Pioneer 11 also encountered Saturn before beginning a solar escape orbit. They carried three *dust* experiments. The use of the dust designation reveals the still prevalent model of non-volatile particles slowly spiraling toward the sun from the asteroid belt under the influence of the Poynting-Robertson effect. Table 1 shows a comparison of the three experiments made in a paper that compared the early results (Soberman et al., 1976). The comparison of the three experimental results resulted in strangely inconsistent information about the distribution of interplanetary matter.

The Meteoroid Detection Experiment (MDE) consisted of thin walled pressure cells that recorded punctures, the puncture rate variation with distance from the sun was a measure of the population distribution of micron sized particles. Each cell detected only the first penetration that caused depressurization. The exposed wall thickness was 25 μm on Pioneer 10 and 50 μm on Pioneer 11 (Humes et al., 1974, 1975). The Imaging Photopolarimeter (IPP) measured the polarization and brightness in two colors of the zodiacal light which is the sunlight scattered from the integrated meteoroid complex (Hanner et al., 1974), hence the optical scattering cross section of interplanetary particles was mapped with distance from the sun. The Asteroid/Meteoroid Detector (AMD) or Sisyphus, was described earlier.

No two of the three experiments agreed about the spatial variation of the dust with solar distance (Soberman et al., 1976). The IPP results showed that the ZL decreased with increasing solar distance at a rate between an inverse square and an inverse cube, implying that the concentration of the dust decreased between an inverse first and second power. This was the only radial dependence result that fit the prevailing model; although it showed an unexpected precipitous decrease with increasing solar distance in the asteroid belt and a signal that became too faint to be measured beyond 3.5 AU (Hanner et al., 1976). The MDE results showed the spatial concentration to be nearly constant with increasing solar radial distance and that has been extended to 18 AU (Humes, 1980). The

TABLE 1. COMPARISON OF PIONEER 10/11 DUST EXPERIMENTS

Experiment	Measurement	Particle Diameter Range	Assumptions	Results
MDE Penetration Detectors	Penetration Rate of Stainless Steel 25 μm 50 μm	 $\sim$ 10 μm $\sim$ 20 μm	Distribution of Orbital Parameters for Relative Velocity	Spatial concentration
IPP Zodiacal Light Mode	Polarization & Brightness in 2 Colors	Micron and/or Sub-micron ?	Mie Theory - Constant Size Distribution	Spatial distribution Size Shape Refractive index
AMD Zodiacal Light Mode	Brightness	Micron and/or Sub-micron ?	Mie Theory - Constant Size Distribution	Spatial distribution
AMD Individual Particle Mode	Peak Intensity Transit Time	50 μm and Larger	Circular Orbit Encounter Vel. - Average Transit Thru View Cone - Diffuse Geometrical Reflection From Spherical Particles	Size distribution Spatial concentration Zodiacal light brightness

Sisyphus individual particle results showed small variations with solar distance to 3.5 AU where they stopped. As discussed in the earlier sections not one of the individual meteoroid events yielded an orbit, while the ZL as calculated from the events was more than 10 times too large compared with the values determined from the other mode of the instrument and those of the IPP.

The disparity of these results and the inability to explain the Sisyphus data with the short period dust model lead to the Sisyphus experiment being discredited (Auer, 1974, 1976), confusion over the spatial distribution of the meteoroid population (McDonnell, 1978) and undoubtedly contributed to the meteoroid experiment not being confirmed on the Voyager missions. Recently it was recognized that Sisyphus had detected that population of near hyperbolic meteoroids which we call cosmoids (Dubin, 1986). Their fragile makeup causes them to break up as a result of charging in the Earth's shadow. Consequently they are not seen as meteors in the atmosphere. They have a very low albedo (2-4%) and can be detected only by instruments with a fast (milliseconds to seconds) response time during jetting of microparticles that increase their solar scatter by orders of magnitude. In interplanetary space this jetting is initiated by solar heating. That cosmoids dominate the meteoroid complex follows from the 283 events measured by Sisyphus during more than three years of interplanetary cruise, not one of which gave a signature that yielded an orbit when calculated in the expected manner. Recognizing that all three meteoroid experiments on the Pioneer 10/11 spacecraft were measuring cosmoid manifestations, it can now be shown that they agree, not only on the large scale solar distance variation, but at the level of some interesting details. The following sections will show that a number of the cosmoid parameters were measured on those early missions.

8. RELATION BETWEEN THE MDE AND SISYPHUS RESULTS

That the MDE and Sisyphus were measuring the same population was recognized early as seen in Figures 4 and 5 (Soberman et al., 1974) that show the Sisyphus computed size distribution extrapolated to the MDE results. The change from what was originally believed to be a solid body to an assemblage of wavelength sized grains scattering sunlight does not affect the agreement. The abscissa should now be understood as an optical scatter dimension. The MDE was likely measuring single or clustered grains in a size region where the physical and scattering dimensions are not too disparate. In Figures 6 and 7 are the results of the Pioneer 10 and 11 MDE experiment (Humes, 1980). Note the high event rate measured when first leaving the Earth. There was also a reported paucity of events between 1.2 and 1.4 AU (Stanley, et al., 1979). The Sisyphus event record (Neste, 1975) shown in Figure 8 also shows an initially high event rate and fewer events starting about 1.25 AU. This agreement of the two instruments between 1 and 3.5 AU gives us confidence that the size distribution of cosmoids can be projected from the MDE results beyond 3.5 AU (where solar induced jetting ceases) to the vicinity of Jupiter and Saturn where jetting is expected in the planetary shadows and magnetospheres. The Sisyphus instruments were not protected from the Jovian radiation but the MDE continued to give data to 18 AU. Pioneer 11 which encountered Saturn had a periapsis inside of 1.5 planetary radii (R_S). The MDE results, which showed a nearly constant particle flux from 1 to 18 AU, indicated an increase of 10^3 inside of 3.1 R_S (Humes, 1980). A similar but less pronounced increase was measured in the Jovian vicinity (Humes, 1976). While Humes (1980) ascribes the increases to ring particles, we attribute most of it to the combined gravitational attraction and jetting induced by the umbra/magnetosphere which cause all the cosmoids to disrupt close to the planet. From an analysis of the MDE data during a spacecraft maneuver performed between 4 and 5 AU, Humes (1980) concludes that the penetrations measured during that time had to have been produced by particles in nearly hyperbolic orbits. Thus, small particles penetrating the MDE's pressurized vessels were moving in highly eccentric orbits. Moreover, the penetration flux was nearly constant from 1 to 18 AU. Small particles separated from cosmoids, composed mainly of volatile materials whose lifetime, because of sublimation, is directly proportional to the square of the solar distance, would explain why the flux remains constant in the face of the gravitational concentration.

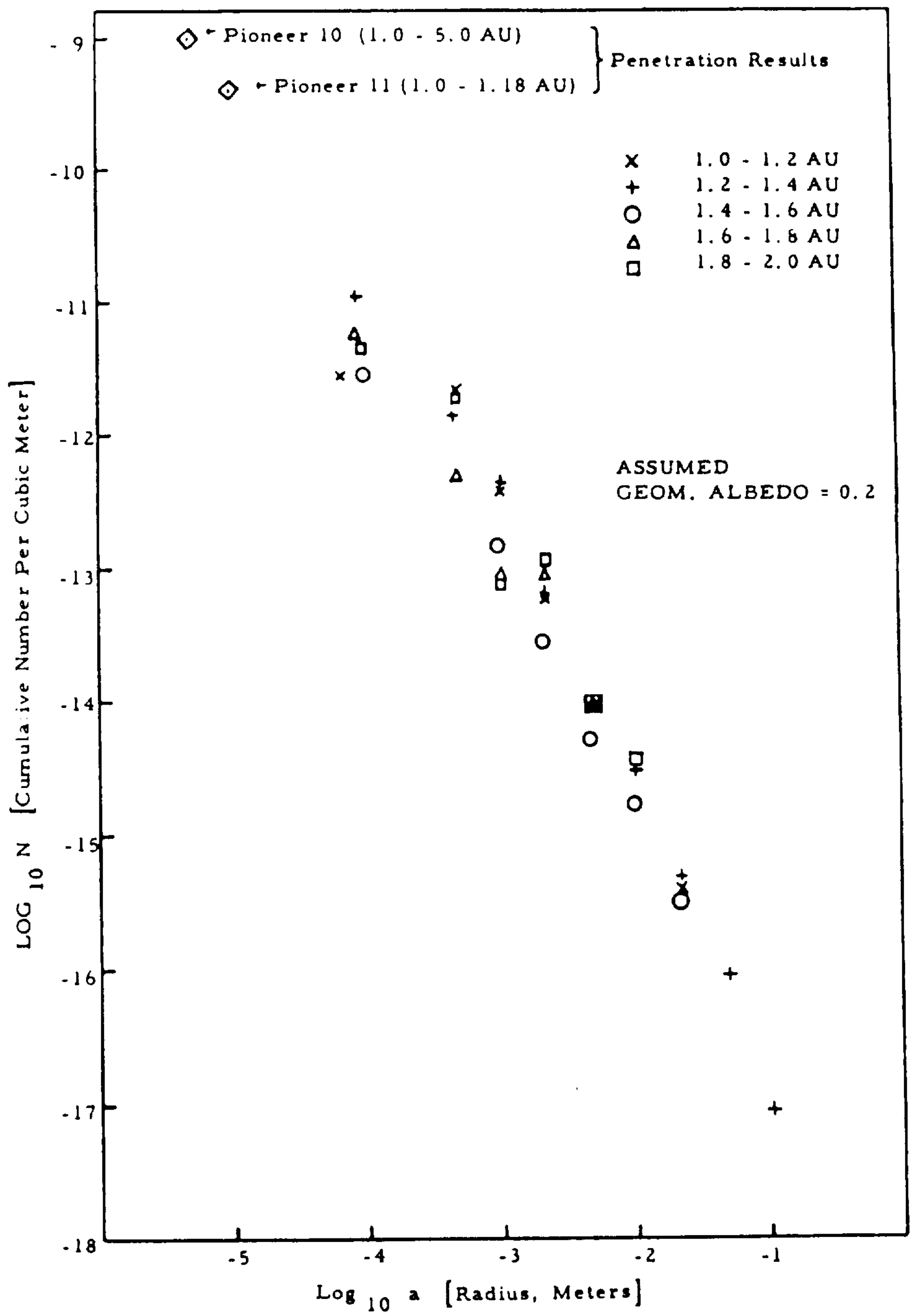

FIGURE 4. ORIGINAL PUBLISHED INTERPLANETARY METEOROID SIZE DISTRIBUTION CALCULATED FROM THE SISYPHUS DATA WITH THE PIONEER 10 AND 11 METEOROID DETECTION EXPERIMENT (MDE) PENETRATION RESULTS BETWEEN 1 AND 2 AU (Soberman et al., 1974).

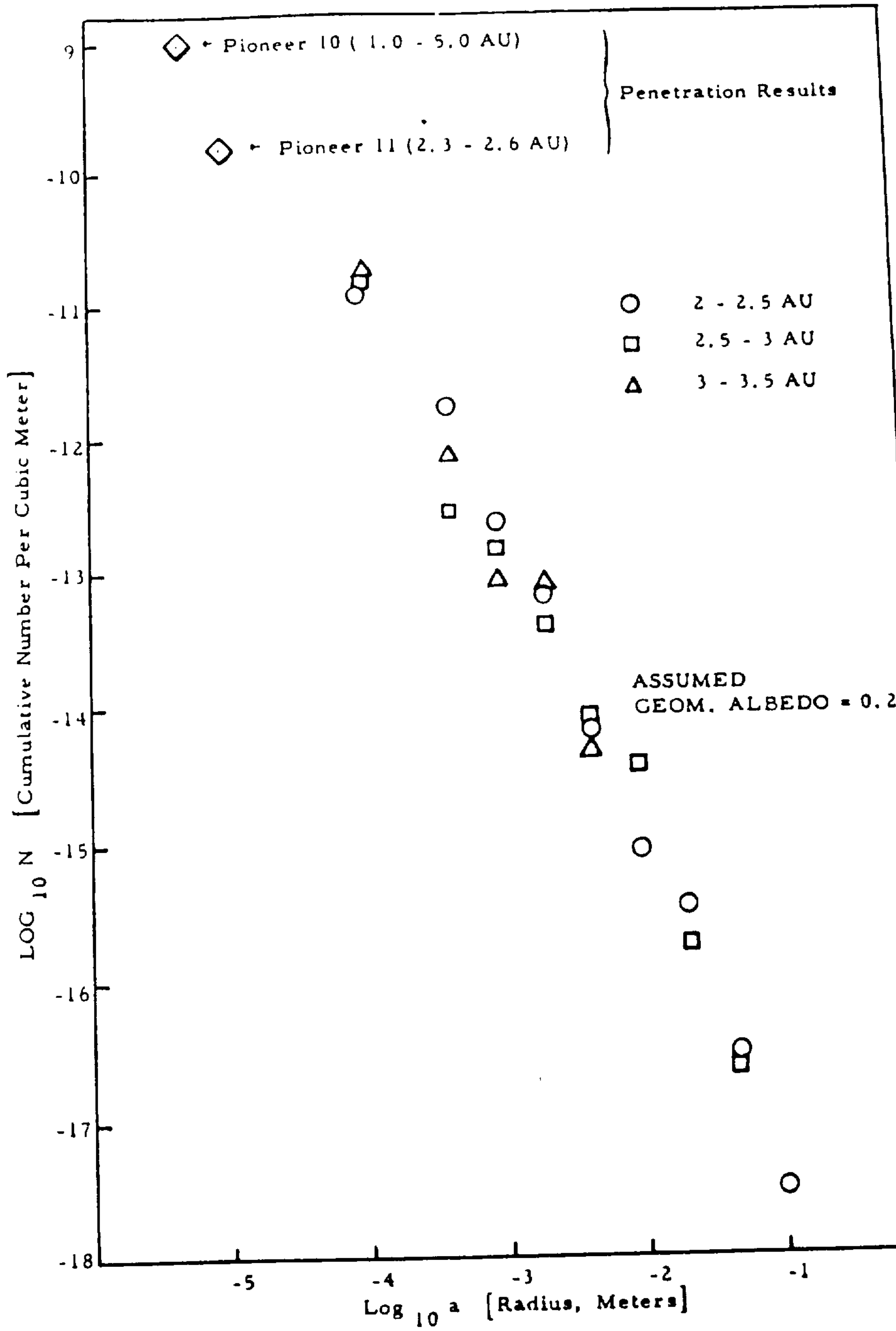

FIGURE 5. ORIGINAL PUBLISHED INTERPLANETARY METEOROID SIZE DISTRIBUTION CALCULATED FROM THE SISYPHUS DATA WITH THE PIONEER 10 AND 11 METEOROID DETECTION EXPERIMENT (MDE) PENETRATION RESULTS BETWEEN 2 AND 3.5 AU (Soberman et al., 1974).

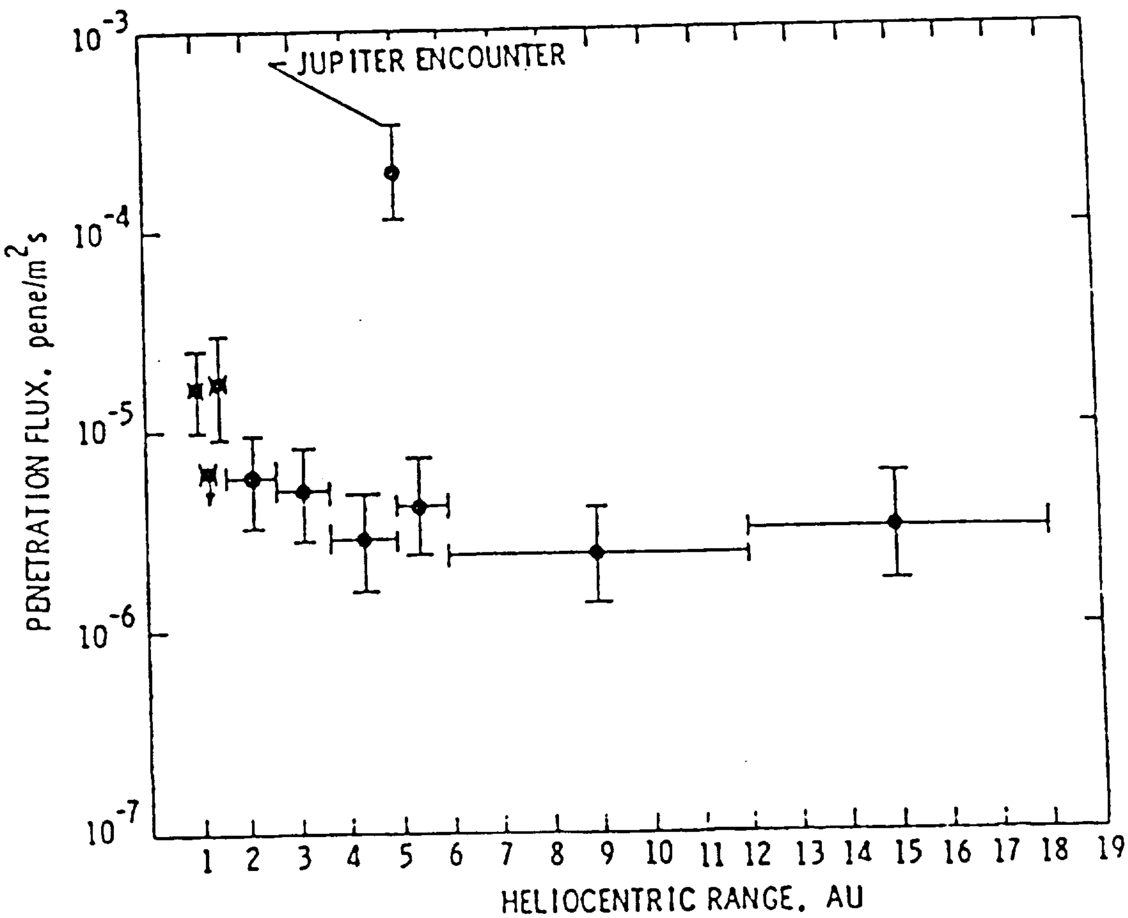

FIGURE 6. PENETRATION FLUX MEASURED BY THE METEOROID DETECTION EXPERIMENT (MDE) FOR 25μm STAINLESS STEEL ON PIONEER 10 (Humes, 1980).

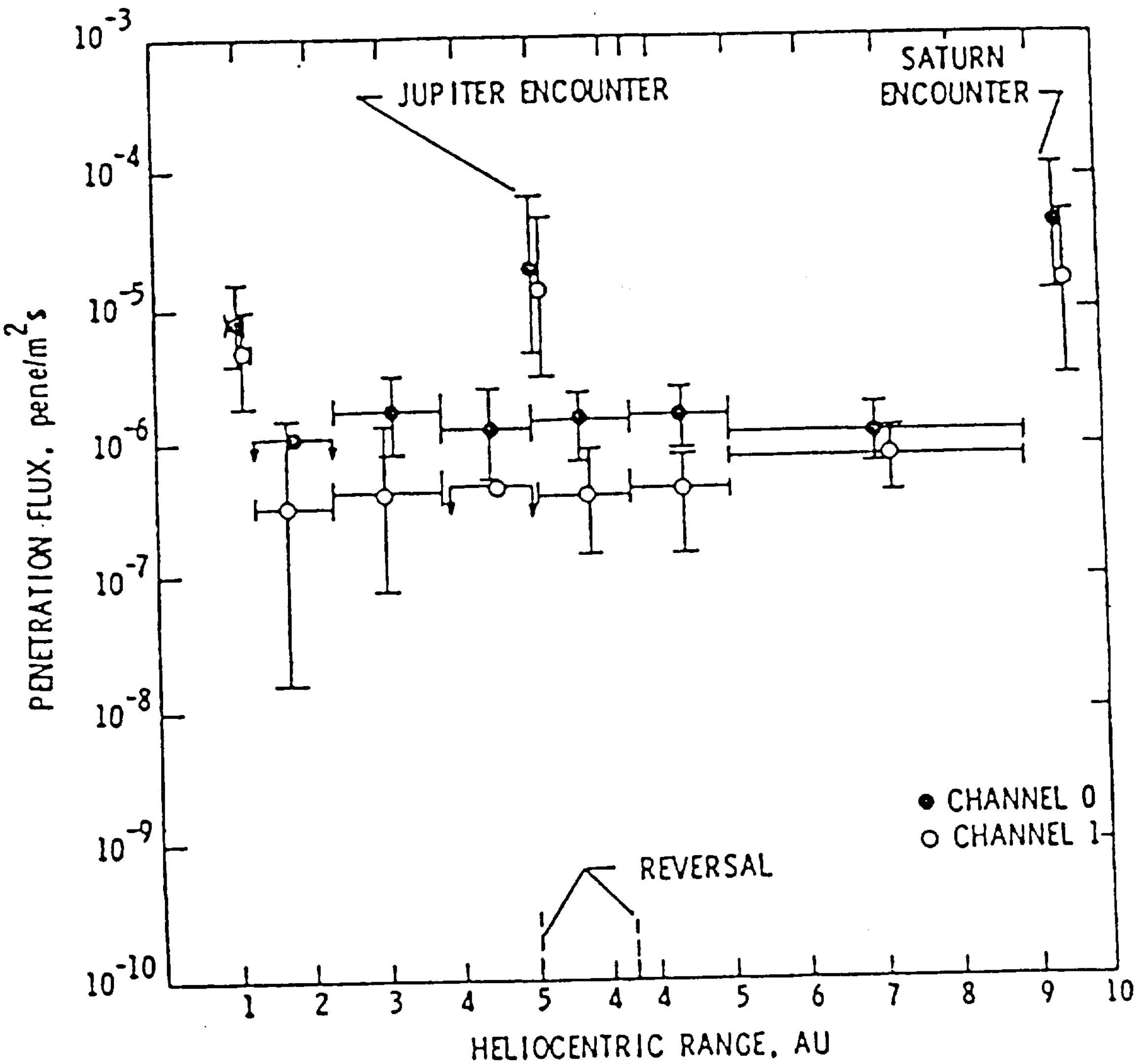

FIGURE 7. PENETRATION FLUX MEASURED BY THE METEOROID DETECTION EXPERIMENT (MDE) FOR 50μm STAINLESS STEEL ON PIONEER 11 (Humes, 1980).

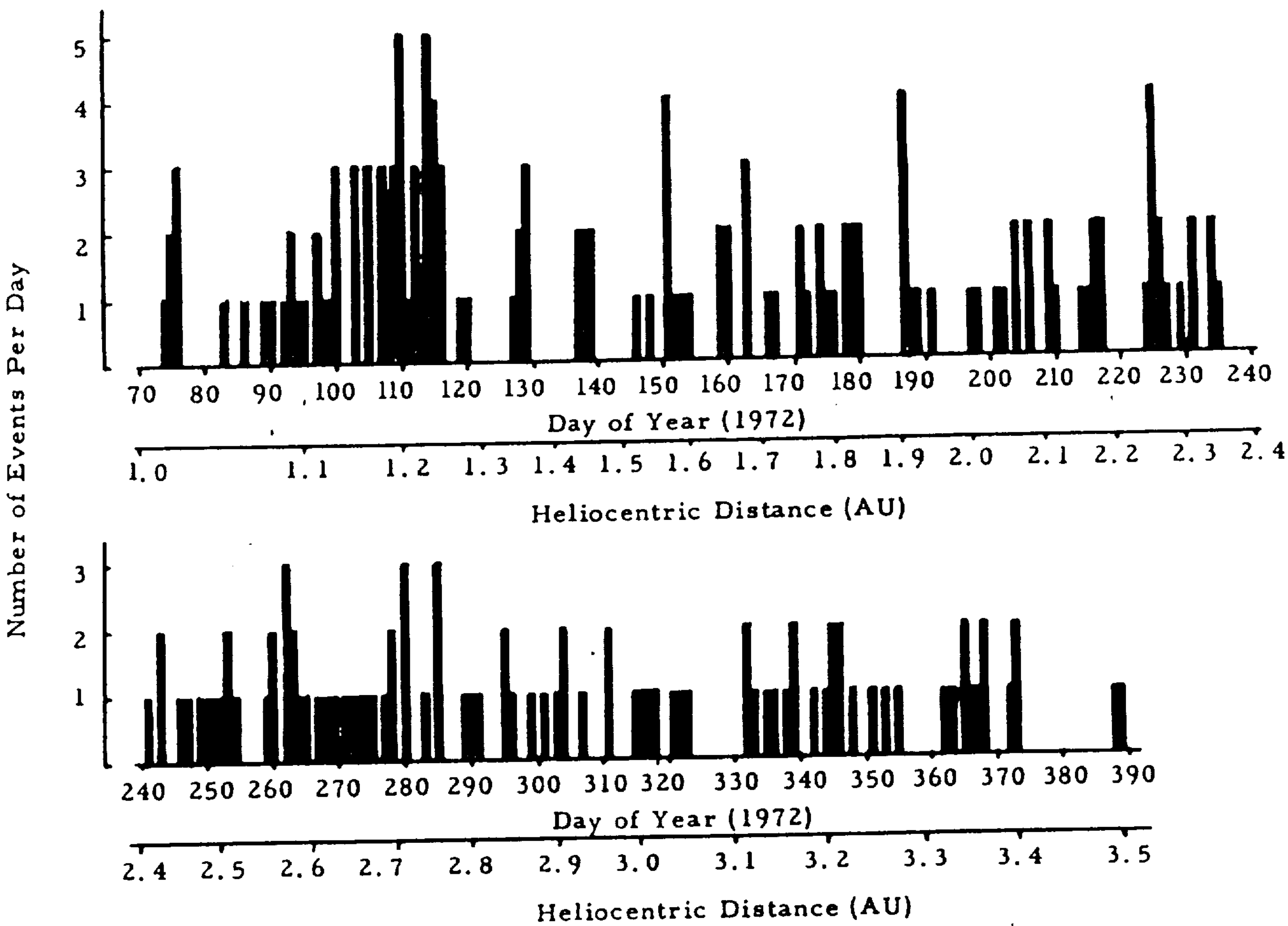

FIGURE 8. EVENT RECORD OF THE PIONEER 10 SISYPHUS INSTRUMENT (Neste, 1975).

9. CONFIRMATION BY HELIOS MICROMETEOROID EXPERIMENTS

The Helios 1 and Helios 2 spacecraft were launched in 1974 and 1976 to orbit the inner solar system with perihelia of approximately 0.3 AU. Each carried two micrometeoroid detectors (Grün et al., 1980) and a ZL polarimeter (Leinert et al., 1977). The micrometeoroid detectors measured the electric charge produced upon impact and the composition of the larger particles by time of flight mass spectrometry. The acceptance angle of the instruments was about 90°; with one on each spacecraft nearly centered on the ecliptic and the other observing higher solar latitudes (south on Helios 1 and north on Helios 2). The spacecraft rotated about an axis perpendicular to the ecliptic plane so that all trajectory angles were examined. A thin film covered the opening of the ecliptic oriented instrument to protect it from direct solar radiation and since penetration of this film was required for measurement, additional information about the physical nature of the impacting particles was obtained by comparing the statistics of the two instruments with overlapping fields of view.

The Helios micrometeoroid detectors measured three populations of particles. One was the submicron β-meteoroids leaving the solar system in hyperbolic orbits (Berg and Grün, 1973). Another, called "apex" particles because they were measured when the ecliptic instrument pointed toward the spacecraft's motion vector (Grün et al., 1980), had the low inclination and small eccentricity expected for dust spiraling into the sun. The third unpredicted population, designated "eccentric" was described as having eccentricities greater than 0.4 and semimajor axes greater than 0.5 AU. Even hyperbolic inbound orbits were not excluded (Grün et al., 1980). They were measured by the higher latitude facing instrument. The Helios investigators determined that since the "eccentric" particles were not detected by the ecliptic instrument although their trajectories should have permitted measurement, they must have been stopped by the thin film that protected that instrument from direct solar radiation. As a consequence, Grün et al. (1980) concluded that this population was "fluffy" and approximately 30% had a bulk density $< 1\ g/cm^3$. This low density, fluffy, eccentric population is consistent with the Pioneer 10/11 measurements and lends confirmatory evidence to the cosmoid hypothesis.

Reporting on the Helios ZL results, Link et al., (1976) stated that the spatial concentration of particles increased as the solar distance decreased; following an inverse 1.3 power. This as a result of assuming a model of the dust slowly spiraling to the sun under the influence of the Poynting-Robertson effect. In that model, the spatial concentration of the dust changes one power less with solar distance than the ZL. From a cursory examination of the published data, it appears that, as with the Pioneer 10/11 ZL results, if the near Earth ($\approx 1\ AU$) measurements are excluded, the remaining points follow a near inverse square variation. This would indicate a near constant spatial concentration as the solar distance decreases to 0.3 AU, and that cosmoids might still dominate the meteoroid complex to that distance. As cited earlier, Giese (1977) modeling the brightness and polarization of the ZL recognized that an important component of the interplanetary dust cloud must be absorbing particles of fluffy structure.

10. EARTH BASED TELESCOPIC OBSERVATIONS

Yeates (1989) reported that 18th visual magnitude tracks of small comets at a distance of $1.4(10)^5$ km had been recorded using a one meter aperture telescope equipped with a charge coupled detector (CCD) camera. Because of the similarity between this and the Sisyphus technique, we believe that the telescope tracks parallel the events measured during the Pioneer 10/11 missions, and were caused by jetting from cosmoids. At the reported range, a flat Lambert law solar reflector with unit reflectivity and an area of 0.4 m^2 could produce the recorded tracks. The given reflector properties serve only for normalization; removing albedo and phase function assumptions. An optical signature of this size is about 16 times larger than required for the largest event measured by Sisyphus, which, as stated above, had a mean threshold of zero visual magnitude (Neste, 1975). There was insufficient observing time compounded by increasing solar distance to expect an event comparable to those measured by Yeates in the Sisyphus data which provided the distribution shown in Figure 7. As can be seen, the Yeates' reported tracks are consistent with the Sisyphus measurements. To calculate the spatial density of the tracks we used the reported volume of $8(10)^{18}$ m^3 for the telescope FOV out to the maximum range Yeates believed detection possible and assumed a ratio of event duration to frame exposure time of 0.3 with one event per 7.5 frames. Note that the figure and the agreement is independent of the jetting cosmoid hypothesis. Cosmoid jets, however, allow us to explain the tracks with less than one kilogram of grains with a mean size of 200 nm and unit specific gravity, which give more than the necessary solar backscatter area. Yeates (1989) ascribes the tracks to Frank et al.'s (1986b) hypothesized 10 m, 10^5 kg small comet nuclei with 2% albedo and no detectable comae.

Recently Frank et al. (1990) reported that, in a series of 48 dual sky exposures using the same one meter aperture telescope with CCD camera utilized by Yeates (1989), they were able to obtain six tracks that continued in the second exposure 36 s after the first. Each of the exposures were of 12 s duration. The theme of the paper is that the tracks are not instrumental artifacts, but the recorded images of dark 4 - 6 m radius miniature comets although the possibility of 10^5 objects in high Earth orbit is considered. Higher reflectivity objects 10 cm in radius are also stated to be consistent with the data. We do not question the measurements, but fault the interpretation with regard to the mass, albedo, and orbit of the objects responsible for the tracks. Frank et al. (1990) were not aware that, with dispersing bodies, those responsible for the dual tracks had to be significantly larger than those reported by Yeates (1989). For the optical phenomena to have lasted about 50 s the bodies had to be about an order of magnitude more massive then those originally reported. No mention is made of the tracks that met all of the reality criteria but did not continue in the second exposure. We conclude that there must be well over 100 such. Allowing for brightness variation at instrument threshold, star trail crossing and other losses, how do they explain such a low percentage of persistent tracks for presumed solid objects? The value of $3(\pm1)(10)^{-20}$ m^{-3} they present for the number density has to be modified for the temporal nature of the phenomena.

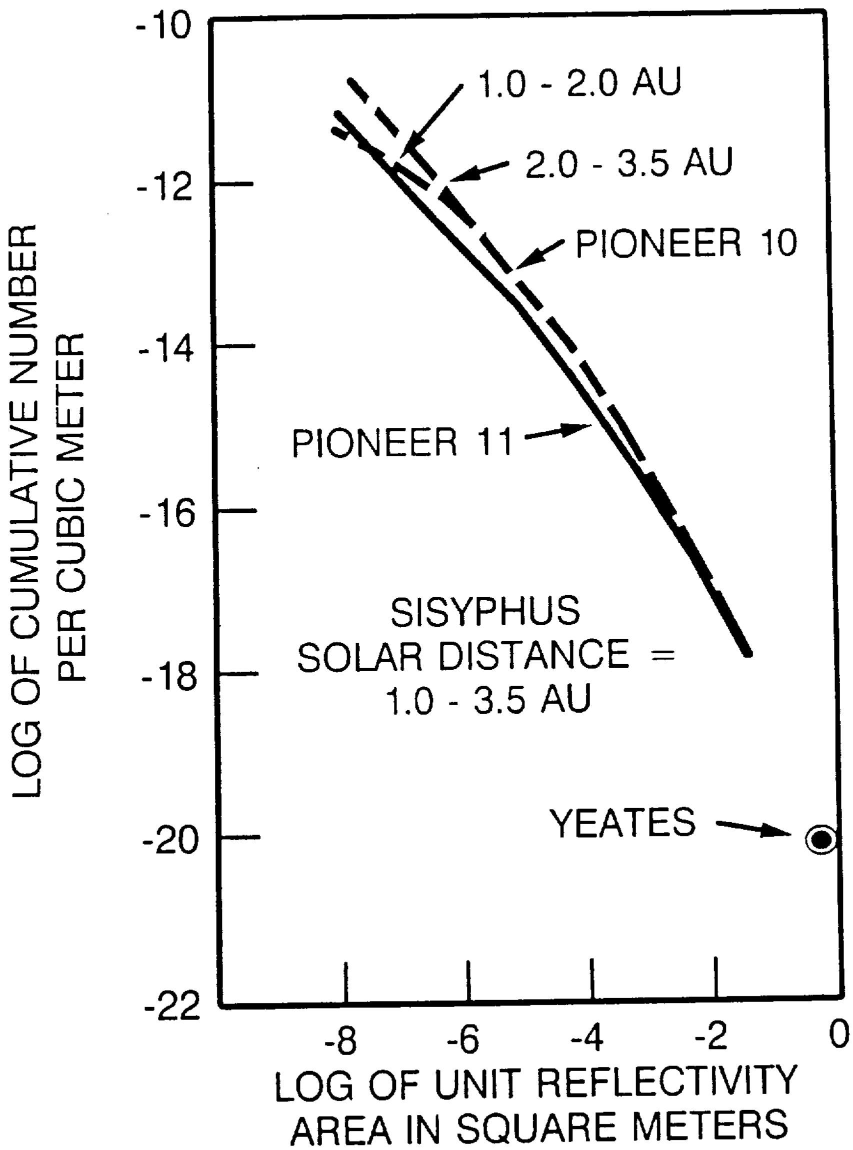

FIGURE 9. COMPARISON OF THE SISYPHUS RESULTS WITH RECENT TELESCOPIC MEASUREMENTS (Yeates, 1989). THE ORDINATE SHOWS THE NUMBER OF OPTICAL EVENTS PER UNIT VOLUME (IMPLICIT IS THE RATIO OF EVENT DURATION TO MEAN TIME BETWEEN EVENTS). THE ABSCISSA HAS BEEN RESTATED FOR SISYPHUS TO ELIMINATE ALL PHASE FUNCTION AND ALBEDO ASSUMPTIONS.

11. BACKLIT SIGNALS FROM DYNAMICS EXPLORER 1

A controversial and well publicized debate followed closely the publication (Frank et al., 1986a,b) of the interpretation of the dark spots in the images of the sunlit Earth obtained from the ultraviolet photometer on the Dynamics Explorer 1 (DE 1) at the wavelength band for resonant scattered atomic oxygen at the 130.4 nm triplet. The dark spots, almost always observed as significant depressions of single pixels of FOV 0.29°, pass a variety of noise tests and had an occurrence rate that was high in the morning and peaked at 14 hours at low latitudes. The statistical distribution of pixel counts showed significant deviations from Poisson and similar deviations for bright contiguous pixels defined as a half annulus; both occurrence frequencies were about a factor of 2 greater at higher spacecraft altitudes (Frank et al., 1987). Similar but weaker spots were found at adjacent wavelengths incorporating the Lyman - Birge - Hopfield bands of molecular nitrogen and absorption in the limb at hydrogen Lyman alpha. Dark pixels were very occasionally found in a second frame 72 s later. These spots in the expected uniformly bright Earth at 130.4 nm may result from extinction between the spacecraft and the Earth, produced by the comae formed from the dispersion of cosmoids.

A jetting cosmoid produces a multitude of submicrometer particles that will scatter radiation, more effectively when particle size and wavelength match. A cosmoid coma with an optical cross section comparable to the FOV will appear as a dark pixel. Therefore, if the number per unit volume decrease faster than the increase in optical cross section, then the observations will be dominated by smaller cosmoid comae that pass close to the instrument. There is, however, a short range limit. A small cloud passing too close to the instrument would move through the FOV in a time that was short compared to the 3.4 ms integration time of the DE 1 photometer and not be noted. Assuming a mean encounter velocity of 42 km/s for near hyperbolic cosmoids, the close-in range is limited to about 20 km, allowing an obscuring cloud to remain in the FOV for more than 1 ms. A cloud with a characteristic grain size of 200 nm and unit specific gravity would have a mass of about 1 kg and a cross section of $8(10)^3\ m^2$ equivalent to the FOV. Furthermore, a bright half-annulus would result from the strong forward scattering of particles as the coma became optically thin, not an annulus. The DE 1 dark pixel rate implies a much higher event rate then measured by Sisyphus, but electromagnetic disruption forces near the Earth become dominant over solar thermal stresses, such that all cosmoids disperse within a few radii; hence the greater frequency at high spacecraft altitudes. The 14 hour local time peak derives from the long period orbit distribution, details of which will be presented in a future report.

By comparison, the existence of an equivalent population of 100 ton comets, in short period, low inclination, prograde orbits with sublimation lifetimes of 10^7 years, striking the Earth at a rate of 20 per minute, breaking up at 2,000 km altitude and flashing into a gaseous cloud in 100 s (Frank et al., 1986b) is extremely hypothetical. Where are the effects expected in the ionosphere, interplanetary space, from lunar impacts, from optical scattering at disruption - all readily detected in the meteoroid population with ten thousand times less mass.

12. COSMOIDS NEAR THE OUTER PLANETS

Using the association of the Pioneer 10/11 Sisyphus and MDE data and the latter's measurements near Saturn and Jupiter, we have estimated the gravitationally attracted cosmoid population near those planets. The telescopic results of Yeates (1989) allow us to extrapolate the distribution to sizes larger than those measured by Sisyphus. The spatial concentration within a few ($\approx 3\ R_S$) radii of Saturn should be 1,000 times the interplanetary value. Estimates of the variation with radial distance from the planet, latitude and angular distance from the umbra and magnetotail are necessary for a better model but have not yet been attempted. We estimate that near Jupiter the mean spatial concentration should be about $\frac{2}{3}$ that near Saturn. This appears to be consistent with the MDE results near those planets (Humes, 1980). This will vary with distance from the planet, latitude and angle from the umbra/magnetotail. We theorize that the relatively reduced population near Jupiter results from enhanced sputtering of the volatile cosmoids by the charged particles in the Jovian magnetosphere. Although the ZL ceases at a solar distance of 3.5 AU, a pronounced Gegenschein or counterglow should be observable in the magnetotails of Jupiter [$\approx 1000\ S_{10}(V)$] and Saturn [$\approx 500\ S_{10}(V)$], based upon our estimate of the cosmoid population near those planets.

As stated earlier, all cosmoids will jet close to the planet. This because of charging and magnetic interaction in the umbra/magnetosphere. While a disrupted cosmoid results in small particles, near the planet we can use the data to estimate the concentration of the parent bodies before jetting, when they present a more serious hazard. Using our estimated spatial density and the velocity, we can compute the anticipated flux. Given the uncertainties in the determination, the relative $\frac{2}{3}$ concentration value near Jupiter is more than compensated by the higher gravitational velocity; so we list one set of values for both locales. Our estimate indicates that cosmoids may pose a serious problem for the Galileo and Cassini Orbiters. In Table 2 the average spatial densities N and fluxes ϕ for .01, .1 and 1 g particles are given for a mean velocity of 10 km/s. Note that even if one assumes that the fluence should be significantly reduced because the orbiters spend most of the time at large (>50 radii) distances compared to where the Pioneer 10/11 MDE data were gathered, the likelihood of kilojoule impacts during several years of orbit is high.

TABLE 2. FLUX OF COSMOIDS ON GALILEO AND CASSINI ORBITERS

m (g)	N (m^{-3})	Φ ($m^{-2}yr^{-1}$)
.01	$4(10)^{-11}$	10
.1	$3(10)^{-12}$	1
1	$2(10)^{-13}$	.06

The gravitational attraction of the giant outer planets for the cosmoid population provides a continuous source of material for building and maintaining rings. The recognition of this influx allows us to understand why the dynamics of ring structures show that they must be much younger than the planets (Esposito et al., 1984). Given this ample supply of material, it is not necessary to hypothesize the destruction of moons to form rings, rather the arcs observed by Voyager 2 in the rings of Neptune (Smith et al., 1989) can now be understood as recent disrupted cosmoid additions that have not yet had time to diffuse uniformly around the planet.

The interaction of the partially charged particles resulting from cosmoid dispersion with the planet's magnetic field creates impulsive electromagnetic disturbances at radio frequencies as the particles are decelerated. We believe that the very intense short radio bursts measured on Voyager 2 by the Plasma Wave (Gurnett et al., 1989) and Planetary Radio Astronomy Experiments (Warwick et al., 1989) near Neptune were the remote signature of charged cosmoid magnetospheric braking. Similar bursts should be found in the earlier Voyager flyby results. If the spacecraft was being impacted by 280 microparticles per second (Gurnett et al., 1989), assuming even a rapidly decreasing size distribution, we would expect a few impacts of larger particles that should have been noted by other effects.

If cosmoids are responsible for the rings surrounding the gas giants, then why the difference in ring appearances? This may result from the interaction of the incoming cosmoids with the planet's magnetosphere and the energetic charged particles therein. Sputtering will remove volatiles, alter the surface texture and size of particles. The energetic charged particle bombardment can also cause radiation darkening. As noted by Giese (1977) and Greenberg (1986), fluffy particles can be light absorbers. Coatings of carbon or other dark chemicals are not the only means of producing a low albedo. Sputtering of volatiles could leave a dark residue particle but magnetospheric interaction as well as the chemical composition must be considered in models of ring particle light scatter properties.

When a large cosmoid jets, dispersing particles, they spread along the orbit in the same way as meteoroids spread along the orbit of a comet (Whipple, 1985). The collisional interaction of such a line of particles, gravitationally directed toward the center of the planet, with the ring particles in Keplerian orbit, will produce a spoke pattern as was observed by the Voyager Spacecraft (Smith et al., 1981, 1982). Since the cosmoids approach from the antisolar direction, the spokes will occur in the shadow, emerge and diffuse as the collisional disturbance is dissipated.

Cosmoids provide material for continuous growth of the moons and planet. As a consequence of the planetary mass increase, the periods of Jupiter's moons should be decreasing proportionately $2(10)^{-6}$ per year which results in a systematic longitude variation of $2''.6\ yr^{-1}$ while Saturn's should decrease $4(10)^{-5}$ per year or about $52''\ yr^{-1}$. The influx also provides a significant energy source that must be considered in any planetary evolution model. As shown above, neglect of this mass and energy can result in misinterpretation of observations.

13. SUMMARY

The results of the Asteroid/Meteoroid Experiment or Sisyphus on the Pioneer 10/11 spacecraft have been shown with extremely high probability to be valid environmental measurements. The experimental results of the three dust experiments on the Pioneer 10 and 11 spacecraft have been used to define the distribution and structural characteristics of the dominant population of interplanetary matter in the inner solar system. Accordingly, interplanetary matter is mainly composed of volatile material moving in highly eccentric orbits subject to impulsive disruption from solar heating and electromagnetic forces. This meteoroid component, called cosmoids, have structures like pristine comets, probably similar composition and low (near 50 K) temperature. The bulk density is low, likely near 0.1 g/cm^3, with very weak cohesive strength. They scatter light with a Lyot like function or Hapke surface such that their albedo is around 2% (Greenberg, 1986).

The inner solar system also contains a population of short period meteoroids, with the characteristics, size distribution, orbital eccentricities and inclinations that have been well measured from optical and radio meteor observations. This short period component has had a long residence time close to the sun, hence the volatiles have sublimated in a fraction of the time needed for planetary encounter. The non-volatile remainder has likely been bonded and sintered by energetic particle and extreme ultraviolet processing. In contrast, cosmoids are small enough that they are completely dispersed during their initial approach to the sun. The weak structure of the cosmoid population leads to essentially complete dispersion in the magnetospheres and tails of the planets, eliminating the meteor signature that results from the hypervelocity interaction deep in the atmosphere where the mean free path becomes comparable to the size of the meteoroid. The Pioneer 10/11 measurements indicate that the cosmoid population is the primary source of the zodiacal light, the polarization of the ZL, and the small particle penetrations of pressurized vessels to 18 AU (Humes, 1980). Close to the sun, both populations have been observed from the Helios spacecraft (Grün et al., 1980).

The experimental basis for the cosmoid population derives mainly from the Sisyphus and MDE results supplemented by the Helios dust measurements. The Sisyphus measurements were critical because of their strangeness for which only now is there a physical rationale. How was it possible that not one of the 283 events measured in over three years of observation could be used to define a gravity driven conic section (Soberman et al., 1977)? The data define the impulsive character of the spontaneous disruption in the telescope FsOV; no short period meteoroids appeared in the data set. The significant variation of the ZL intensity derived from the event data is further evidence of disruption. The abrupt cut-off of events near 3.5 AU is still further evidence of cosmoid disruption; a probability of no events between 3.5 AU and Jupiter of $(10)^{-69}$ is beyond likelihood. The theory is reasonable and is consistent with the observations. Solid bodies fracture when physical stresses exceed material strength, yet have infinite lifetimes (to fracture) under moderate stress.

The MDE data has a parallel significance. How is it possible to explain a population of penetrating particles of mass $\approx (10)^{-9}$ g with nearly a constant flux from 1 to 18 AU, a flux not effected by solar gravity. The MDE shows significant effects on approaching Jupiter and Saturn (Humes, 1980). Cosmoid disruption with particles composed of volatile material offer a reasonable explanation; the sublimation lifetime from solar radiation is proportional to the square of the radial distance compensating for the flux concentration on approaching the sun. Eccentric orbits are required and were measured for a period by the MDE. The volatile nature of the disrupted material is evidenced in the ZL intensity derived from the Sisyphus event data compared to the wide angle ZL measurements. Further, the scattering from small wavelength size particles or somewhat larger fluffy particles explain the ZL polarization; the wavelength sizes, β-meteoroids are removed from the solar system by radiation pressure in less than a year.

The Helios measurements that occurred later are consistent with the Pioneer 10/11 ZL results (Link et al., 1976), but show what appears to be significant evidence of a cosmoid population. The data describe a class of particles different from the expected short period, near circular orbits approaching the sun under the influence of the Poynting-Robertson effect. The population had eccentricities greater than 0.4, the limit of measurement of the instruments. A low density or fluffy characteristic was implied by the inability to penetrate a thin film covering one of each pair of the Helios dust instruments (Grün et al., 1980).

More recently, ground based telescopic measurements using reflected sunlight like Sisyphus (Yeates, 1989)(Frank et al., 1990) with a CCD array at the focal plane appear to have detected interplanetary material. Modeling this data as measurements of cosmoids during dispersion yields rates consistent with the distribution measured by Sisyphus and the MDE when extrapolated to larger sizes. The signals measured by the ultraviolet photometer on the Dynamics Explorer 1 satellite (Frank et al., 1986a) also appear to be consistent with disruption of cosmoids in the Earth vicinity.

Consider again the relative importance of the short period meteoroids to the long period or cosmoid population. The Sisyphus results indicate that the short period meteoroids were not detected in the event measurements, while the event optical signatures are sufficient to explain the entire zodiacal light. The polarization of the ZL is uniquely explained with the cosmoid component without having to invoke a complex particle construction. A signature for short period meteoroids is absent in the penetration data of the MDE. In fact, the constant penetration flux measured to 18 AU is inconsistent with a significant short period population. Helios measured two inbound populations of meteoroids to 0.3 AU. Those and the meteor population are the only evidence of a short period component. It appears, accordingly, that the zodiacal cloud is a signature of the cosmoid population.

The relation of the cosmoid population to the planets is of interest and the subject of future efforts. At the Earth, the relation to noctilucent clouds, the Gegenschein, equatorial spread-F, sporadic E and sodium in the atmosphere require further study. The effects of the cosmoid population on the outer planets has potential significance because of the lifetime of volatiles beyond 10 AU and the large gravitational potential far from the sun. Cosmoid disruption occurs in the umbra and magnetotail of the gas giants as a consequence of charging and magnetic braking. Gravitational focusing and capture by those planets provides a source of mass and energy for rings, moons and the planets that must be considered in any phenomenological or evolutionary model. The Dust Analyzer on the Galileo Spacecraft (Göller and Grün, 1989) should confirm the antisolar radiant of the influx and measure approximately 700 times the interplanetary level in the Jovian locale. We conclude that the Galileo and Cassini Orbiters have a high probability of suffering kilojoule cosmoid impacts after spending months near Jupiter and Saturn respectively.

The very intense short radio bursts measured on Voyager 2 near Neptune (Gurnett et al., 1989)(Warwick et al., 1989) are concluded to be the remote signature of charged cosmoid magnetospheric braking. Similar bursts should be found in the earlier Voyager flyby results.

The observed spokes in Saturn's rings (Smith et al., 1981, 1982) are the product of collisions between large disrupted cosmoids which result in a radial line of microparticles at escape velocity and larger orbiting ring particles. As these and the radio bursts referred to above are both consequences of cosmoid/magnetosphere interaction, large impulsive radio bursts, time correlated with the observed spokes should be present in the Voyager Saturn encounter data. Disrupted cosmoids in the umbra and magnetotail of the gas giants should produce a Gegenschein beyond the 3.5 AU limit where the zodiacal light ceases. We predict that this should measure $\approx 1000 S_{10}(V)$ or approximately 3 times the average starlight background at Jupiter and $\approx 500 S_{10}(V)$ at Saturn. The orbital periods of Jupiter's moons should be decreasing proportionately at the rate of $2(10)^{-6}$ per year while Saturn's should decrease at the rate of $4(10)^{-5}$ per year.

Summarizing, the theory, a cosmoid population dispersing in the inner solar system to explain the Sisyphus measurements and those of the other two dust experiments on Pioneer 10 and 11 is almost self evident when compared to the characteristics of comets. The parallel should not surprise; that cosmoids can be identified with the nuclei of long-period comets in both physical and orbital characteristics. With the exception of Halley, nuclei of comets have never been observed despite their size. Halley, a very massive comet was seen following the extremely close approach of the Giotto and Vega Spacecraft when the nearly black nucleus was illuminated by a huge area of particulate solar scatterers and contrasted against the background of the bright coma (Balsiger et al., 1988). It is of little wonder that a dark cosmoid would be invisible to the Sisyphus telescopes against a star background, but become observable for the short time of its coma generation. Cosmoids observed from Pioneer 10 and 11 represent the lower extremety of the population of comets with high eccentricities. They appear responsible for the major optical signature of the zodiacal cloud and the microparticle impact effects on spacecraft in the inner solar system. Recognition of a cosmoid population raises concern about the amount of such matter in the inner solar system, which exceeds by several orders of magnitude that derived from the population of observable long-period comets. The distribution of cosmoids implies a primordial population of small cometary nuclei, much smaller than the 10^{16} to 10^{18} g mass of telescopic comets.

14. FUTURE EFFORT

The recognition of cosmoids in the solar system opens many avenues of research. Most apparent from the current study is the wealth of information still in the data of the three Pioneer 10/11 meteoroid investigations. It would, for example, be important to prove that the ZL followed an inverse square solar dependence. The paucity of meteoroid (cosmoid) detections between 1.2 and 1.4 AU begs an explanation that might be hidden in the data. While an objective of the current study was the reduction of orbits from the Sisyphus data, we are only midway through that effort. It would be valuable to complete the effort to confirm the results of the Helios Dust Analyzer and the Pioneer MDE that indicated high eccentricity orbits for cosmoids.

As indicated above, additional information about cosmoids would not only be scientifically valuable but would assist in the engineering of future missions. Better models of the cosmoid environment surrounding the outer planets are needed. As of this writing, the possibility remains that the star trackers of the Magellan Venus orbiter might have tracked jetting cosmoids close to that planet which would have disrupted orbital maneuvering. The absence of a planetary magnetic field would cause disruption much closer than would occur at the Earth or the outer planets. Lastly, the effects of cosmoids on the inner and outer planets will require extensive research.

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