2 IN SITU MEASUREMENTS OF INTERPLANETARY DUST

2.1 Measurements from Satellites and Space Probes

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2.1.1 In-Situ Records of Interplanetary Dust Particles - Methods and Results

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Abstract

A review is given on the techniques used to record and to quantitatively measure data of individual interplanetary dust particles. New developments in detection techniques are briefly discussed.

The main results from recent space missions at about 1 AU and in the earth-moon neighborhood are discussed and compared with the flux results from lunar microcrater studies. Spatial anisotropies and time fluctuations are found indicating that the earth is exposed to two main micrometeoroid dust populations: the "apex"-population and the ß-meteoroids. The near planet-dust enrichments measured by HEOS 2 near the earth and by the Pioneer 10/11 near Jupiter are emphasized. The experimental data strongly suggest a fragmentation process associated with the earth. The role of the moon as a dust source is discussed. The important problems in the dust field for future space missions are summarized.

I. Techniques

The active detectors used for in situ experiments to detect interplanetary dust are listed in Table 1. The indicated sensitivities have been obtained for an impact velocity of appr. 10 km/sec. Some of the techniques listed are not used any more. Some other detectors, however, which have first been used more than 10 years ago are still in use today and are gaining important new results: the pressurized cells on the Pioneer 10/11 mission (Humes et al., 1974). The use of

Table 1: Active detector techniques used for in situ experiments to detect interplanetary dust

Type	Sensitivity at 10 km/sec
Piezoelectric Microphone Systems	10^{-11} - 10^{-9} g
Penetration Detectors: thin wires, photocells, pressurized cells etc.	10^{-9} - 10^{-7} g
Capacitor Detectors	10^{-12} - 10^{-10} g
Ionisation Detectors	10^{-15} - 10^{-12} g
Semiconductor Detectors	$\sim 10^{-15}$ g

semiconductors as detectors for interplanetary dust has been investigated by Kassel (1973) and by Rauser (1974). The Langley group has employed a semiconductor detector on the MTS satellite for the

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first time (Alvarez et al., 1975).

The most important and most frequently used detector technique is still the ionisation detector. The plasma produced during the impact of high velocity dust particles into a solid target (preferably a heavy metal like gold or tungsten) is detected. The amplitude of the signal produced by the plasma is measured and in one case (HEOS-, Helios-experiments) its risetime. Coincident events for electrons and positive ions are detected using electrically biased collectors. Different versions of these detectors have repeatedly been described in detail earlier by Berg and Gerloff (1971), Adams and Smith (1971), Dietzel et al. (1973) and Bedford (1975). The sensitivities are ranging between 10 μ diameter particles at 1 km/sec down to 1/10 diameter particles at approximately 40 km/sec.

The technique to collect particles using thin films and metal plates as collectors has been sucessfully used by Hemenway and Hallgren (1970). The inflight shadowing technique to identify collected particles vs. contaminant particles seems to be a reliable technique. This technique, however, is limited to low relative collecting velocities and is preferably to be used in the upper atmosphere. The collection experiments in deep space are based on impact craters or penetration holes produced by high speed particles (Hemenway et al., 1974, Nagel et al., 1976).

II. Interplanetary Dust at 1 AU

The knowledge of the dust population at 1 AU from the sun has been gained mainly by the Pioneer 8/9 dust experiments and from the investigation of lunar microcraters produced by impacting interplanetary dust particles. (See also Dohnanyi, 1972, for an earlier review). Pioneer 8/9 results: According to Berg and Gerloff (1971) and Berg and Grün (1973) the Pioneer 8/9 dust experiments recorded dust particles intercepting the sensors from all directions in the ecliptic plane.

Table 2 shows the number of events from particles intercepting the sensors from sun-, apex-, antiapex- and antisun-direction; the apex-direction is the direction of the velocity of the orbiting satellite around the sun. The majority of these particles are hitting the sensor mainly from 2 directions: the sun- and the apex-direction. From time of flight measurements Berg and Gerloff (1971) calculated the impact velocity of the apex-particles; they obtained values in the range of 2

Table 2: Numbers of Particles recorded from Pioneer 8/9 dust experiments per year

Viewing Direction	Number of events per Year (orbit)	%
Sun	90	56
Apex	40	25
Antiapex	20	12,5
Antisun	10	6,5
Total	160	100

to 20 km/sec. Thus, a meteoroid flux for the apex-particles could be determined to be $\phi_{apex} = 2 \times 10^{-4}\ m^{-2} sec^{-1}\ (2\pi ster)^{-1}$ for $m \geqslant 10^{-12}$ g. For the "sun"-particles, however, Berg and Grün (1973) did not obtain any velocity measurements and, therefore, no fluxes could be calculated. The authors conclude that the "sun"-particles are extremely small ($<$ 1 µ in diameter) and fast moving ($>$50 km/sec).

Lunar Microcraters: The lunar surface samples are exhibiting micron- and submicron-sized impact craters down to 0.2 µ in diameters (Schneider et al., 1973) and even down to 250 Å in diameters (Blanford et al., 1974). The overall micron- and submicron-sized crater statistics shows a bimodal distribution as shown in Fig. 1 for the lunar sample 15205 (Hartung and Storzer, 1974): a steep part for craters $<$5 µ in diameter and a flat part for craters $>$5 µ in diameter. Using suitable simulation results (Fechtig et al., 1974) and dated samples according to the heavy ion track dating method (Schneider et al., 1973), the crater distributions could be converted into dust particle fluxes. Fig. 2 shows the result. It was assumed that the flat part in the crater size distribution represents the "apex"-component, whereas the steep part is due to the "sun"-component. A comparison with flux data from the HEOS 2 dust experiment

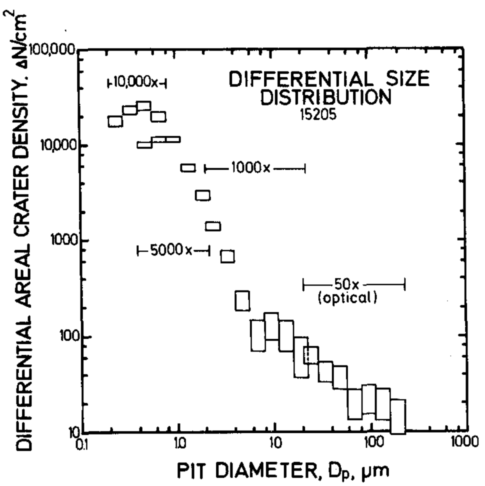

Fig. 1

Differential crater number densities on lunar sample 15205.

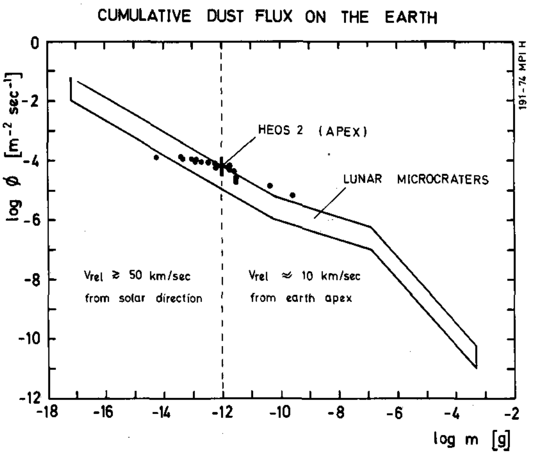

Fig. 2

Cumulative dust flux at 1 AU derived from lunar crater statistics and HEOS 2 dust experiments

(Hoffmann et al., 1975b) indeed shows an agreement with the lunar data in both absolute numbers and slope. A calculation using the lunar, Pioneer 8/9 and HEOS 2 results yield a number frequency vs. mass plot. The results are in agreement with the observed zodiacal light brightness (Giese and Grün, 1976). Detailed summaries of the results from lunar microcrater investigations are presented by Hörz et al. (1975) and by Fechtig et al. (1974).

Zook and Berg (1975), Zook (1975), Dohnanyi (1976) and Whipple (1976) have discussed a possible production mechanism of the "sun"-particles, which are called ß-meteoroids (according to a suggestion by Zook and Berg (1975)). Between 1 AU and the sun meteoroids are spiralling in towards the sun because of the Poynting-Robertson effect (Wyatt and Whipple, 1950); they frequently collide with each other and with the ß-meteoroids producing a large number of fragments. Generally the fragments are smaller than a critical minimum mass and are hence accelerated outward from the sun by radiation pressure which now overpowers the attractive force of gravity. These fragments are therefore approaching the spacecraft from the sun-direction and are in a hyperbolic orbit leaving the solar system.

A second possibility is that particles approaching the sun are vaporised until they are small enough to be accelerated outward by radiation pressure; particles consisting of different chemical components can even be fragmentated by this process because of their different melting and vaporization temperatures. Huebner (1970) has considered this mechanism when he discussed the presence of a heavy solar wind component. Kaiser (1970) has discussed this process, too, in an effort to explain observations of spectral lines in the infrared close to the sun by Peterson (1967) and McQueen (1968). Sekanina (1976) has calculated the dynamics of particles produced by this mechanism close to the sun. He found that this mechanism could account for the observed ß-meteoroids.

A third alternative, finally, is suggested by Hemenway et al. (1972): from their measurements the authors conclude that at least a substantial part of the ß-meteorites are originated directly from the surface of the sun (see Hemenway, 1976).

III. Interplanetary Dust near the Earth

An enhancement in the number density of interplanetary dust particles near the earth has for a long time been the subject of discussion. Early measurements using microphone detectors (Alexander et al., 1963) and particle collection results (Hemenway and Soberman, 1962) indicated the existence of a dust cloud around the earth. Later measurements, however, showed that part of the microphone pulses were due to noise signals (Nilsson, 1966) and part of the collected particles obviously were contaminants (Fechtig and Feuerstein, 1969). However, there still remains a considerable difference between near earth and deep space results in particle number densities (Fechtig, 1973).

The orbit of the HEOS 2 earth satellite with its high eccentric orbit above the North pole (apogee: 240.000 km, perigee: $\leq$ 3.000 km) offered a good chance to study the spatial particle distribution as a function of the distance from the earth. The main results have already been published (Hoffmann et al., 1975a, b); some of the overall results are summarized here for the whole mission period. A total of 431 particles have been recorded during the lifetime of the satellite from February 7, 1972, through August 2, 1974. Table 3 shows a summary

Table 3: HEOS 2-dust experiment: Summary of registered particles on the 100 cm^2 surface detector and measured quantities

Type of measurement	Number of particles	Measured quantities
Counted events:	174	events
Half quantitative measurements:	191	Impact produced charge $Q \sim m \cdot v^{3.5}$
Quantitative measurements:	66	Charge $Q \sim m \cdot v^{3.5}$ Rise time $t_{rise} = f(\frac{1}{v})$
Total	431	

of the detected particles: some of the 431 particles are counted, some are half-quantitatively measured (by measuring only the pulse amplitude) and others are observed from measurements of their pulse ampli-

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tudes and the pulse rise time. In Fig. 3 the number of events is plotted as a function of the time differences between subsequent events for the whole time period. These data are divided somewhat arbitrarily into 3 categories: swarms with 1 or more events per 15 minutes, groups ranging between 1 event per 15 minutes and 2 events per day, random particles with 2 or less events per day. In Table 4 the number of swarm-, group- and random particles is listed for different viewing directions of the experiment. Unfortunately it was not possible to turn the experiment into the sun-direction because of technical reasons. From the event rates we find that the apex-particles are most frequent, the ecliptic south particles are, however, almost as frequent as the apex particles. A detailed analysis, however, showed that the ecliptic south particles are much smaller and faster than the apex-particles (Hoffmann et al., 1975b). The corresponding fluxes are therefore much lower for the ecliptic south particles. It is believed that these particles are fragmentation products from larger micrometeoroids.

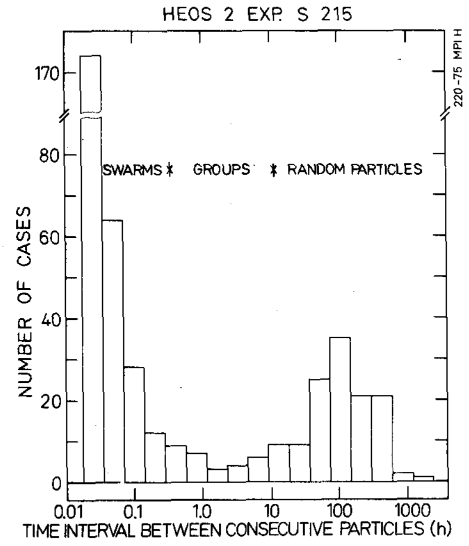

Fig. 3

HEOS 2 dust experiment: Temporal distribution of the dust particles. Each individual pair of consecutive particles is represented by a box.

The results during the activities of meteor showers are listed in Table 4 as well. No significant contributions in the dust size range could be found. This result is in agreement with the general knowledge of the size distributions in meteor showers (Millman and McIntosh, 1964, 1966, Millman, 1970, Dohnanyi, 1970).

In order to further discuss these results the 3 categories of particles are plotted in Fig. 4 as a function of geocentric radius. An important overall result is that more than 80 % of all registered particles are clustered, that means they appear in swarms or groups. In the perigee region ($<$ 67.000 km) even more than 93 % of the registered particles are clustered. In Fig. 4 one can see that the swarms are overwhelmingly

Table 4: HEOS 2-dust experiment: Number of recorded particles per 100 cm^2 sensor surface for different viewing directions

Region		Duration (days)	Swarms Number	Swarms Particles	Groups Number	Groups Particles	Number of random particles	Particles per day
Inter-planetary Region (>67.000 km)	Apex	289.0	1	32	5	11	32	0.11
	Antiapex	55.1	1	51	1	4	3	0.05
	Ecl. North	263.9	-	-	3	7	14	0.05
	Ecl. South	114.4	-	-	2	5	12	0.11
Meteor Showers	Perseids 1972	14.8	-	-	1	5	2	0.14
	Perseids 1973	19.3	-	-	1	2	4	0.27
	Draconids 1972	21.2	-	-	-	-	1	0.05
	Quadrantids 1973	29.4	-	-	-	-	4	0.14
	Quadrantids 1974	16.9	-	-	-	-	-	-
	Ursids 1973	13.8	-	-	-	-	2	0.15
Perigee Region (<67.000 km)	all directions	69.8	11	206	9	18	16	0.23
	Total:	907.6	13	289	22	52	90	0.10

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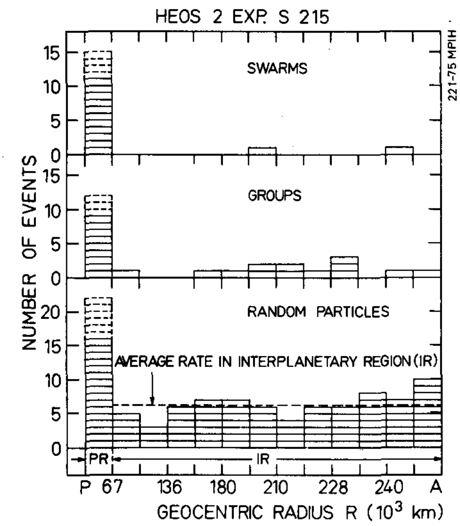

Fig. 4

Rate of swarms, groups and random particles as a function of the geocentric radius R; each box represents a group, swarm or random particle; dashed boxes are due to the bad data coverage in the PR; P = perigee, A = apogee, PR = perigee region.

most frequent in the perigee region, while the groups are more or less equally distributed over the whole altitude range (except for a modest enrichment in the perigee region).

The random particles clearly show an enhancement in the particle frequency of about a factor of 5 in the perigee region ($\lesssim$ 67.000 km) compared with the interplanetary region ($\gtrsim$ 67.000 km).

In Fig. 5 the fluxes are plotted for various viewing directions in the interplanetary region. As described in detail by Hoffmann et al. (1975b) the average impact velocity of the apex particles is about 10 km/sec; this is based on a spread ranging from 1 to 20 km/sec. The corresponding flux has been calculated to be

$$\phi_{apex} = 7 \cdot 10^{-5}\ m^{-2}sec^{-1} \text{ for masses } \geq 10^{-12}\ g.$$

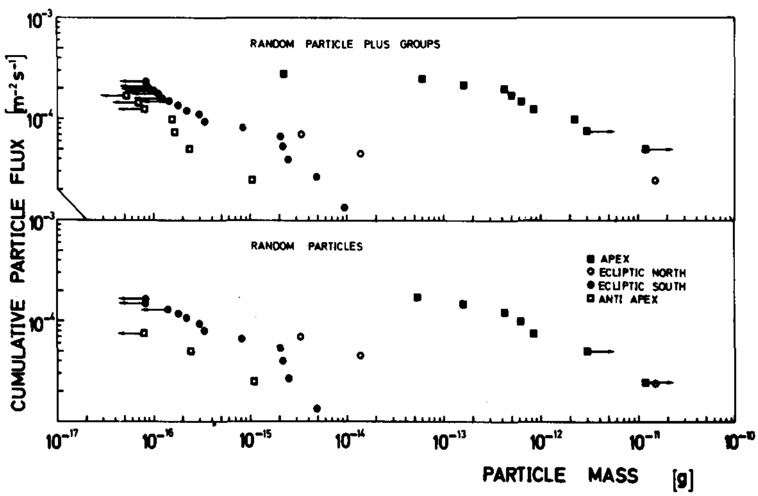

Fig. 5: HEOS 2 Experiment S 215: Uncorrected cumulative flux of random particles plus groups and random particles only as function of the particle mass.

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In order to compare this flux value with the Pioneer 8/9- and the Mariner 4-fluxes (Alexander and Bohn, 1974) the HEOS 2 flux has to be expressed as a function of a viewing solid angle of 2π steradians (the given flux value ϕ_{apex} relates to the opening angle of the HEOS 2 dust experiment appr. 60^o solid angle). The fluxes are:

HEOS 2: $\phi_{apex} = 4\cdot 10^{-4}\ m^{-2} sec^{-1}\ (2\pi st)^{-1}$

Pioneer 8/9: $\phi_{apex} = 2\cdot 10^{-4}\ m^{-2} sec^{-1}\ (2\pi st)^{-1}$

Mariner IV: $\phi_{apex} = 3\cdot 10^{-4}\ m^{-2} sec^{-1}\ (2\pi st)^{-1}$

for masses $m \gtrsim 10^{-12}$ g

The fluxes in the other directions are at least one order of magnitude lower and the impact speed is $\approx$20 km/sec.

Besides the enhancement of groups in the perigee region (Fig. 4), they seem to be more or less equally distributed as a function of distance from the earth in the interplanetary region. There is, however, a correlation with the position of the moon (lunar aspect angle) relative to the experiment viewing direction. As shown in Fig. 6 most of the groups in the interplanetary region appear within lunar aspect angles smaller 60^o, which is in agreement with a lunar origin as shown by detailed trajectory calculations by Hoffmann et al. (1975b). (The groups within the perigee region and during meteor showers are not to be considered to originate from the moon since the corresponding angle distribution is no criterion.) In contrary random particle events show an overall distribution independent from the lunar aspect angle and are therefore not correlated with the moon. Almost all swarms appear in the perigee region. Laboratory investigations by Eichhorn (1976) using the impact light flash technique have shown that even at low impact velocities ($\sim$ 5 km/sec) a relatively small amount of submicronsized ejecta are produced at low angles relative to

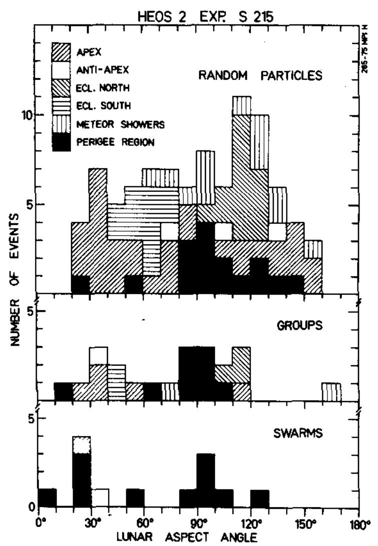

Fig. 6

Distribution of the directions under which the random particles and groups would encounter the detector assuming a lunar origin.

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the target and at velocities as high as 30 km/sec. Schneider (1975) has performed light gas guns experiments and concluded that under lunar conditions a small fraction of the impact produced ejecta even leave the lunar gravitational field (also see Gault et al., 1963). A theoretical analysis by Dohnanyi (1975) shows that this lunar origin is in agreement with an ejecta origin caused by impacting meteorites in the kg-size range on the lunar surface.

The swarms do not show any correlation with the position of the moon. They seem, however, to be associated with the perigee region. Kaiser (Hughes, 1974) has suggested that meteors at grazing incident angles are producing similar dust. A corresponding observation has been published by Rawcliff et al. (1974) and by Bigg and Thomson (1969).

The Prospero dust satellite experiment supports the HEOS 2 results of the clustered dust particles near the earth (Bedford et al., 1975). As a result of a detailed analysis these authors give a comparison of fluxes between HEOS 2 and Prospero as a function of the geocentric distance. The diagram is given in Fig. 7. The fluxes are plotted for masses $\gtrsim 10^{-14}$ g and $\gtrsim 10^{-15}$ g for Prospero, HEOS-near earth, HEOS-interplanetary and some lunar data (Fechtig et al., 1974; Smith et al., 1974). This interpretation also allows one to understand other discrepancies: the results by Nazarova and Rybakov (1974) from the soviet spacecrafts Cosmos and Intercosmos reasonably well correspond to a near earth distance

$$\phi_{cosmos} = 2\cdot 10^{-3}\ m^{-2} sec^{-1}\ (2\pi st)^{-1} \text{ for masses } m \gtrsim 10^{-11} \text{ g and}$$

$$\phi_{intercosmos} = 10^{-4}\ m^{-2} sec^{-1}\ (2\pi st)^{-1} \text{ for masses } m \gtrsim 10^{-9} \text{ g}$$

(Nazarova and Rybakov, 1974). New measurements of these authors (Nazarova and Rybakov, 1975) report much lower fluxes measured by Lunar Orbiter Luna 22 ($\phi_{sporadic} = 5\cdot 10^{-5}\ m^{-2} sec^{-1}\ (2\pi st)^{-1}$ for masses $m \gtrsim 10^{-11}$ g) in good agreement with the results on the Lunar Explorer 35

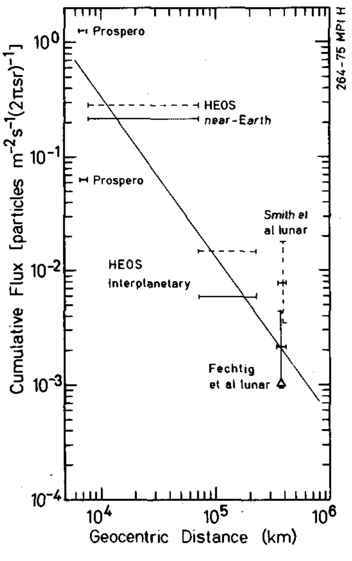

Fig. 7

Cumulative micrometeoroid flux for masses $\geqslant 10^{-14}$ g (solid lines) and $\geqslant 10^{-15}$ g (dotted lines) as a function of geocentric distance according to Bedford et al. (1975).

(Alexander et al., 1972) as well as with results on the Mars 7 spacecraft ($\phi = 2 \cdot 10^{-5}$ $m^{-2}sec^{-1}$ $(2\pi st)^{-1}$) (Nazarova and Rybakov, 1975). Because of their lunar or even larger distances from the earth, the low fluxes of those experiments agree well with the interplanetary fluxex found by Pioneer 8/9 and HEOS 2. Humes et al. (1974) have reported a particle enhancement of 2 orders of magnitude from the Pioneer 10-11 dust experiments when approaching the Planet Jupiter.

The moon is obviously a source for small dust. The upper atmosphere also might produce dust from grazing meteors. Two or even three orders of magnitudes, however, can not easily be explained by these two sources alone. A comparison of these results with collection experiment results (Hemenway, 1973) lead to the conclusion that an effective, but unknown fragmentation process causes this enhancement. In another paper (Fechtig and Hemenway, 1976) the evidences for this fragmentation process are summarized and possible fragmentation mechanisms are discussed. It looks very likely that extremly porous meteors are producing dust by their disintegration somewhere between the moon and the earth's upper atmosphere. This problem is still open, however, and should be further explored in future experiments.

IV. Future Techniques and Scientific Problems

Future Techniques:

The techniques to detect interplanetary dust particles in deep space are low level type measurements. The event rates range from 1 event per month to 1 event per hour. Only in special cases, for example close to a planet, the event rate may be higher. To differentiate real events from electrical and oscillating noise it is therefore essential to use coincidence techniques. The HEOS 2 detector takes advantage of the positive and negative charge pulses which were measured in coincidence. The Helios detector uses a third signal: the mass spectrum of positive ions.

Eichhorn (1976) has investigated the mass- and velocity-dependences of the impact light flash during high velocity impacts. The maximum of the differential light intensity reads:

$$I_{diff.} \sim m\, v^{4,1}$$

while the integral light flash depends differently:

$$I_{int.} \sim m\, v^{3,2}$$

From these relations it is possible to determine mass m and impact velocity v of a projectile. As shown in detail by Eichhorn (1976) the sensitivity of this technique is comparable to the sensitivity of the impact plasma detector. Therefore, this technique is suitable to be used as a further coincidence signal.

Auer (1975) has published the principles of a detector which is based on the fact that charged particles are influencing charges on a conductor. The proposed technique works, if the interplanetary dust grains are sufficiently charged up. This method is of especially great interest for orbit determinations.

Not only for technical reasons should future dust experiments be of coincidental type, however. Because of scientific reasons, one should more and more combine different types of measurements. Optical and direct measurements as well as joint detection and collection experiments should be performed to explore the various parameters for the same dust particles.

Scientific Problems:

More precise and quantitative measurements are needed to understand the dynamics and the evolution of the interplanetary dust cloud of the solar system. The following topics should be further explored:

ß-meteoroids: besides the existence of the ß-meteoroids and their mass range we do not know much more. The important problems like origin (collissions, vaporization, direct sun origin?), dynamics and composition are still unsolved. Any interplanetary or near earth mission is suitable for these measurements.

Near planets dust dynamics: the HEOS 2- and the Prospero-results strongly suggest an enhancement of dust near the earth. The Pioneer 10/11 results (Humes et al., 1974) show a strong enhancement of the dust population near Jupiter. The mechanisms of gravitational enhancements, fragmentation processes, impacting induced ejecta production or other still unknown enhancement mechanisms have to be investigated. The future missions Lunar Orbiter, Jupiter Orbiter and Space shuttle/Space Lab are suitable missions.

Sources: one still does not know from direct measurements which sources contribute to the solar dust cloud and to what extent. Any possible mission should be used to directly study the sources. The most interesting mission presently in discussion is a cometary mission for example, to Comet Encke (Yeates et al., 1976).

A lot of interesting scientific work ought to be done in the future.

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