REEXAMINATION OF DATA FROM THE ASTEROID/METEOROID DETECTOR

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EXECUTIVE SUMMARY

The discovery of the existence of cosmoids, a class of meteoroid in near hyperbolic orbits, characterized by a weakly bound collection of volatile submicrometer grains, was made in a reevaluation of the Sisyphus Experiment on Pioneer 10 and 11. This experiment measured the spontaneous jetting of cosmoids and showed that the dispersion and increase in brightness occurs in microseconds and lasts only briefly; tens of microseconds to fractions of a second, depending on the size of the parent body and the disruptive forces. Cosmoid jetting caused multiple telescope thresholds to be exceeded simultaneously, an effect that explains the earlier inability to compute trajectories from the measured times in the FsOV. That the originally calculated zodiacal light brightness was so much greater than the direct photometric measurements was a consequence of using a model that assumed solid meteoroids in short period orbits. A new calculation shows that the Sisyphus individual "event" measurements correlate directly with the Zodiacal Light. That not one event of the 283 measured by Sisyphus yielded an orbit when subjected to the originally assumed model, demonstrates quantitatively that the meteoroid population is dominated by cosmoids. Solar reflection from a solid; even one that was "black" and of meter size would have provided an orbit signature. The reported (Yeates, 1988) telescopic small comets, measured by a similar optical technique, appears consistent with the Sisyphus results. The characteristic jetting times measured by Sisyphus also show that the volatile cosmoids could not survive in short period orbits. The controversy over the 130.4 nm Earth image holes, including the "bright optically-thin half-limbs", may accordingly be explained with dispersed cosmoids of a few hundred grams mass, 10^5x less than the 100 tons used by Frank et al. (1986b).

Much of the reanalysis of the Sisyphus data remains to be performed. With the effects of the jetting to the entry and exit times understood, an effort is underway to compute orbits for those events that gave sufficient information for that purpose.

1. BACKGROUND

1.1 PIONEER 10/11 ASTEROID/METEOROID DETECTOR

The Asteroid/Meteoroid Detector or Sisyphus operated on the Pioneer 10 and 11 spacecraft to Jupiter. It consisted of four optical telescopes with photomultipliers. Each had a 7.5° field of view (FOV). Their optic 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, Sysyphus could measure individual meteoroids or asteroids as they passed through the fields of view (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. Of the 283 events recorded in over 3 years, not one yielded an orbit (Soberman et al., 1974). 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 zodiacal light 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 zodiacal light (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 microseconds. 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, 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, on the same power supply. The operating levels of the telescopes were background limited, consequently dark current and other noise inherent in the photomultipliers 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 zodiacal light 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 zodiacal light values (Auer, 1974, 1976).

1.2 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 gas and fine 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 jet explains the coincident FOV entries. Since most of the sunlight is scattered from submicrometer grains, the polarization of the zodiacal light as well as the anomalous brightness derived by classical analysis of the Sisyphus meteoroid results may now be understood.

Because of the small mass of the cosmoids entering the inner solar system in highly elliptic orbits, 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., 1974) or small particle heliocentric variation (Stanley et al., 1979). The micrometer and submicrometer 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.

2. CURRENT INVESTIGATION

2.1 HELIOCENTRIC EVENT DISTRIBUTION AND RANDOM EVENT PROBABILITY

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 some skeptical of the results and others expressing uncertainty as to the relationship with existing models of the meteoroid distribution (McDonnell, 1978). For this reason the initial effort of the current investigation was directed at validating the data.

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 inside of 3.5 AU. The lower event rate for the Pioneer 11 instrument was a consequence of a malfunction in one of the photomultipliers 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 seem to 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 is what was reported for the meteoroid penetration detectors which were on the same spacecraft (Stanley et al., 1979). 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 also brings to mind that the penetration detectors behaved anomalously between 1.2 and 1.4 AU.

That the Pioneer 10/11 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 just inside 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 (see below). At about 3.5 AU is where inbound comets begin to jet (Whipple, 1985) and has been shown to be a consequence of the energy released in the transition from amorphous to crystalline water ice that occurs at 140 kelvin, the expected temperature at that solar distance (Patashnick et al., 1974). This is also the same radial distance at which the zodiacal light dropped below the sensitivity of both Sisyphus in its background measurement mode (Zook and Soberman, 1974) and the Imaging Photopolarimeter in its Zodiacal Light 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

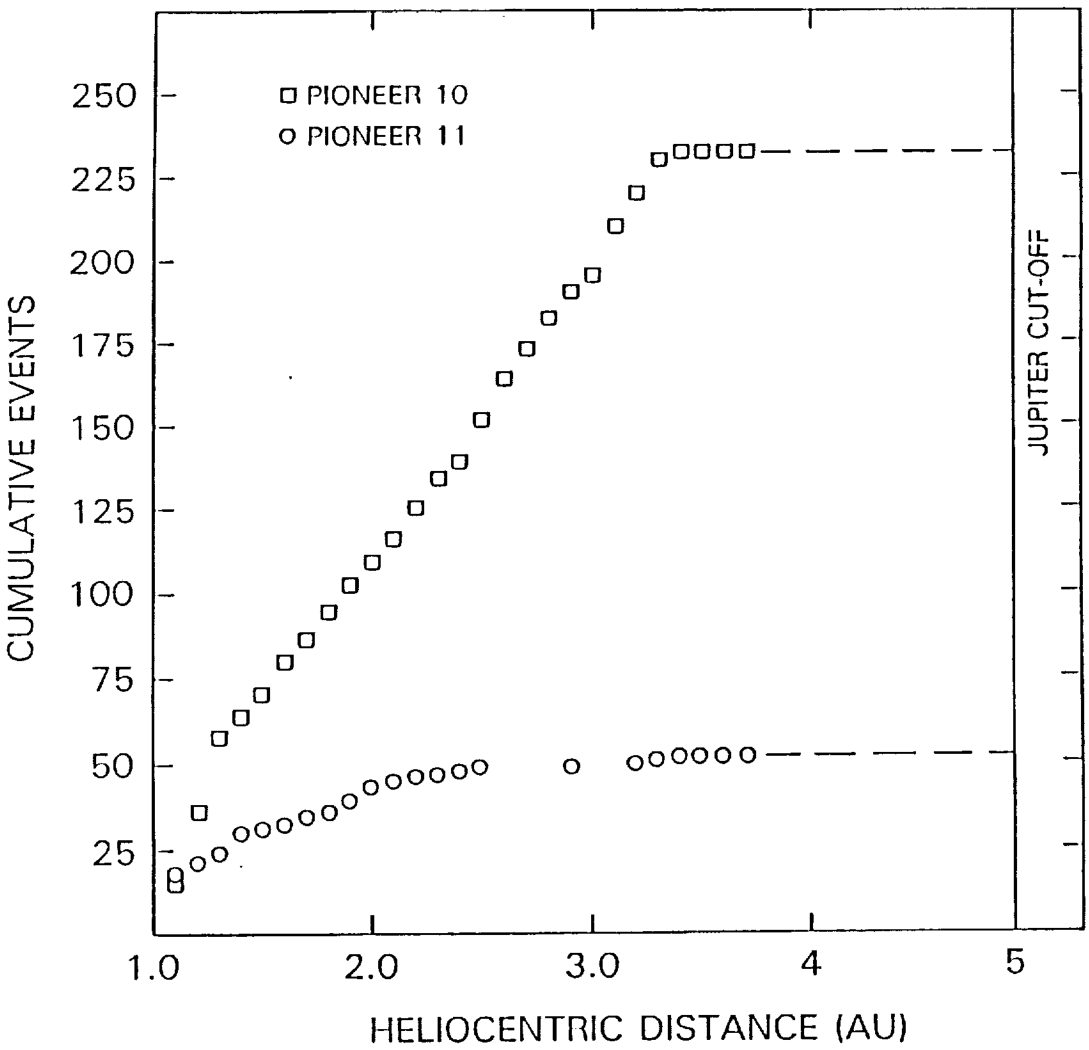

Figure 1. Pioneer 10 and 11 Sisyphus cumulative event rate as a function of heliocentric distance in astronomical units.

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 (a) is:

$$P(k) = \frac{a^k e^{-a}}{k!} \qquad (1)$$

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

$$P(0) = e^{-a} \qquad (2)$$

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:

$$P(0)_{3.5-5.2} = [9.1(10)^{-5}]^{17} = 2(10)^{-69} \qquad (3)$$

As stated earlier, that the instrument was still functioning was demonstrated by its response to Jupiter that was growing in the annular sweep of the sky made by FsOV of the telescopes. The star exclusion circuitry allowed the instrument to ignore the effected sectors until very close to the planet where the charged particle flux destroyed the photomultipliers (as predicted in the design). 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 tenth 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 (6) tenth AU intervals in which no events were measured that passed the screening tests. The Poisson probability for a single null interval is 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 has a probability of $3.2(10)^{-13}$.

2.2 RADIAL VARIATION OF THE ZODIACAL LIGHT

To establish that Sisyphus in the individual meteoroid measurement mode had indeed measured the radial variation of the Zodiacal Light, and that the discrepancy in the original analysis that was cited above was a consequence of trying to fit a model that assumed meteoroids in short period orbits, we performed the following calculation. The instrument was reduced to its simplest form; a four fold coincident photometer that measures the light incident in the FsOV in its 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 that was traversed by Sisyphus.

The brightness observed by Sisyphus can be written:

$$B_s = \int \frac{L\,dv}{4\pi r^2} \tag{4}$$

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:

$$dv = \Omega_s r^2\,dr \tag{5}$$

where (Ω_s) is the solid angle subtended by the FOV equal to 0.135 steradians. Substituting into Eq. (4) we obtain:

$$B_s = \frac{L\,\Omega_s}{4\pi} \int_{r_{min}}^{r_{max}} dr \tag{6}$$

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

$$B_s = \frac{L\,\Omega_s\,r_{max}}{4\pi} \tag{7}$$

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

$$B_o = \frac{L\,\Omega_o (R_{max} - R_{min})}{4\pi} \tag{8}$$

where we distinguish ranges for the conventional photometer by the upper case (R). Taking the ratio of the two brightnesses, we obtain:

$$\frac{B_o}{B_s} = \frac{\Omega_o}{\Omega_s}\,\frac{(R_{max} - R_{min})}{r_{max}} \tag{9}$$

Zodiacal light levels are generally presented in units of $S_{10}(V)$, which are equivalent tenth 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 millisecond 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 (the luminosity of a zero magnitude source compared to a tenth magnitude source). This brightness level must then be averaged for the fraction of the time that events were being measured. This indicates that the Gegenschein brightness (the Zodiacal Light in the antisolar direction) in $S_{10}(V)$ units should be:

$$B_0 = 226 \frac{(R_{max} - R_{min})}{r_{max}} \frac{\Sigma\tau}{T} \tag{10}$$

where ($\Sigma\tau$) is the time events were being measured, and (T) is the total time the instrument was observing. Equation (10) leaves us with a parameter that we must specify, the maximum range at which the instrument observed events. The present effort has as a primary objective the calculation of orbits from the data. We should point out, however, that we are unlikely to determine the maximum range because the baseline of the instrument (about 25 centimeters) was too small for triangulation at large distances (> 100 m) from the instrument. Thus (r_{max}) will remain an assumption. By choosing the proper value, we can obtain any single Gegenschein 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 ($R_{max} - R_{min}$) 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 kilometers, 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 milliseconds. At a relative encounter velocity of 30 kilometers per second, a body would travel about 1.1 kilometers during that time. At a range of 10 kilometers the diameter of the FOV is 1.3 kilometers, 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 which 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 kilometers, since one event lasted 63 milliseconds. A maximum range of 2.5 kilometers was used for the integration between 1.1 and 3.5 AU; the longest lasting event measuring approximately 9.7 milliseconds 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) that was on the same Pioneer 10/11 spacecraft (Hanner et al., 1976). As mentioned above, the Sisyphus instrument also measured the Zodiacal Light 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 decrease

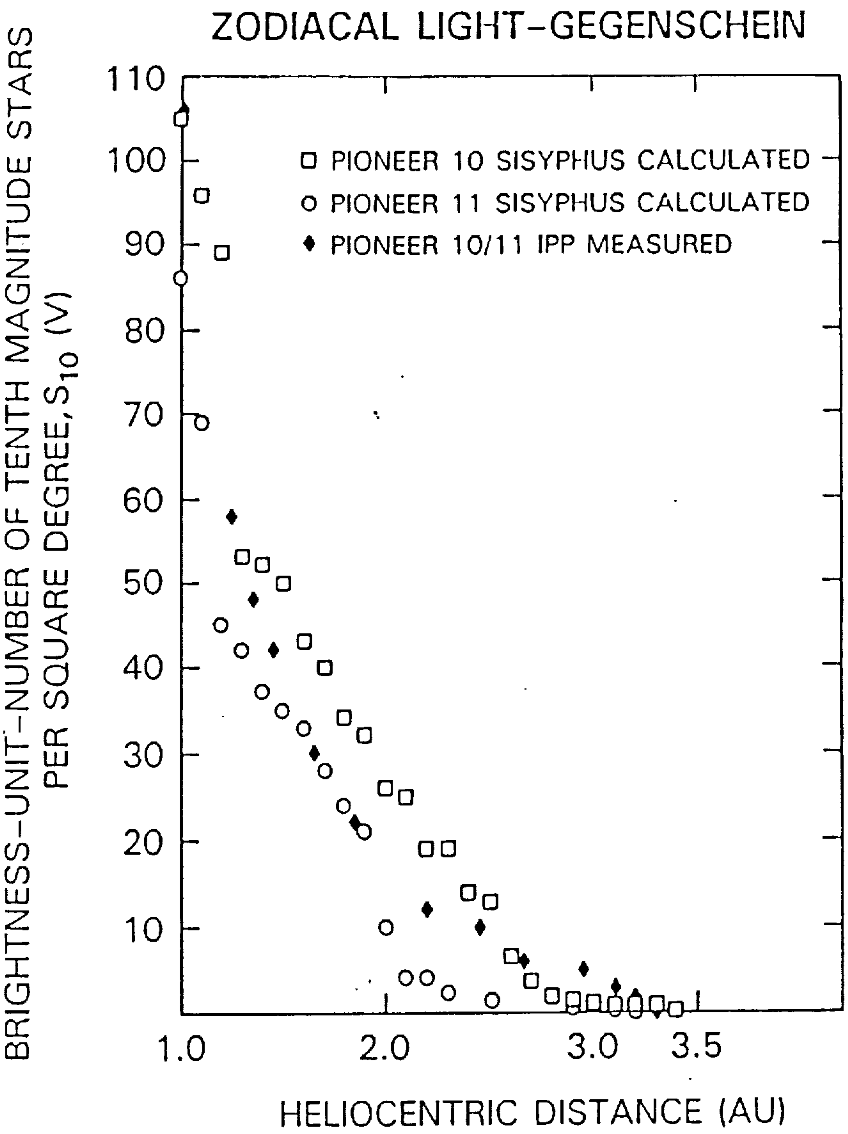

Figure 2. The variation with heliocentric distance of the Zodiacal Light in the antisolar direction (Gegenschein) as calculated from the Pioneer 10 and 11 Sisyphus individual event measurements and as determined from the Imaging Photopolarimeter (IPP)(from Hanner et al., 1976) on the same spacecraft.

beyond 2.5 AU and that the Zodiacal Light 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 Gegenschein radial dependence, we have avoided any interpretation of the events; specifically no reference was made to cosmoids. What the foregoing establishes is that the data are valid and strongly correlated with the Zodiacal Light. We are certain, however, that the cosmoid hypothesis explains the Sisyphus data and allows us to uncover much about this meteoroid population that is still in the results of that experiment.

2.3 DIFFERENTIAL ENTRY AND EXIT TIMES

To show graphically the anomalous differential entry times which were referred to earlier, and that lead to the conclusion that cosmoid jetting occurs in a time scale of microseconds, we plotted the graphs shown in Figures 3, 4 and 5. Better representations are currently being prepared for a publication soon to be submitted to Geophysical Research Letters (see below).

3. RELATED MEASUREMENTS

3.1 TELESCOPIC (VISIBLE) OBSERVATIONS

Yeates (1988) recently reported that 18th visual magnitude tracks of small comets at a distance of $1.4(10)^5$ km had been recorded using the Spacewatch Telescope with a charge coupled device (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 Lambertian solar reflector with unit reflectivity and an area of 0.4 m^2 could produce the proffered tracks (the reflector properties serve only for normalization; removing albedo and phase function assumptions). This size optical signature is about 16 times larger that required for the largest event measured by Sisyphus (which, as stated above, had a mean threshold of zero visual magnitude) during the Pioneer 10/11 missions (Neste, 1975). There was insufficient observing time compounded by increasing solar distance to expect an event comparable to those observed by Yeates in the Sisyphus data which provided the distribution shown in Figure 6. As can be seen, the Yeates' tracks are consistent with the Sisyphus measurements. For 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 hypothesis. Cosmoid jets, however, allow us to explain the tracks with less than one kilogram of grains with a mean size of 200 nanometers and unit specific gravity, which give more than the necessary solar backscatter area. Yeates, however,

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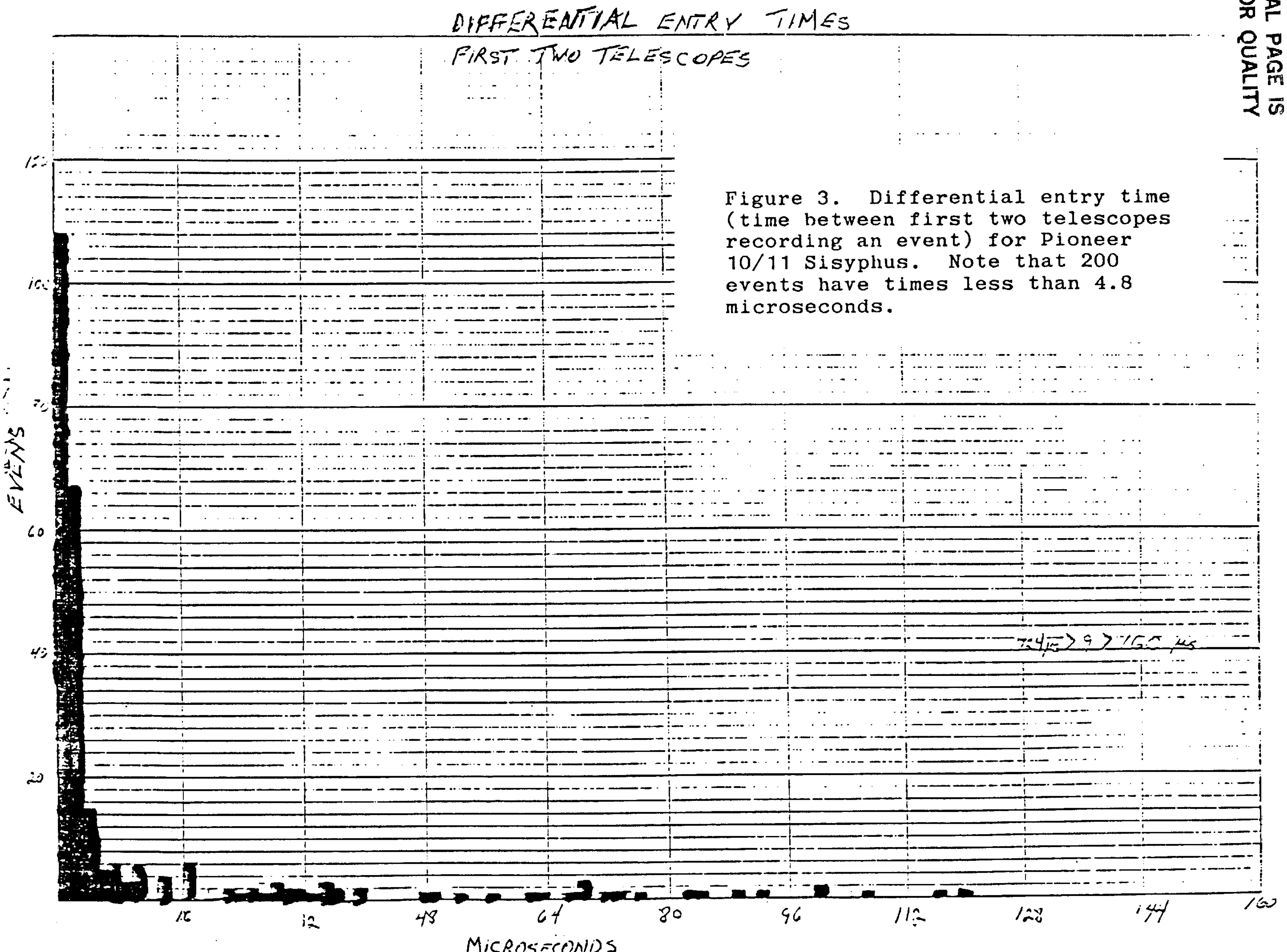

Figure 3. Differential entry time (time between first two telescopes recording an event) for Pioneer 10/11 Sisyphus. Note that 200 events have times less than 4.8 microseconds.

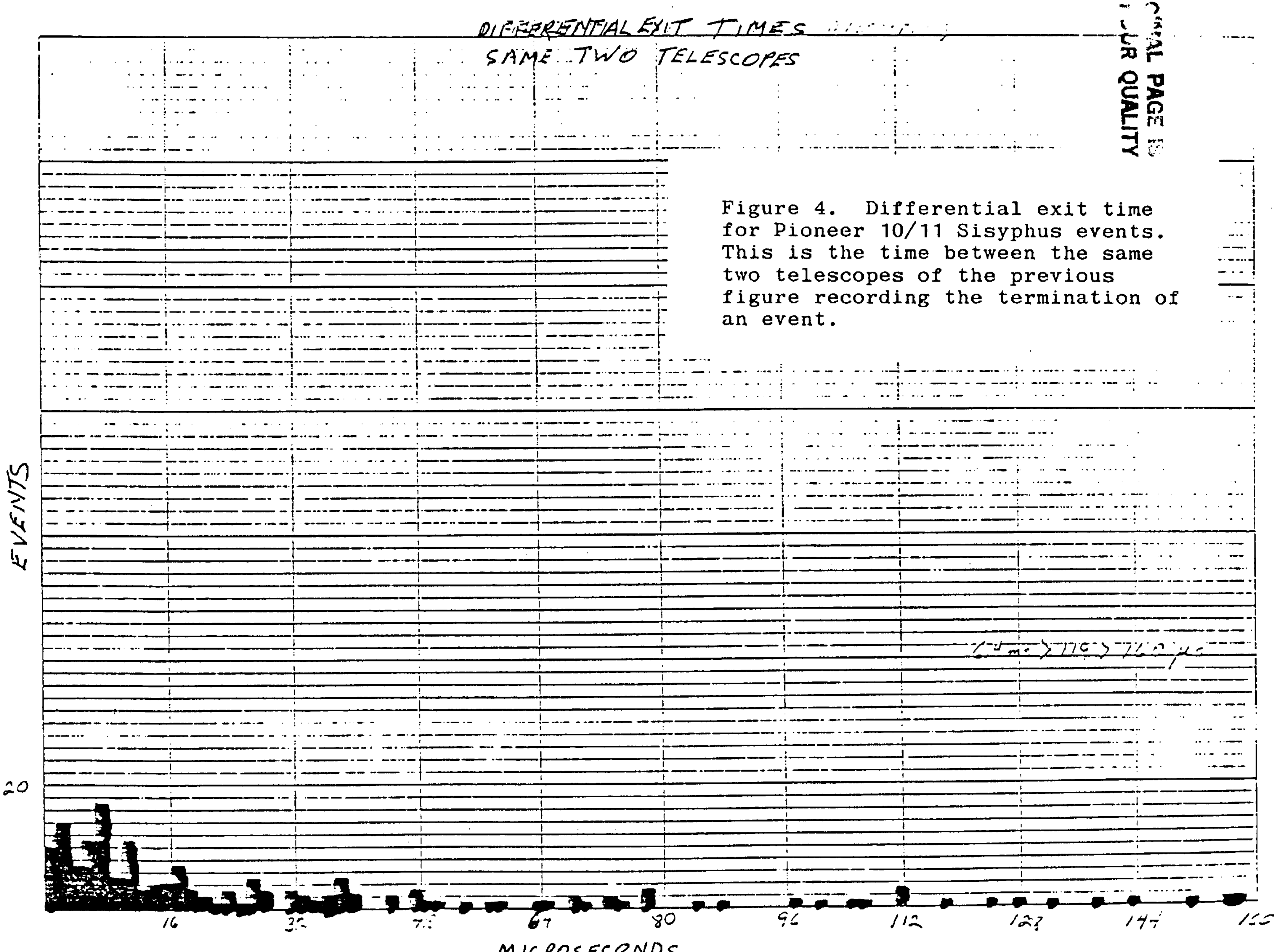

Figure 4. Differential exit time for Pioneer 10/11 Sisyphus events. This is the time between the same two telescopes of the previous figure recording the termination of an event.

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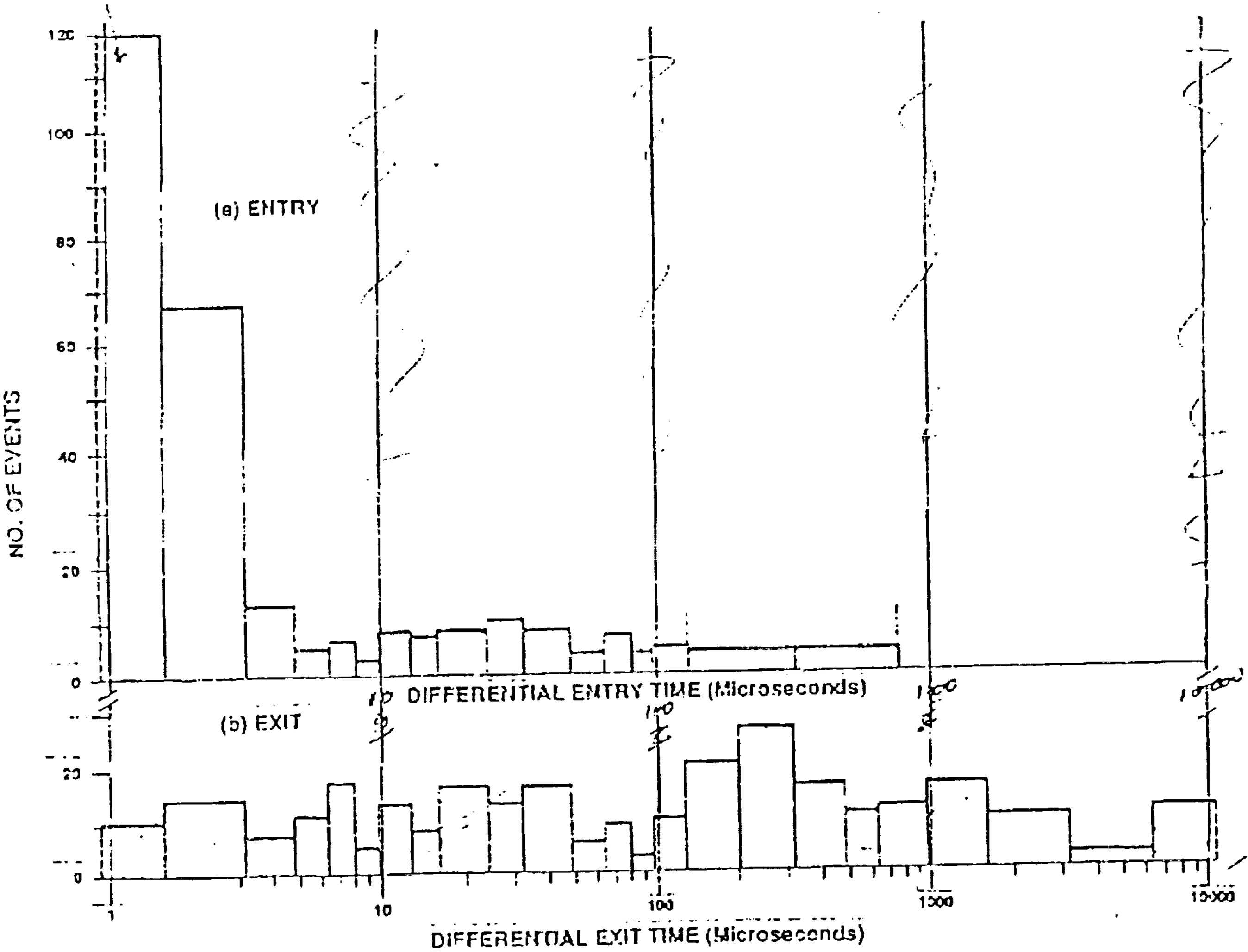

Figure 5. Differential entry (first two telescopes) and exit (same two telescopes) times from the Pioneer 10 and 11 Sisyphus measurements (logarithmic time scale). Note the small peak at about 200 microseconds in the differential exit time. With a separation of approximately 25 cm between telescopes, this represents a transverse velocity of about 12 km/s.

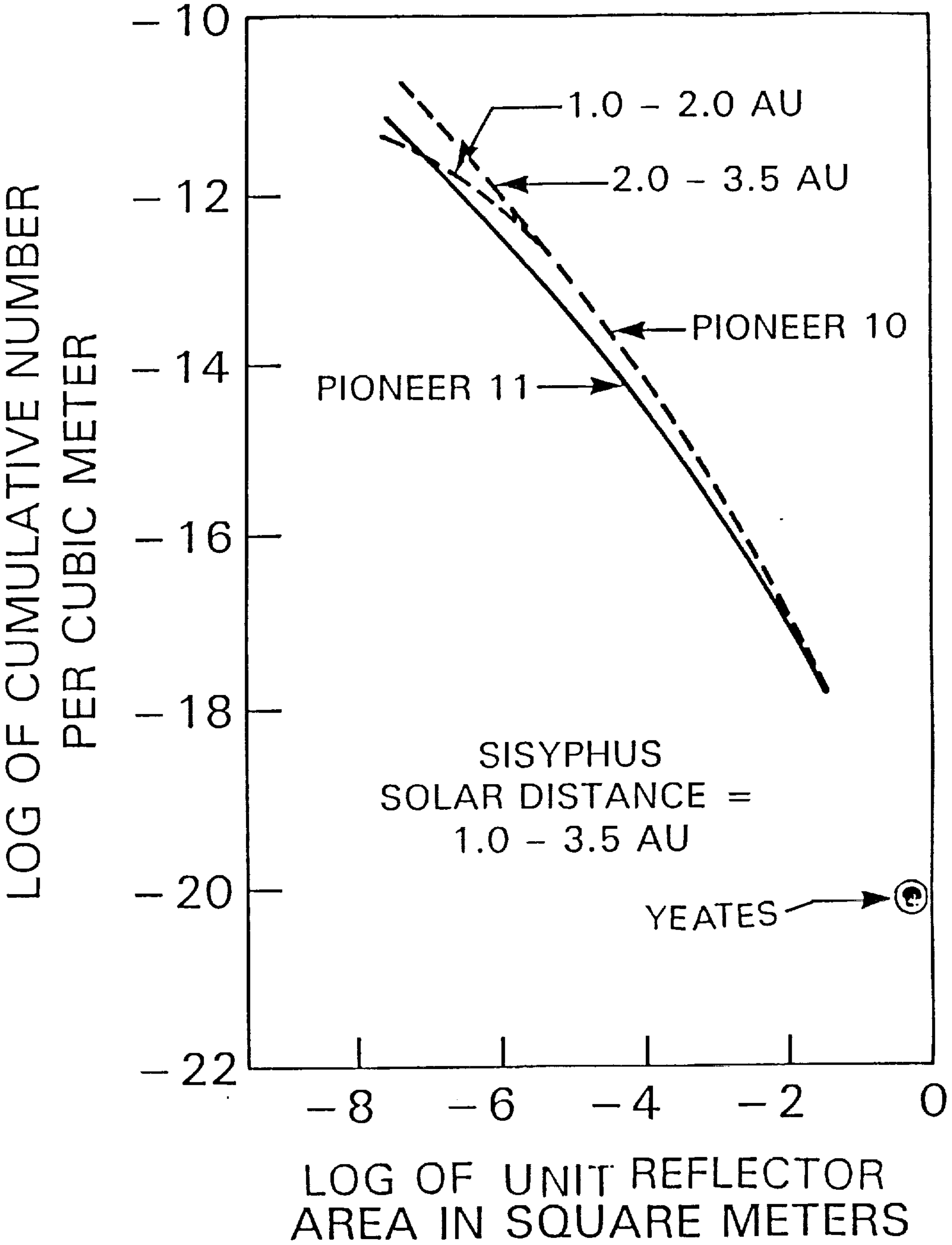

Figure 6. Comparison of Sisyphus results (Soberman et al., 1977) to ground telescopic measurements (Yeates, 1988). The ordinate shows the log number of optical events per unit volume (implicit is the ratio of event duration to mean time between events). The abscissa has been restated for Sisyphus to eliminate phase function and reflectivity assumptions.

ascribes the tracks to Frank et al.'s (1986b) hypothesized 10 meter, 10^5 kilogram small comet nuclei with 2 percent albedo and no detectable comae.

3.2 BACKLIT SIGNALS FROM DYNAMICS EXPLORER 1 (DE 1) AT 130.4 NM

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 at the wavelength band for resonantly scattered atomic oxygen at the 130.4 nanometer 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 two 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 absorptions in the limb at hydrogen Lyman alpha. Dark pixels were very occasionally found in a second frame 72 seconds later. These spots in the expected uniformly bright Earth at 130.4 nm may result from extinction between the spacecraft and the Earth caused by the comae 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 spatial density decreases faster than the increase in optical cross section, then the measured events 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 millisecond integration time of the DE 1 photometer and not be noted. Assuming a mean encounter velocity of 42 kilometers per second for near hyperbolic cosmoids, the close in range is limited to about 20 kilometers, allowing an obscuring cloud to remain in the FOV for more than one millisecond. A cloud with a characteristic grain size of 200 nanometers and unit specific gravity would have a mass of about one kilogram 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 as will be shown in a forthcoming publication (see below).

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 seconds (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 10,000 times less mass.

3.3 CONTINUING EFFORT

With the recognition that the cosmoids were in the FsOV of the Sisyphus telescopes when the began jetting and crossed the threshold for measurement, it became possible to attempt to reconstruct the orbits of some of the events. A small number of events measured at close range by all four telescopes have been selected as the first for this attempt at orbit determination. This is first being done graphically and by hand to gain experience before a mathematical solution will be attempted by computer.

4. PRESENTATIONS AND SUBMITTED PUBLICATIONS

A presentation was made to the American Geophysical Union (AGU) 1989 spring meeting on the some of the above results:

Soberman, R. K., and M. Dubin, Pioneer Sisyphus Results Show DE 1 Holes Caused by Kilogram Cosmoids, Eos, 70, 384, 1989.

A paper on some of the above results will be resubmitted shortly to Geophysical Research Letters along with a letter comment on the DE 1 results.

A presentation will be made to the American Astronomical Association, 175th Meeting, January 9-13, 1990 in Washington, DC:

Soberman, R. K., and M. Dubin, Cosmoids; the Primary Source of Material for Planetary Rings.

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