interplanetary dust

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PREFACE

This book was begun almost fifteen years ago, a most unpropitious time for a book on this subject. The field was in turmoil; satellite data on interplanetary dust were in violent disagreement, high-altitude balloon collections were only beginning to provide uncontaminated samples for laboratory analysis, and lunar cratering studies were still waiting for the Apollo program. Meteoritic dust was just on the verge of becoming a field based on reliable data. Its previous history was a patch-work of enthusiastic attempts, dreadfully bad luck, naive interpretations and blissful amateurism. It was a poor time to try to summarize the field, and so I wrote very slowly.

By now the field has reached a certain degree of maturity. Largely because of the space program and the marvelous recent progress in techniques for microchemical and microphysical analysis, we now know fairly reliably how much interplanetary dust there is, what its size distribution is, and what its chemical and physical properties are. There are still many mysteries; - where does the dust come from? is it mostly cometary in origin as seems to be implied by present evidence? how is it distributed in the solar system? what has been its history over the age of the sun? are any of the particles truly interstellar in origin? These and other questions remain to be answered with certainty, but enough of a basic understanding has been reached at last that I feel that my writing project can finally be brought to an end.

I am indebted to many people for their help over the years. Donald Brownlee, whose pioneering work has helped to revolutionize the entire field, was a constant source of inspiration. Many people, too numerous to list here but readily discovered in the Bibliography at the end of the book, sent me preprints and reprints as their work progressed. I must specially mention Fred Whipple, who fired my interest years ago at Harvard, and Frances Wright, who kept the Smithsonian Dust Project going for many years. I also must thank the personnel of Gordon and Breach, who have patiently waited many years for me to complete this manuscript.

Paul Hodge

Seattle, 1980

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CONTENTS

1. THE QUEST FOR COSMIC DUST

I. Introduction

Interplanetary dust has been an elusive target for scientific research. It has been the subject of concentrated searches by scientists for over a hundred years, but only in the recent decade has the true nature of the dust come to light. The study of this dust by a wide variety of techniques has been thwarted by innumerable complications that have misled or discouraged many investigators who have engaged in this research. The field has finally achieved success only because of the unusual advantages presented for this kind of work by the space effort. Even then, it took years of error and misinterpretations of the space data before the problem was properly solved.

II. Early Attempts

The earliest attempts to identify and study interplanetary dust go back to the earliest periods in the history of meteorite research. Scientists of the 19th Century, after the true nature of meteorites had been established, realized the possibility that large numbers of cosmic particles of small size fly onto the earth, as do the meteorites. The occasional occurrence of meteorite falls that were accompanied by a rain of small meteorite particles, resulting from the breakup of the meteorite in the atmosphere, led several investigators to the conclusion that rains of dust might be frequent occurrences and might be often if not always due to cosmic particles. For example, Chladni (1819) catalogued many examples of dust falls that might be attributed to cosmic particles falling to the earth. These have appeared in literature going back as far in history as 472 A.D. Modern interpretation of these data suggest that few if any are probably connected with interplanetary dust falls, but rather most are probably examples of the deposition of terrestrial

Fig. 1-1. History records many incidents in which dust fell to earth, apparently from out of the heavens. Some incidents were reported as having occurred at sea.

dust blown from a distance by unusually heavy-laden air. Meteorologists have demonstrated that occasionally winds can carry, almost bodily, dust storms over thousands of miles. Sahara sands have been found to fall occasionally at large distances from Africa, for example, in the Swiss Alps and in the Caribbean. Without proper chemical evidence, of course, it is impossible to say whether the dust fall incidents reported by Chladni are exclusively terrestrial in origin. The existance of well authenticated falls of meteoritic dust in connection with the falls of meteorites suggests that perhaps some events in the literature may represent true meteoritic material falling as dust.

One of the most interesting discoveries of the exploration of the ocean bottom that flourished in the latter part of the 19th Century was the discovery of what Murray and Reynard (1884) termed "cosmic spherules". In the deep ocean away from the continental shelf, fairly common constituents of the ocean bottom sediments, the spherules were found to be chemically fairly similar to meteorites. These objects have been studied extensively by increasingly sophisticated analysis techniques in the past hundred years (e.g., see Blanchard et al. 1979), and they indeed do seem to represent truly extraterrestrial objects. They are relatively abundant and it is found that they even sometimes include unaltered examples of interplanetary dust accumulated by the earth.

Research activity during the first half of the 20th century centered on attempts to collect interplanetary dust falling regularly to the surface of the earth. These attempts ranged from placing magnets in rain water downspouts (Nininger 1941) to placing buckets on rooftops (Thomsen 1953).

III. Backyard Collections

Most of the scientific literature on interplanetary dust produced during the middle part of the twentieth century resulted from simple collection experiments, often made without regard specifically to a clean site; frequently, in fact, in the investigator's back yard.

An example from the extensive literature based on "backyard" collections of dust is the study published by Thomsen (1953). Using various techniques of collection, principally basins of water left for several days at a time on the rooftops of buildings of a university in Iowa, Thomsen filtered out the residue and examined it microscopically and spectroscopically. He found large numbers of black spherules of the type apparently described by others and his analysis indicated that they contained large amounts of iron. He calculated that the total dust fall to the earth must be incredibly large, on the order of 2×10^9 kg/yr.

Thomsen's results were a turning point in the history of meteoritic dust collection because they were the first results of the "backyard" collectors to be widely criticized. As explained in Chapter 4, several scientists then pointed to the strong similarity in appearance between the magnetic black spherules assumed to be meteoritic and black spheres of man-made origin that are extremely numerous components of urban air.

It was thus realized in the mid-1950's that contamination of samples was a serious problem when collections of interplanetary dust were attempted at the surface of the earth. It could easily be demonstrated that most of the hitherto identified "cosmic spherules" were most likely largely made up of samples contaminated by the presence of unknown amounts of similar-appearing "industrial" spherules, derived from combustion in populated and industrial areas. For that reason, scientists moved their attention to collecting samples from areas far remote from population centers.

IV. The Consensus of 1960

By approximately 1960 data from the different sources on the amount of interplanetary dust falling to the earth, which until then had been so disparate, began to converge on a commonly accepted value. Table 1-1 summarizes the situation at that time and shows that the various sources all agreed on approximately the same total mass influx to the earth, between 500,000 and 1 million tons per year over the earth.

The convergence of data was the result of many factors and, as hindsight now shows, many errors of interpretation. The study of the ubiquitous black spherules had become pretty much limited to fairly remote sites, where the rate of fall was found to be much smaller than in the early investigations. Similar objects were being discovered in the atmosphere above the tropopause by newly developed aircraft collectors flying in excess of 40,000 feet. Within the uncertainties of these early aircraft experiments, the density of "cosmic" spherules found in the middle atmosphere was consistent with the rate at which they were found to fall to the surface at remote sites. Balloon collections in the upper atmosphere had been made and these seemed to demonstrate that even above 100,000 feet the atmosphere contained large numbers of dust particles and that the flux calculated from the balloon data was consistent with that found otherwise.

By 1960 another new and much more precise type of experiment was possible, using artificial satellites. Many of the first scientific experiments by artificial satellites

Table 1-1. The Consensus of 1960.

Type of object	Method	Rate of deposit, tons/year
Meteorites	Observed falls	10^2
Meteors	Visual counts	10^3
Dust spherules	Deep-sea deposits	10^2
Dust spherules	Antarctic ice	2×10^5
Dust spherules	Arctic ice	2×10^5
Dust spherules	Arctic air	5×10^5
Dust spherules	California mountains	5×10^5
Dust spherules	New Mexico mountains	2×10^5
Dust spherules	Stratosphere	2×10^5
All dust	Nickel in deep sea	10^6
All dust	Zodiacal cloud	10^6
All dust	Satellite data	10^6

launched both by the United States and by the USSR were designed to measure the space density of the interplanetary dust near the earth. Using various kinds of acoustic and photoelectric detectors, the satellite experiments also showed the presence of large numbers of dust particles and indicated in the early space age years that the particle density was approximately consistent with the earth-based influx data. Related experiments, which had been going on in the late 50's, used similar detectors to measure the density of dust by means of rockets, whose brief excursions carried them through the upper atmosphere and into the nearby extraterrestrial space. Although the rocket data was not always self-consistent, the average for many flights and for different experiments was nevertheless approximately in agreement with the data from both the ground and the satellites.

Thus by 1960 evidence from a large number of different kinds of sources was in agreement that approximately 1 million tons of interplanetary material was accreted by the earth each year in the form of dust particles. The only evidence that did not seem to agree with this consensus was in two forms: most analysis of the zodiacal light resulted in a prediction that only a few tens of thousands of tons of dust should be accreted by the earth if it all comes from the zodiacal light cloud; and second, a few satellites with very large apogees seemed to indicate that at large distances from the earth the dust density was very much less than derived for near earth orbit. In the case of the zodiacal cloud the architects of the 1960 consensus could argue that the optical interpretation of zodiacal cloud brightness was at best difficult and not unique. On the other hand, they explained the low densities of dust detected by large orbit satellites as evidence for a concentrated circumterrestrial dust cloud. The dust cloud hypothesis was worked out in considerable detail and several models were developed on theoretical grounds to explain this concentration. Unfortunately for the hypothesis, it was rather soon shown that not only were the observations upon which it was based completely faulty, but none of the theoretical models made physical sense when examined in detail.

It was not until the late 1960's that many of the false starts and errors of the previous hundred years' research in the field of interplanetary dust were discovered and put right. Largely because of greatly improved technology, the cosmic dust has been correctly identified and captured at last.

2. THE ZODIACAL LIGHT

I. Introduction

Until very recently the only quantitative information available on the nature of the dust between the planets was optical data. A faint glow in the sky, brightest near the sun and extending along the ecliptic, has been studied for centuries and is called the zodiacal light because it occupies the constellations of the zodiac. It is best seen in the early evening or just before dawn. It is virtually invisible at midnight, but at an angle of only 30^{o} from the sun it is as bright as the Milky Way. For a long time it was not known what gave rise to the zodiacal light, but one of the more commonly believed hypotheses has always been that the light is reflected sunlight from a band of dust particles concentrated to the ecliptic. It wasn't until the 1950's, however, that this hypothesis was proven correct through the detailed analysis of the spectrum and the polarizing properties of the zodiacal light.

Until recently, the zodiacal light has been studied mainly photographically and with specially-built photoelectric photometers and polarimeters. In order to avoid the complications brought about by the superimposed night sky light, astronomers studying the zodiacal light frequency went to high altitude observatories, including a station in the Bolivian Andes at an altitude over 5,000 meters. An active mountain top observatory was operated for many years by the University of Hawaii at a 3,000 meter altitude at Haleakala.

More recently the ultimate dark sky has been reached by putting zodiacal light photometers on spacecraft. The most interesting results from these studies have come from those interplanetary vehicles that provide information on the distribution of zodiacal light brightness with solar distance.

Fig. 2-1. The zodiacal light (from an old wood cut).

II. Early Studies

Modern astronomical studies of the zodiacal light can be dated as beginning in about the year 1946, at which time two independently-working astronomers carried out the first reliable detailed analyses of zodiacal light measurements and interpreted them in terms of the properties of the interplanetary dust. Allen (1946) and van de Hulst (1947) each worked out the geometry of the light scattering process from dust particles in the ecliptic plane and showed how the observed brightness distribution in both the zodiacal light and the outer solar corona could be interpreted as being part of the same dust cloud.

Not enough precise photometry and polarimetry had been done at that time for an exhaustive analysis of the dust particles, although van de Hulst was able to estimate some of the properties of the particles, including the space density and approximate size, in both cases coming close to values more recently derived from precise photometry.

Table 2.1

Early Observations of the Zodiacal Light

(after Blackwell and Ingham)

Observer	Latitude	Height (m)	Date	Brightness
Behr and Siedentopf	$+46^{\circ}$	3600	1952	3.17
Barbier	$+44^{\circ}$	585	1952/3	3.35
Roach et al	$+36^{\circ}$	1666	1952/3	5.38
Regener	$+34^{\circ}$	2850	1953/4	5.52
Blackwell	-16°	2800	1955	2.90
Elsasser	-29°	1400	1956	2.85
Divari and Asaad	$+24^{\circ}$	200	1957	3.26
Blackwell and Ingham	-16°	5200	1958	4.42

Because several early measurements disagreed strikingly, attempts in the 1950's were made to improve on the accuracy of the data. Most of the new measurements were made at high altitudes, in order to avoid as much as possible the problem of the atmosphere and the superimposed foreground of the night sky, which swamped the zodiacal light at even modest elongations from the sun. Another problem of low altitude observations comes from the importance of extinction by the atmosphere, which must be reliably determined in order to evaluate the zodiacal light measurements made, as they often are, near the horizon. Since both of these corrections can be minimized from mountain tops, starting in 1952 most measurements were made there. The first was made by Behr and Siedentopf (1952), who measured the characteristics of the zodiacal light from the Swiss Alps, where their photometry was carried out at an altitude of 11,700 feet (3,600 meters). At about the same time, Barbier was making measurements in France at approximately 600 meters altitude, while Roach and Elvey were measuring it photoelectrically at 1,670 meters. Even though these measurements were made with great care and with relatively modern equipment, the spread in the results was surprisingly large. Even the brightness measured by Roach and Elvey did not agree with Behr and Siedentopf's, being greater by a factor of about 50%. Regener made measurements in 1953-4 at an altitude of nearly 3,000 meters and got an even brighter value than Roach and Elvey. On the other hand, Blackwell in 1955 at about the same altitude found a brightness that was approximately half that found by Regener. It was thought at the time that some of the difference might be due to variations in the luminosity and other properties of the zodiacal light, but it has been found that most of what caused the difference can be attributed to observational errors caused by the great difficulty of the measurements.

A very extensive photoelectric study was carried out in 1956 by Elsässer, who did a complete map of the zodiacal light from the Boyden Observatory in Africa, at an altitude of 1,700 meters. The completeness of Elsässer's study was not exceeded until the now classical study by Blackwell and Ingham (1961), who went to the extreme of carrying their equipment to 17,000 foot high Mt. Chacaltaya. Although it was very difficult to work at such altitudes, Blackwell and Ingham's persistence resulted in a very complete and reliable study of the absolute surface brightness at 3 wavelengths, the polarization at 2 wavelengths, and a complete map of the position of the zodiacal light. They found that it was possible at these high elevations to measure the brightness and polarization of the light to as close as 19° from the sun.

The fundamental importance of the Chacaltaya observations was the careful determination of the spectrum of the zodiacal light, analyzed in detail by Blackwell and Ingham. The dispersion was 38A/mm and this was found to be adequate to plot the hydrogen line profile in considerable detail. They were encouraged to take such spectra by the results of Behr and Siedentopf (1953), who had interpreted the polarization of the zodiacal light in terms of a concentration of free electrons to the ecliptic. Theirs were the first reliable measurements of polarization and the results were surprisingly large; a maximum value of about 23% was reported for elongations on the order of 30°. This seemed to Behr and Siedentopf to be unlikely to be accounted for entirely by dust particles and therefore they supposed that there must be

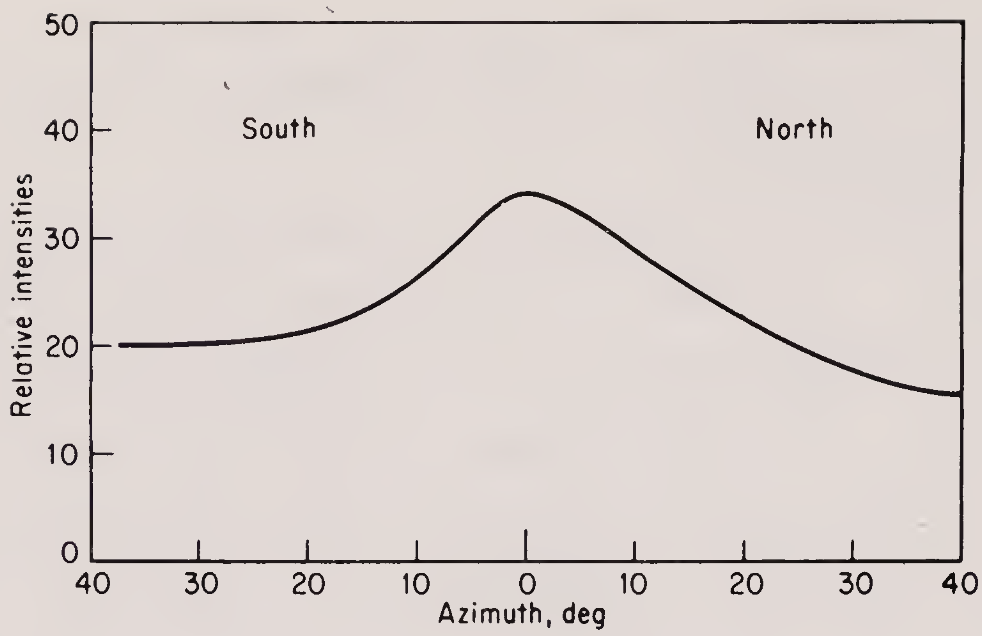

Fig. 2-2. A sample photometric scan of the zodiacal light intensity made by Blackwell and Ingham. Reproduced from Brandt and Hodge (1965), courtesy McGraw-Hill Book Co.

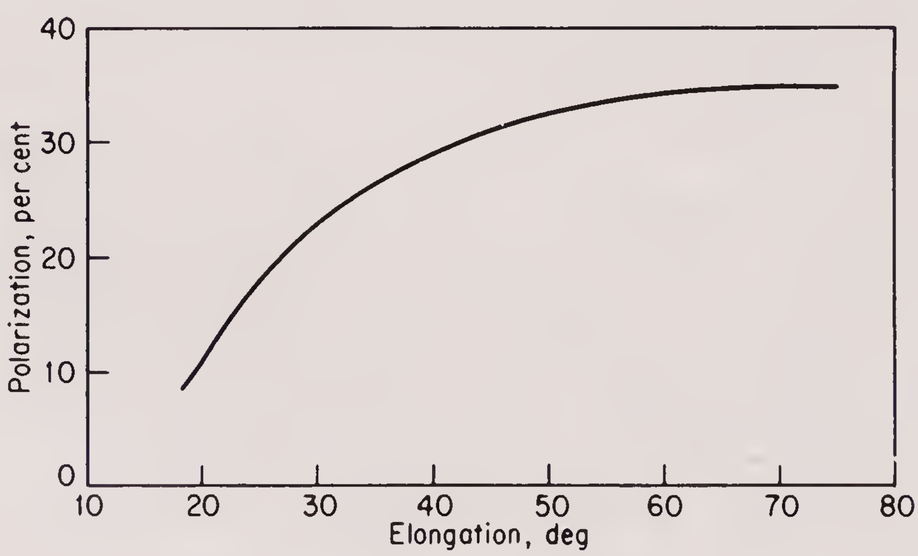

Fig. 2-3. Blackwell and Ingham's polarization curve for the zodiacal light. Reproduced from Brandt and Hodge (1965), courtesy McGraw-Hill Book Co.

a considerable contribution from electron scattering, probably as much as 50% of the light coming from that source. If it were assumed that the dust did not polarize light and that all polarization was due to electrons, then they calculated that the density of electrons in the zodiacal cloud must be as large as 600 per cubic centimeter at a distance of 1 AU from the sun. An apparent confirmation of this was obtained by Beckers (1959) who analysed an old spectrum of the zodiacal light obtained years before by Hoffmeister (1939). Beckers concluded that on the order of half of the zodiacal light must be due to electron scattering.

However, Blackwell and Ingham's spectra showed no contribution from electrons, and they deduced that the electron density at the earth's distance from the sun must be less than 120 per cubic centimeter. This is much too small a density to account for the polarization of the zodiacal light, and it was therefore concluded that the polarization must be due primarily to the dust particles themselves.

Blackwell and Ingham's measurement of the color of the zodiacal light agreed with most previous careful measurements in showing that it is very similar to the color of the sun. They found it slightly more red, whereas Behr and Siedentopf had found it slightly more blue. In either case, it was an indication that the particles were moderately large, not on the order of the size of the wavelengths used. Most particles are found to be in the range of approximately 1 to 10 microns. Scattered light from particles smaller than 1 or 2 microns is always bluer than the light incident on them, whereas particles larger than approximately 100 microns make the light redder.

III. Recent Studies

In the years since the mid-1950's, great effort has

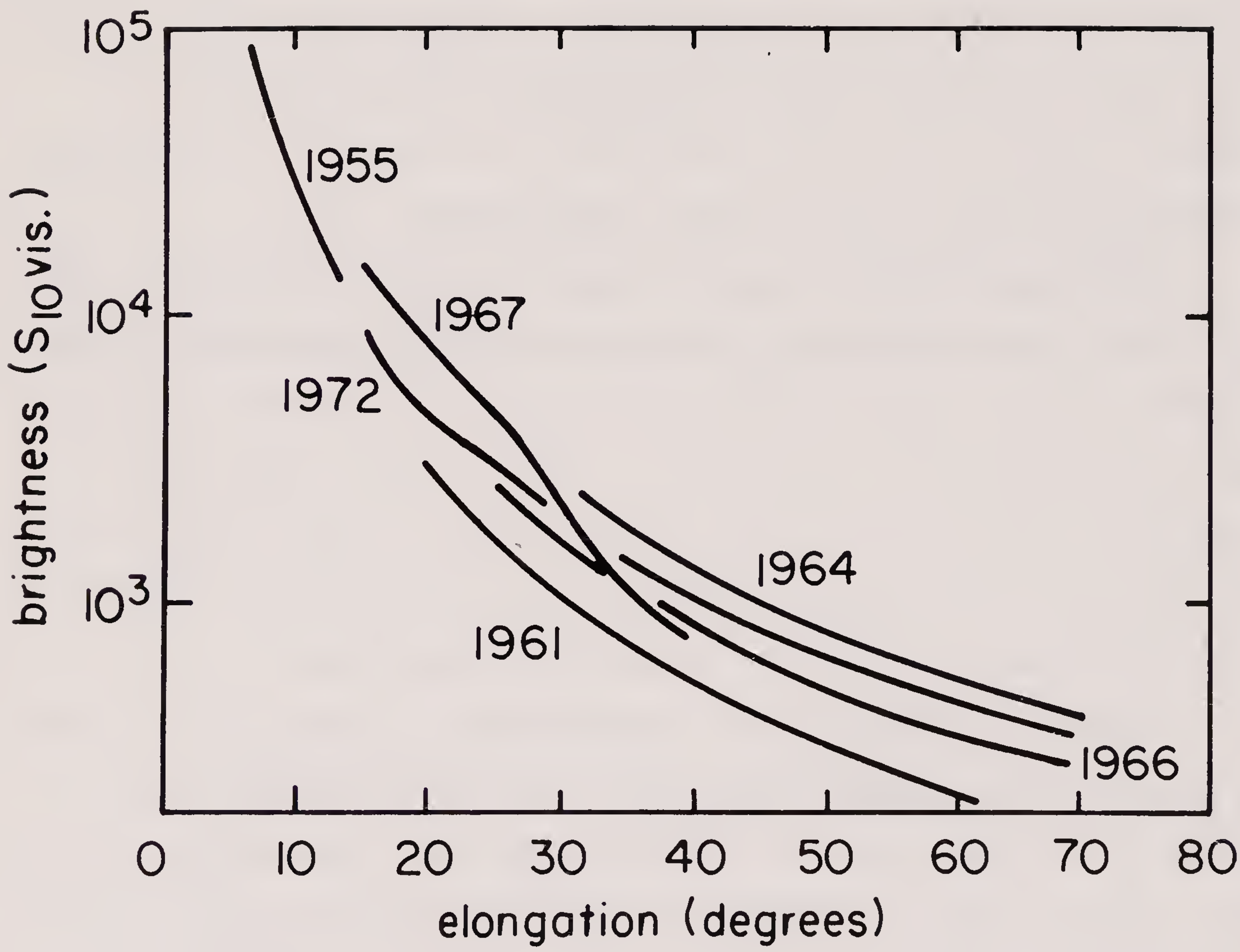

Fig. 2-4. A comparison of traditional and modern measures of zodiacal cloud brightness.

been made towards refining the observations of the zodiacal light, both using ground-based photometry and satellite-borne instrumentation. Weinberg (1964), Roach and Smith (1964), Gillet (1967) and Wolstencroft and Rose (1967) provide examples of the many important modern measurements of the brightness and polarization of the zodiacal light at elongation angles in the range 20° to 70°. Figure 2-4 shows a comparison of these data with the earlier measurements by Elsässer (1958) and Blackwell and Ingham (1961). It shows that the mean value has an uncertainty of about 50%, and that the early data, carried out in the 1950's, tend to be lower than the more recent measurements.

It is also found in these recent studies that the color of the zodiacal light is very similar to the sun at most elongations. Figure 2-5 shows the color of the sun compared to measurements made at elongations ranging from 20° to 130°, illustrating the fact that there is an apparent change in color to redder values at the large elongations. At elongations smaller than 60°, the color of the zodiacal light is indistinguishable, within observational uncertainties, from the sun, while the data for large elongations indicate an approximately 30% redder color, possibly showing the influence of larger particles. All of the data in Figure 2-5 are from rocket and spacecraft measurements. Color measurements even from high altitude ground-based observatories are usually quite uncertain.

Modern measurements of the polarization of the zodiacal light are less well in accord with the older measurements. Figure 2-6 compares the polarization curves derived in the 1950's with several derived in the 60's and 70's. It is clear that the results found in earlier times were considerably too large, leading to the quandry alluded to above in interpretation. Because it is very difficult to explain polarizations as large as 30° for light that is polarized purely by the influence of dust particle scattering, the new measurements, which do not exceed 20%, are in better agreement with theoretical interpretation.

The advent of photometers carried on board interplanetary space vehicles has recently allowed the determination of the radial dependence of the zodiacal light brightness. For example, the Pioneer 10 Jupiter probe passed through the asteroid belt and out into Jupiter's environment in 1973, and the asteroid-meteoroid detector on board was used by Soberman, et al. (1974) and the imaging photopolarimeter by Weinberg et al. (1973) to study the zodiacal light (see Ch. 10).

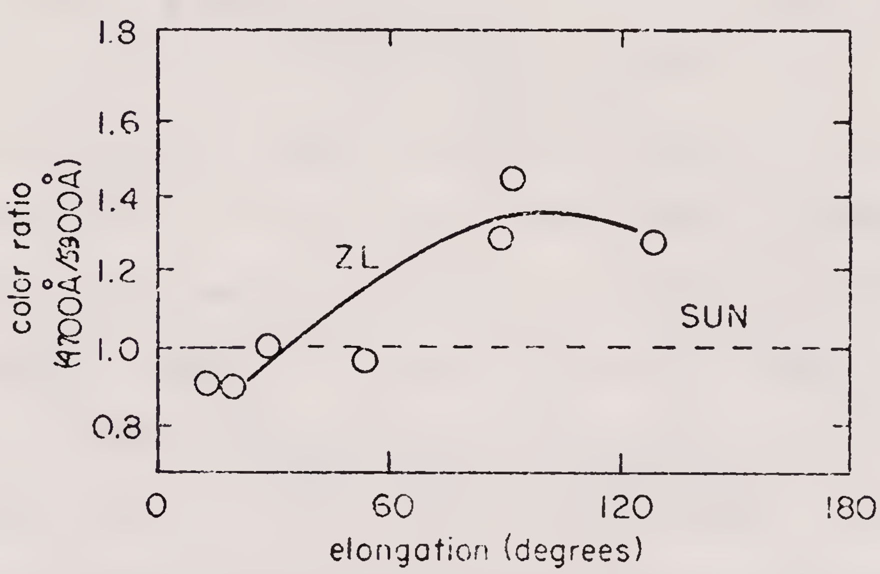

Fig. 2-5. Measures of the color of the zodiacal light compared to the sun's color.

IV. The Gegenschein

Although not at first included as a related phenomenon in most discussions of the zodiacal light, the gegenshein is now recognized to be a manifestation of the same objects.

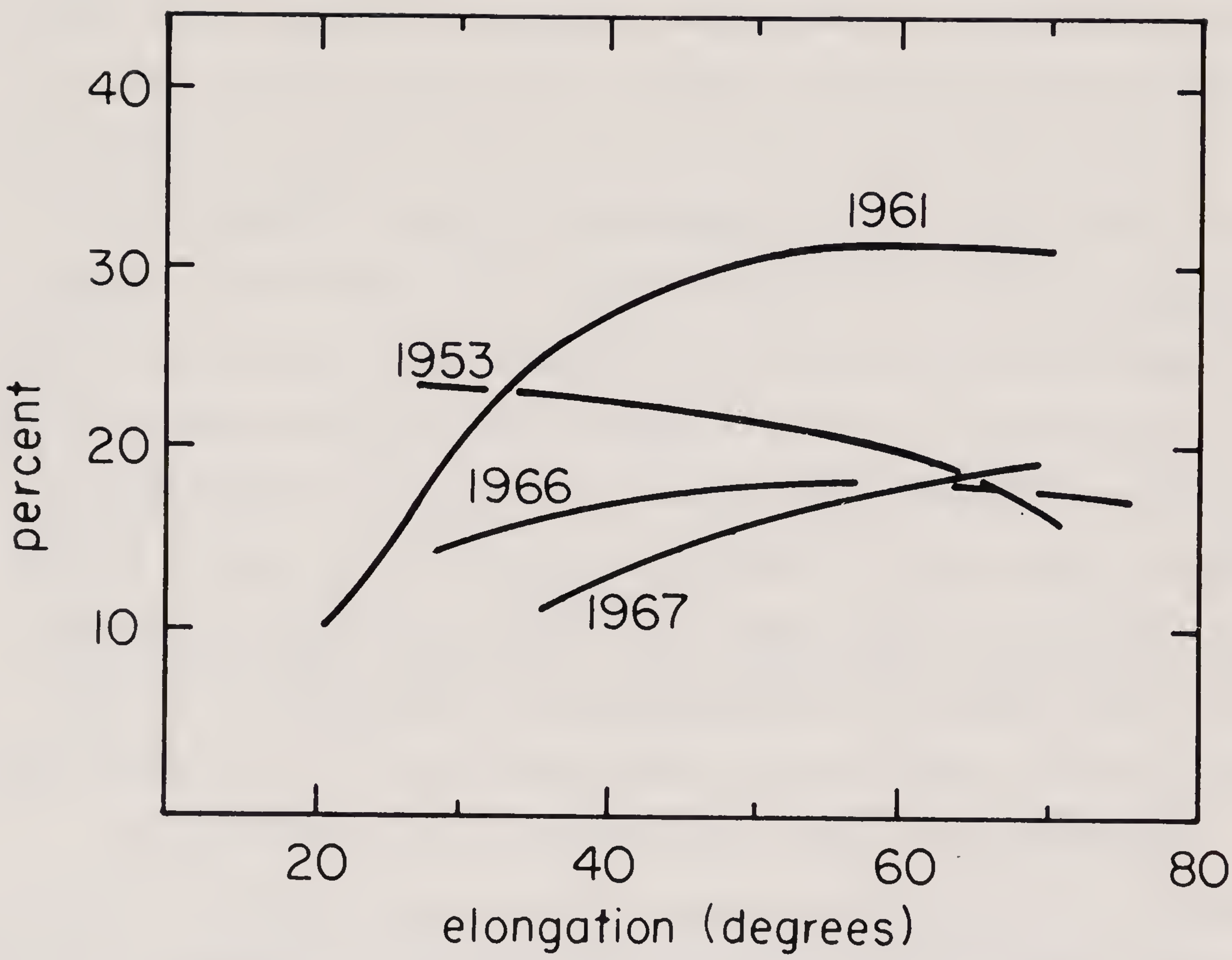

Fig. 2-6. Recent polarization measures compared to traditional ones for the zodiacal light.

The gegenschein was given its name because of its location, almost exactly opposite the sun in the sky. It is a small (10-20^{o}) elliptical spot of light of low intensity that can be seen in the anti-solar position when the sky is exceptionally dark. Recent ground based measures of the gegenschein have been made by Roach and Rees (1976), Weinberg (1964), Dumont (1965) and Smith, Roach, and Owen (1965). All of these measurements have shown an extent of some 5 or 10^{o} in radius for the brightest parts of the gegenschein, with a tail in the brightness distribution extending to distances as large as 20^{o} from the anti-solar point. Figure 2-7 shows these data and compares them with even more recent data measured on the Pioneer 10 spacecraft, as well as similar data obtained from the orbiting solar observatory OSO-6 (Ruoy et al 1972). The Pioneer 10 data were obtained by Weinberg et al (1973) and agree well with the OSO-6 data, but both sets of spacecraft measurements disagree significantly with the ground-based data in brightness. It is probably not a significant difference but it is considered that the difficulty from the ground of determining the brightness at the exact center of the gegenschein is considerable because of its very low surface brightness, which requires large-diaphram photometry to be carried out. This can possibly cause a flattening of the intensity distribution at the center that is artificial.

The gegenschein was originally a puzzle as to its origin, with many conflicting theories having been proposed. Some of these involved close earth-associated dust, such as a dust tail for the earth similar to a comet tail or other localized concentrations. It was even suggested that the gegenschein might be due to dust concentrations located at the quasi-stable position of the antisolar libration point

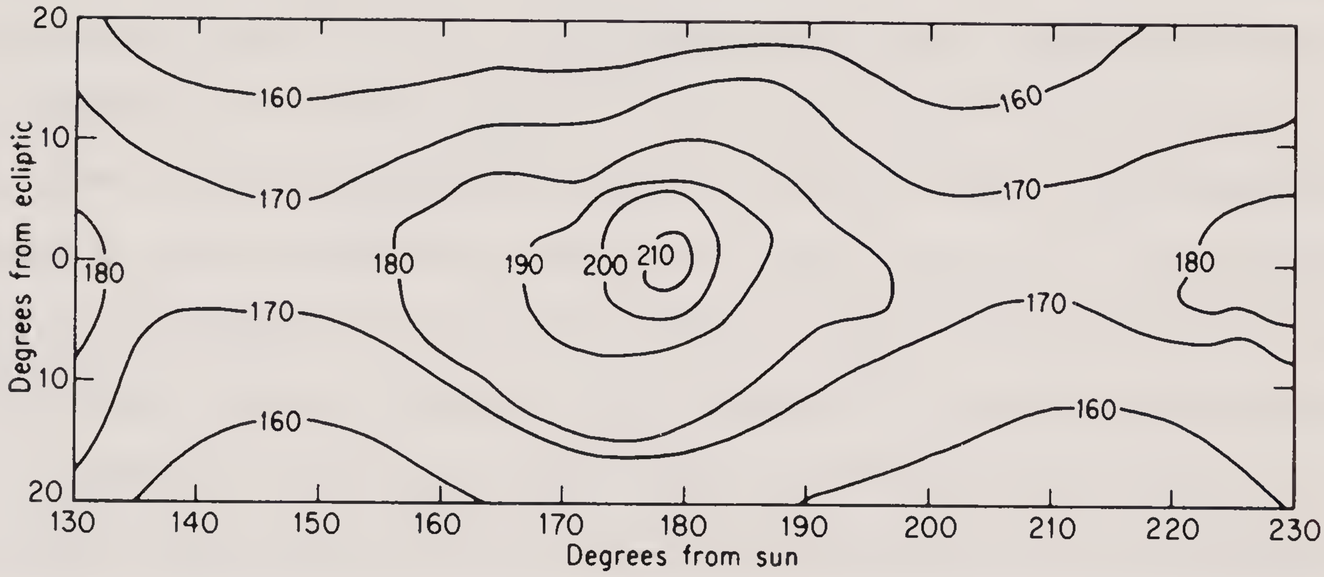

Fig. 2-7. Isophotes of the gegenschein derived from the photoelectric scans of Roach and Rees. The units are numbers of 10th magnitude stars per square degree.

of the earth-sun system. Careful calculations, however, indicate that the total amount of luminosity in the gegenschein is too great to be explained by the relatively small number of particles that would be expected to be caught and concentrated by the libration effect. Other ideas have involved a gaseous tail, suggesting that the observed light is a result of excitation of gases from the earth's atmosphere that are excited by the interplanetary gas. All of these tentative suggestions were put to the test by the spacecraft measurements, which have shown that the gegenschein is made of dust and that the dust particles have the same properties as the zodiacal light particles and in fact are probably the same objects. The reason for the brightness at the anti-sun direction is the fact that the phase function shows a maximum at 180° phase angle, a not unreasonable result for dust with a wide variety of properties. Roosen (1970) had similarly concluded this before the spacecraft data became available, basing his deduction on an extensive photometric study carried out at the McDonald Observatory in Texas.

V. Interpretation

If the zodiacal light is interpreted to be due to solid particles distributed along the ecliptic between the earth and the sun, then it is possible from the observed brightness curve (luminosity vs. elongation) to gain some idea of the true space density of these particles by simple geometry. If we take I to be the flux of solar radiation measured in ergs/sec/cm^2 at the Earth, then we can consider how much energy is received by a cylinder with its axis in the line of sight, with a length dx, a cross section a, and a distance from the sun y, with a distance from the earth x (see Figure 2-8). The energy received per second by the particles in this cylinder depends on the space density of

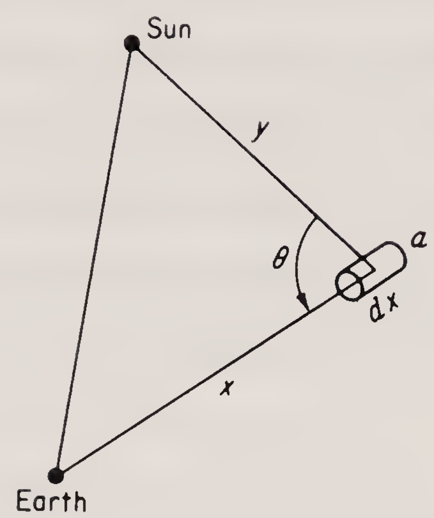

Fig. 2-8. Geometry of the zodiacal light (reproduced from Brandt and Hodge, 1965, courtesy of the McGraw-Hill Book Co.).

these particles (ρ, in number per cubic centimeter) and on the mean cross-sectional area of the particles, A. This energy is simply

$$\frac{I\rho aAdx}{y^2}.$$

Some of this radiation will be scattered towards the earth through an angle θ. The intensity of that radiation will depend on the distance between the earth and the cylinder, and on the efficiency of the process of scattering for the particular angle θ, called the phase function f(θ). If we use this to calculate how much radiation the earth receives from such a cylinder, it is found to be

$$\frac{I\rho A(a/x^2)f(\theta)dx}{y^2}.$$

If we now consider the solid angle subtended by a at x, which is a/x^2, then the flux per unit solid angle becomes

$$\frac{I\rho Af(\theta)dx}{y^2}.$$

It is now a simple matter to calculate the surface brightness in the sky that we will see from the earth at a particular angle, ϵ, from the sun. If the total surface brightness at a given elongation angle is defined as $B(\epsilon)$, then we find

$$B(\epsilon) = I\int_0^\infty \frac{\rho Af(\theta)}{y^2}\,dx.$$

This can be expressed in terms of the scattering angle by using the following relationships

$$y = \frac{\sin\epsilon}{\sin\theta} \quad \text{and} \quad dx = \frac{\sin\epsilon . d\theta}{\sin^2\theta}$$

These lead to the following equation

$$B(\epsilon) = \frac{I}{\sin\epsilon}\int_\epsilon^\pi \rho Af(\theta)d\theta$$

Since this equation includes the known intensity of the sun, I, the elongation angle, which is also known, and properties of the dust (the density, size, and phase function), it is possible to derive a considerable amount of information about the zodiacal cloud, including the distribution of particles in space, by the way in which B varies with solar elongation angle.

A large number of attempts have been made to determine scattering functions for likely kinds of particles so that a reliable value for f(θ) can be used in the above equations. Most simple comparisons have used Mie theory and spherical particles, but since such particles are not likely to be realistic models of the particles in space, this simple theoretical analysis is unreliable. An example of some fairly sophisticated attempts to use Mie theory was given by Giese and Siedentopf (1962). Table 2-2 is taken from their analysis and shows that the number of particles and the types of particles are closely interrelated. Their data was unfortunately influenced by their attempt to fit polarization measurements that were made from the ground, and that are now known to be too large. This forced them to assume large numbers of electrons (as many as 300 per cubic centimeter) in the zodiacal cloud. Particle radii in their calculations ranged from 0.2 microns to 10 microns and the dust spatial density law showed a falloff with distance from the sun that is approximately cubic for water and approximately as $r^{\frac{1}{2}}$ for iron dust particles.

It is of some interest to compare the results of such calculations with the known properties of the interplanetary dust as deduced recently by various means (spacecraft and high altitude aircraft). Blackwell and Ingham, for example, found that the lower limit to the size of the particles that could be responsible for the zodiacal light was on the order of 0.3 microns, whereas the upper limit seemed to be on the order of 1 mm. The mass densities and number densities are on the order of 1.4×10^{-26} grams per cubic cm and 200 per cubic km, respectively. These values, of course, depend on the assumed physical density of the particles themselves, which in this case was taken to be 1.1 grams per cubic cm by Ingham (1961).

The values of these physical parameters are surprisingly close to those recently determined directly by impact with space probes. They were, however, in very poor agreement with the early spacecraft dust detectors, which at that time lead to considerable consternation among the zodiacal light workers. It was assumed that there must be some large factor that was not being taken into account in the analysis and a great deal of needless searching for this factor went on before eventually it was shown that the early spacecraft measurements themselves were at fault.

The most promising recent zodiacal light research involves the work of Giese and his colleagues, who are examining the optical properties of large, low-density, fluffy particles. Such models compare well with current photometric and polarimetric measurements of the zodiacal light.

Table 2-2

Two Models of Giese and Siedentopf

	Composition	Spatial Density Law	Particle Radius (μ)
Model I	Dielectric dust H_2O (m = 1.33)	$n_d = \frac{10^{-15}}{r^{3.5}} + 5\times10^{-13}$ (cm^{-3})	$1 \leq a \leq 10$
	Electrons	$n_e = \frac{0.5}{r^3} + \frac{10^3}{r^{0.5}}$ (cm^{-3})	----
Model II	Dielectric dust H_2O (m = 1.33)	$n_d = \frac{3\times10^{-15}}{r^3}$ (cm^{-3})	$1 \leq a \leq 10$
	Metallic Dust Fe (m = 1.27-1.37i)	$n_d = \frac{1.5 \times 10^{-13}}{r^{0.5}}$ (cm^{-3})	$0.2 \leq a \leq 10$
	Electrons	$n_e = \frac{5}{r^3} + \frac{300}{r^{0.5}}$ (cm^{-3})	----

I. Introduction

It was recognized over a hundred years ago (Nordenskiold 1874) that interplanetary dust could be collected by searching for deposits in terrestrial sediments, especially in ice sediments at the polar regions, where other kinds of dust should be minimal in amount. The recognition and study of such dust particles has turned out to be much more difficult than was originally assumed and there still remains a considerable amount of uncertainty about the particles so collected. We will term such samples "fossil collections", to indicate that they were collected in sediments at the earth's surface, regardless of whether they are in ice deposits, in sedimentary rocks, or in soil or beach deposits.

II. Types of Particles Recognized

The different kinds of particles collected in fossil deposits can be divided into four different classifications.

1. Opaque micron-sized spheres, often called "cosmic spherules".
2. Transparent spherical particles, either clear or colored.
3. Irregular particles, usually with a metallic sheen.
4. Particles that are not actually seen in the samples, but are detected by the bulk analysis of samples by chemical means and by recognition of the cosmic component from its chemical abundances.

These different types of particles are not necessarily divided above into physically or chemically distinct groups, but the classification is the result of the necessary separation of objects under the microscopes by their appearance. The "cosmic spherules" range in detailed physical appearance from spheres that have a shiny smooth metallic luster to those that have a dull black color and low albedo. They have been found virtually everywhere, from the bottom of the ocean to the surface of the moon. Obviously, because of the broad and general nature of this classification, particles of this sort come from a wide variety of different sources, including both extra-terrestrial sources for a few and terrestrial for probably the majority of such spherules studied in the laboratory.

The transparent spherules on the other hand, have not been so thoroughly studied, partly because of their somewhat smaller numbers in most deposits and partly because of their less obvious connection with meteoritic material. Table 3-1 summarizes the frequency of occurance of those three different kinds of spherules identified in Greenland glacier samples. Most of the spherules, both transparent and opaque, are smaller than about 100 microns, though Langway reports a glassy spherule as large as 230 microns in diameter from Greenland ice deposits.

Primarily because of the difficuly of recognizing them under the microscope and because of the historical lack of conviction that such particles can be separated easily from the vast numbers of terrestrial particles of this nature, irregular cosmic particles in fossil deposits have been rarely discussed in the literature. It is well known that even in the polar regions there are fairly large numbers of particles of terrestrial origin transported by winds from land masses and therefore that the chances of finding an irregular particle in the ice deposits that can be proven to be interplanetary in origin are very small. Wright, Hodge, and Langway (1963) used a microprobe to analyze fifty-seven different irregular particles, primarily from ice deposits both from the south polar regions and from Greenland. They

Table 3-1. Frequency of Types of Microscopic Spherules in Greenland Samples (from Langway's Classification).

Microscopic Appearance	Spherules (%)
Black or gray, metallic	59.1
Black, vitreous	21.7
Colored	19.2

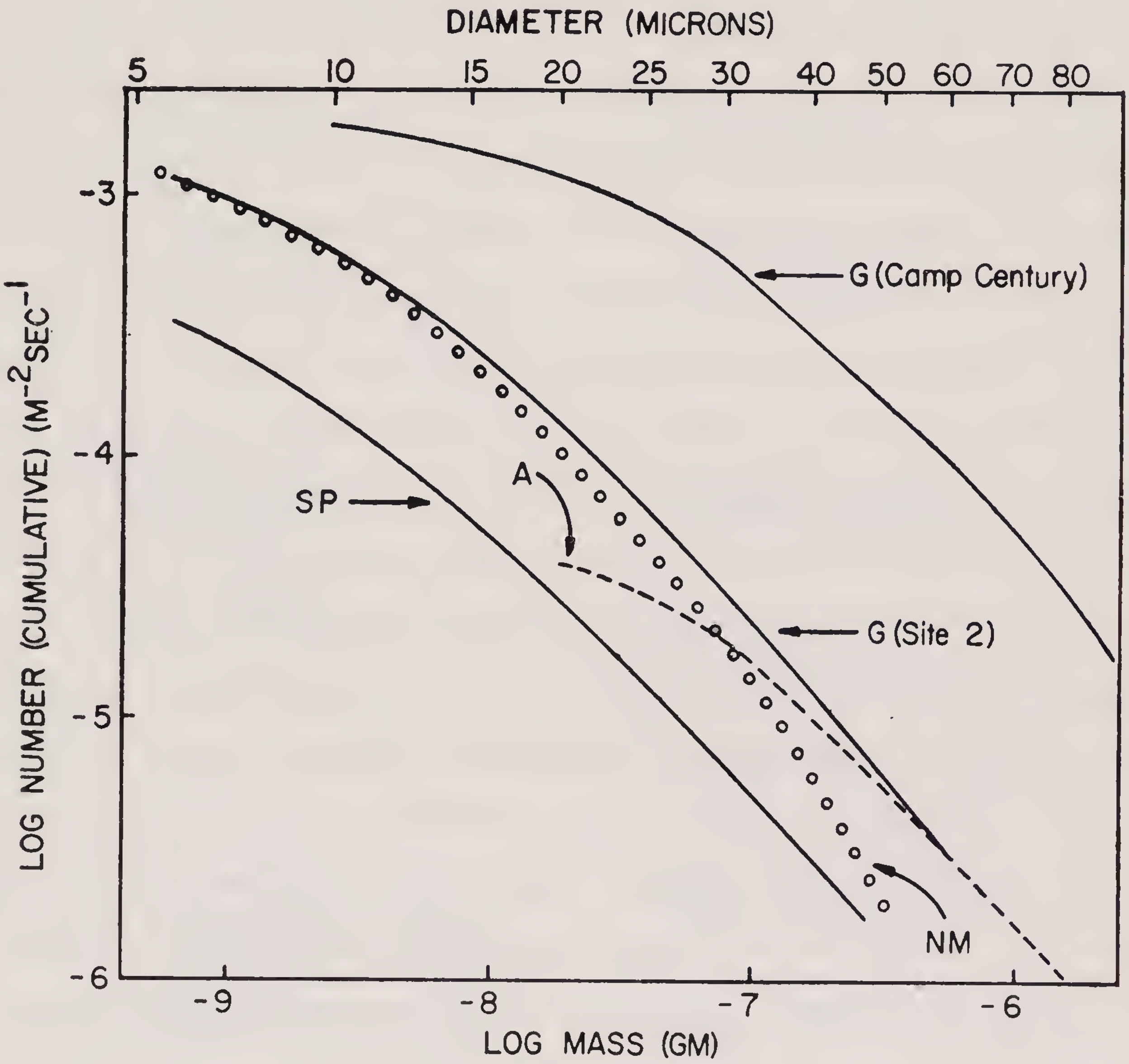

Figure 3-1. Cumulative size distributions of numerical rates of deposition of spherules. SP, south pole spherules; A, antarctic spherules reported by Thiel and Schmidt; NM, Crozier's spherules; counts of G (site 2), Greenland spherules; G (Camp Century), Greenland spherules (after Hodge et al., 1964).

subdivided the particles into six different classes according to their microscopic appearance and found that they could be divided chemically into four different groups: those with large amounts of iron and measurable amounts of nickel (assumed to be meteoritic in origin), those that were iron-rich but contained no detectable nickel, those that were silicon-rich, and a miscellaneous group that contained particles with a wide variety of different chemical abundances.

III. Spherules in Geological Deposits

The environments in which the first class of particles, the iron-rich spherules, have been found are summarized in Table 3-2. Two examples from a wide variety of sedimentary rock samples are given in that table as environments #10 and 11, dealt with in the literature by Mutch (1964) and Lougheed (1966), respectively. Both scientists found that the terrestrial sediments examined, which had a wide range of geological ages all greater by far than the period of possible terrestrial contamination by artificial means, were rich in the presence of black spherules of supposed extra-terrestrial origin. Mutch's (1964) analysis of Paleozoic salts showed that such spherules, relatively common in the sediments, were similar in composition, size distribution, and surface appearance to those collected at other sites and in some more recent sediments, such as the glacial deposits and deep sea samples. Other studies of geological samples in which these spherules occur have been published by Crozier (1960), Skolnick (1961), Hunter and Parkin (1961), Viyding (1965), Kaye and Mrose (1965), Marvin and Einaudi (1967), and Manecki and Skowronski (1970).

IV. Particles in Glacial Deposits

Sites and Ages. Table 3-2 lists four different examples

Table 3-2. Environments in Which Iron-Rich Spherules Have Been Identified (from Hodge and Wright 1967).

Location	Description
Atmosphere	
1. Settling at surface at isolated sites	~3 to 100 μ in size, uniform rate of deposit over large part of earth
2. At 10–15 km in stratosphere	Very rare, small
3. At 25 km in stratosphere	Rare, small
4. Upper atmosphere above 80 km	Extremely rare, small
Ocean sediments	
5. Magnetic fraction	Large spherules
Ice deposits	
6. Greenland 750-yr-old ice	Relatively common
7. Antarctic 55-yr-old ice?	Relatively common
8. South Pole 55-yr-old ice	Relatively common
9. Ice Island T 3, various depths	Relatively common
Sedimentary rocks	
10. Paleozoic salts	Relatively common
11. Other sediments	Relatively common
Meteorite craters	
12. Sikhote-Alin	Spherules in soil and on meteorite surfaces
13. Arizona (Canyon Diablo)	Rough spherules in soil
14. Henbury	Smooth, perfect spherules in soil
Volcanic ash	
15. Pacific Islands	Rare, perfect spherules
16. North, Central, and South America, and Hawaiian volcanoes	Rare, perfect spherules
17. Various volcanic deposits	Rare, perfect spherules
Industrial smoke	
18. Fly ash	Spherules common
19. City air	Spherules common

of glacial deposits in polar regions that have been used to study the possible extra-terrestrial dust particles. These include only studies of individual particles and do not include other kinds of studies such as the important French studies dealing with the bulk analysis of South Pole deposits reported by Brocas and Picciotto (1967) and Hanappe et al (1968). Bulk analyses of melted ice from central Greenland have also been made (McCorkell, Fireman and Langway 1967).

In the four sites listed in Table 3-2, large numbers of black magnetic spherules were detected. The sites range from deep ice cores from the center of Greenland, to cores near the edge of the Greenland ice cap, to shallow and deep cores taken from floating north polar ice islands, to cores taken at various locations in Antarctica. Their ages range from 750 years for some of the Greenland ice samples to relatively young ages, on the order of 50 years, for the Antarctic samples. Even younger samples were collected from ice caves in the Paradise Glacier of Mt. Rainier (Wright, Hodge and Langway 1963). Other studies have been reported by Shima and Yabuki (1968) and Hanappe et al (1968).

Methods of Collection. Most of the glacial deposits were collected by standard glaciological methods of obtaining ice cores and then subsequent melting and filtering the sediments. A wide variety of different individual ways of carrying this out and of avoiding contamination of the samples was described by Langway (1966). Schmidt (1963) has also discussed the procedures for collecting dust in a contamination-free manner, in this case from Antarctica. After melting the samples, all further analysis procedures were carried out in a dust free box. Others (Hodge, Wright, Langway 1967) have also found that it is essential to make analyses of particles (filtering, counting, micro-photography, etc.) in a dust free room because of the large numbers of similar-appearing particles that are common in the neighborhood of all centers of population.

Particle Counts. In order to determine the number of particles of various types that fall to the surface at the polar regions and that are trapped in glacial deposits, it is necessary to know the rate of deposit of the ice itself and and to make particle counts in the ice. The rate of snow deposit and ice accumulation (as well as the age of the ice) can be obtained from cores in which the seasonal change in ratio of oxygen 16 to oxygen 18 is monitored. Detailed particle counts are available only for the most easily recognized particles, the spherules. Table 3-3 is the result of a study of the rate of deposition of spherules in Greenland ice (Wright, Hodge and Langway 1963). The number of particles in each size range from 95 microns down to 8 microns is shown, both the cumulative number counted in the samples examined and the cumulative number calculated to have been deposited per second per square meter on the Greenland ice sheet.

By comparing the rate of deposition of different kinds of particles from different times and different regions over the earth, it should be possible to distinguish particles of an extra-terrestrial origin from those of a local origin, unless of course there are terrestrial particles that are so widely dispersed over the earth that their rate of deposition is essentially uniform. Figure 3-1 shows a comparison of four cumulative deposition-size distributions for glacial deposits (spherules only), and compares them with a similar diagram for spherules deposited at remote sites at the surface of the earth in modern times (Crozier 1962). The

Table 3-3. The Rate of Deposition of Spherules in Greenland Ice (from Wright et al. 1963).

Diameter, μ	Cumulative Number Counted	Cumulative Number ($m^{-2}sec^{-1}$) X10^5
>5	336	
>15	152	13.9
>25	51	4.6
>35	21	1.9
>45	8	0.73
>55	3	0.27
>65	1	0.066
>75	1	0.066
>85	1	0.066
>95	1	0.066

Table 3-4. Different Chemical Classes of Particles From Glacial Ice (after Wright et al. 1963).

Class	Chemical Properties
Group I	Iron-rich spherules with nickel
Group II	Iron-rich spherules without nickel
Group III	Silicon-rich spherules
Group IV	Other spherules
Group V	Iron-rich irregular particles with nickel
Group VI	Iron-rich irregular particles
Group VII	Silicon-rich irregular particles
Group VIII	Other irregular particles

various sources of information agree fairly well, considering the uncertainties involved in the calculation of deposition rate and considering the different methods used by the different investigative teams. This, combined with the fact that these sources also have particles of similar chemistry (see below), led to the conclusion at the time these data were obtained that the black magnetic materials found in glacial deposits must be primarily interplanetary in origin. However, the cumulative graph does show differences that might be considered significant especially at the large size distributions (though, of course, the numbers of large particles in all cases were small and statistics poor). Thus there was some indication for doubt about the agreement of the results of different sites in detail, and this was taken to be most likely interpretable in terms of uncertainty in the rate calculations rather than in large differences in the rates. The largest discrepancy occurs for Camp Century, collected from the same ice sheet as Greenland Site 2.

If a cosmic origin is assigned to the iron-rich Greenland spherules obtained from the 9.3 years Site 2 profile studied by Wright, Hodge and Langway (1963) in snow deposited 750 years ago, the total influx over the earth of extra-terrestrial dust of this form is calculated to amount to 2 x 10^5 tons per year. Thiel and Schmidt (1961), from Antarctic ice samples, calculated 1.8 x 10^5 tons per year as the rate of deposit for similar spherules, and we see, therefore, that the integrated rate of deposition from the two polar regions is very similar.

Particle Chemistry. Large numbers of particles from glacial sediments have been analyzed for their chemical abundances, primarily by microprobe techniques. Table 3-4 gives as an example the main chemical constituents of 8 different groupings based on chemical abundances for a wide variety of particles from glacial ice. By far the majority of particles from Greenland ice, for example, are of composition group 2, with probably an equal number for composition group 8, which is primarily a miscellaneous grouping of a variety of different chemical patterns. Of most interest from the point of view of extra-terrestrial origin are particles from groups 1 and 5, both involving large amounts of iron with significant amounts of nickel. Particles from group 1 were found to be rarer in the glacial ice deposits than the iron-rich spherules, on the order of 5% as abundant. Particles of composition class 5, on the other hand, were somewhat more common, making up some 15% of the sample. Table 3-5 gives compostion data for several particles of these types, all of which are indistinguishable from the composition of iron meteorites. Also in Table 3-5 are a few examples of the iron-rich spherules that do not contain detectable nickel.

The different chemical classes of particles found in polar ice deposits have been assigned possible origins and rates of deposition (in metric tons per year) in Table 3-6, which is based on calculations published by Hodge, Wright and Langway (1964). The origin of the iron-rich spherules is still highly questionable and will be discussed below. The rate of deposition of the iron-rich irregular particles given in Table 3-6 is highly approximate, not reliably determinable from the data used because of the uncertainty in the frequency of particles of this chemical type and how this frequency might have been influenced by the collection process.

Bulk Analysis. Several important studies have been made of the bulk chemistry of polar ice deposits, comparing these with abundances and abundance ratios for terrestrial and

Table 3-5. Chemical Abundances in Some Individual Spherules From Glacial Ice (from Wright et al. 1963). (Percent by Weight)

Mean Diam., μ	Al	Si	Ca	Ti	Cr	Mn	Fe	Co	Ni
13		∿3	4-5				60-65		10-12
50							30-35		∿5
15			∿0.5	1-2		t*	70-75		
20		t			1-2	3-4	80-85		
20						t	80-85		
50		∿10	1-2				75-80		
30					1-2	2-3	70-75		
15		∿1			1-2	3-4	70-75		
15		∿3	∿0.5	∿0.5			70-75		
17	t?		3				70	t	

Table 3-6. Rates of Deposition Calculated for Glacial Particles of Different Types (from Hodge et al. 1967).

Type of Particle	Probable Origin	Rate of Deposition tons/yr
Fe-Ni spherules	Meteoritic ablation	10,000
Fe-rich spherules	?	200,000
Si-rich spherules	?	40,000
Fe-Si-Al-Ca-Ti spherules	Volcanic	50,000
Fe-Ni irregular particles	Micrometeorites or meteorite fragmentation	∿200,000
Fe-rich irregular particles	?	∿200,000
Si-rich irregular particles	?	∿400,000

"cosmic" bulk chemistry. For example, Hodge and Wright (1967) derived bulk elemental abundances for 14 key elements based on their counts and particle microprobe data, comparing polar dust with chondritic and cosmic abundances (Table 3-7). Table 3-8 compares these with McCorkell, Fireman and Langway's (1967) results from large-scale bulk analyses of Greenland ice and Table 3-9 compares them with the interesting data collected from bulk analyses by Brocas and Picciotto (1967). The relative depletions seen in the data of Table 3-9 with respect to the mean earth crust ratios is very conspicuous, and leads to the conclusion that a large fraction of the polar dust is sufficiently different chemically from terrestrial materials to argue for further intensive study of its origin.

Isotope Abundances. The anomalous abundances of both radioactive and stable isotopes in extra-terrestrial material, caused by the incidence of solar wind cosmic rays, can also be used to distinguish the presence of extra-terrestrial material in terrestrial sediments (McCorkell et al, 1967). Lal and Venkatavaradan (1966), for example, examined the Al^{26}/Be^{10} ratio for sea sediments, from which it was concluded that an excess in the Al^{26} is due to extra-terrestrial material. An influx rate of about 3×10^5 tons per year was deduced (Parkin and Tilles, 1968); this value is consistent with the conclusions based on a similar experiment carried out by Wasson, Alder and Oeschger (1967) and McCorkell et al (1967).

Sea sediments were searched for Cl^{36} by Shaeffer, Megrue and Thompson (1964), who derived an upper limit of $\sim 2 \times 10^6$ tons/year. Argon abundances (Tilles 1966) and He^3 concentrations (Merrihue 1964) have also been examined in deep sea deposits and evidence for extra-terrestrial material

Table 3-7. Weighted Average Chemistry of Polar Dust Compared with Chondritic and Cosmic Abundances (Relative to Iron; from Hodge and Wright 1967).

Element	Polar Dust	Chondrites	Cosmic
Mg	1.7	90	680
Al	4.1	10	45
Si	76	130	850
P	0.01	0.6	6.8
S	0.7	12	600
K	0.3	0.4	1.8
Ca	5.8	12	42
Ti	1.0	0.6	2.1
Cr	2.7	2.6	6.5
Mn	0.7	1.3	3.5
Fe	100	100	100
Co	1.0	0.5	1.5
Ni	2.4	7.1	24
Zn	0.07	0.002	0.5

Table 3-8. Comparison of Averaged Abundances in Glacial Spherules with Bulk Analyses of Greenland Ice Residue (Relative to Iron).

Element	Polar dust	Bulk polar	Chondrites	Earth crust
Fe..........	100	100	100	100
Co..........	1.0	0.09	0.5	0.04
Ni..........	2.4	0.2	7.1	0.12

Table 3-9. Comparison of Averaged Abundances in Glacial Spherules with Bulk Analysis of Antarctic Ice Residue

Element	Hodge and Wright (1967)	Brocas and Picciotto (1967)	Earth crust
Mg/Ni	0.7	4	260
K/Ni	0.14	5.4	320
Ca/Ni	2.4	5.4	455

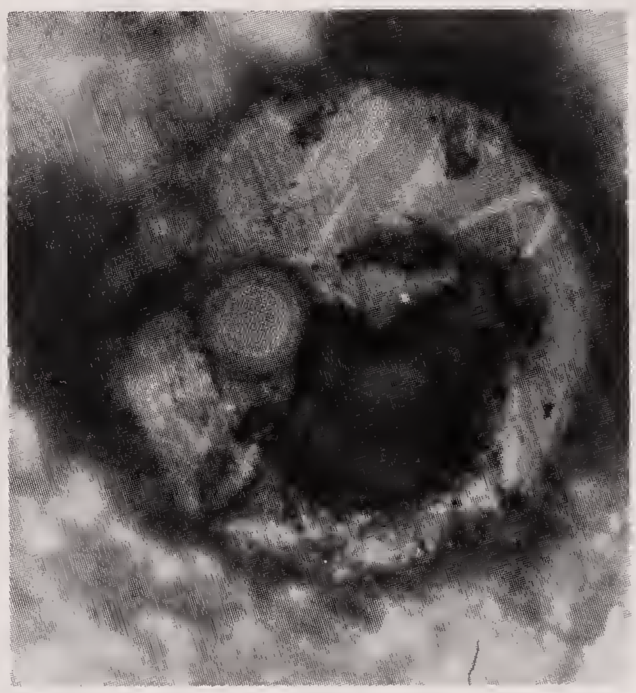

Figure 3-2. A spherule from Antarctic ice that has been sectioned and analyzed. It is almost pure magnetite. Note the large cavity.

resulted. Difficulties in interpreting the data, due to lack of detailed knowledge of isotope abundances in pure extra-terrestrial dust in space, make it impossible, however, to derive rates of fall. Various assumptions were made to derive at least an upper limit, approximtely 2 x 10^6 tons/year (Parkin and Tilles 1968). Some representative data are given in Table 3.10.

Bibron et al (1974) measured the Mn^{53} (half-life 3.7 x 10^6 years) abundance in Antarctic ice. They deduce a probable mass influx of 10^5 tons/year by making reasonable assumptions about the mode of production of the Mn^{53}.

V. Origin of the Particles

Origin of the irregular particles. Since most of the literature on fossil collections of interplanetary dust deals with the black magnetic spherules found in sediments in a wide variety of places and times, most of this section will deal with the question of the origin of these spherules. The nonspherical particles, especially those collected in polar ice deposits, are also of considerable interest, but very little comprehensive research has been done on them and therefore there is only a small amount of literature dealing with their origin. Many of these irregular particles have chemical abundances that indicate that they most probably have a terrestrial origin. A small percentage of those examined contain iron and nickel in approximately meteoritic proportions (Table 3-4), and it is likely that these have an extra-terrestrial origin. For these, because of their rare occurrence in the deposits, we have only a very rough idea of the rate of deposit. Published data by Wright, Hodge and Langway (1963) suggest a total rate of deposit surprisingly large, on the order of 200,000 tons per year, for the

Table 3-10. Rates of Deposit of Meteoritic Material Compared To Spherules (Data from Wright et al. 1963).

Type of Particle	Method	Diameter	Rate of Deposit, tons/yr
Meteorites	Observed falls	>5cm	10^2
Meteors	Visual counts	>5mm	10^3
Spherules	Deep sea	>25μ	10^2
Spherules	Antarctic ice	>15μ	$1.8x10^5$
Spherules	Greenland ice	>5 μ	$2x10^5$
Spherules	New Mexico air	>5 μ	$1.6x10^5$
Spherules	Arctic air	>3 μ	$5x10^5$
Spherules	Stratosphere	>3 μ	$2x10^5$
All dust	Polar ice	>5 μ	10^6
All dust	Ni in deep sea	All	10^6
All dust	Zodiacal cloud	All	10^6
All dust	Satellite	All	10^6
All dust	Al^{26} in sea sediment	All	$3x10^5$
All dust	Cl^{36} in sea sediment	All	$<2x10^6$
All dust	Argon in sea sediment	All	$<2x10^6$
All dust	Mn^{53} in Antarctic ice	All	10^5

nickel-iron irregular particles collected from Greenland ice (Table 3-6). This seems too large for an extra-terrestrial origin for these particles, but when the great uncertainty in the calculation is taken into account, it is seen that the true value may be an order of magnitude or so smaller. In that case, these particles would be reasonable candidates for micrometeorites and segments of broken-up meteoritic material, ablated in the atmosphere.

Origin of the spherules. There are at least five different hypotheses regarding the origin of the magnetic spherules found in terrestrial deposits. The current status of these ideas can be summarized as follows:

1. Meteoritic origin. Those few spherules, making up only 1-5% of the total, that have iron and nickel ratios like those of iron meteorites are hypothesized to be ablation spheres melted from the surface of iron meteorites, probably of very small size, entering the atmosphere. The most convincing evidence for this hypothesis is the chemical abundances for the particles, but it is also true that their shape can be considered a useful indicator of this type of origin, as was clearly demonstrated in the case of the Sikhote-Alin meteorite fall studied by Krinov (1955). This fall, involving a large number of iron-nickel meteorites, over 100 of which made craters, produced immense numbers of microscopic iron-nickel spheres similar chemically and in appearance to the particles in sediments (Wright, Hodge and Langway 1963). The major question that remains is the question of the abundance of these particles and whether other evidence regarding the mass influx of iron-nickel meteorites can conceivably be brought into agreement with the mass influx calculated from the sediments. The question remains unresolved, as Table 3-10 shows, because the evidence suggests several

orders of magnitude more mass in the form of iron-nickel spherules than in the form of ponderable iron meteorites. The only way of reconciling these figures is to hypothesize that the spherules come almost exclusively from meteorites that are too small generally to reach all the way to the ground, ablating completely in the atmosphere to produce the spherules that we collect. The evidence from balloons and high altitude aircraft suggests that this may be at least partly true, but currently the sediment data is still indicative of too large a mass influx for their origin to be considered a closed question at this time.

2. Meteoric Ablation. The iron-nickel particles may in fact be ablation droplets from bodies that are not iron-nickel meteorites. It has been suggested that the iron-nickel spheres may be produced by the ablation of large meteoric objects of cometary origin which are broken up entirely in the atmosphere because of their fragile, low density nature. In particular, it has been suggested that the large fireballs detected by the Prairie Network Meteor Project (McCrosky and Boeschenstein 1965). The black spherules in the glacial deposits might be ablation products from rare but possibly very massive fireballs detected in the Prairie Network search. It is difficult to be certain that sufficient mass influx to the earth in the form of these fireballs exists, because of the difficulty of the physical interpretation of their properties and of determining their rate of incidence. However, it is possible that the data might admit the interpretation that even the iron-rich spherules might have this kind of extra-terrestrial origin. As Table 3-6 shows, however, the total mass influx of the magnetite (iron-rich spherules) is very large; it would require a rather optimistic interpretation of the fireball

data. Furthermore, the most recent balloon and high altitude aircraft data do not confirm the existence of the large number of magnetite spherules (Brownlee et al., 1975). The only way that this fact can be reconciled with the hypothesis of the fireball origin is to suggest that the fireballs occur sufficiently rarely that they reside in the atmosphere only during a small percentage of each year for any particular part of the earth.

3. Volcanic Particles. It has also been suggested that the black spherules may be emitted by volcanoes (see Ch. 4). The evidence for such a possibility lies in the vast amounts of particles that are calculated to be ejected into the terrestrial atmosphere by volcanic activity. The Agung eruption of 1963, for example, deposited so much fine dust into the upper atmosphere (above the tropopause) that it remained there for over a year and spread out over the entire earth. However, microprobe analyses of the particles from a variety of volcanic eruptions indicate that there are no similarities between most of the magnetite spherules and those few spherical and quasi-spherical particles in volcanic dust.

4. Industrial Sources. It has been found that collections of dust in populated areas contain large numbers of black magnetic spherules that are similar in appearance to those collected in remote deposits. However, the comparison in detail shows that they are dissimilar; first, the rate of deposit is orders of magnitude greater in populated areas than in polar deposits, and second, the detailed chemistry of these objects is different.

5. Forest Fire Particles. One suggested origin for the ubiquitious black magnetic spherules that has not yet been sufficiently examined is the possibility that they are produced by large scale fires. If they do not have an extraterrestrial origin, it is argued that they must have a natural origin involving melting or combustion and that must involve a phenomenon that can occur over a wide variety of different places on the earth. Forest fires seem to meet these requirements, but experimental evidence that such fires can produce iron-rich magnetite spheres is still lacking.

4. SURFACE COLLECTIONS

I. Introduction

The problem of collecting small particles of extraterrestrial origin at or near the earth's surface is made extremely difficult because of the predominance in the air of terrestrial dust. For many years this problem was underestimated and as a result the historical literature, particularly that pervading the first sixty years of the twentieth century, is full of examples of completely incorrect deductions. It is now known that if a sample of dust even from a remote part of the terrestrial surface is examined under a microscope, fewer than about 1 in 10^9 of the dust particles examined can be interplanetary in origin. For that reason surface collections are no longer attempted except under very special circumstances, for example at the location of fall of meteorites or near meteorite craters. Since only a small amount of information on surface collections in the vast literature on the subject can be taken at face value, what follows is primarily a summary of the major attempts to make surface collections and a comparison of techniques, all given for historical purposes only.

II. Early Studies

Interest in making collections of meteoritic dust was first stirred by the discovery of material of cosmic origin in the deep sea sediments in the latter part of the 19th century (see "Deep Sea Sediments"). An example is the work of Nordenskiold (1870). He found particles on and in the ice of Greenland and suggested that their chemistry was similar to that of carbonaceous chondrites. He found that they contained iron, cobalt, and phosphorous.

A more comprehensive study was carried out in the early part of this century by Rudaux (1930), who made collections of atmospheric dust in France during and between meteor showers in an attempt to find a correlation between the incidence of certain kinds of dust and the presence of large numbers of visible meteors. Rudaux's data were fragmentary, but seemed to indicate an increase in the number of black magnetic spherules after a meteor shower occurrence. Because this particular experiment has not been found by others to be repeatable, it is now thought that Rudaux's correlation was probably accidental.

Another extensive study was made for many years by Buddhue (1950). Using glass microscope slides covered with sticky substances, Buddhue made daily collections of atmospheric fallout in the canyon Arroyo Seco, just north of Los Angeles, near the present location of the Jet Propulsion Laboratory. Buddhue found large numbers of black magnetic spherules and plotted their size distribution and frequency as a function of time. His bulk chemical analyses showed that these spherules were primarily iron oxide with little or no nickel, a fact which immediately brought suspicion on their identification as meteoritic material. Nevertheless, Buddhue's extensive and carefully documented work on the particles remains an important source of archival information, regardless of what their origin turns out to be.

In the early 1950's, a study was begun for a master's thesis at Iowa State University by Thomsen (1953), who collected particles by using large plastic buckets of water on the rooftops of campus buildings. After approximately a month's residence on the roofs, these buckets were brought to the lab and the water was filtered and the residue was examined under the microscope. Thomsen identified a very large number of black magnetic spherules that seemed to be similar in all properties to those reported by Buddhue and predecessors. From counts of the frequency of these,

Figure 4-1. Black magnetic spherules collected from the California Desert (courtesy of K. Fredriksson).

Thomsen calculated the total incidence of mass in this form onto the earth's surface, if they were extra-terrestrial and if they were falling at the measured rate throughout the earth, as being approximately 10^{11} kg of materials per year. He carried out some spectroscopic analyses of a few particles which showed the presence of iron. Crude as this identification was, it nevertheless was taken to confirm the extra-terrestrial origin of these particles and to indicate that the influx of material in this form from outer space was very much larger than had previously been supposed.

Immediately after Thomsen's article was published, Handy and Davidson (1955) pointed out difficulties with the blanket acceptance of such particles as of extra-terrestrial origin. They showed that particles with identical appearance could be collected in vast numbers near any industrial center and were in fact produced abundantly by most kinds of industrial combustion, having the common name "fly ash". A similar conclusion was published by Hoppe and Zimmermann (1954).

At about this same time Hodge began collections of these kinds of particles in a variety of more remote locations, attempting to establish which kinds of particles might be of industrial origin and which might be interplanetary. In 1954 he found that spherical black shiny magnetic particles, most of them less than 10 microns in diameter, fell from the atmosphere at two locations separated by approximately 100 miles and at elevation differences of approximately 10,000 feet, at the same rate (Hodge 1956). At both locations these were considerably less abundant than the particles reported by Thomsen.

A similar study, more extensive in scope, was carried out by Crozier (1956, 1960). In Crozier's case, magnetic spherules larger than 5 microns in diameter were extracted from collections made at two sites in the San Mateo mountains of New Mexico, differing in altitude by about 6,000 feet. He found that over several years' time the rates of fall and the size distributions of the spherules at the two collection sites agreed well. He further showed that the numbers of particles that he was collecting were smaller than those reported by Thomsen, suggesting that Thomsen's samples were indeed contaminated by the collection's proximity to many sources of fly ash.

An additional test of the local origin for black magnetic spherules found in more urban regions was carried out in 1956 by Hodge, who made collections of atmospheric dust in the city of New Haven, Connecticut (Hodge and Wildt 1958). These collections showed a very large number of spherical particles, some relatively smooth, like the so-called "cosmic spherules" and others rough-surfaced and cindery. Near the center of the city approximately 100 spherules larger than 5 microns in diameter were collected per square centimeter per day. Most of these particles had diameters of about 20 microns; that they were predominantly industrial in origin was clear from the fact that their number dropped by a factor of two on Sundays and by a factor of 4 at a site approximately 10 miles from the center of the city.

From these and other similar experiments carried out in the 1950's, it was clear that if there were such things as black magnetic spherules of cosmic origin in the terrestrial atmospheric sediment, they would have to be looked for at very remote locations, far from the many industrial sources of similar particles. Furthermore, it would be necessary, before any candidate particles could be accepted as possibly cosmic in origin, to show that they fall to the surface of

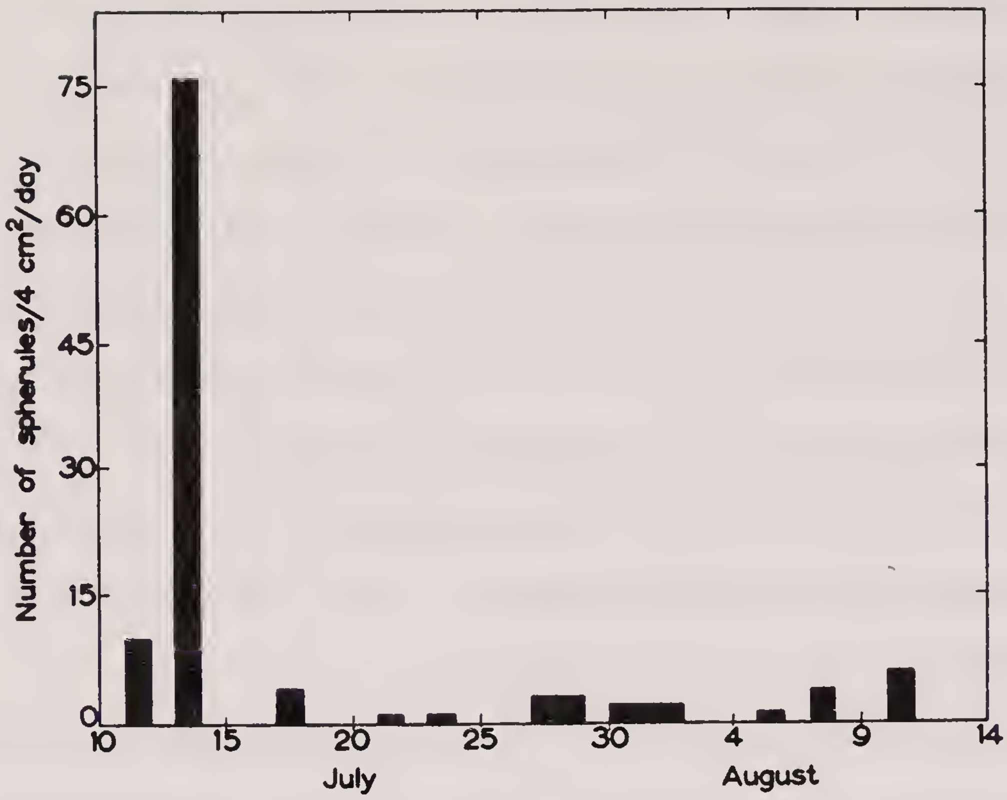

Figure 4-2. The rate of fall of black magnetic spherules at Whidbey Island, Washington, USA.

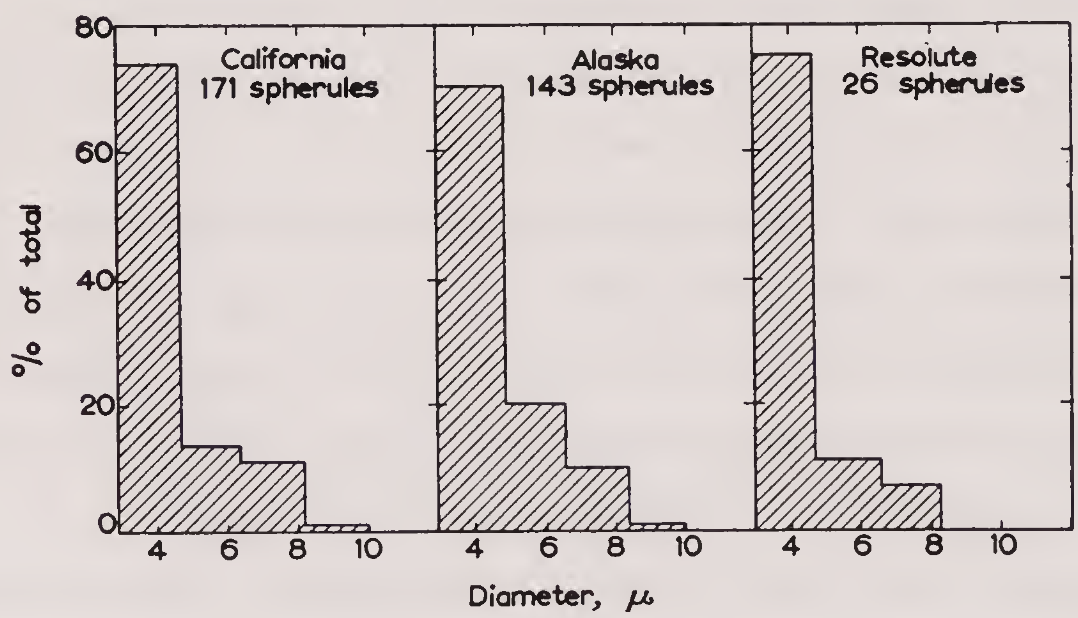

Figure 4-3. The size distribution of black magnetic spherules collected at three remote sites.

the earth at the same rate at widely differing locales. Using these two criteria, Hodge and Wildt (1958) undertook a year-long survey at three widely separated and remote locations. The sites were the observing station of the Meteorological Service of Canada at Resolute, Northwest Territory on Cornwallis Island in the Arctic, the field site of the Geophysical Institute in Central Alaska, and the Smithsonian Astrophysical Observatory Table Mountain Station above the Mojave Desert of California. The program involved daily collections of atmospheric dust made simultaneously at these three stations from July 1955 to June 1956.

All collected particles larger than 3 microns in diameter were examined under the microscope and the number of opaque black spherules was recorded for each day on which collections were obtained. Especially for the arctic collections, there were some days for which bad weather made collections impossible.

The principal result of this program was the fact that the collections at all three stations contained spherules that were indistinguishable in their physical properties from those that had been identified in previous tests at remote locales. The frequency-size distributions at all three sites were essentially identical.

Perhaps the most interesting result of this study was the comparison of the rate of fall of these particles at these widely separated sites. Fig. 4-4 shows the numbers of spherules per square centimeter per day in the collections during the spring of 1956 and Table 4-1 gives the average rate of fall of spherules larger than 3 microns in diameter at the three sites. It is clear that the average rate of fall at the sites is virtually identical. It is also clear that the fall of particles was highly irregular in rate.

Table 4-1. Rate of Fall of Spherules

Collecting Site	Rate of fall
Table Mountain, California	1·0 spherules per cm^2/day
Central Alaska	1·2 spherules per cm^2/day
Resolute Bay, Canada	1·1 spherules per cm^2/day

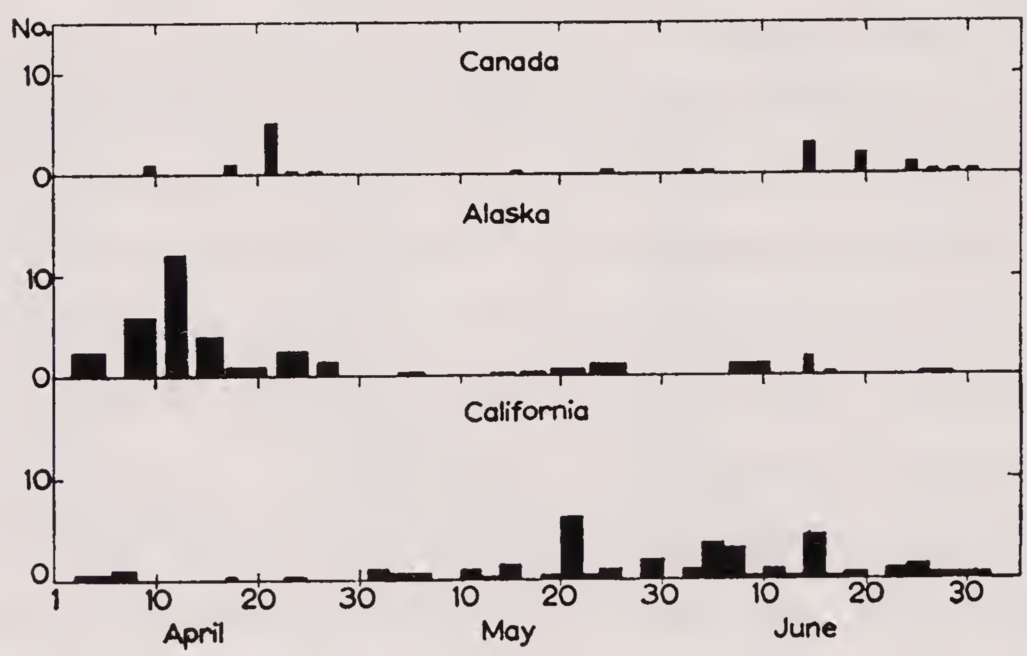

Figure 4-4. The rate of fall of black spherules at three remote locales in the spring of 1956.

The Alaska sample showed a strong maximum in mid-April, whereas the Canadian and California samples did not show such a maximum, but rather showed an irregular pattern with small peaks at other times. This suggested that if in fact all of the particles were from the same source, their rate of fall at any given time within a period of days must be determined by local effects, such as weather and wind currents.

Accepting as presumably world-wide the rate of fallout of particles and their size distribution as found in that study, the computed accretion for the entire earth would be 5×10^8 kilograms per year (assuming a density for the particles of about 4 grams per cubic centimeter). At the time these figures were derived, this seemed like a reasonable amount of material and agreed approximately with the estimated mass of material in the form of meteors entering the earth's atmosphere.

A related and more mineralogically complete examination of surface collections is the study by Fredriksson and Gowdy (1963), who collected material from the southern California desert. Their collecting method involved dragging a magnet through the soil of the desert, sampling approximately 0.1 cubic meters of desert material. From their collection, 100 grams of material was examined, all of it dust smaller than 1 mm in size. They found 32 black magnetic spherules in the size range from 30 to 300 microns in this material and considered that they were very similar in appearance to the "cosmic spherules" that had been described in the literature up until then. These particles were mounted in epoxy and polished to examine their interiors. Most of them consisted entirely of iron oxide but two particles showed the presence of metallic inclusions that suggested they might be cosmic in origin. One of them, 120 microns in diameter, had a metallic nucleus and a nickel to iron ratio that falls within the observed ratio for iron meteorites. The metallic inclusions were very rich in Ni, and it was supposed that this was the result of the melting of material of a meteorite in the atmosphere, with the accumulation of the Ni in localized areas. The other interesting particle with metallic inclusions was somewhat larger (about 300 microns in major dimension). It was a silicate particle with Ni-Fe-Co inclusions and was judged to be an ablation sphere from a stony meteorite. They found that the silicate showed a structure similar to the radiating pyroxene condrules that are common in chondritic meteorites.

Among the millions of dust particles examined from surface collections, Fredriksson and Gowdy's two spheres are probably the only ones for which there exists good evidence of an extraterrestrial origin. Other, similar particles have, however, been found in studies of terrestrial sediments, including polar ice (see "Fossil Collections"). The other spherules, the vast numbers of pure magnetite ones, are far too numerous to be derived from extraterrestrial sources, as we now know them. This was graphically demonstrated in 1968, when Hodge and Wright (1968) compared the flux of particles detected on satellites with the flux of spherules collected from various sources (see Figure 4-5). Approximately two orders of magnitude too many magnetite spherules are collected even at remote sites for them to possibly be meteoritic in origin.

Even after it was thus shown that most of the particles collected in the above studies were probably not extra-terrestrial in origin, scientists continued sporadically to attempt to identify meteoritic material in sur-

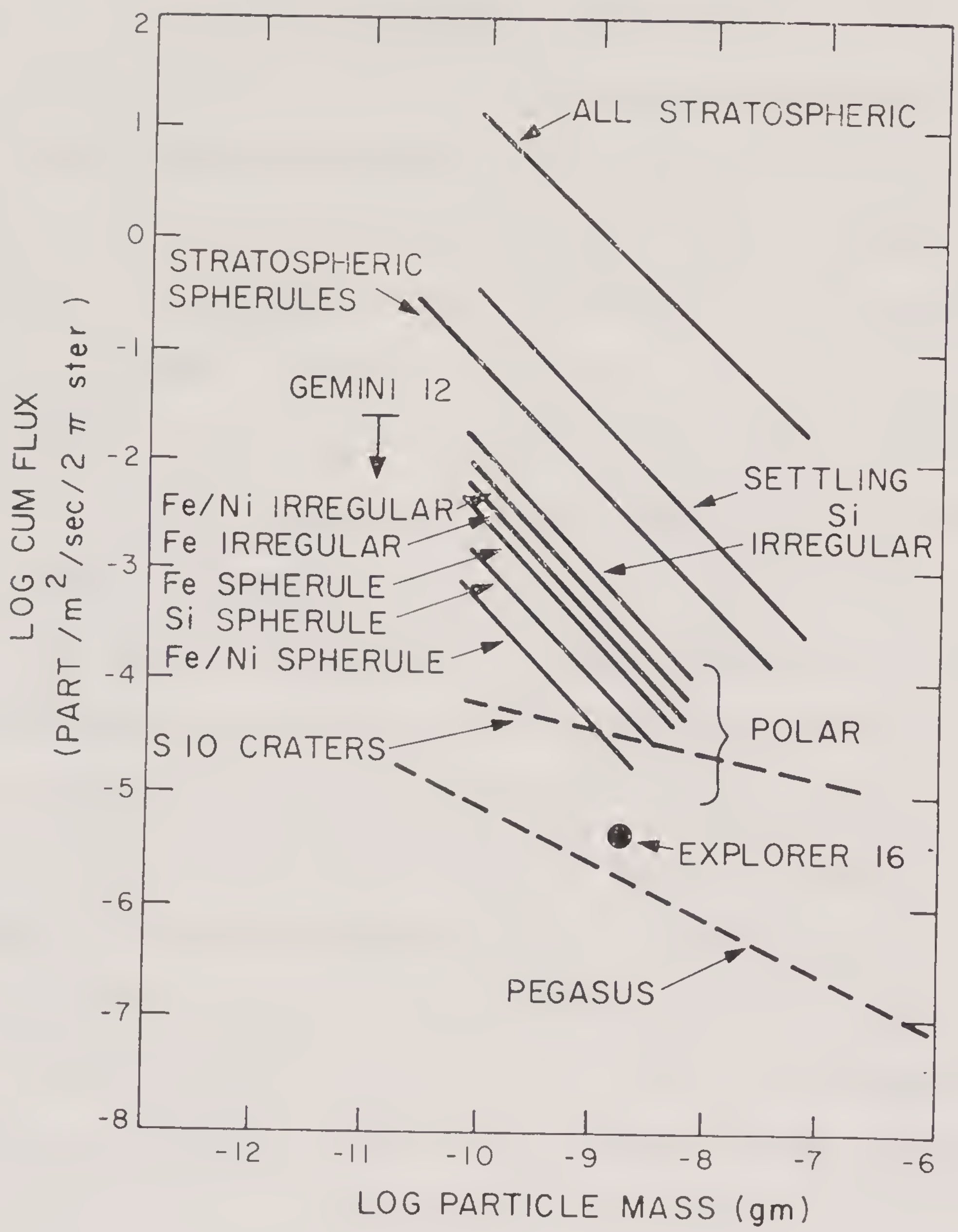

Figure 4-5. A comparison of satellite influx data with that calculated from ground-based spherule collections (after Hodge and Wright, 1968).

face collections. An example is a study by Benedetto (1971), who examined large numbers of spherules in Italian soil samples from the Po river area, the Apennines, and the Pontina Plain.

III. Properties of the "Cosmic Spherules"

In order to understand the extensive literature on the surface collections of presumably meteoritic material, it is necessary to know to what extent different authors are describing the same kind of object. It is clear from the above summaries of various experimental programs that in many cases authors were dealing with very different numbers and kinds of objects, although using the same terms. The important question is, can the results from these various studies be intercompared so as to deduce any general conclusions about the particles involved? It appears that the answer is probably positive, although the detailed properties of the particles collected seem to differ very much depending on whether the collecting site is a remote one or is near civilization. In what follows in the way of general conclusions about the properties of the "cosmic spherules", only those collections that were made at relatively remote locations will be considered. Clearly, for example, we are not talking about the same kinds of particles in the Thomsen collections as we are talking about in the Crozier collections, as between two and three orders of magnitude more particles fell into the samplers at Iowa City than onto the surfaces exposed by Crozier in his remote locations in New Mexico.

If we look only at the remote surface collections, we can deduce that the geographical occurrence of the black magnetic spherules is fairly uniform. The most comprehensive data come from Hodge and Wildt (1958) and from Crozier (1960), and combining these two sources leads to a roughly equal accumulation of particles for the five sites. The fact that the rates of fall calculated by the different authors are not exactly the same probably can be explained in terms of different laboratory techniques for separating and measuring the rates of fall. There are, of course, no surface collections in the experiments listed above for the southern hemisphere, but we know that the same kinds of particles exist in about the same numbers in the southern hemisphere, as determined from Antarctic ice deposits (see "Fossil Collections").

The physical characteristics of these particles are fairly simply described. Up until the abandonment by most people of the technique of searching for such particles in the bottom of the atmosphere, very little was available for looking at the physical characteristics of individual particles in the 3 to 10 micron size range. Therefore we mainly have reports only on their optical and surface properties. Generally, they are uniformly described as being black and smooth-surfaced. They are highly magnetic, and occasionally hollow when broken. Under very high magnification, their surfaces sometimes show a very fine ridged character, which may be related to minerological features (Figure 4-6). However, no detailed minerological examination has been carried out for the vast majority of the small "cosmic spherules".

Chemically, the particles in the surface collections are fairly uniform. They are almost all iron-rich, and those few for which individual chemical abundances were determined are made up of magnetite. Bulk analyses by Buddhue and others are consistent with the magnetite composition and very few of the small, common spherules have been sectioned to see if they are magnetite throughout. The large particles collected in the California desert by Fred-

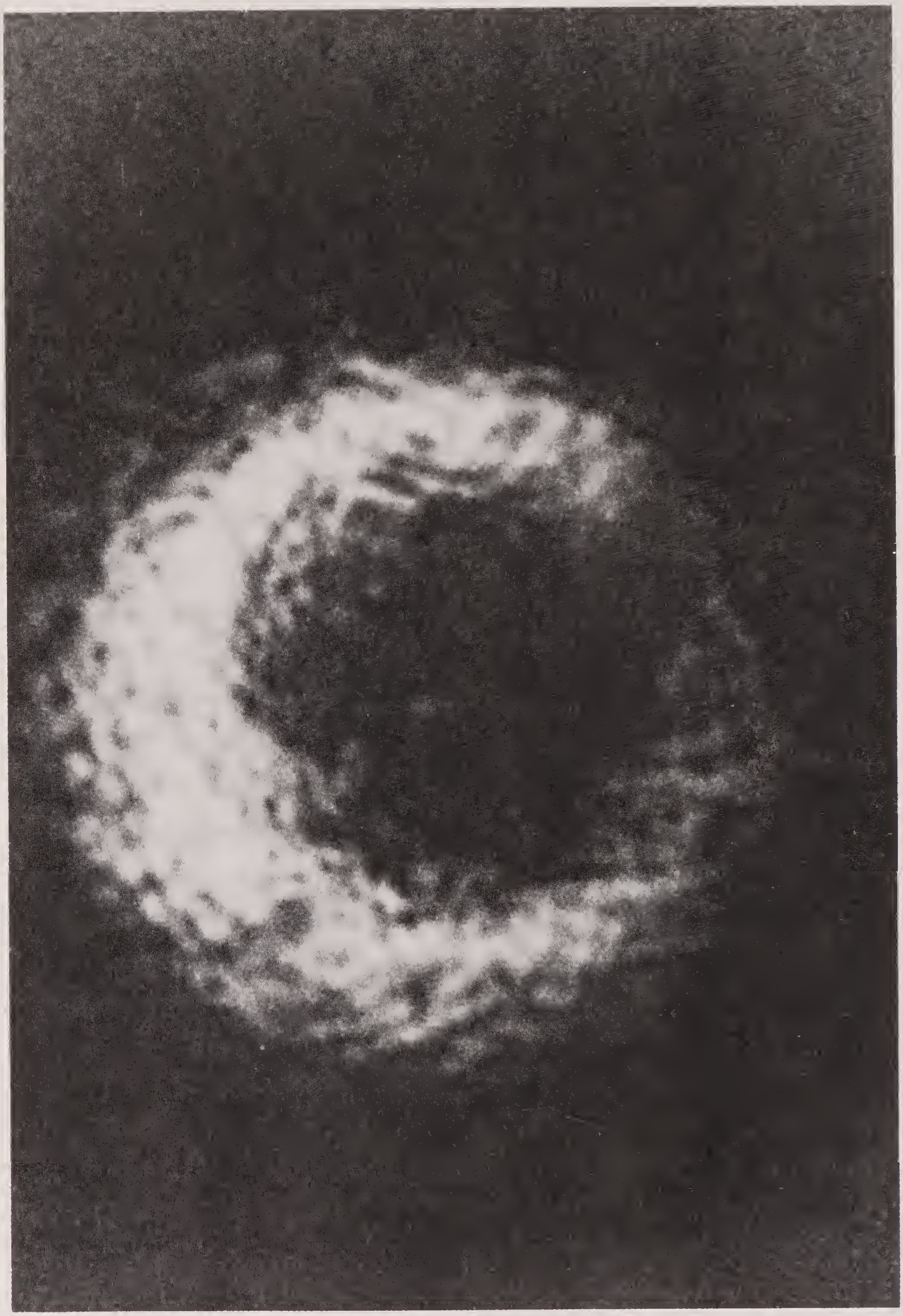

Figure 4-6. Ridged surface of a black magnetic spherule.

riksson and Gowdy (1963) consisted primarily of particles that were pure magnetite.

The rate of fall of these particles has been found to be approximately 1 particle larger than 3 microns in diameter per square centimeter per day for the earth's surface.

IV. Origins of the "Cosmic Spherules"

If it is true that few if any of the cosmic spherules are indeed cosmic, then what is their origin? One of the suggestions is that they may all be of industrial origin, derived from the production of fly ash by whatever combustion there may be anywhere on earth. Because of the fact that we are dealing with very small particles in the remote sources (where most particles are on the order of 3 microns in diameter), it is not unreasonable to suppose that such industrial particles might be carried by winds so as to make them fall fairly uniformly to the surface of the earth throughout the northern hemisphere. It would be of interest, if we did not have other contrary evidence regarding this hypothesis, to compare their rate of fall in the southern hemisphere, where the number of sources would be expected to be significantly smaller. However, the industrial origin was made highly unlikely as an explanation for these particles by the discovery that similar particles have been falling to the earth at about the same rate throughout the testable geological history of the earth, including times long before man existed (see Chapter 3).

Another attractive possibility for an explanation of these particles is that they have a volcanic origin. Volcanoes are certainly energetic enough to implant vast numbers of small particles in the upper atmosphere, where winds might have dispersed them globally. There is ample evidence that major volcanic eruptions have indeed effected such

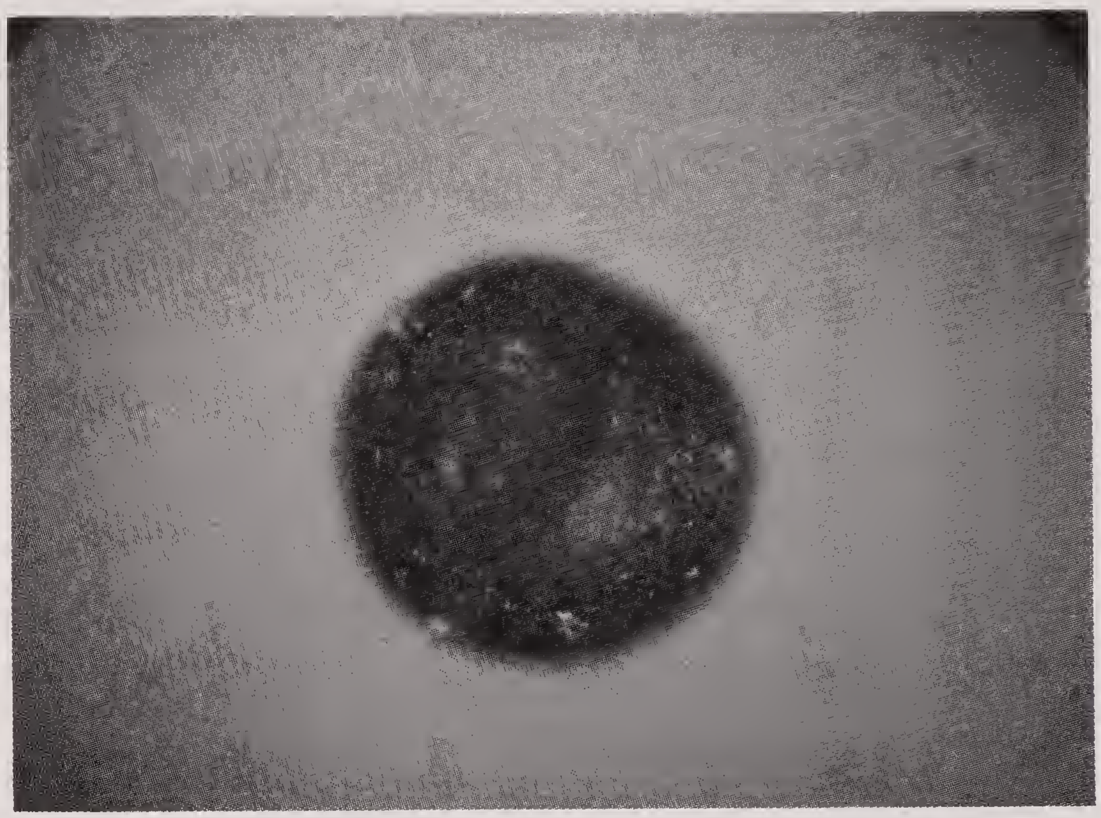

Figure 4-7. Black spheroid from Surtsey volcano, Iceland.

global dispersion of dust, as in the example of Agung and Krakatoa, the optical effects of the dust from which was observed for over a year after the eruptions. Indeed, Fredriksson and Martin (1963) suggested that the magnetic spherules found in isolated sites as well as in fossil collections were probably all volcanic in origin. This suggestion was disproven, however, by studies by Wright and Hodge (1964, 1965). Their first paper analyzed volcanic deposits collected from Cascade range volcanoes in California and Oregon, which showed that although there were small microscopic black spherical particles present in small numbers in the volcanic sediments, both their physical and chemical properties were conspicuously different from those of the "cosmic spherules" (Figure 4-7). The second paper reports on collections made from sediments of currently and recently active volcanoes, which provided very similar results. The volcanoes were Irazu, Kilauea Iki and Ubinas (Table 4-2). They showed a wide variation in the fraction of volcanic dust that is magnetic, both from source to source and from site to site at the same source. The Ubinas samples were most rich in iron, where approximately 63% of the particles were magnetic, whereas the Kilauea Iki particles were the least rich (0.1%). The average magnetic fraction was approximately 22%. Of these magnetic particles, very small numbers were spherules similar to those suspected to be cosmic. In Irazu, for example, true spherules made up less than 5×10^{-4} of the magnetic fraction of the sample. This is typical of both the fresh and the historical volcanic sediments.

The majority of the volcanic spherules showed more irregular and rough surfaces than the cosmic spherules, but the most conspicuous difference was chemical. Table 4-3

Table 4-2. Volcanic Samples Searched for Black Magnetic Spherules

Volcano	Reference
Mt. Rainier, Wash.	Hodge, 1956
Mt. St. Helens, Wash.	Hodge et al., in prep.
Mt. Hood, Ore.	Hodge and Wright, 1964
Mt. Mazama, Ore.	Hodge and Wright, 1964
Lava Butte, Ore.	Hodge and Wright, 1964
Black Butte, Calif.	Hodge and Wright, 1964
Mt. Shasta	Hodge and Wright, 1964
Irazú, Costa Rica	Wright and Hodge, 1965
Kilauea Iki, Hawaii	Wright and Hodge, 1965
Ubinas, Peru	Wright and Hodge, 1965
Huainaputina, Peru	Wright and Hodge, 1965
Mt. Aso, Japan	Wright et al., 1966
Surtsey, Iceland	Wright et al., 1966

Table 4-3. Chemical Abundances of Volcanic Spherules

	Per Cent of Element by Weight							
	Al	Si	Ca	Ti	Cr	Mn	Fe	K
Irazú	11	19	6	3	0-1	t	14	2
Kilauea Iki	10	24	11	2	0	t	14	0.5
Ubinas	11	26	3	2	0	t	23	0.4
Huainaputina	7	21	4	6	0-t	t	28	0.8
Pacific Coast	7	15	3	7	0-1	t	31	1
Av. Comp. Volcanic Natural	5-9	21-25	5-9	0.6-2		t	5-15	0.1-0.9
Glacier Spherules	2	6	t	0.7	t	0.6	52	0-2

Figure 4-8. The Mt. St. Helens area after the devastating eruption on May 18, 1980.

shows the mean chemical compositions of volcanic magnetic spheroids from five different volcanic sources. These are compared with the mean composition of "cosmic spherules" and with the average composition of volcanic material (Barth 1950). It is clear that the chemistry is extremely different between volcanic particles and so-called "cosmic" particles. Iron is much less abundant and aluminum conspicuously more abundant for the volcanic spherules than for the cosmic spherules, and an examination of the table shows that there are other conspicuous differences for other elements. Clearly, although volcanic explosions can deposit large quantities of dust in the air, the vast majority of these are very unlike the particles in question. Out of hundreds of volcanic spherules examined, not one was found to be similar chemically or physically to the cosmic spherules.

One possibility that has been suggested (but not examined in any detail) to explain the ubiquitous occurrence of the black magnetic spherules throughout the earth in time and in space is that they are produced by forest fires. This is an attractive suggestion in the sense that forest fires are occurring at almost any given time on the globe and no doubt were approximately as important in ancient geological time as now, though we have little to go on in the way of rates of occurrence in geological time. Furthermore, it seems reasonable that combustion in a forest fire might produce objects not very different from those produced in other combustion processes (e.g., fly ash) and that therefore it may be possible to explain the physical and chemical properties of the spherules. However it remains a speculation, and until they can be found to definitely be products of forest fires, it will continue to be an untested idea.

V. Are Any Cosmic?

Although it is clear that most particles collected from the surface of the earth that have in the past been identified as cosmic have little likelihood of being truly of cosmic origin, there is nevertheless the possibility that some of the particles in various collections are indeed interplanetary. Criteria to establish their cosmic nature must at the present be primarily chemical. If we find particles that have a Ni-Fe-Co ratio like that of iron meteorites, there is very little likelihood that these particles can have a terrestrial origin. Similarly, if we find particles that in detail mimic the chemical properties of chondritic meteorites, then we again have a strong argument for a cosmic origin. In particular, if we can find particles that show abundances of trace elements like those of carbonaceous chondrites, as was done in the case of deep sea particles, then the evidence will be very convincing. A further criterion that may be helpful is the detection of inclusions of, for example, meteoritic metal in silicate rich particles, which on their own might not be easily distinguished from terrestrial silicate particles.

Few examples of these tests have been carried out on surface collections of dust, primarily because the techniques for many of the chemical abundance determinations have only recently become available for very small particles. One example of the application of these criteria is that of Fredriksson and Gowdy (1963), described above, who found two particular particles that seemed indubitably to be meteoritic.

Table 4-4 shows examples of compositions of artificially produced iron and stony iron ablation spheres and illustrates that there is a wide variety in the abundances of nickel, iron, and cobalt in spherules from iron meteorites and in the silicates to metals ratio in artificially-produced spheres made from stony-iron meteorites. This fact, of course, means that strict criteria are very difficult to apply on the basis of the chemistry of the major elements. For that reason it would be preferable to base such identifications primarily on trace elements , as done for deep sea particles by Ganapathy et al (1978). This has not yet been done for particles collected at the earth's surface.

Table 4-4. Chemical Abundances in Seven Representative Artificially-Produced Ablation Spherules (from Wright and Hodge, 1965).

Particle Diameter (μ)	Al	Si	Ca	Ti	Cr	Mn	Fe	Co	Ni	Remarks
From An Iron Meteorite										
50							67-72		0.5-1.0	very porous
30						0.1-0.5	68-73			solid
42							65-70	0.5-1.0	4-5	solid
From a Mesosiderite										
36							65-70	0.5-1.0	6-8	solid
63							65-70	0.5-1.0	5-6	solid
43	0.5-1.0		4-6	0.1-0.5	0.1-0.5	0.1-0.5	40-45			solid
31	1-2	8-10	6-8	0.1-0.5	0.1-0.5	0.1-0.5	28-33			solid

I. Introduction

Because of the heavy contamination of the lower terrestrial atmosphere by dust particles carried from the ground, it was recognized in the mid 20th century that the collection of true interplanetary dust must be done either at high altitudes or in space. The technical difficulties of non-destructively capturing particles in space are sufficiently great that the upper atmosphere was readily recognized as the most promising area for collection. Because of the gradual density increase of the atmosphere inward from outer space, interplanetary dust particles are decelerated slowly when they encounter the earth and, if small enough, do not heat up enough to become destroyed (see Chapter 11). They then fall slowly through the stratosphere, eventually mingling with terrestrial dust in the troposphere. At high enough altitudes where terrestrial dust is not overwhelming, it is possible to make appropriate collections that include large fractions of the extraterrestrial component. The 1950's saw several experiments carried aloft by aircraft and scientific balloons to determine how high collections must be made before the interplanetary dust sufficiently dominates that it can be recognized and separated from the terrestrial particles.

II. Early Attempts

Among the various attempts to use airplanes as vehicles for collecting the interplanetary dust were several made by the Smithsonian Astrophysical Observatory in the 1950's and 1960's (Hodge 1961). The first of these used a U-2 aircraft which, at the time of use, was of limited scientific usefulness because the aircraft's various characteristics, including altitude and duration of flight, were classified.

Figure 5-1. U2 collector of the Smithsonian's early experiments.

Nevertheless, it was found that collections made using an airtrap of rather simple design (Figure 5-1) included significant numbers of small particles of various kinds. Most of the particles were on the order of a few microns in diameter, and because techniques at that time had not yet been developed for the chemical analysis of such particles, very little information was obtained on their physical and chemical nature.

By the early 1960's, the Smithsonian program had evolved to include more aerodynamically-designed collecting devices and aircraft available had expanded to include B-52 airplanes, which made collections at altitudes near the tropopause (at about 40,000 feet) and NASA F-104A aircraft, which made collections at altitudes up to 87,000 feet. A study of the numbers of particles as a function of altitude showed that the space density of dust in the stratosphere decreases steeply upward but does not reach a value of zero at even the maximum altitudes attained (Hodge 1961, Wright and Hodge 1962, Hodge and Wright 1962). The rate of fall of all opaque particles collected in these experiments was found to be approximately 30 particles larger than 3 microns in mean dimention per square centimeter per day onto the earth. Hodge and Wright (1968) calculated, on the basis of the unreasonable assumption that all such dust at these altitudes is extraterrestrial, that the cumulative flux for 3 micron particles is 14 per square meter per second per 2π steradians. The size distribution was found to be quite steep (Figure 5-2), and parallel to size distributions for suspected interplanetary particles found previously in ground collections and subsequently in space.

A small percentage of the particles collected in these early Smithsonian aircraft experiments were black magnetic

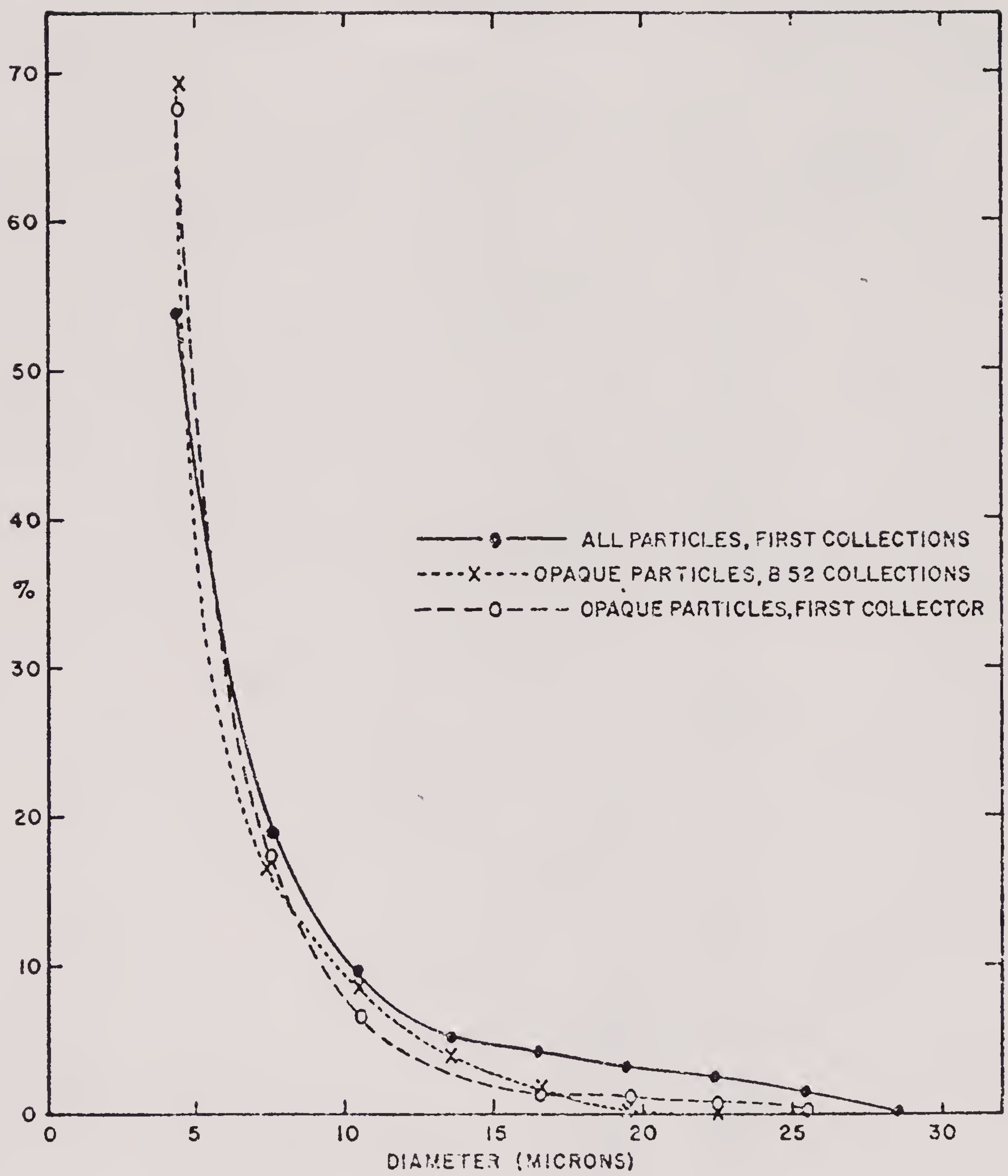

Figure 5-2. Size distribution of particles collected by B-52 aircraft in the Smithsonian experiments.

spherules of the type identified as probably meteoritic ablation droplets in previous ground based studies. These made up a sufficiently small fraction of all stratospheric particles that their cumulative flux was calculated to be only 0.1 per square meter per second per 2π steradians for those larger than 3 microns in mean dimension. Study of these spherules using optical microscopy and microprobe chemical analysis indicated that they were primarily iron oxide, with only a very few containing detectable nickel (Riggs et al 1962). In that sense, they are very similar chemically to the particles of like appearance collected on the ground. Nevertheless, the numbers of these particles from the B-52 flights at 40,000 feet were far too large to be reconciled with the expected number of interplanetary dust particles, so that it was clear from these data that extensive numbers of terrestrial particles still contaminated the sampling.

For the F-104A flights, the numbers were much smaller and the particles also had a mean size that was considerably smaller. These were probably more valuable as samples, but it remained throughout the early 1960's to prove that any one of these particles collected by these means was truly extra-terrestrial. Chemical analyses were still too crude, and the probability of a considerable terrestrial contamination still too large for the circumstantial evidence regarding their origin to be believed. Furthermore, experiments with the collecting mechanism itself indicated that there were still several improvements that would have to be made before the technique was thoroughly free of sources of contamination from the aircraft, from various parts of the collecting mechanism, and from dust from the ground that accumulated thereon.

At about the same time that the Smithsonian Observatory was attempting to make airplane collections of interplanetary dust, a group at the CSIRO in Australia was carrying out similar experiments (Mossop 1963, 1964). Using a U-2 aircraft, Mossop and his colleagues discovered large numbers of water-soluable dust particles on the order of 1μm in diameter. They were impacted onto millipore filters and had the appearance of flattened rosettes of material with a small nucleus near the center, usually on the order of 0.1 microns in size. The number of particles was found to be approximately 30 per liter, larger than 0.2 microns in size, which implies a space density of 0.006 particles per cubic centimeter. The water-soluable material was found to be ammonium sulfate and persulfate, in agreement with the findings of Junge and Manson (1961), who had found similar particles from balloon flights (see below). This material coated what was thought by Mossop to be extraterrestrial kernels, which in passing through the atmosphere presumably were acting as condensation nuclei for the formation of the ammonium sulfates.

The Australian collections were temporarily side-tracked in 1964, when the volcano Agung in Bali erupted violently, extensively contaminating the stratosphere in the southern hemisphere to altitudes beyond 20 km. Mossop found that the particles collected following the eruption were larger and more angular than those collected prior to it. Their average concentration was 100 particles per liter greater than 0.2 microns. They were covered with the same kind of water-soluable material as found previously, and were found to have a median diameter that decreased with time, as did the spatial concentration. Spheres of the type described above made up only about 0.1% of these particles.

In an attempt to improve on the purity of aircraft

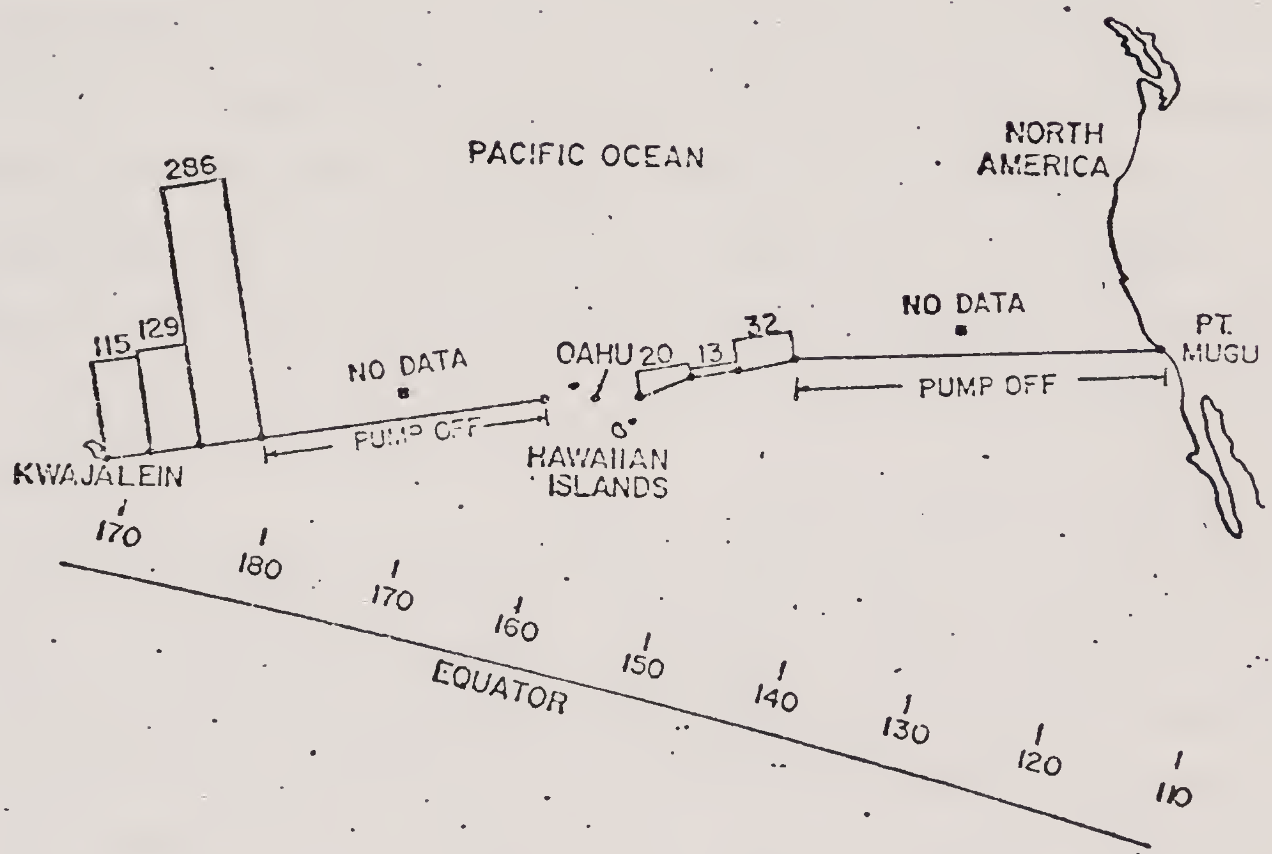

Figure 5-3. Aircraft collections of particles over the Pacific (from Hodge and Wright, 1971).

samples, in the mid-1960's the University of Washington's Interplanetary Dust Laboratory cooperated with the Bishop Museum in examining several samples collected from mid-Pacific Ocean flights, the primary purpose of which was to study air-borne biological dispersion of species (Hodge and Wright 1971). Figure 5-3 shows a summary of the results of such collections, which did indicate that over the vast expanse of the Pacific Ocean the density of terrestrial dust decreased dramatically compared to that over the continents. Nevertheless, these particles were not completely free of recognizeable terrestrial components, and therefore the experiments emphasized the desirability of making collections at as high an altitude as possible.

III. Balloon Collections

The first balloon-borne experiments designed to study upper atmospheric dust particles included some made by Junge and Manson (1961). Their primary interest was in locating the sub-micron particles in the stratosphere and in determining their chemical nature and origin. They found that most of the particles in the desired size range were primarily sulfates and had an obvious terrestrial origin, though as Mossop (1963) showed later the particles probably contained even smaller nuclei that might have been extra-terrestrial in origin.

Attempts to start an extended balloon collection program in 1958 by the Smithsonian Observatory were not entirely successful but did prove the importance of using a collecting device that was thoroughly isolated from the cloud of dust produced by the balloon itself (Hodge and Rhee 1960). Collections, such as those made by Hemenway et al (1961), that utilized collectors mounted in the usual experiment payload area below the balloon were found to be subject to large amounts of contamination from the apparatus and the balloon. The SAO balloon flights used collectors that were placed at the top of the balloon, thereby avoiding much of the falling debris. However, the Dudley Observatory balloon flights (Hemenway et al 1961), which also turned to this kind of collector, seemed to detect very large concentrations of dust in the stratosphere and are now believed to have been contaminated by the balloon, possibly by the means of circulation of warm air up along the surface of the balloon, concentrating and depositing dust at the top. Hemenway's "Sesame" settling balloon collector (Hemenway et al 1967) was found to give particle concentrations about five orders of magnitude too large compared to what is expected on the basis of later satellite measurements. It is very likely that these concentrations refer to large amounts of contamination, although a detailed analysis of what went wrong with the Sesame experiments has not been published.

IV. Recent Balloon Collections

In order to improve the reliability and the efficiency of balloon collections, three recent experiments were carried out. The first two involved experiments using ordinary single day balloon flights and the third took advantage of the long time-area products available from superpressure balloons on circumnavigational flights. In each case the efficiency of collection was greatly enhanced, by as much as a factor of 100 over the collection rate for the simple settling plate collectors used previously.

The first of these new generation balloon experiments was developed by Brownlee (Hodge and Brownlee 1969) and was first flown in 1968. In order to make a large volume collection, Brownlee built an instrument with a long rotating arm that swept a large cylindrical volume. Particles were collected by inertial impact onto cylindrical collection rods, approximately 5 cm x 0.5 cm, mounted at the end of the 3 meter long boom. The arm rotated about its center, moving the rods through ambiant air with a velocity of 10 m/sec. The principle aim in designing this collector was to have a high efficiency collection of large particles (greater than 5 microns) with a low contamination level, and trials showed that the collector efficiency was nearly 100% for particles larger than this limit. Double protection of the collection rods was provided, so that contamination from the instruments and on the ground prior to launch could be minimized. The entire mechanism was provided with an outer cover encasing the entire arm, and cylindrical covers were mounted at the ends of the rotating boom to protect the impaction rods.

Because of the dust contamination of earlier samples by the immense surface area of the balloon itself, this experiment was provided with a special reeling device that on command lowered the entire collecting device nearly 1,000 meters below the main balloon payload. With the normal winds at the altitudes where collections were made, this took the experiment completely out of the dust stream originating at the balloon. When the payload was open and collecting, all upward facing surfaces were cleaned white epoxy paint. None of these surfaces had been exposed to ambient air during transit from the preparation clean room all the way until float altitude was achieved. All other surfaces (the bottom surfaces of the experiment and supporting line) were coated. with a thin film of silicone oil in order to trap any dust and prevent further contamination. A large number of easily recognized characteristic tracer particles were scattered

Figure 5-4. Brownlee's rotating arm collector.

over exposed surfaces in order to indicate in the final investigations whether or not contamination from the instrument is a problem on any given flight. In no cases was it found to be significant.

The flights of the rotating arm collector had time-area products of approximately 10^5 m^2 sec, 100 times greater than achieved for most previous balloon experiments. A further advantage of this experiment was the efficient concentration effect that localized the particles onto a small area. This made scanning more rapid and efficient and reduced relative contamination concentrations.

A second innovation in balloon-borne interplanetary dust collector design was also developed by Brownlee (Brownlee and Hodge 1973a). This collector, called by Brownlee the "Vacuum Monster", was a clean air sampling system designed to collect particles down to 2 microns in diameter. This instrument used a large hydrazene-filled air injector pump in order to sample a large volume of air. The pump pulled air past an inertial impaction device, consisting of 0.6 cm diameter rods. The air flow was approximately 200 meters per second and a total volume of nearly 10^4 cubic meters of air could be sampled during one 8-hour flight. Similar methods to those for the rotating arm were used to ensure contamination-free sampling, including a reel that lowered the collector below the dust tail of the balloon and a large wind vane on an extended boom which ensured that the collector was oriented into the wind, farther ensuring against contamination from above.

Collections with the Vacuum Monster instrument made at elevations of 35 km have resulted in the collection of nearly 100 particles. However, most of the particles found were aluminum oxide spheres, which were later found to be exhaust from solid fuel rockets (Brownlee 1972). Approximately 10

Figure 5-5. Brownlee's "Clam Shell" balloon-borne collector just before flight from Palestine, Texas.

of the remaining particles have been investigated in detail by microprobe analysis and found to be very likely of extraterrestrial origin (Brownlee and Hodge 1973b). The elemental abundance ratios for these particles are very similar to those found in meteorites. In particular, most of them have compositions very similar to that of chondritic meteorites, with another of them being a sphere of nickel-iron. Two have iron, sulphur and nickel as their main constituents. A further confirmation of their probable extraterrestrial origin comes from the implied flux based on these collections, which is 2×10^{-5} particles/m^2/sec for all particles larger than 3 microns in diameter. Unlike the flux calculated from the Sesame settling plate balloon experiment, this is in excellent agreement with results from spacecraft measurements.

The third recently-developed instrument is the "Magellan" collector which involves the establishment of a collecting device on a superpressure balloon that can remain at altitude for several months. In view of the fact that the rotating arm collector and vacuum monster collector were able to collect only a few particles larger than three microns in diameter, any hope of getting very large particles (larger than 50 or 100 microns) can only rely on extremely large time-area products. Wlochowicz et al (1976) report on their use of a settling plate design that consists of a large cone-shaped funnel with a 20 square meter opening. The funnel points upward and particles fall into it, concentrating at the funnel's narrow point. Particles smaller than approximately 50 microns are lost because they adhere to the funnel wall, but larger particles roll down the wall onto the collecting surface. A flight in 1975 lasted for 210 days and would have probably provided several large particles for analysis had it been recovered. Unfortunately it was lost.

This section closes with mention of an additional experiment that also was apparently not successful. Bhandari et al (1968) developed a 10 square meter surface area screen that they suspended below a balloon flown at 22 km elevation. The screen was made up of 280 micron monofilament fibers of nylon which was bulk washed after the flight to remove any collected particles. Although approximately 10^6 cubic meters of ambient air was sampled, no particles of possible cosmic origin were found. Rosen (1969), however, suggests that the wind actually blew around the screen rather than through it and that therefore the collection efficiency of this experiment was not as high as originally reported.

V. Recent Aircraft Collections

During the early 1960's, as it became realized that the flux of interplanetary dust particles was vastly smaller than originally thought, attempts to collect particles by means of aircraft were virtually abandoned. At that time balloons seemed to be the best means of collecting interplanetary dust for eventual analysis. However, the various difficulties with contamination from balloons and the loss of small particles by the more efficient balloon collection techniques were a disadvantage that was quickly recognized. The University of Washington Interplanetary Dust Laboratory, therefore, reinvestigated the possibilities of using high altitude aircraft. By this time, U-2 aircraft had been declassified and extensively used for scientific experiments. The particularly advantageous characteristics of the U-2 aircraft for sampling purposes are its relatively high altitude (20 km) and its relatively low velocity. Brownlee et al (1976) developed an inertial impaction device to be

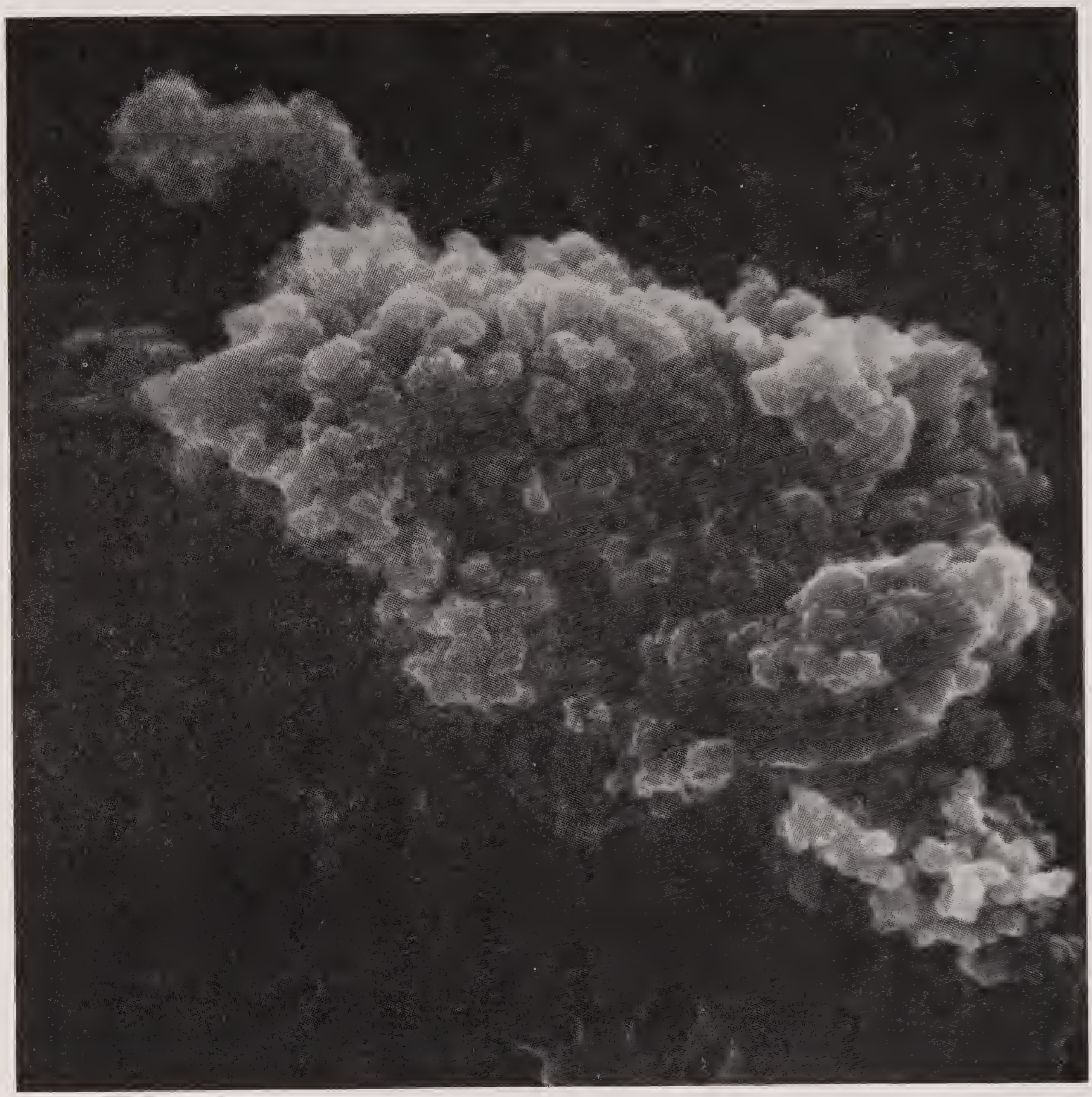

Figure 5-6 . A U-2 particle with chondritic abundances (courtesy D. Brownlee).

mounted on the wing (near the tip) of a NASA U-2 scientific experiment aircraft. This was first flown in 1974 and was shown to be highly efficient. The impaction surface consists of an area of 20 square cm, coated with a thin film of high viscosity silicone oil. It collects particles down to sub-micron sizes.

About 90% of the particles collected in the U-2 flights in the 3 micron to 8 micron size range are transparent aluminum oxide spheres. These are identical to those found in the balloon flights of Brownlee et al (1972) and have been identified as due to solid fuel rocket exhaust (Brownlee et al 1976a). Actual flights through the exhaust plumes of Titan III rockets by Ferry and Lem (1974) showed that these particles are extremely abundant as by-products of the burning of the solid fuel of such rockets. Fortunately, these objects are very pure in chemistry (pure Al_2O_3) and are very easily recognized by optical microscopy; they therefore do not present a contamination problem. Brownlee et al (1976a) showed that the concentration of these particles remains nearly constant at different altitudes; for particles larger than 5 microns in diameter, the density is 10^{-2} spheres per cubic meter.

From approximately 10 U-2 flights so far successfully accomplished, Brownlee and his co-workers have identified nearly 300 particles as being probably extra-terrestrial in origin. This represents nearly half of the particles that are not clearly solid fuel rocket exhaust products. They are characterized by very close agreement in bulk composition with that of chondritic meteorites. The elemental abundances vary from those that are similar to carbonaceous chondrites of type C-1 to those like iron-nickel meteorites, with the latter being relatively rare.

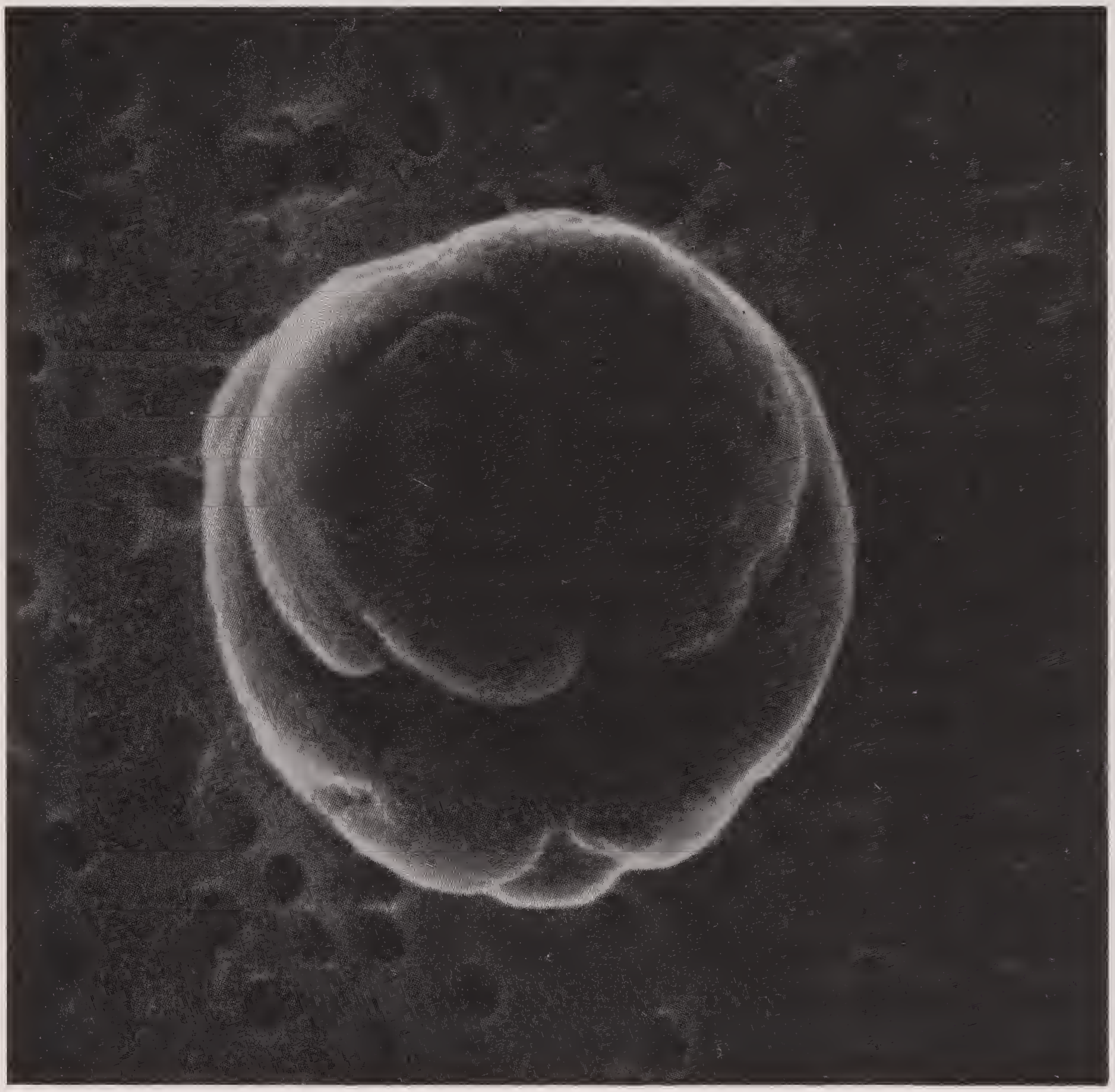

Figure 5-7. A U-2 iron-nickel-sulfur spherule (courtesy D. Brownlee).

Proof that most of these particles have an extraterrestrial origin came with the discovery of large amounts of solar wind implanted helium in them (Brownlee et al 1976b). The helium was found in concentrations of approximately 10^{-2} cm^3 gm^{-1} to 10^{-1} cm^3 gm^{-1}. In order to have this large a helium content, the particles must have been in the extraterrestrial environment, bombarded by the solar helium wind, and must not have been heated appreciably in their collision with the earth's upper atmosphere. Because such helium abundances do not exist for any terrestrial materials and because they are extremely common in lunar particles, which are exposed to the solar wind on the lunar surface, this evidence is excellent proof of extraterrestrial origin for any given particle. Approximately half of the particles tested that had chrondritic abundances did not contain detectable helium from the solar wind, and it is concluded that these probably were heated enough in encountering the atmosphere that their helium was lost.

The nickel-iron spheres collected by the U-2 experiment, although rare, are also demonstrably extraterrestrial in origin. X-ray defraction analysis of one of them showed a defraction pattern indicating the presence of taenite and wüstite. These minerals are both very strong evidence that the spherule in question was produced by ablation from an iron-nickel meteorite. Wüstite in particular is a metastable oxide that is found in the ablation products artificially produced by meteorites in the laboratory and is considered a positive proof of the meteoritic origin of any iron oxide.

Figure 5-8 compares the flux of meteoritic particles detected in the U-2 collections with that expected on other grounds and shows that the particles are consistent in number

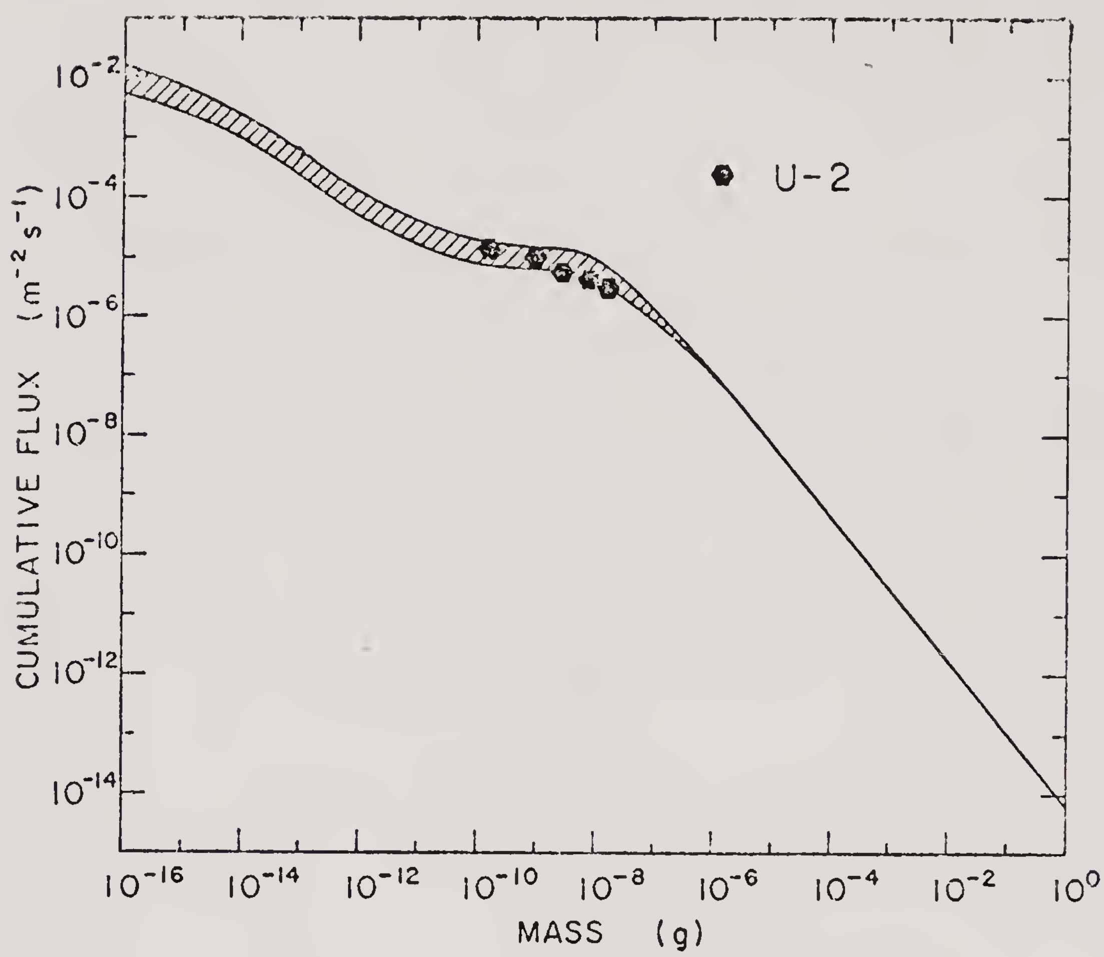

Figure 5-8. The flux of U-2 meteoritic particles compared to that determined from satellites.

with the extraterrestrial flux measurements. The calculated flux is approximately $3 \times 10^{-6}\ m^{-2} s^{-1}$ for particles larger than 10 microns in diameter; this value agrees well with those of the rotating arm and Vacuum Monster balloon collections and with the general consensus regarding the extraterrestrial flux.

The detailed physical and chemical properties of the large numbers of particles collected by Brownlee and his colleagues is discussed more fully in Chapter 13, where the origin of the interplanetary dust particles is discussed.

I. Introduction

The presence of interplanetary dust in deep sea sediments has both the longest established history and the least developed progress of any branch of the field of interplanetary dust investigation. The famous "Challenger" expedition of the 19th century made pioneering collections of material from ocean bottom sediments and in these Murray and Renard (1891) found large numbers of microscopic spherules, which they interpreted as ablation material from meteors. Arguing that when a meteor passes through the atmosphere, the skin of the meteor should be melted by the heat, they suggested that spheres then formed from the molten material. This seemed completely reasonable in view of the chemical properties of the meteoritic spherules found, which resembled abundances in larger meteorites. In particular, the most magnetic of the spheres found contained primarily iron and nickel and these were in approximately meteoritic proportion (about 10 to 1). They also found stoney spheres with abundances like stoney meteorites, but in the over 100 years since the initial discovery of such objects, almost nothing was done scientifically with the stoney meteoritic spherules. A bibliography that includes most of the papers published before 1961 on the deep sea spherules has been given by Hodge and Hoffleit (1962), and a review of some of the more important early work on the spherules was published by Parkin and Tilles (1968).

Most of the work in the mid-20th century dealt with the iron-rich deep sea particles and showed with very little question that these have only one reasonable possible origin, namely as ablation spheres from iron meteorites passing through the atmosphere. In some sense this should have been surprising, as iron meteorites are relatively rare among falls. Analytical methods of the time were particularly appropriate for the measurement of iron and nickel in large quantities and not yet sufficiently powerful for the determination of very small amounts of other elements, such as characterize the trace constituents of the iron spherules and such as are present in larger amounts in the stoney spherules. Thus the only convincing test at first was the iron to nickel ratio, and because iron and nickel are relatively small constituents of stoney spherules, techniques were not adequate for unquestionably assigning the latter to a hypothesized origin.

Schmidt and Keil (1966) examined several iron-rich deep sea spherules and showed convincingly that their properties were like those of iron meteorites. Other similar studies were carried out by Laevastu and Mellis (1960), and Hodge, Wright, and Langway (1960). Table 6-1 gives a summary of chemical abundance analyses of several iron-rich deep sea spherules.

II. Recent Investigations of the Iron-Rich Spherules

Techniques for analyzing small particles improved considerably in the 1970's and it was possible to do a great deal more investigation of the specific chemical, physical, and mineralogical properties of the iron-rich spherules. In the paragraphs that follow, the work of Brownlee et al (1978) and Blanchard et al (1979) will be discussed in some detail. A great deal of new data will no doubt come from the revolutionary new techniques for mining these particles from the ocean bottom developed by Brownlee and Pilachowski and only put into operation in 1979.

It is particularly instructive in interpreting the properties of the deep sea spherules to compare them with

Table 6-1. Compositions of Some Iron-Rich Deep Sea Spherules (from Schmidt and Keil 1966).

Particle	Fe	Ni	Co	Mn	Al	Si
1 (rim)	64	1.9	0.3	0.03	0.3	0.2
1(trevorite)	41	20	0.4	0.09	0.8	
1(metal area)	22	77	1.2	0.08	<0.02	
1(magnetite)	71	1.4	0.3	<0.02	0.2	
1(Si-rich area)	56	-	-	-	-	
2	65	1.6	0.4	-	-	-
3	68	0.7	0.3	-	-	-
4	37	0.06	0.04	0.2	1.7	0.8
5 (rim)	64	4.0	0.6	0.04	0.09	0.08
5(magnetite)	71	3.9	0.6	0.5	0.1	0.05

Figure 6-1. A deep-sea spherule with a button-shaped protuberance.

both artificially produced spherules from high velocity pellet experiments (Blanchard and David 1978) and meteorite fusion crusts (Blanchard and Cunningham 1974, see also related experiments with iron and stoney-iron meteorites by Hodge and Wright 1966). Table 4-4 shows some of the chemical properties of ablation spheres from the latter source and illustrates two important points: most ablation spheres are rich in oxidized iron, primarily magnetite, and most are relatively poor in nickel compared to the parent meteoritic body.

The three most common minerals from meteorite parent bodies are magnetite, wüstite, and hematite. Apparently due to the fact that nickel, under these circumstances, oxidizes more slowly than iron, it therefore is usually found in the metallic phase. This also appears to explain the fact that some of the analyses (Table 4-4) show anomalously small amounts of nickel, because the metallic phase is usually concentrated in a small distinct core near the center or edge of the particle, and is therefore not detected by surface analysis techniques.

Deep sea sediments contain fairly large numbers of iron-rich spherules. For example, Brownlee and Hodge (1978) report that in a 100 km sample of Pacific red clay collected from the mid-Pacific at water depths of 5,000 meters, iron-rich spheres were found to constitute approximately 10-20 ppb of the material by mass. This concentration is unusually large in Pacific red clay because of a very slow sedimentation rate (roughly 100 cm of sediment per 10^6 years); the concentration in other locations is usually much less. For example, spheres in this same study were also extracted from 3 km of globigerina ooze, and the concentration was found to be approximately 100 times smaller.

All recent investigators have found that the iron spheres can be readily separated from the rest of the sediment magnetically, as they make up a fairly high percentage of the magnetic fraction of the sediment. Millard and Finkelman (1970) and Hunter and Parkin (1960) used this method, as did the more recent studies (Brownlee et al 1978).

After magnetic separation, the iron spheres are easily recognized by their black and shiny surfaces and perfect or near-perfect spherical shape. A few are found to have button-shaped protuberances (Figure 6-1). These possibly represent bubbles in the original surface, which has since broken away. Table 6-1 gives a sample of the range of elemental abundances determined by recent microprobe analyses of several iron rich spherules. It is shown that they are made up primarily of iron with a range in the amounts of other elements, primarily nickel. Occasionally very minor amounts of aluminum, silicon and sulfur are found.

It is common among iron spheres for there to be central or eccentric nickel cores made up primarily of taenite. In some cases, the nickel-rich cores are oxidized. A particularly good example of this is shown in Figure 6-2, which is an iron sphere studied by Blanchard et al (1979). It contains a magnetite-rich outer shell that also has nickel in it, an inner metallic core that is crescent shaped and made up of nickel and iron (about 90% nickel), and a circular central core of oxidized material, about 50% NiO and 7% SiO_2. Blanchard et al (1979) identify the core as made up of a siliceous, nickeliferous trevorite.

Generally the outer parts exterior to the nickel core are made up of various iron oxides, sometimes including metal. The most common oxide is magnetite, but wüstite and hematite are also often present. Blanchard et al (1979)

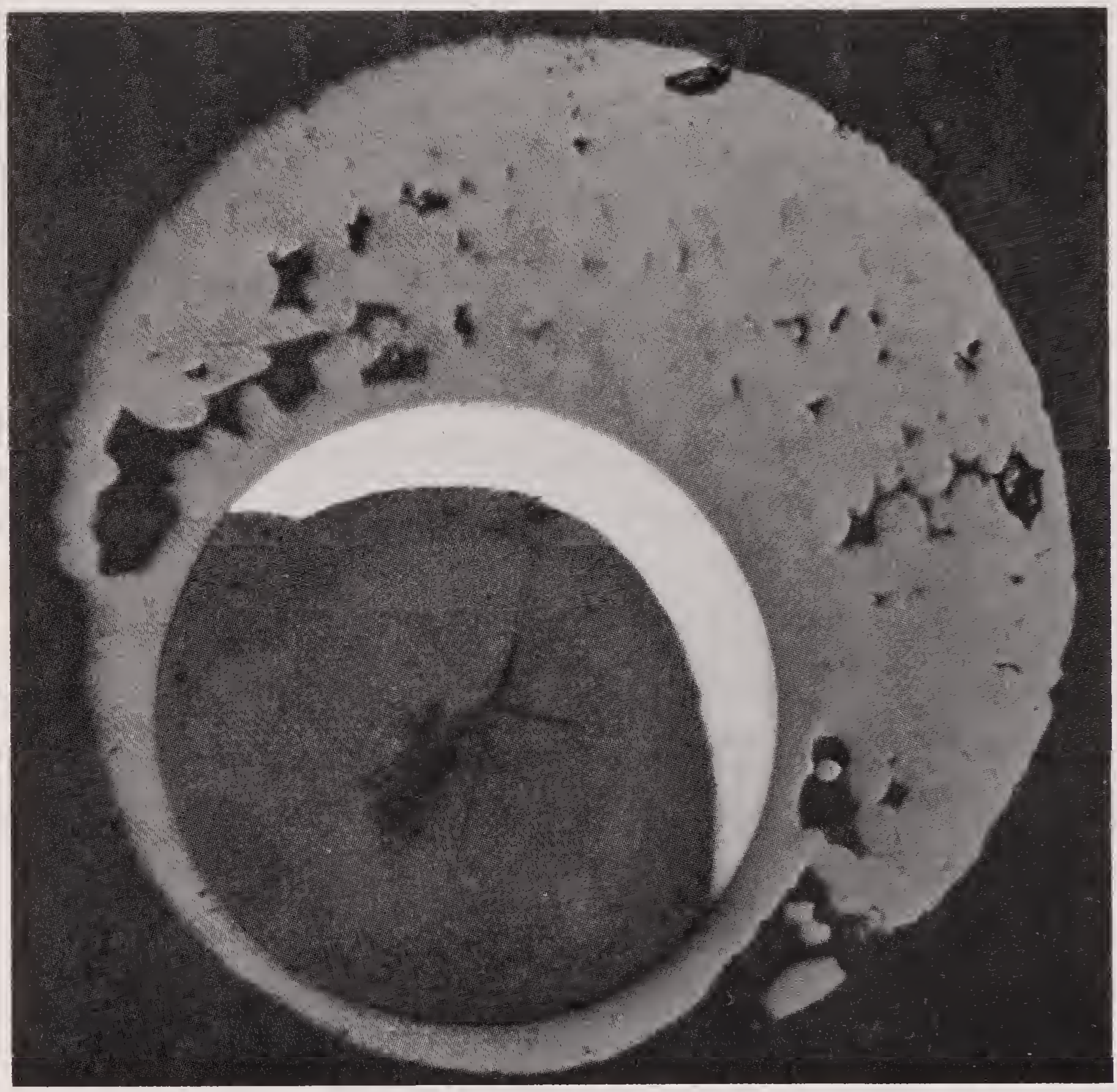

Figure 6-2. An iron spherule with a nickel-rich metallic and oxide core.

have shown that the metal phase, when it is found in the outer parts of a spherule, is usually taenite. Figure 6-3 shows an SEM image of an iron spherule showing magnetite and wüstite aggregates built up from oriented multi-crystalline interlocking components.

The most satisfying aspect of the study of these objects is the general agreement on their properties and the fairly straight-forward interpretation in terms of their origin from iron meteorites. Analyses carried out by Castaing and Fredriksson (1958), Petterson and Fredriksson (1958), Fechtig and Utech (1964), Marvin and Einaudi (1967), Finkelman (1970, 1972), and Jedwab (1970) are all in basic agreement. By comparing the observed properties with those of ablation products of different kinds of meteorites it is quite clear that iron meteorites are the parent bodies that give rise to these spheres. Never does a silicate meteorite produce individual droplets that are exclusively or primarily metal. Laboratory analysis shows that, in fact, ablating iron meteorites primarily go into the form of iron spheres (perhaps as much as 50% of the material ending up in this form), while ablation experiments with stoney meteorite samples show that a much smaller quantity (less than 25%) is likely to end up as silicate spheres. That is probably one of the reasons why a large number of iron spheres is found in the ocean sediment compared to what might be expected on the basis of observed meteorite falls on the ground. The many aspects of minerology, chemistry, and the physical characteristics of the ocean sediment spheres are virtually identical to those found in laboratory experiments, and this is generally considered sufficient evidence that such particles have a cosmic origin.

III. Properties of the Silicate Spherules

The most abundant component of extraterrestrial origin in the deep sea sediments seems to be the silicate spherules, which have been only recently studied in any detail. The earliest attempts to establish their properties in a general way were made in 1955 by Bruun, Langer, and Pauly (1955). More recently Parkin, Sullivan, and Andrews (1977) rediscovered their importance and carried out a preliminary survey of their distribution in the deep sea sediments. The most complete work to date is that published by Blanchard et al (1978), which includes discussions of their physical properties, their abundance in sediments, their chemical properties, and their mineralogy.

As in the case of iron spheres, it is instructive first to review the nature of ablation products from meteorites artificially accelerated in the laboratory and to examine the fusion crusts of various kinds of meteorites. For chondritic materials (Blanchard and Davis 1978) the ablation materials are fairly complex. Generally it is found that two melt phases result, a silicate melt phase and a metal melt phase. Spheres sprayed from an ablating chondritic meteoroid can be exclusively either one or the other or, more commonly, both. The silicate melt phase is characterized by a recrystallization of grains of zoned euhedral olivine and magnetite. These grains are found to be encased in a matrix of glass that is primarily Ca, Fe, Al, and Si. The metal melt phase is much rarer and it crystallizes into iron oxide and iron sulfide. The minerals are generally magnetite, wüstite, pyrrhotite and pentlandite.

A typical meteoritic separation from Pacific red clay sediments shows large numbers of these silicate spherules. Typically, they make up more than half of the recognized

Table 6-2. Abundances in Silicate Spherules Compared with Chondrites (from Blanchard et al. 1979).

Ratio	Deep Sea Spheres	Cl Condrites
Mg/Si	0.9	1.1
Fe/Si	0.8	0.9
Ca/Si	0.05	0.07
Al/Si	0.08	0.08
Ni/Si	0.02	0.05
Cr/Si	0.008	0.01
Mn/Si	0.006	0.009
Ti/Si	0.002	0.002

Figure 6-3. An SEM image of an iron spherule.

spherule population, and possibly as much as 75%. Some, because of the small iron or iron oxide content, are only weakly magnetic, while others are more strongly so; therefore, it is necessary to do a very thorough magnetic separation in order to be sure that the bulk of the silicate spherules are separated from the sediments.

The silicate spherules are different in optical appearance from the iron spherules, and are easily separated on that basis. Their surfaces are rougher and less shiny and often show a fine ridged network of parallel furrows in the surface. Their color is generally more gray than the black shiny surface of the iron spherules. They are often ellipsoidal rather than truly spherical; in some cases irregular fragments of spheres can be located by their optical appearance. They are less strong structurally than the iron spheres, easily breaking under pressure, usually along a cleavage plane. Figure 6-4 and Figure 6-5 show some typical sphere surfaces of particles identified chemically as silicate spheres. In the case of Figure 6-5, the sea water has etched away the presumed original smooth surface, revealing a somewhat chaotic arrangement of olivine and magnetite grains. Figure 6-4, on the other hand, shows a typical section of a silicate sphere in which the olivine and magnetite crystals are neatly alligned in a regular pattern.

Large numbers of these silicate spheres have been sectioned and examined mineralogically by Blanchard et al (1978), who found that there is a large variety in many of their properties, though the chemical abundances of the silicate spheres is generally not very variable. Most spherules are made up of olivine and magnetite crystals embedded in glass. The general appearance is virtually indentical to that of artificial silicate spheres produced in the laboratory. The

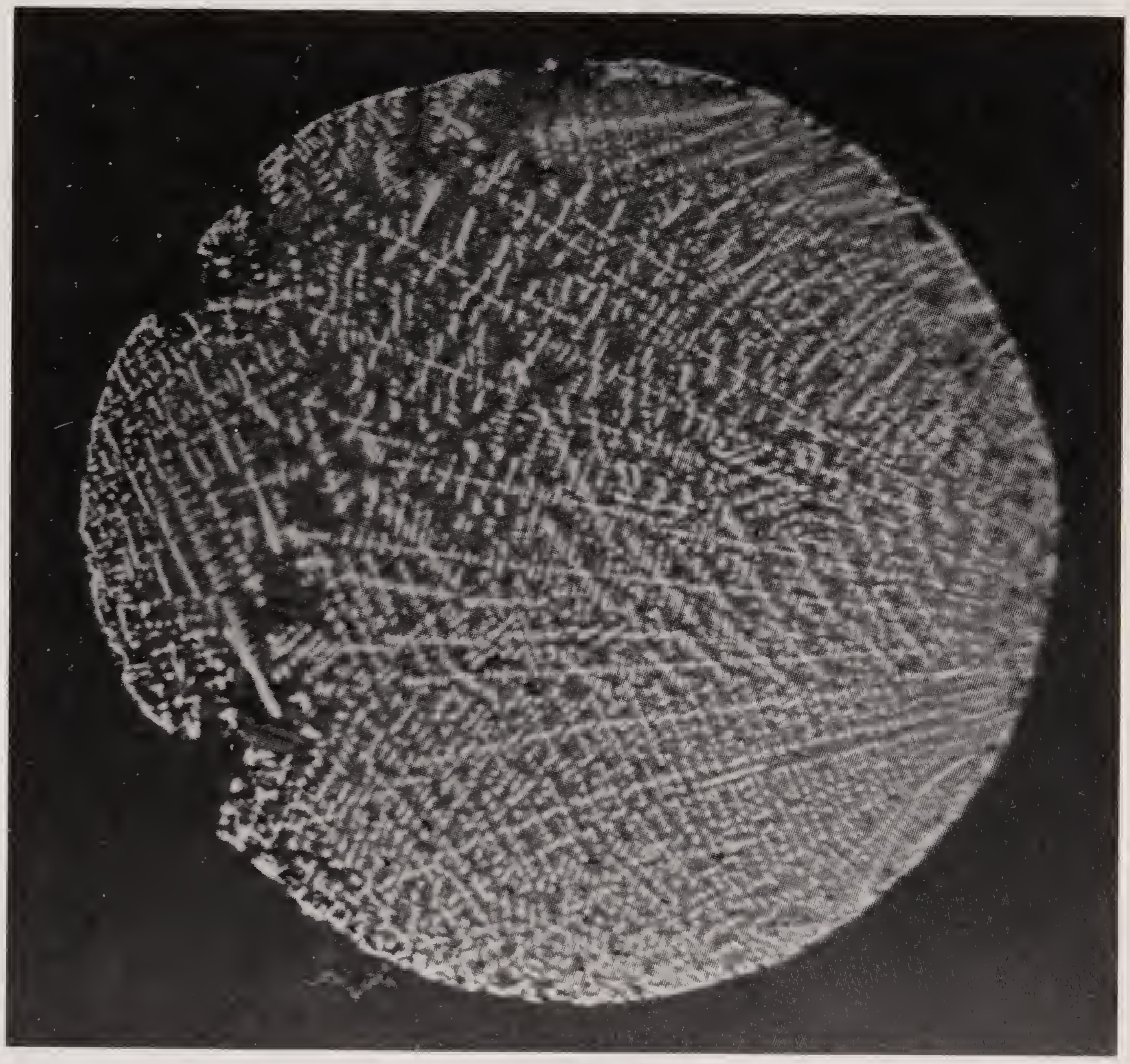

Figure 6-4. A silicate deep-sea spherule with a regular pattern of magnetite and olivine crystals.

Figure 6-5. A highly-etched silicate deep sea spherule.

general pattern is occasionally interrupted by voids and by small metallic or metal oxide grains. The most noteable variation from one spherule to the next is in the grain size of the crystals. The magnetite crystals range from sub-micron size to as much as ten microns, while the range for olivine crystals is from about one micron to nearly 50 microns.

Two common arrangements of these crystals are illustrated in Figures 6-6 and 6-7. In Figure 6-6 the olivine crystals are unoriented and surrounded by smaller magnetite crystals, which in turn are surrounded by interstitial glass. Figure 6-7 shows that in more ordered spherules, the euhedral olivine crystals are arranged in parallel flat planes, with the smaller magnetite grains filling in the pattern, and glass occupying the remaining space. A close examination of the olivine crystals in Figure 6-6 and 6-7 shows a shading towards the edge of each crystal, which was shown by Blanchard et al (1978) to be due to an iron rich boundary area. The magnetite crystals are found often to be pure Fe_3O_4, although sometimes there is substitution of titanium, aluminum, or chromium for part of the Fe.

The interstitial glass is primarily an iron-rich silica, though the detailed composition is highly variable from one sphere to another. The glass seems to contain most of the calcium in the spheres, but virtually no magnesium. There are small amounts of aluminum present.

Figure 6-8 shows a photomicrograph of a silicate sphere that contains sulfides. At the center of the sphere is a bubble, which is surrounded by pentlandite crystals distributed throughout the sphere, as well as concentrated along the outer surface. Figure 6-9 shows an SEM photomicrograph of a sphere in which the magnetite is found only near the

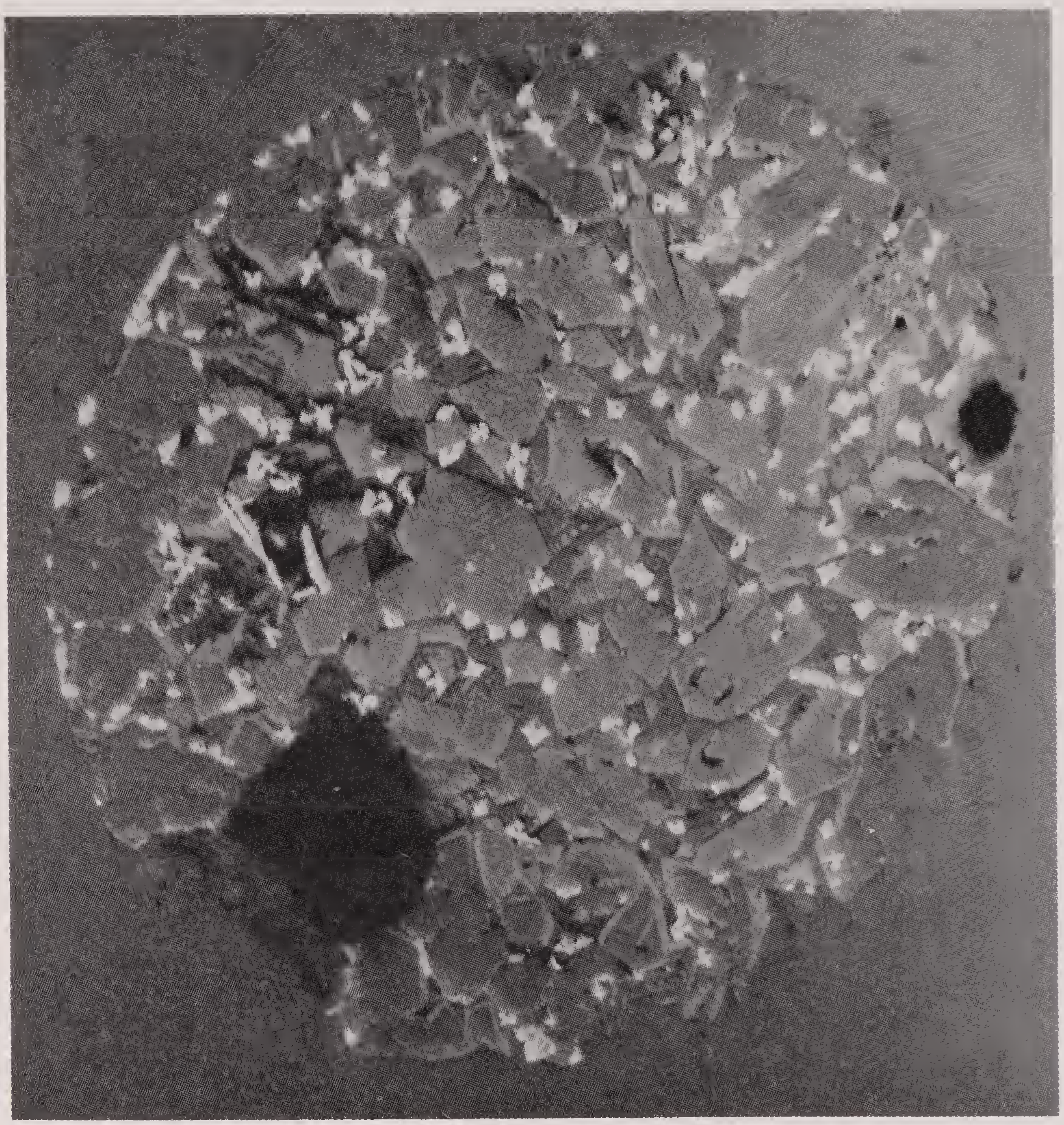

Figure 6-6. An SEM image of a silicate spherule (polished section).

Figure 6-7. An SEM image of a silicate spherule with olivine crystals arranged in parallel flat planes.

outer edges but which contains near its center many small grains of pendlandite and troilite. This particular sphere is of interest because of the large number of voids, bubbles interpreted as having been produced when the volatile gasses of the parent body left the matrix in melting.

The general chemical abundances for the silicate spheres are very similar to those for chondritic meteorites. Table 6-4 shows a comparison of the general abundance pattern with that for terrestrial rocks and for chondrites, showing the very strong resemblance with the latter. Figure 6-10 displays a result of a neutron activation analysis of one of the silicate spheres (Ganapathy et al 1978). This shows that the trace elements also agree very well with those in chondrites. The few elements in Figure 6-10 that are somewhat difficient compared to chondrites are those that would be expected to be preferentially lost in the ablation process.

Conspicuous in most of the photomicrographs of the silicate spheres is the considerable amount of loss of material that is attributed to etching by sea water. In a few cases the spheres have been etched almost completely to the center. The etching seems preferentially to attack the interstitial glass, leaving a skeleton matrix of olivine and magnetite crystals. In a few cases, even the magnesium-rich centers of olivine crystals have been etched away, leaving just the iron-rich crystal walls.

A particularly important discovery made by Brownlee et al (1978) is that some of the silicate spheres have what appear to be relict grains in their centers (Figure 6-11). These are apparently small portions of the parent meteorite which were preserved during ablation and surrounded by moulten material. Approximately 5% of the silicate spheres show what are believed to be relict grains of this type, and their

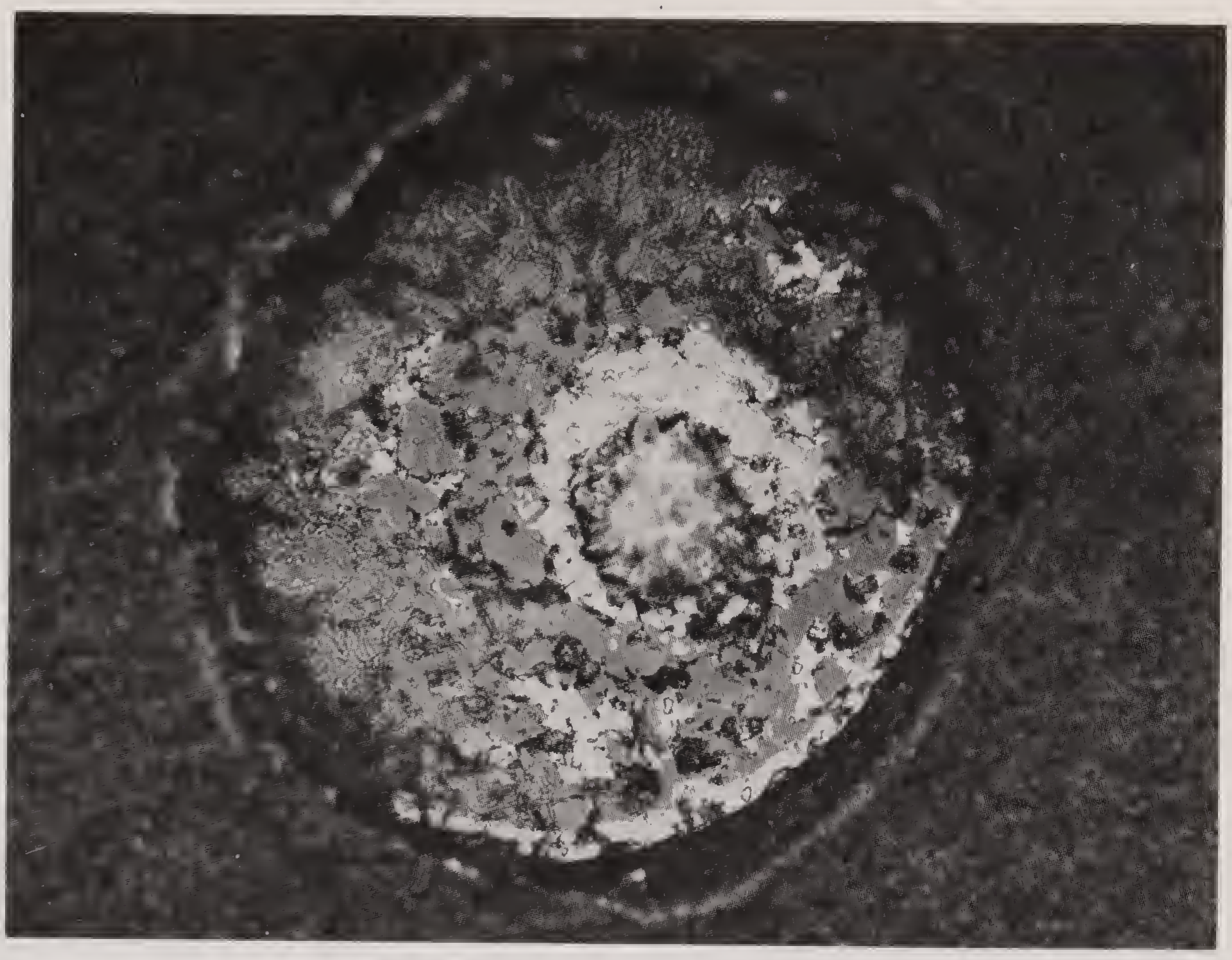

Figure 6-8. A silicate spherule that contains pentlandite, conspicuous as bright spots surrounding the central bubble.

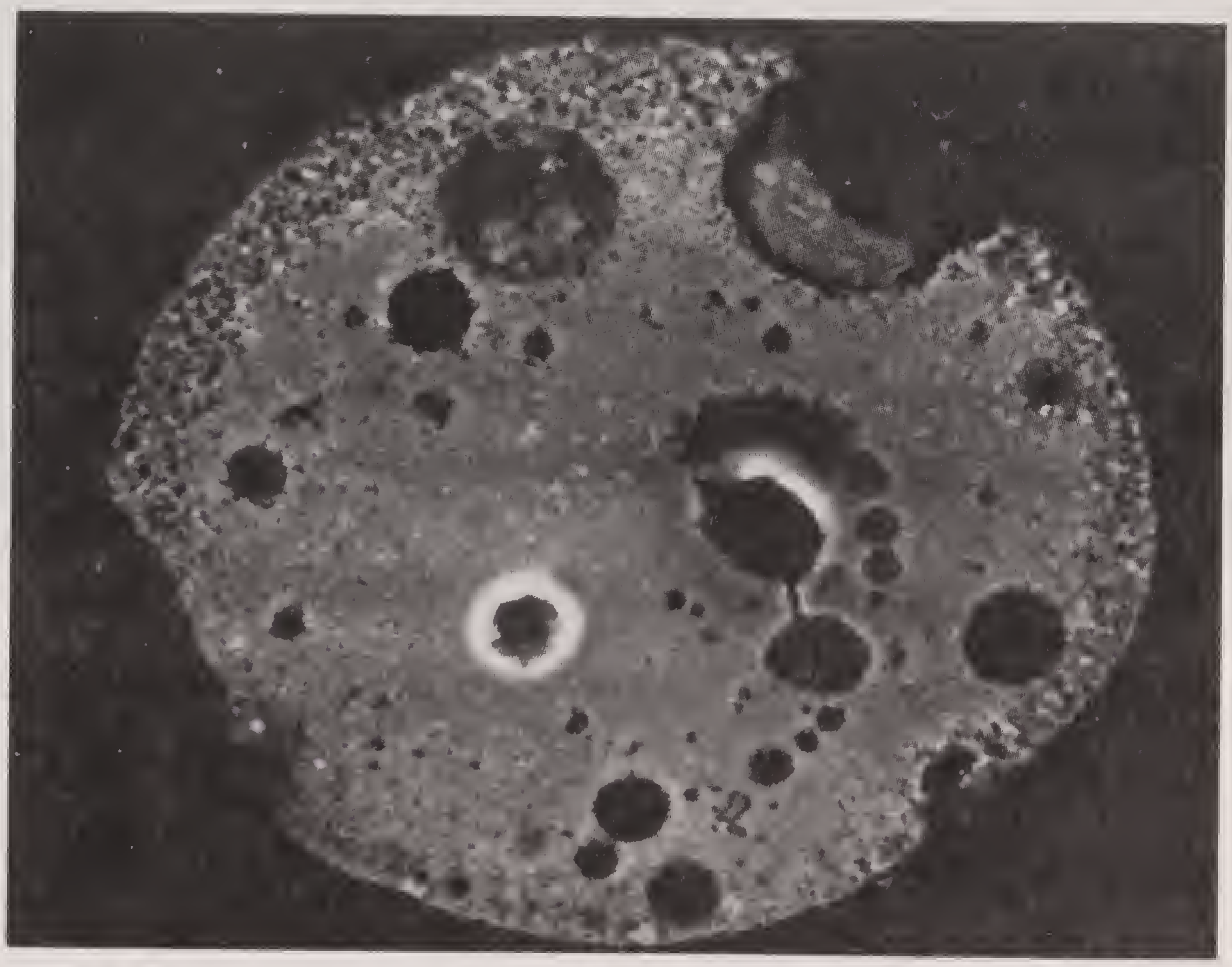

Figure 6-9. A silicate spherule with small grains of pentlandite and troilite near its center.

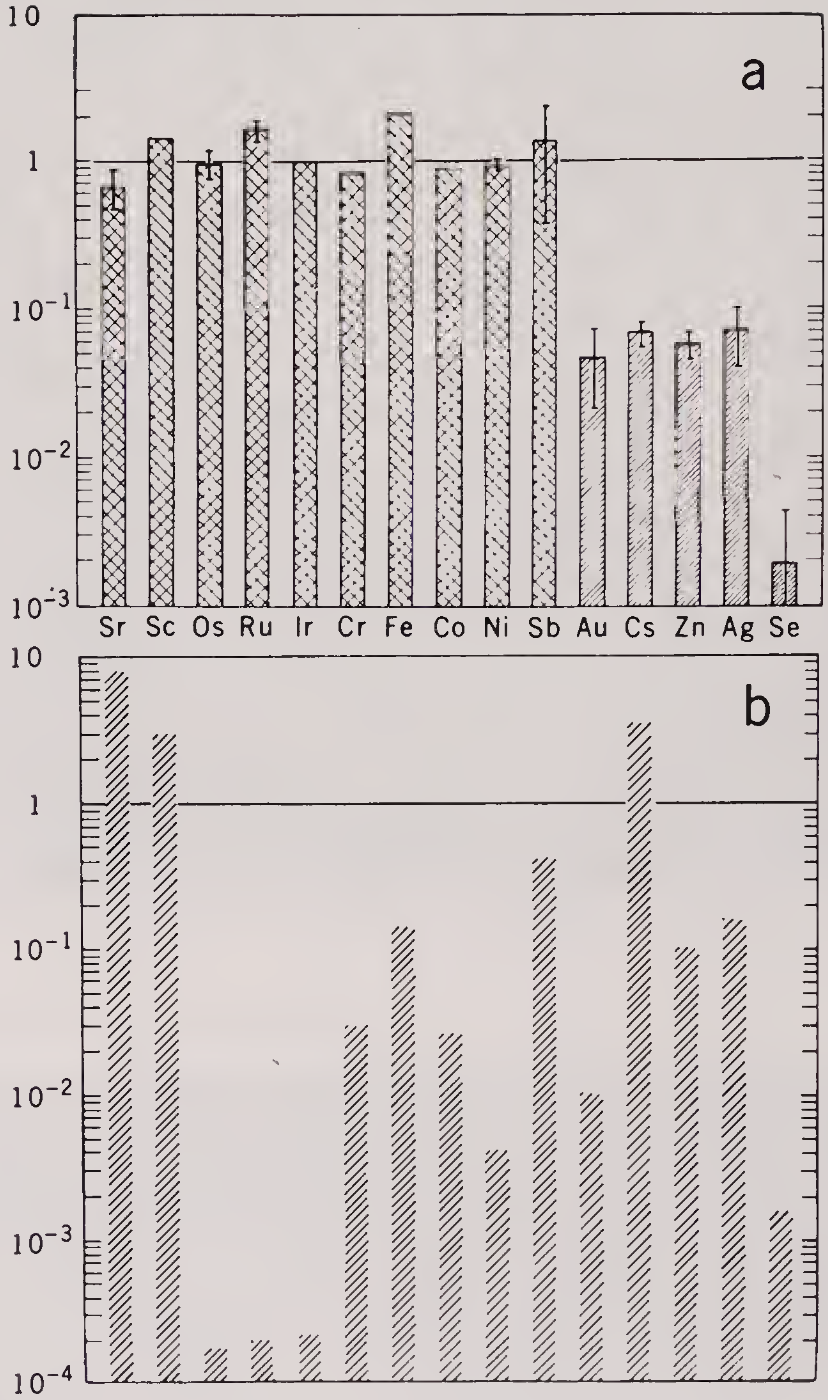

Figure 6-10. Trace element abundances in a silicate sphere compared with chondritic abundances (a), showing a good agreement for all but the heaviest elements. Part (b) shows a comparable comparison for the earth's crust. From Ganapathy, Brownlee and Hodge 1978.

Figure 6-11. A silicate sphere with a virtually undisturbed relict grain of forsterite.

great importance is due to the fact that they are the best source of evidence about the nature of the meteoroids which produce these spherules. Most relict grains are olivine crystals with magnesium-rich cores. In many cases it is possible to see the effects of the heating of the outer parts of the grains. Blanchard et al (1978) have identified grains of olivine, enstatite, ferrous spinel, chromite, and pentlandite. There is also some evidence of nickel-iron metal. The relict grains indicate that at least most pre-atmospheric bodies must have been carbonaceous chondrites. The large numbers of circular voids seem to point to escaping volatiles produced by the decomposition of low temperature minerals during ablation, and the large crystals of the high temperature minerals are associated with a very small-grained volatile-rich matrix of low temperature material. This suggests that the parent body must have been volatile-rich and carbonaceous chondrites are the most reasonable candidate.

IV. Glassy Spheres

A small component of the collected spherules are made up primarily of glass. This glass is not similar to the interstitial glass of the silicate spherules, but rather is very rich in iron and contains considerably less silicon, calcium, and aluminum. One of these particles is illustrated in Figure 6-12. They do not contain any silicate minerals at all, and this combination suggests that they are produced by the ablation of metal-rich chondrites.

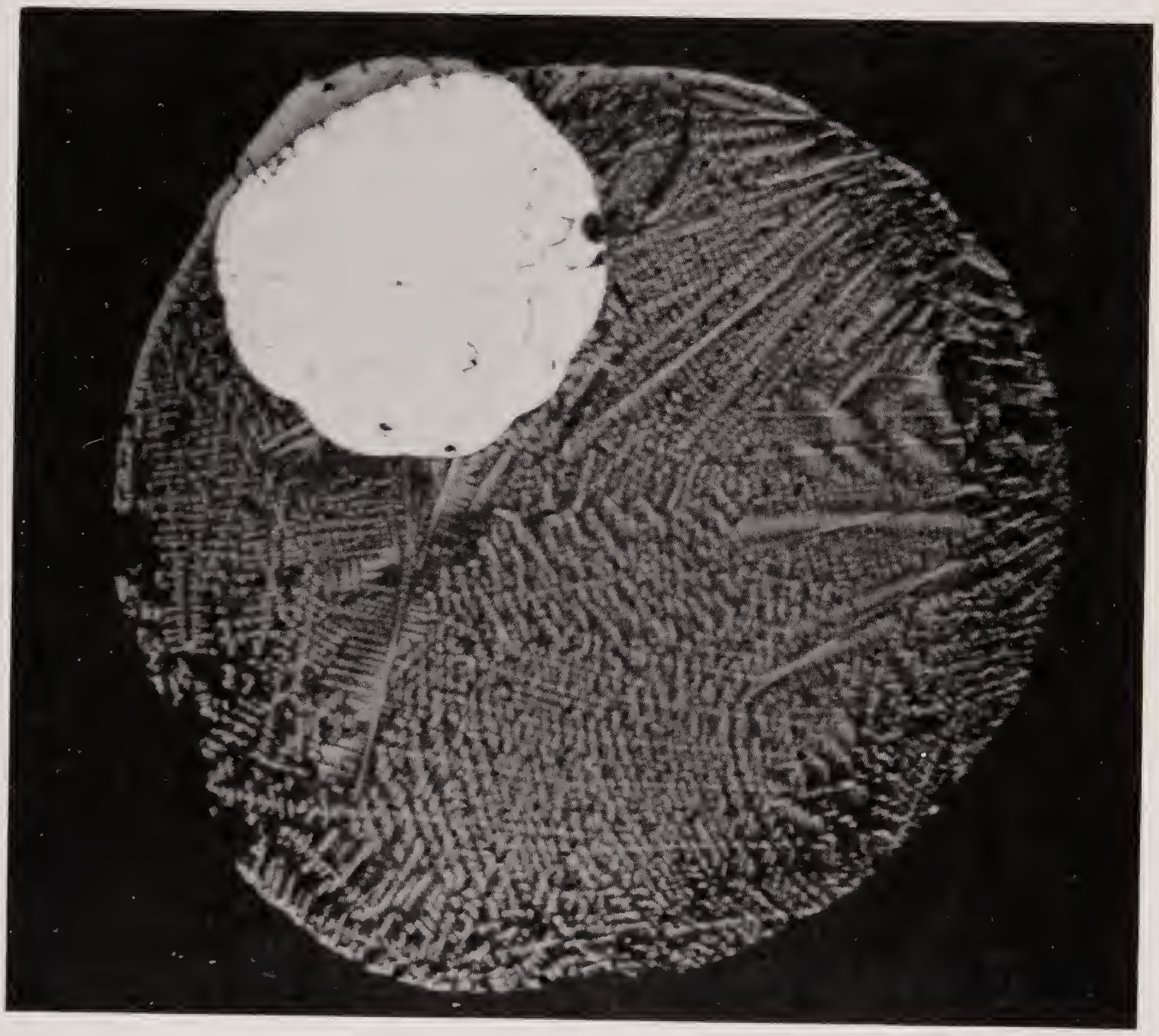

Figure 6-12. A glassy deep-sea spherule with an inclusion of iron-nickle metal.

I. Introduction

In the early days of rocket experiments, one of the primary scientific goals was the detection of interplanetary particles above the atmosphere. Part of the reason for this early interest was, of course, the desire to get above the contaminated atmosphere to obtain a pure sample. But even more important was the more practical fact that the unknown density of particles in space made the planning of eventual spacecraft flights in the solar system difficult and uncertain. Because the derived particle density from various sources of measurement from the ground differed by several orders of magnitude, spacecraft design could not reliably take into account the possibly disastrous effects of erosion in space by dust. According to some estimates, optical surfaces in space would be "sand-blasted" into uselessness in only a few days and the metal spacecraft skin would be badly damaged in weeks, unless a special outer skin (a "meteor bumper") were used.

With the advent of earth satellites, rocket activity in this field became less important, as the few seconds in space of a particular rocket were replaced by weeks and months of orbiting spacecraft. Nevertheless, a modest rocket program continued, especially to establish the chemical nature of the dust, since the first satellite experiments were not returnable, and to sample the noctilucent clouds.

II. Early Experiments

The pioneer effort to detect interplanetary particles in space was that of Berg and Meredith (1956), who mounted an impact detector on a sounding rocket and found that all detected impacts occurred at altitudes above 85 km. At nearly the same time, Burgess (1956), using a microphone-type detector, found no such altitude dependence. This stark disagreement, not unusual among pioneer experiments, was nevertheless both a harbinger of things to come and an extension to space of the wildly-divergent results that had been obtained from below.

By 1961 new techniques were available for rocket experiments, to take advantage of their recoverability. Earth satellites were by then using a variety of impact detectors, including microphones, films and wire grids, but the only possibility of <u>collecting</u> particles remained below satellite altitudes, where particles had already been somewhat decelerated by the outer terrestrial atmosphere. In space, the particle velocities are so large that the particle is always destroyed by the impact, and so chemical studies (except those involving particle residue in craters, as described in Chapter 8), must be done below at least a portion of the earth's atmospheric cushion.

Hemenway and Soberman (1962) invented the Venus Flytrap to exploit the opportunity that sounding rockets provided to sample particles in the upper atmosphere. It was a device that consisted of prepared panels that opened up like petals of a flower at altitude and then closed before returning to the more contaminated lower atmosphere. Flown on an Aerobee rocket, the Venus Flytrap sampled at heights of 68-168 km. Large numbers of particles were collected, which the Hemenway group studied in detail, separating them into three different types:

(1) dense spheres, making up 16% of the sample,
(2) irregularly-shaped sub-micron particles (72%), and
(3) irregular, fluffy particles of low density (12%).

Sizes were in the range 0.1-1.0μm and there was little or no evidence for high impact velocity, which caused the scientists to suggest that they might have been earth-orbital.

III. Advanced Techniques

As methods became available for improving both contamination prevention and identification, the early rocket results were not completely confirmed. Groups at the Max Planck Institute (e.g., Weihrauch et al., 1968), at Lund (Lindblad et al., 1970), at NASA-Ames (Farlow et al., 1966), in Tel-Aviv (Yaniv and Shafrir 1968) and at the NRC in Ottawa (Wlochowicz 1974) attempted various methods of unambiguously detecting, identifying, and analyzing interplanetary dust with rockets.

Particularly important were the attempts by the NASA-Ames group, which used several Luster sounding rockets, starting in 1965, to attempt collections under the strictest possible contamination controls (Blanchard and Farlow, 1966). Not only were preventive measures especially stringent, but the Ames group also went to great pains to identify in the final samples the origin of all contamination particles, which were found to come from a surprizingly diverse range of sources, including the clean room and clean bench, the clean garments, the inside of the collector, and the rocket. With all of these eliminated, there remained no significant number of collected particles,-the control surfaces had just as many sub-micron particles as the exposed surfaces. The estimated density of particles in the region sampled was at least one, and probably several orders of magnitude smaller than that derived from the Venus Flytrap experiments (Figure 7-1). They did identify a few particles as possible

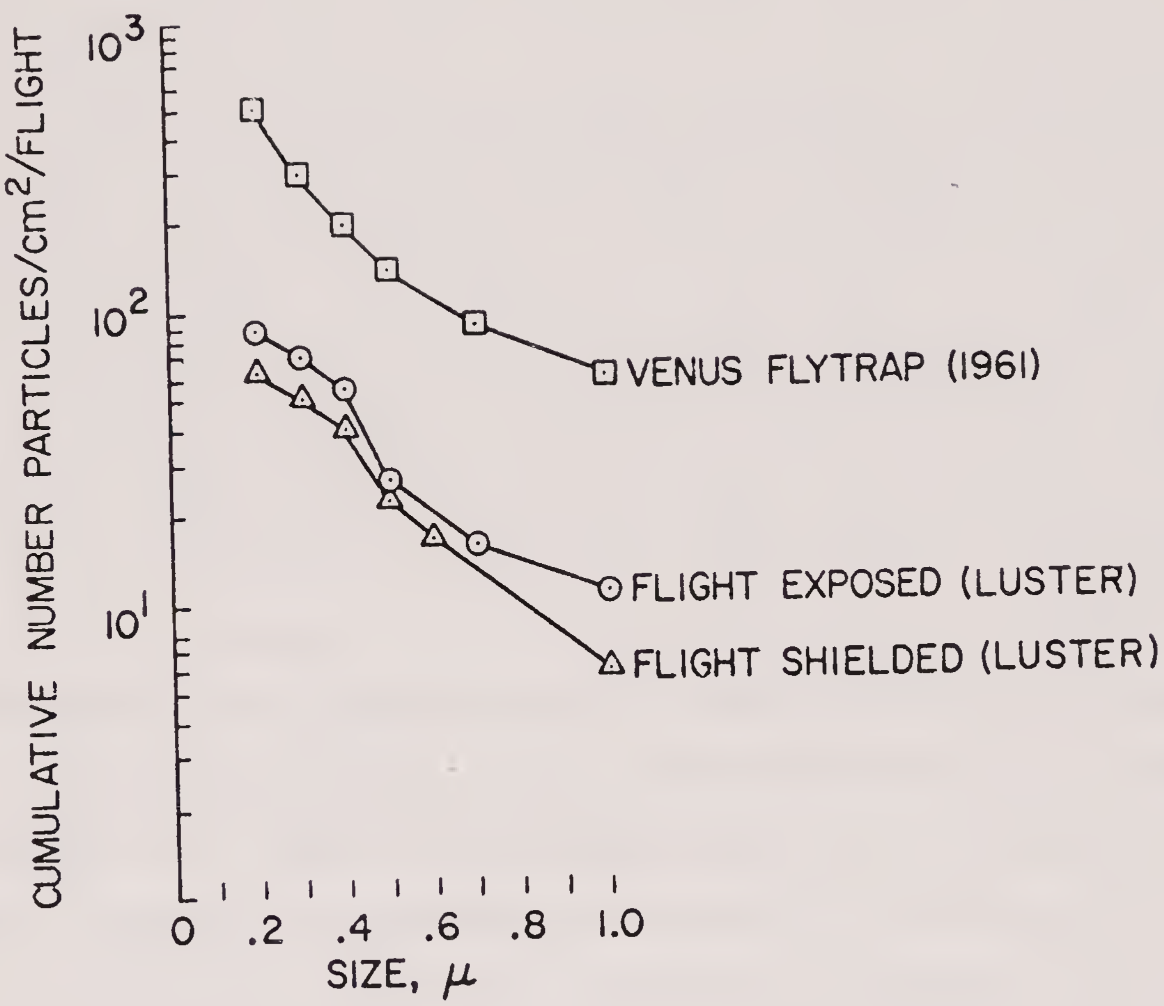

Table 7-1. Particle concentrations on the 1967 Luster experiment, reported by Farlow (1968). Courtesy of N. Farlow and NASA.

candidates for extraterrestrial particles.

The Heidelberg group (Weihrauch et al., 1968) reached a similar conclusion. They separated out a chemically-distinct component of the dust that did not show up on the control surfaces and suggested that they were cosmic. In the October 1966 Luster flight, which sampled for 200 sec in the range 60-160 km, they found only five possibly cosmic particles on the metal plates. These were identified by their chemistry, which was typically Al, Si, Ca, and Fe in varying proportions.

Other methods of utilizing rockets have been pursued by the Lund group (Lindblad et al., 1970). Using a variety of collection and detection instruments, including acoustical piezoelectric detectors, their aim was to sample the near-earth micrometeorite flux with different techniques simultaneously on the same rocket so as to detect any sources of spurious particle data. Using Centaure rockets launched from the Kirune range, Lindblad and his colleagues detected several impacts believed to be caused by interplanetary dust. As for the NASA-Ames results, however, the deduced particle flux was considerably smaller than that found in earlier flights, by 2-3 orders of magnitude at log particle mass ≈ -14 to -12. Above 110 km the particles were mostly impacting onto the membranes of the detectors from random directions, while below this height they were nearly stationery, presumably suspended in the upper atmosphere.

Wlochowicz (1974 and several subsequent papers) developed a different approach to rocket utilization. The collections are made from a device that is ejected from the rocket near apogee. It opens to collect particles on the way down as soon as parachute drag is sufficient to slow it, and makes

Table 7-1. Particles of Possibly Extraterrestrial Origin, Identified in the Luster 1965 Samples by Farlow et al. (1968).

Elemental composition groups	Number isolated	% of analyzed particles	Projected maximum ρ on flight surfaces, (no./m^2/flight)
Fe with Si or Fe alone (no Cr,Cu,Ag,Ni)	82	12.4	205
Ni with Fe or Ni alone (no Ag)	21	3.2	53
Ca with Si or Ca with trace elements (no Cr, Cu,Ag,Fe,Ni)	31	4.7	78
(K,Na,Ba) with Si (no Cr,Cu,Ag,Fe,Ni)	15	2.3	38
Si only or Si with trace elements (no Cr,Cu,Ag,Fe)	47	7.1	117
Zn with S or S only (no Cr,Cu,Ag,Fe,Ni)	2	0.3	5
	198		496

particle collections in the altitude range ~70km to ~30km. The flight of this device was made with a Black Brant VI rocket in March, 1974 and several possibly cosmic particles were collected.

IV. Sampling Meteor Showers

After the apparent great success of the Venus Flytrap rocket collections in 1961, the technique was turned to the specific problem of attempting to sample meteoritic particles from specific meteor showers. Because shower meteors are known from their light curves to differ significantly in their density from one shower to another, it seemed of great interest to try to collect individual particles from different showers to compare their physical and chemical properties directly.

Hemenway and Hallgren (1967) deployed a Pandora collection experiment on November 18, 1965, one day after the peak of the Leonid shower. Among the single shadow particles (the sample surfaces were shadowed before and after flight to separate out pre-existing contamination particles) detected included some low-density sub-micron particles that were not found on control surfaces.

Blanchard et al. (1968) attempted to sample the same shower, using a Luster rocket launched on November 16, 1965. Sampling occurred over the range 63km to 145km, and occupied 206 seconds. The number of particles found on both flight and control surfaces was essentially identical over the size range 0.1μm to several microns. After analyzing ~1200 particles, they concluded that almost all particles collected on the flight surfaces could be identified as contamination. Although they identified a few particles, especially some showing Ni, as possibly cosmic in origin, their numbers were very small, indicating a far smaller influx rate than the earlier non-shower flight of the Venus Flytrap.

Trying again in 1966, the same authors (Ferry et al., 1970) attempted to collect particles from the Orionid (October 22, 1966) and Leonid (November 17, 1966) showers. Results were the same: no significant increase in the number of particles was found for either flight above background contamination levels. Particles with certain compositions (in this case, Ni particles, Fe particles, those with Fe and Si, and Ca, Ba or K-rich particles) did seem to be more common on the flight surfaces, in both cases by the same amount. Thus, if these are truly shower meteor particles, the chemistry of the two meteor showers must be similar.

V. Noctilucent Cloud Experiments

As techniques for rocket-borne experiments improved in the 1960's a new idea arose. The "noctilucent clouds" had long been a source of interest to astronomers because the prevailing hypothesis about their origin was that they formed from extraterrestrial material that settled down to concentrate in the mesosphere, above altitudes of about 25km. From ground-based observations the clouds had been understood to be made up of sub-micron particles of dust, with sizes predominantly in the Mie scattering range. They have polarizing properties such that, if their size distribution can be described by a power of the radius, r, then the exponent of r must be greater than 3.

The pioneering efforts of Hemenway and Soberman (1962) involved an adaptation of their rocket techniques to allow collection of the noctilucent cloud particles. The two first successful flights were made in August, 1962, using a Nike Cajun rocket launched from northern Sweden. One flight passed through a noctilucent cloud and the other did not, acting as a control. The results, presented in a collection of papers (Hemenway et al., 1964), suggested that the collection surfaces did collect particles at the noctilucent cloud altitudes, that the size distribution of the particles had the predicted form, that many particles were ice-coated, and that the particle density was three orders of magnitude higher in the clouds than in their absence at the altitudes sampled. The authors argued, principally on grounds of particle transport in the atmosphere, that they

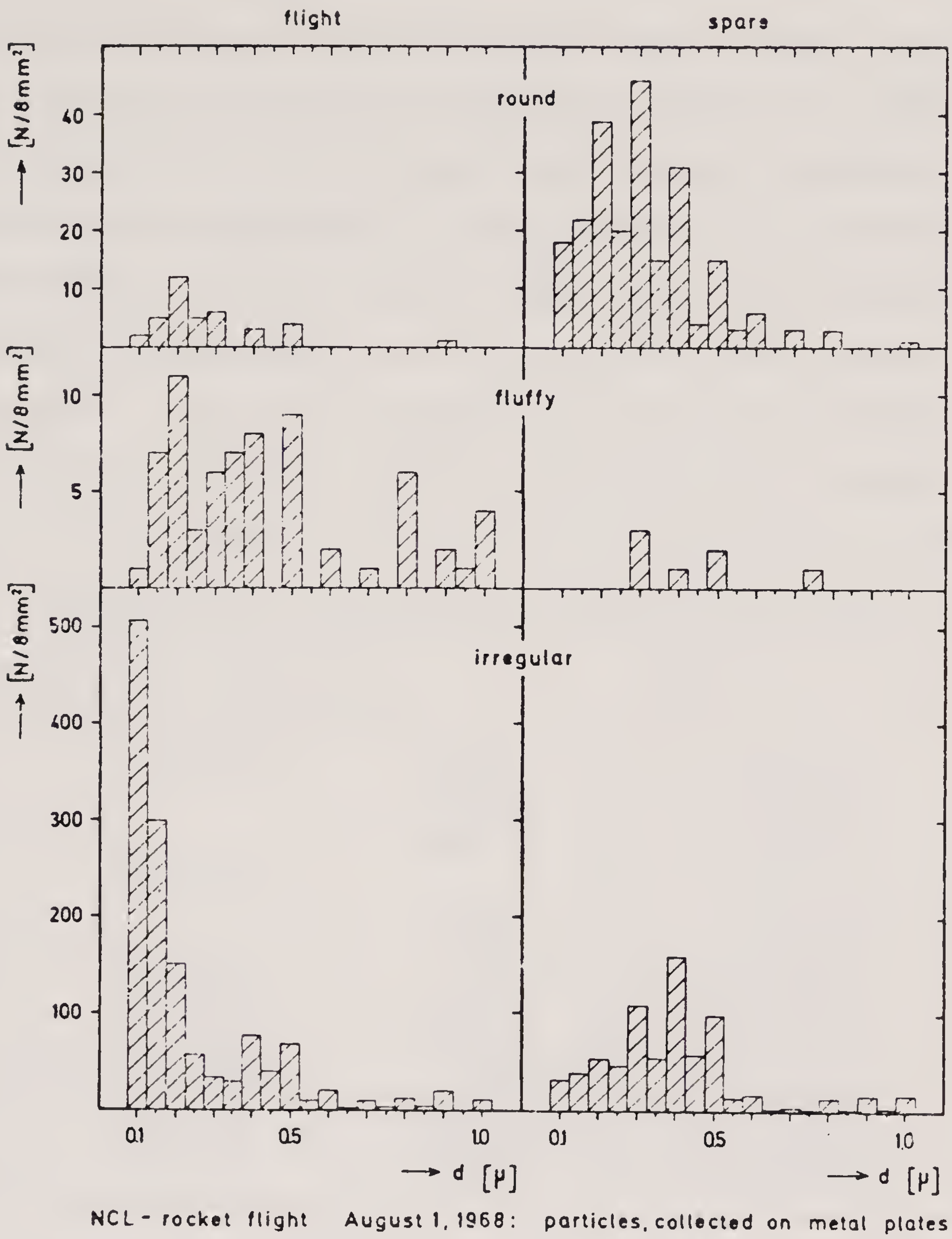

Table 7-2. Particle concentrations by type identified by Fechtig et al. (1970) from collections made in 1968 during a weak noctilucent cloud display. Courtesy H. Fechtig.

are most likely extraterrestrial in origin.

However, similar experiments in 1964 and 1965 (Soberman et al., 1968) gave somewhat different results (lower fluxes, no ice-covered particles), and there was increased interest in attempts to unravel the puzzle of how many particles were there and where they came from. Many further flights were launched (Table 7-3), using collectors, detectors, and even elaborate devices designed to measure velocities. Highly variable results were reported and the conclusion of one of these later studies (Farlow et al., 1970) was that the

Table 7-3 Some Noctilucent Cloud Rocket Experiments

Date	Authors	Altitudes Sampled (km)
1962	Hemenway et al. (1964)	75-98
1964	Soberman et al. (1968)	
1965	Soberman et al. (1968)	
1967	Lindblad (1969)	60-130
1968	Fechtig et al. (1969)	
1970	Rauser et al. (1971)	61-114
1970	Hallgren et al. (1972)	82-128
1970	Hallgren et al. (1972)	85-113
1971	Rauser et al. (1972)	70-115 (3 flights)
1971	Hemenway et al. (1973)	76-106
1971	Hemenway et al. (1973)	79-113

space density of noctilucent cloud particles is not always large and that the particles seem to be uplifted from lower altitudes. They felt that a terrestrial origin was possible. However, the general consensus now is that an extraterrestrial component is not needed; the noctilucent cloud nuclei are probably terrestrial atmospheric condensates.

The recent experiments with meteoritic dust collectors on rockets have rather convincingly demonstrated that the technique will collect actual particles only when some special circumstance (maybe noctilucent clouds, or passage of a bolide through the atmosphere, possibly a meteor shower) has greatly enhanced the particle density. Under normal conditions it is difficult if not impossible to collect even one particle that can be unambiguously identified as extraterrestrial in origin.

I. Introduction

The real space age began in 1957 with the launching of Sputnik, the first earth-orbital satellite. Because the space environment is nearly but not quite empty, with interplanetary dust an important part of its sparse contents, dust experiments featured prominently among the first satellite payloads. As the initial launching countries became more and more proficient at rocketry, control, and telemetry, science could be devoted more space and attention. Eventually, as we describe below, elaborate satellites were devised that were dedicated entirely to measuring the properties of the interplanetary dust.

II. First Results

Many of the earliest detectors flown on earth satellites involved the use of microphone devices that recorded the momentum exchanged between the incoming particle and a thin capacitor or piezo-electric crystal. In all cases the particles were destroyed on impact and at first, at least, the information gained was simply a count of particles. This could be translated into an integrated flux above a certain mass limit after the detector was suitably calibrated and if the velocities of the particles could be assumed.

Initial results for microphone detectors (e.g. Dubin 1960, La Gow and Alexander 1960, Alexander 1962) gave integrated particle fluxes that agreed rather well with the rocket data of that time (Ch. 7).

Often the flux was quoted in terms of tons of material incident onto the earth, and values from Satellite 1958α, for instance, were approximately 10^4 tons/day. Comparison of results from different satellites, for example 1958α and

Pioneer I (Dubin 1960), indicated reasonably good agreement. Dubin calculated a space density near the earth, assuming a particle velocity of 30 km/sec, of 5×10^{-22} gm/cm^3. Nazarova (1961) reported similar results from Soviet spacecraft, especially noting a high variability in particle density with both time and position. On May 15, 1958, for instance, there appeared to be a 10^4 increase in particle flux, according to her analysis. An increase noted by Satellite 1959η was subsequently attributed to passage of the spacecraft through the Leonid meteor stream.

These kinds of results typified the extensive literature up through 1962. The US satellite data was reviewed by Dubin and McCracken (1962), who derived a cumulative distribution curve of the form

$$\log I = -17.0 - 1.70 \log m$$

where I is the flux in particles/m^2/sec, m is in gm and the range is from 10^{-10} gm to 10^{-6} gm. The spatial mass density was 10^{-20} gm/cm (with a 10^3 increase near the earth) and the total accretion rate for the earth was given as 5×10^4 T/day. For particles large enough to be detected, an impact rate of 4×10^{-2}/m^2/sec was calculated for US experiments. This implied that 4×10^{18} particles were hitting the earth each day.

The Soviet results, summarized at about the same time, also suggested a high accretion rate (0.5 to 1.0×10^4 T/day) and a concentrated dust cloud around the earth having a maximum density at ~ 150 km from the surface. Using a ballistic sensitive plate, they found approximately 10^{-4} particles /m^2/sec incident for the mass range 8×10^{-9} to 2.6×10^{-8} gm.

We now know that most, if not all, of these early results were completely erroneous. Apparently the strains of the extraterrestrial environment, including rapidly changing temperature and the frequent noisy commands transmitted between earth and spacecraft, caused a large number of unrecognized spurious events to be recorded. As more sophisticated detectors were devised, especially those that involved coincidence techniques, the true story gradually emerged. It is one of the lessons of science that the various early satellite experiments, both in the US and the USSR, agreed so well and seemed to fit in so well with the rocket, balloon-based, and ground-based data, and yet all of them were wrong. Although this is not the proper place to analyze thoroughly this remarkable fact, it can be suggested, at least, that it is probably partly the result of the fact that spurious signals always add, never subtract, from the real signal in experiments of this sort, and partly the result of the subconscious selection of both data and assumptions that make one's results look reasonable. A proper analysis of the problems that befell these experiments should perhaps be carried out some day by a trained historian of science. This example is particulary interesting, because of the great amounts of money spent, and the huge error (a factor of 10^5 for the extreme values of small particle flux.)

III. Detectors in Earth Orbit

Even before 1962 it was realized that inconsistancies in satellite particle flux results were pointing to some kind of problem. For example, Soberman and Della Lucca (1961) compared their results for the Midas II (1960ζ1) satellite. Two wire grid detectors and three acoustic microphone detectors were used and the latter indicated a considerably higher particle flux than the former, even taking into account the fact that the size range being detected

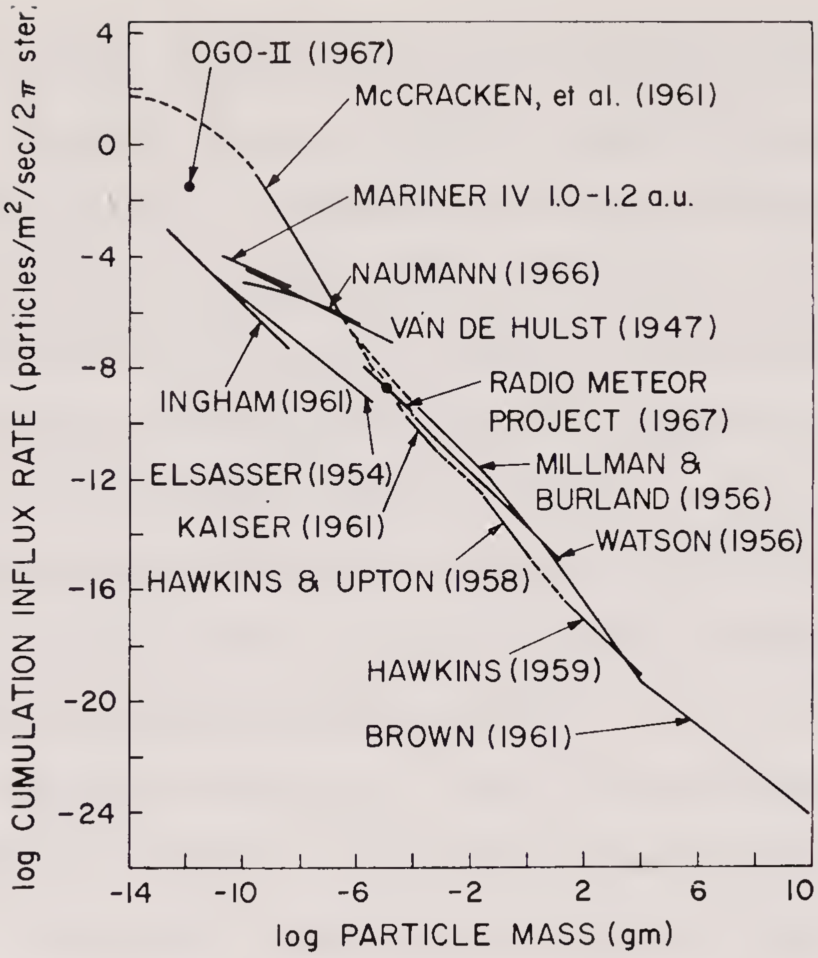

Fig. 8-1. Early flux data from satellites compared to other sources, including zodiacal light curves and meteor and meteorite data (after Dubin and McCracken, 1962).

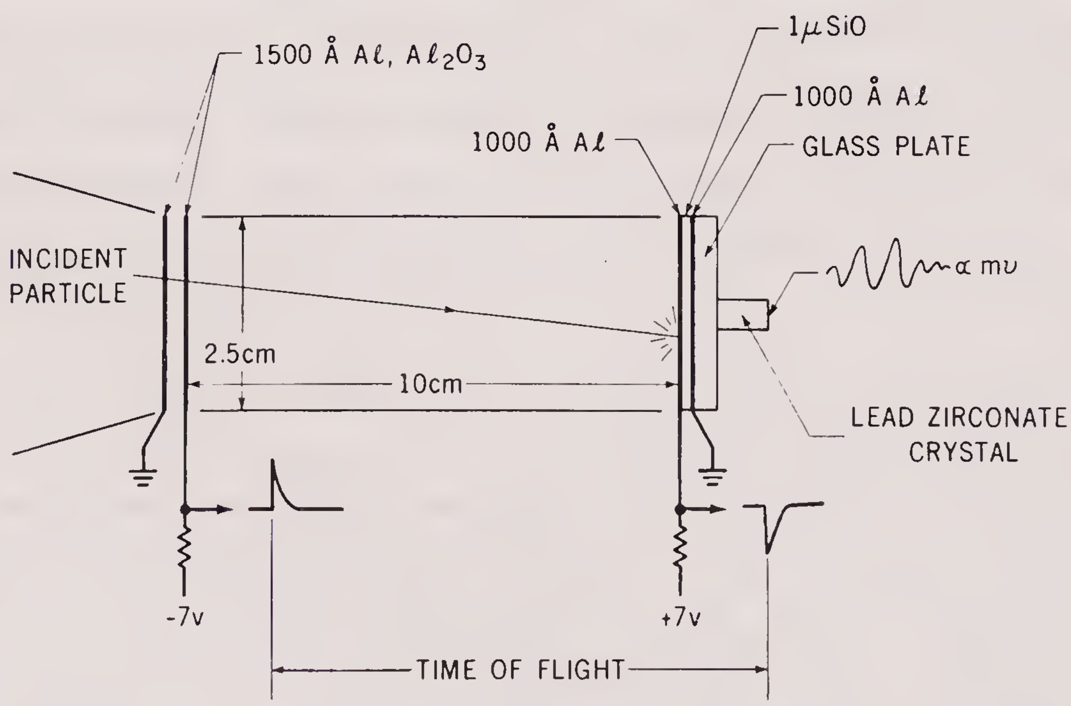

Fig. 8-2. The OGO-II micrometeoroid experiment (from Nilsson et al., 1969).

was not the same. Data were obtained for four partial orbits and in this time (2.5×10^4 seconds) none of the wire grids was broken. A break would have indicated the presence of particles on the order of 10 microns in size. The acoustic detectors, on the other hand, recorded 67 events, all interpreted to result from particles with relative momenta greater than 3×10^{-4} gm cm/sec. Assuming a velocity of 15 km/sec and particle density of 3 gm/cm^3 would give a flux for particles 5 microns or more in diameter of $0.25/m^2/sec$. This should be compared to the upper limit for the wire grids, which for particles 10 microns or more in diameter was $< 5 \times 10^{-4}/m^2/sec$. As the size distribution is approximately an r^{-3} relation in virtually all experiments and predictions, the expected flux at 10 microns, based on the acoustic detector results, would have been $3 \times 10^{-2}/m^2/sec$, almost two orders of magnitude larger than the actual observed upper limit. This was an example of early evidence that something was wrong.

A somewhat later example was provided by the Orbiting Geophysical Observatories (Nilsson et al. 1969). The spacecraft OGO1, 2, 3, and 4 had rather sophisticated instrumentation that was designed to measure the properties of the earth's dust cloud, found by the early microphone experiments, and now known not to exist. Fig. 8-2 shows the design of the OGO-2 micrometeoroid detector tubes, which were 10 cm long and 2.5 cm in diameter. The tube acted as a collimator in order to provide approximate directional information, and four were mounted on the spacecraft, three in mutually perpendicular directions, with the fourth reserved for a control. An incoming particle first penetrates through two 1500Å films, causing a small plasma pulse that is recorded in order to measure the velocity of the particle from its time of flight through the 10 cm length of the tube. At the back of the tube is a thin film capacitor deposited on a glass disk, on which the particle impacts, stopping the time-of-flight oscillator. Attached to the back of the glass disk is a lead zirconate crystal that provides an acoustical measurement of the particle momentum.

Results from the OGO 2 and 4 experiments were important primarily because they showed conclusively that several unexpected sources of noise can lead to grossly inaccurate data rates for microphone experiments in space. Temperature fluctuations, noise due to commands from earth, and other transients were detected and actually accounted for several hundred events, compared to the two (for OGO 2) that might have been caused by real particles. Thousands of hours of data from OGO 2 and 4 led Nilsson et al. (1969) to conclude that the flux of particles is definitely far lower than the early data indicated. Their most likely value, taking into account the various probable spurious events due to noise, was $2x10^{-3}$ particles/m^2 sec 2π ster for particles of mass greater than ~ 10^{-12} gm. This is 6 orders of magnitude lower than the original Venus Fly Trap results (Ch. 7).

Many other satellite experiments were reaching similar conclusions by the mid-1960's. The Pegasus wire grid detectors (Naumann 1966), working at a threshold of 10^{-7} gm, found a flux of only 10^{-6} particles/m^2 sec 2π ster, a value several orders of magnitude lower than earlier results. Similarly, Explorer 16 (and later Explorer 23), which used Be-Cu pressure cells to detect penetrations, found only 10^{-5} particles/m^2 sec 2π ster at a mass of 10^{-9} gm. The Soviet piezoelectric detectors were also by now giving lower fluxes, as shown in Fig. 8-3, where results from Cosmos 135

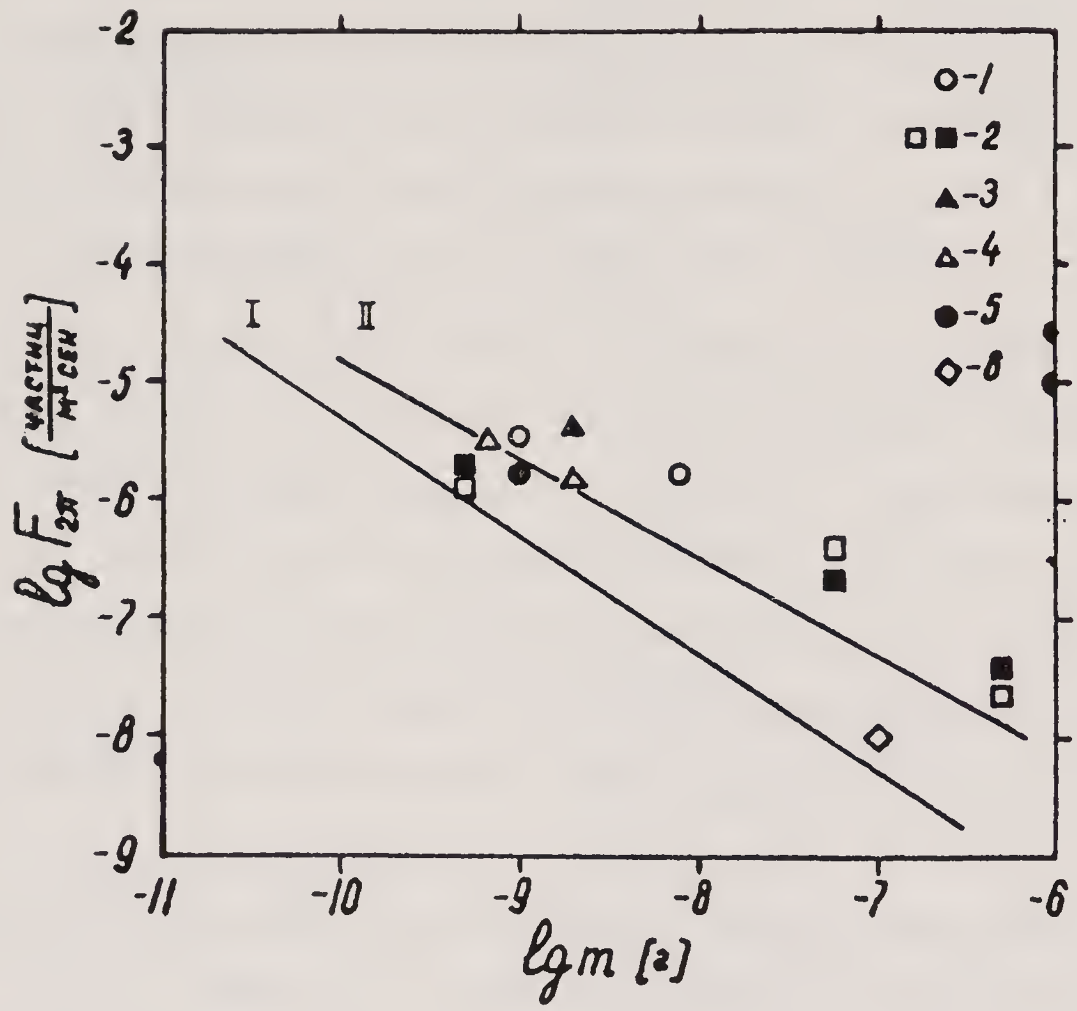

Fig. 8-3. Soviet flux measurements compared with US satellite data. The axes are as in Fig. 8-1. Data are coded: 1: Explorers 16 and 23; 2: Pegasus 1 and 2; 3: Cosmos-135; 4: Cosmos-163; 5: Lunar Orbiter; 6: Radio Meteors; Line I: Ingham's Zodiacal Light Curve; Line II: Beard's Zodiacal Light Curve. (From Konstantinov et al. 1969).

and Cosmos 163 are compared with other data (Konstantinov et al. 1969).

Among the most comprehensive attempts to determine the small-particle flux was the elaborate MTS, the Meteoroid Detection Satellite, devoted entirely to solving this problem. Using a thin dielectric capacitance discharge sensor (Alvarez 1970), the MTS was exceptionally sensitive for a penetration device, giving data on particles about two orders of magnitude smaller than did Explorer 16 and 23 (small enough to penetrate ~ 1 micron of unsupported aluminum foil). Unfortunately, the MTS malfunctioned after two weeks in orbit, but was re-activated two years later, giving results that were quite different from the brief initial period for the smallest size range, so their interpretation remains uncertain.

Other important recent results have come from the impact plasma detectors mounted on HEOS 2 (Hoffman et al. 1974) and on Prospero (Bedford 1975), both of which gave higher fluxes than the penetration experiments, for reasons which are still unclear. The HEOS 2 experiments included directional and velocity data; as well as mass measurement, and suggested that the distribution in space is highly inhomogeneous and the flux is extremely anisotropic. From the earth's apex direction, the flux at 10^{-12} gm was found to be $7x10^{-5}/m^2$ sec, which is more than an order of magnitude higher than in other directions. Average velocities in the apex direction were 10 km/sec, while those measured in other directions were on the order of 20 km/sec. Swarms of particles, attributed to a very local near-earth origin, were detected and seemed to account for the majority of the particles in the 10^{-12} gm regime.

Table 8-1. Some Important Satellite Micrometeorite Experiments

Satellite	Type of Experiment	Year of Publication of Results
1958 α	Wire grid	1959
Cosmos Series	ballistic impact sensor	1960
Explorer 8	microphone sensor	1961
Vangard 3	mylar abrasion	1961
Explorer 16	penetration, gas release	1963
Explorer 23	penetration, gas release	1963
OGO II	penetration and microphone	1965
Pegasus Series	wire grids	1966
Ariel II	penetration photometer	1967
Gemini 19	returned surfaces	1968
Gemini 12	returned surfaces	1968
Cosmos 135	penetration and microphone	1968
OGO IV	penetration, plasma and microphone	1969
Cosmos 163	penetration and microphone	1969
Pioneer 8	piezoelectric and TOF	1969
Pioneer 9	piezoelectric and TOF	1969
Apollo 7	window impacts	1973
Apollo 8	window impacts	1973
Helios I	electrometer amplifier	1973

Table 8-1 continued.

Satellite	Type of Experiment	Year of Publication of Results
OGO III	plasma detector	1974
Cosmos 470	microphone (ballistic)	1974
Cosmos 502	microphone (ballistic)	1974
Intercosmos 6	microphone (ballistic)	1974
Electron 2 & 4	microphone (ballistic)	1974
Prospero	impact plasma detector	1975
HEOS II	TOF plasma detectors	1975
MTS	penetration detectors	1975

IV. Detectors Returned to Earth

One of the simplest and most effective measures of the dust density at satellite altitudes was that obtained by the returnable experiments flown on two of the Gemini missions. These experiments, named S-10 and S-12 in the Gemini program, were designed by Hemenway and his collaborators (Hemenway, Hallgren, Coon, and Bourdillon 1967).

The S-10 collectors were placed on the outside of the Agena rockets by astronauts and left there in an open position for two to four months, until a rendezvous with a subsequent Gemini launch. The collector was an assemblage of variously-prepared surfaces, all mounted on a unit 16 cm by 14 cm. Various technical difficulties, however, resulted in the deployment and recovery of only one S-10 unit, that placed on the Gemini 8 Agena on March 16, 1966 and recovered by the Gemini 10 astronauts 126 days later. Difficulties with the Gemini spacecraft had made it impossible for the Gemini 8 astronauts to open the S-10 experiment, but, fortunately, four prepared surfaces had been mounted on the outside of the box, which were therefore exposed to the four-month's space flight and provided a modest amount of information on the particles encountered. Several impact sites were identified, including two that were large enough to be seen without a microscope. However, the damage to the surfaces caused by handling and by the accumulation of dirt from the thrusters, spacecraft and containers, made the results difficult to obtain and somewhat ambiguous.

A much more successful experiment was the S-12 program that was flown on Gemini 9 and 12. Because it was exposed to the space environment only during a few hours available during the Gemini orbital flights, it was intended to study the higher-flux, smaller particles that might be detectable on a short time scale. Approximately twice as large as the S-10 unit, the S-12 box contained 24 different sample locations, outfitted by 11 different scientific laboratories from several countries. Details of the two successful flights are given in Table 8-3. In both cases the exposures were made while the astronauts were sleeping and minimal spacecraft activity was occurring.

Results from the Gemini 9 and 12 experiments were extremely valuable. The variety of approaches of both the experiments and the methods of analysis provided by the large number of independent investigators led to a more reliable consensus than could have been possible otherwise, and the fact that the surfaces could actually be examined in detail back in the laboratory removed much of the doubt that

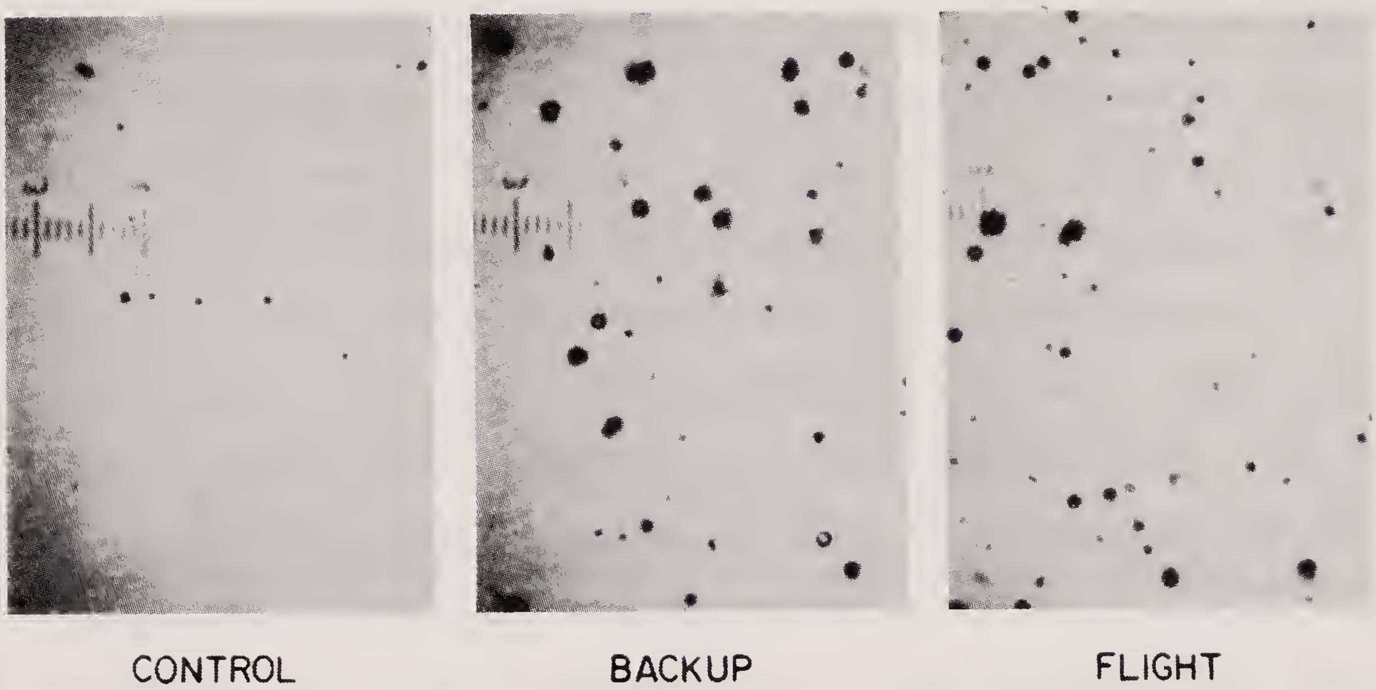

Fig. 8-4. Areas on S-12 surfaces. The flight sample was flown on Gemini 12.

Table 8-2. Successful S-12 Experiments

	Gemini 9	Gemini 12
Launch Date	June 3, 1966	Nov. 11, 1966
Launch Time	8^h40^m EST	15^h47^m EST
Altitude Range	288 to 320 km.	288 to 310 km.
First Exposure Began	9^h29^m after launch	8^h05^m after launch
First Exposure Ended	7^h10^m after launch	14^h29^m after launch
Second Exposure Began	35^h48^m after launch	None
Second Exposure Ended	44^h54^m after launch	None
Total Exposure	16^h47^m	6^h24^m
Direction of Exposure	Random tumbling	Facing away from earth

plagued remote sensing techniques. Examples of the successful use of these experiments are papers by Farlow et al. (1980), Weihrauch et al. (1968), Brownlee et al. (1968), and Hemenway et al. (1968).

The important conclusions of the S-12 experiments flown on the Gemini program were simple: the number of impacts was far smaller than predicted by the "high flux" detections, but consistent with the penetration satellite detectors. Table 8-3, for example, gives Brownlee et al's. (1968) values for the number of craters with diameters > 3μm that they expected on their prepared surfaces flown on Gemini 12 on the basis of various sources of flux values. They found none. These investigators also noted that large numbers of contaminating particles were acquired by the flight surfaces in spite of the great care exercised by the Dudley Observatory team in avoiding contamination (Fig. 8-4).

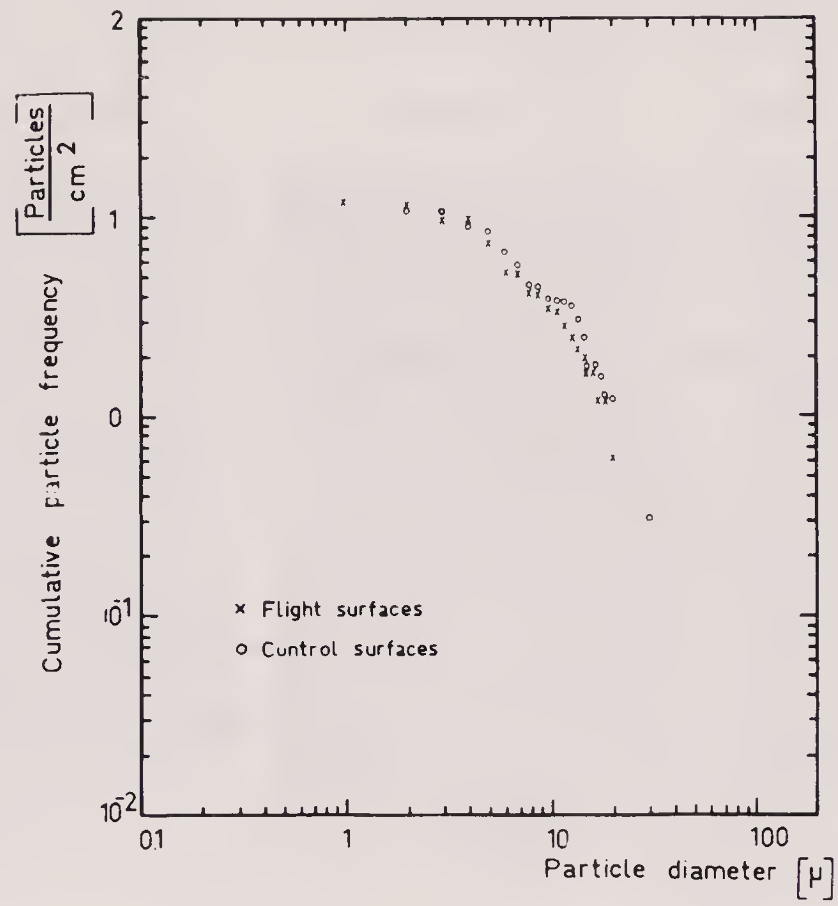

Fig. 8-5. Particle frequencies for control and flight surfaces from the Gemini 9 experiment (from Weihrauch et al. 1968).

Table 8-3. Predicted Impacts, Gemini 12

Source of Prediction	Number of Impact Craters Detectable on Surfaces C-6 and D-4
Sounding Rockets	10,000
Acoustical Satellite Experiments	500
Penetration Satellite Experiments	0.01
Zodiacal Light	0.0005

The problem of contaminating particles on these experiments was also studied by Weihrauch et al. (1968), who counted and analyzed particles of various sizes. Fig. 8-5 shows the results for their Gemini 9 surfaces, illustrating the fact that the number of particles on the control was fully as large as on the flight surfaces at all sizes. Thus the Gemini experiments showed both that the impact rate (and therefore particle flux) was far smaller than the acoustical satellite experiments had indicated and that, not unexpectedly, no cosmic particles were collected by the experimental surfaces.

A serendipitous event in 1970 added further weight to the conclusion being reached at the end of the 1960's, namely, that the flux of interplanetary particles must be considerably smaller than first believed. The Apollo 12 spacecraft landed, primarily for purposes of answering practical, space-engineering questions, near to the resting place of the Surveyor III spacecraft, which by then had been on the lunar surface for 2.6 years (see details in Ch. 9).

Several smooth parts of the Surveyor craft were examined and conclusions about the micrometeorite influx rate could

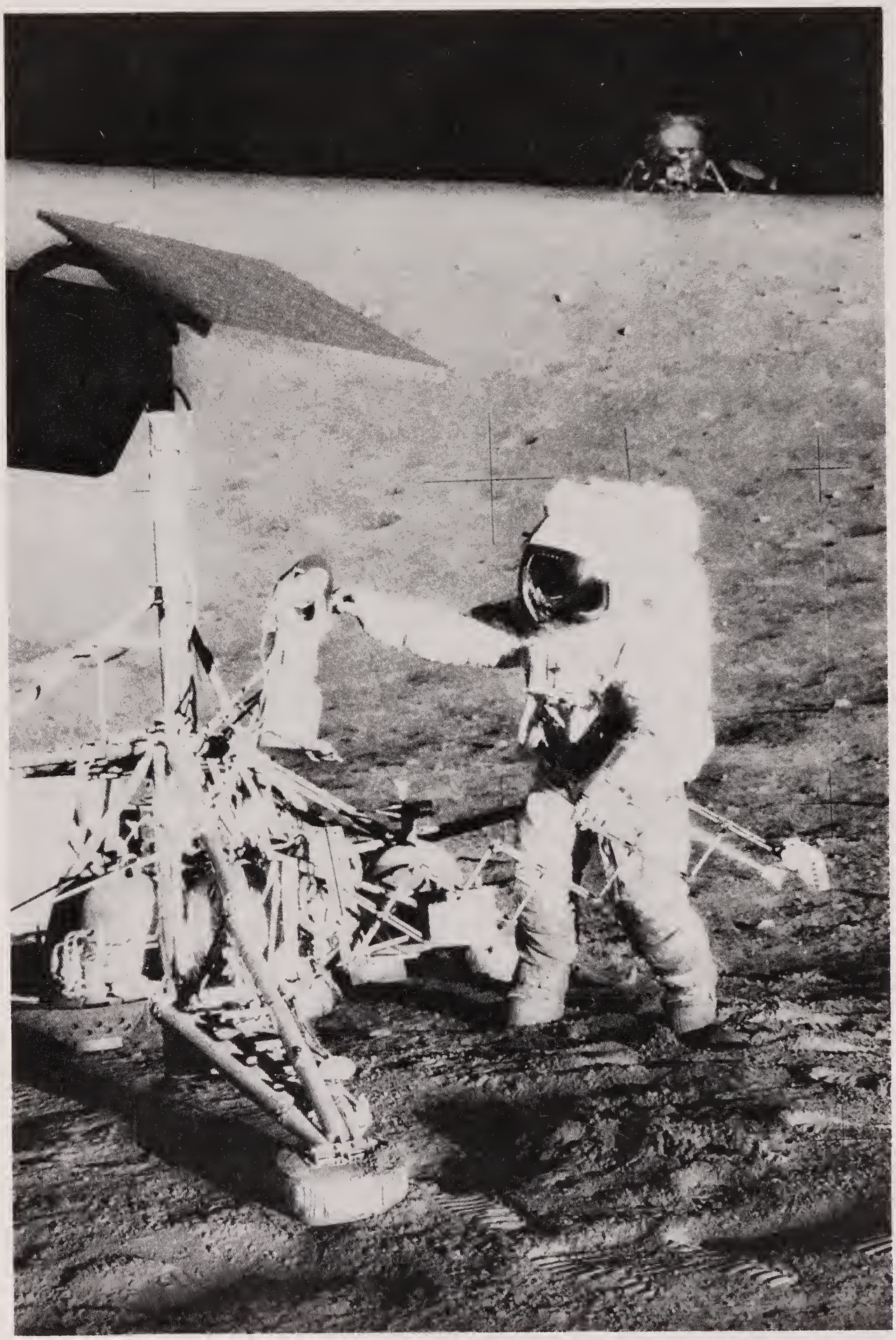

Fig. 8-6. Surveyor III being dismantled by the Apollo 12 crew (courtesy NASA).

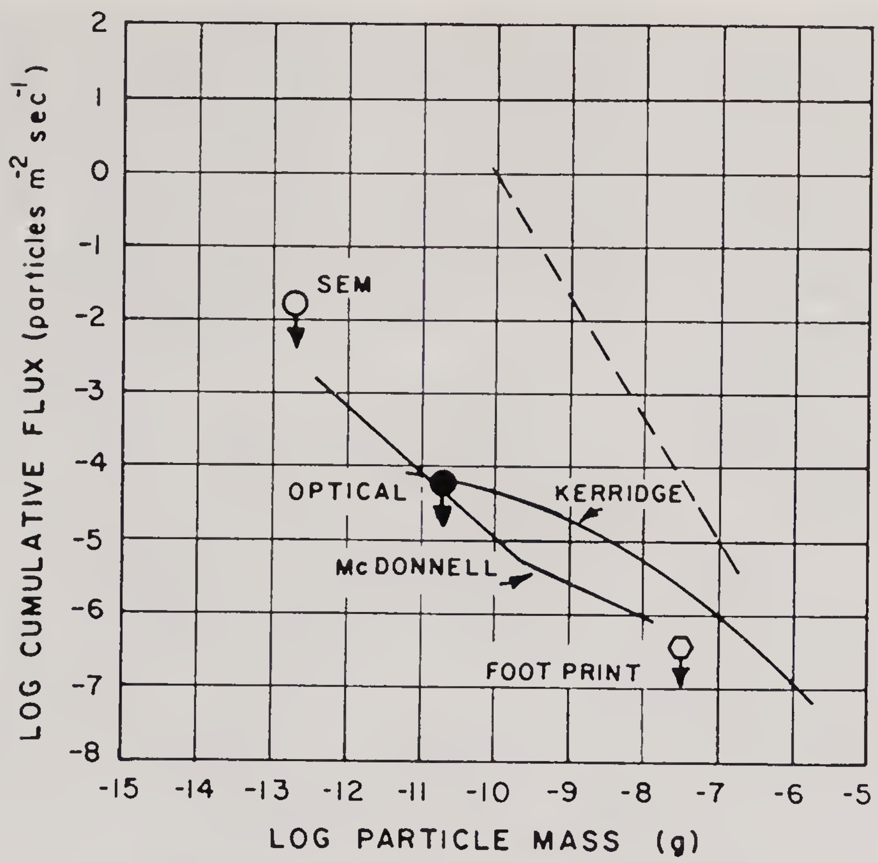

Fig. 8-7. Particle flux upper limits from the Surveyor III camera's filters. The dashed line is based on the early microphone results from satellites. (See also Fig. 9-1).

be reached by studying the damage detected. A unique example was the degradation of a print left by one of the Surveyor's "feet" (see the point in Fig. 8-7 labeled "foot print"), as described by Jaffe (1970).

Throughout the early manned spacecraft program, scientists at NASA Houston were concerned about the impacts of meteoritic dust on spacecraft windows. By the end of the Apollo program they had examined surfaces with a time-area product of 10^5 cm^2 days. At least one clear case of hypervelocity impact was found for each of the missions involved in the study, which included the Mercury, Gemini, and Apollo programs. The data agreed well with the satellite penetration experiment flux curves.

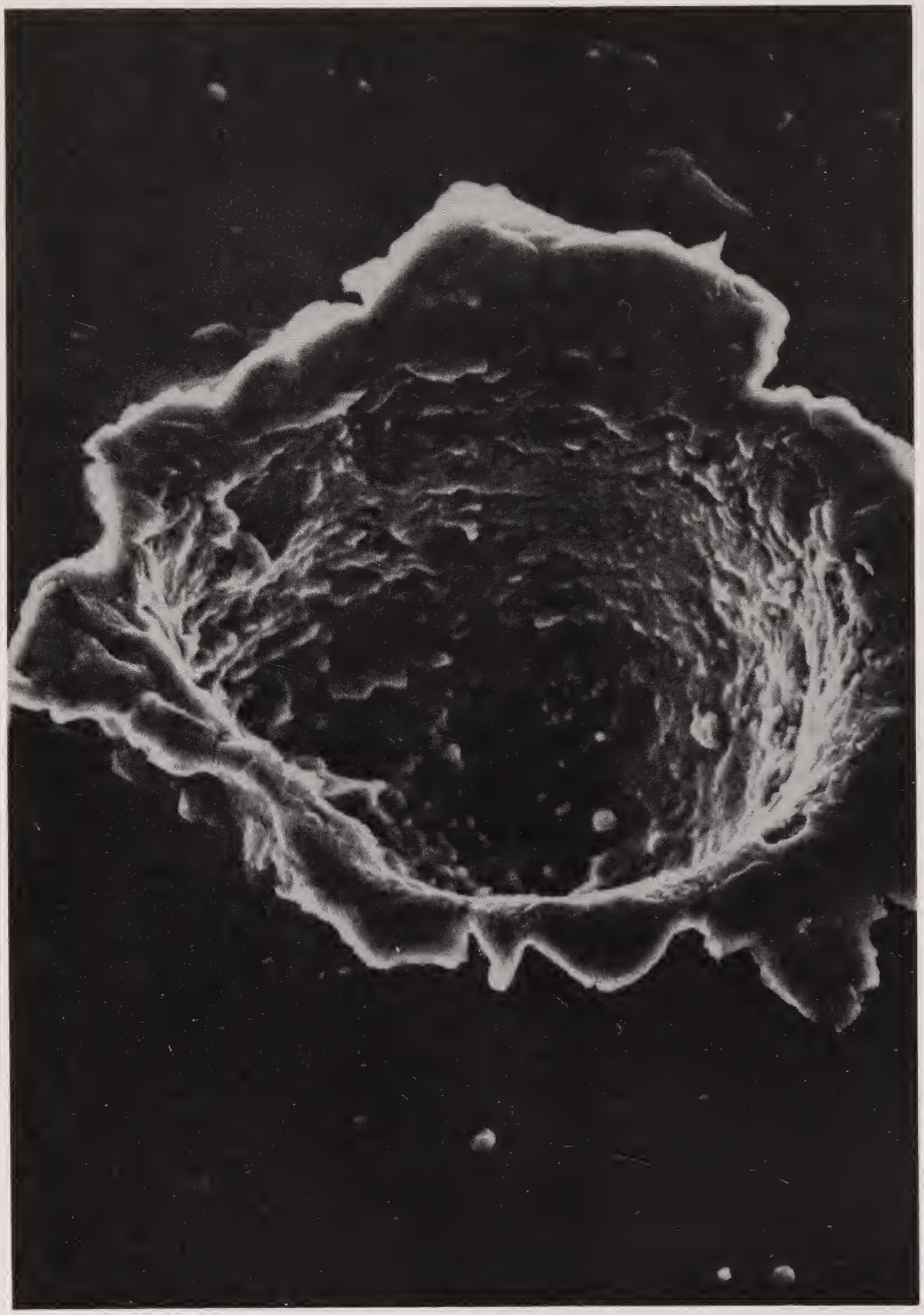

Fig. 8-3. A 110μm impact crater from Skylab IV.

The most recent recoverable interplanetary dust experiments were flown on the Skylab missions, which provided longer exposures and more controlled conditions of handling than the previous manned missions. For example, Skylab IV had a transuranic cosmic-ray experiment that was exposed to space for 69 days and was subsequently made available for study of its aluminum surface to detect impact craters (Brownlee et al. 1974). Fig. 8-8 shows a large micrometeorite crater, unambiguously-identified by comparing its morphology in detail with laboratory-simulated craters, that was of particular interest because of evidence that there remained meteoroid residue in the interior of the crater that could be analyzed chemically. Brownlee et al. (1974) found that the blobs of residue contained Fe, Mg, Si, Ca, Cr, Mn and Ni in nearly chondritic meteoritic proportions (Fig. 8-9). From laboratory calibrations, the size of the cratering particle was deduced to be ~ 30μm and it was concluded that it must have been composed of an aggregate of small mineral grains, as no known single mineral has chondritic abundances. A smaller crater, 35μm in diameter, was found to contain a residue of Fe and S, with trace amounts of Ni and Mg. This particle was probably a grain of troilite (FeS), a common mineral in most types of meteorites. These results, the first chemical analyses for particles demonstrably collected by hypervelocity impact, provided evidence that agreed well with results from the lunar surface (Ch. 9) and with the recent high-altitude aircraft experiments (Ch. 5).

After a notably shaky start, satellite study of the interplanetary medium finally made progress in the 1970's. The future use of satellites for this research is not very promising; the basic questions are now fairly well answered,

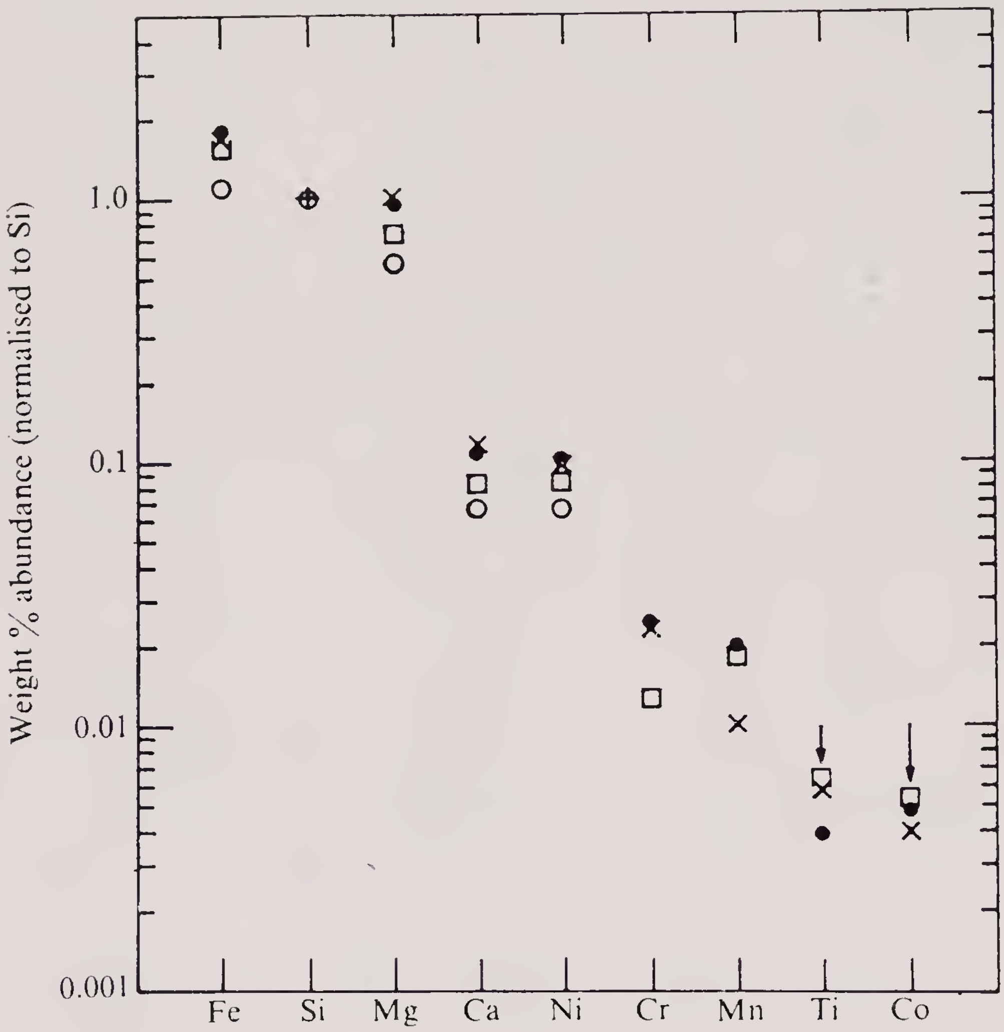

Fig. 8-9. Elemental abundances for residue in the crater shown in Fig. 8-8 (open squares and open circles) compared to carbonaceous chondrites of type C1 (filled circles) and C3 (crosses). From Brownlee et al. (1974).

the engineering requirements for survival in the satellite realm are known, and other challenges, such as cometary encounter missions, are facing the scientists interested in both the appropriate technology and the remaining scientific questions. The most interesting questions remaining for satellite research center on the determination of accurate orbital elements, and the measurement of fluxes of very small (<1000Å) particles.

I. Introduction

The moon is in many ways an ideal source of information on interplanetary dust. It is sufficiently distant from the earth that contamination from terrestrial sources is completely impossible. It is without an atmosphere so that interplanetary dust impinges on the lunar surface unablated, with its cosmic velocity changed only very little by the lunar gravitational field. It has been a receiver of interplanetary dust over billions of years and because of its lack of much geological activity throughout most of its history it provides a relatively undisturbed long-term historical record.

As soon as it became possible to retrieve materials from the lunar surface, they were used to obtain information on the interplanetary impinging particles. The most fruitful information comes from the microcraters left by the collision of interplanetary dust onto smooth surfaces of lunar material. Information can also come in a more general way from the chemistry of the lunar surface material, and this has shown that the interplanetary component is not primarily nickel-iron in composition, as the nickel-iron enrichment of the lunar surface materials is small. In what follows the emphasis will be on information coming from the study of the microcraters themselves.

II. Surveyor III Experiments

A particularly important experiment was made possible when NASA planned the landing site for the Apollo 12 Lunar Mission. This site was placed on Oceanus Procellarum in a position immediately adjacent to the Surveyor III spacecraft. This was done so as to make it possible for the astronauts from Apollo 12 to visit the spacecraft and to ascertain the various effects on the spacecraft hardware of its intervening 2.6 years existance on the lunar surface. Although there are various important engineering aspects to this examination, one of the interesting scientific results was relevant to the fact that the material was exposed to the lunar sky for an order of magnitude longer period than any other man-made object had been exposed in space and brought back for analysis. Determination of the number of micrometeorite impact craters on the surfaces held promise of establishing a better source of information on the micrometeoroid environment.

The most optimal surfaces of the Surveyor III spacecraft were found on the television camera, which was brought back by the Apollo 12 astronauts for analysis in terrestrial laboratories. Most of the surfaces of the camera that were exposed upward unfortunately were very rough, with surface characteristics that showed large numbers of indentations due to manufacture and handling, rendering the detection of micron-sized micrometeorite craters highly unreliable. Because at the time Surveyor III was launched there was no opportunity to make pre-mission documentation of the microscopic features of the surfaces of the instrument, no reliable records on the surfaces could be used for comparing with post-mission documentation.

Of the camera surfaces, the most smooth were the top surfaces of the glass optical filters, which, of course, had an optical polish. These filters were shielded from high velocity dust generated by the lunar module as it landed and by the Surveyor landing, so that there are few low velocity marks caused by lunar dust impinging upon them. They were mounted horizontally inside the camera and exposed to a segment of the lunar sky extending from approximately the horizon to an elevation of 70°, giving an azimuthal window of about 150°. Other surfaces also have been examined from the television camera, yielding larger surface areas, but having less reliability because of the non-optical nature of these surfaces.

Figure 9-1 and Table 9-1 give information that was gleaned from an extensive microscopic survey of the four optical filters from Surveyor III (Hodge et al., 1972). In no case was a clear hypervelocity impact crater found. The scanning electron microscope examination had a detection limit of 0.2 microns and reached a flux limit at that size as small as $4.5 \times 10^{-1}/m^2/sec/2\pi$ steradians. These limits

Table 9-1. Surveyor III Results

	Area scanned	Detection limit	Flux limit
Optical	$28.9\ cm^2$	5 μm	$7.5 \times 10^{-5} m^{-2} s^{-1} (2\pi\ sr)^{-1}$
SEM	$10.9\ cm^2$	1 μm	$1.1 \times 10^{-2} m^{-2} s^{-1} (2\pi\ sr)^{-1}$
SEM	$0.27\ mm^2$	0.2 μm	$4.5 \times 10^{-1} m^{-2} s^{-1} (2\pi\ sr)^{-1}$

were found to be right at or slightly above the predicted numbers of hypervelocity craters based on the most conservative estimates available at that time. For example, Figure 9-1 shows McDonnell's model of the cumulative flux and illustrates the close agreement between that model and the data from Surveyor III.

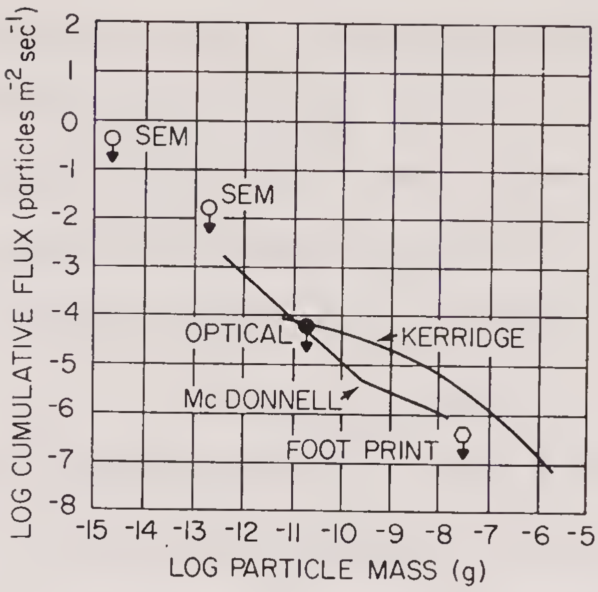

Figure 9-1. Surveyor optical and SEM (scanning electron microscope) flux limits compared with various models (from Hodge et al., 1972).

Although no hyper-velocity impact craters were found on the surfaces, several artifacts on the surface were identified as probably the result of secondary microcraters, the impact sites of low-velocity lunar ejecta. Because micron-sized particles that are ejected from any impact crater event on the moon will have velocities that are less than the lunar escape velocity, they will impact onto the lunar surface with a velocity that is too small to produce the characteristic hypervelocity crater shape. The probable secondary impact craters found on the Surveyor III glass surfaces are typically depressions that have an irregular shape and a slightly raised rim at one edge. In most cases the crater itself consists primarily of a chipping away of the coating, which is a 1,500 angstrom magnesium fluoride anti-reflection coat. In most cases the orientation of the crater agrees with the expected orientation, considering the exposure windows of the glass filters. Brownlee et al. (1972) found that the control filter, one that was identical to the flight filter but which did not go on the spacecraft to the moon, showed no such marks. The spatial density that was calculated for secondary craters larger than 0.5 micron in radius is about $200/cm^2$. This is approximately 1,000 times higher than the expected rate for primary micrometeoroids.

Because the results from Surveyor III produced some interesting and unexpected information, NASA decided subsequently to fly on Apollo 17 a package that was designed to be left on the lunar surface and returned after a very extensive period (not presently determined and probably on the order of many tens of years). This experiment is still on the moon, waiting for a future resurgence of interest in lunar exploration. In order to provide proper control, NASA established extensive photodocumentation of the surface of the lunar Apollo 17 ALSEP package. Thus the NASA archives contain an excellent record of the various surfaces of this experiment that are presently being exposed to the interplanetary medium.

III. Natural Glass Surfaces on the Moon

The Surveyor experiment was exposed on the lunar surface for too short a time to have very many, if any, microcraters from hypervelocity impacting particles. On the other hand, lunar rocks presently at the surface have been exposed to the meteoroid environment for millions, or in some cases billions, of years. Most lunar rocks have a highly irregular surface and are inappropriate for studies of impacting meteorites, but all seem to show the effects of erosion by these events. Fortunately, there are natural smooth glass surfaces on some lunar rocks and these have been extensively utilized to determine the properties of the lunar bombardment by micrometeorites. Some of the most useful surfaces for this purpose are those of the small glass spheres that were apparently produced by the melting of lunar rock by large impacting events. Other surfaces available include those made by the splash of glass onto a rock at the time of an impact. Because the exposure age of a lunar rock can be determined from the study of solar flare particle tracks in the rock (Price et al. 1971), the measurement of the number of craters leads to a direct determination of the flux of particles on the lunar surface. This, of course, is an integrated flux over the entire exposure age, and therefore there is some hope of obtaining some information on the history of this flux, a kind of information that presently cannot be obtained in very many other ways (one other way being the similar studies of micro-craters on the surfaces of chondrules in chondritic meteorites).

A further aspect of the study of the natural glass surfaces on the moon is the fact that it is possible to determine the direction faced by these surfaces and the history of this direction, and therefore to put together some information of a directional nature on the impact bodies. A particularly advantageous circumstance occasionally occurs when a lunar rock has a bubble-shaped cavity, a "vug", that is open at one end so that it acts as a focused receptor of incoming impacting bodies. Several "pin hole vugs" of this nature have been used to derive information of the impact rate onto the lunar surface from different directions, although at the present there are too few of these for any generalizations about directional flux to be very reliable.

IV. Crater Morphology

The expected shapes of lunar microcraters have been explored by a large number of laboratory crater studies using electrostatic accelerators (Vedder 1971, Fechtig et al. 1975, Mandeville 1973, and others). These laboratory studies have been carried out with a wide variety of types of projectiles and of impact surfaces. They have shown that the morphology of a hypervelocity crater is dependent on a number of parameters, including the size of the particle, the velocity of the particle, the density of the particle, and the nature of the impacting surface. For particles smaller than 1/10 of a micron and up to one micron in diameter, the craters tend to be cup-shaped depressions, often called in the literature "pits", with rims of molten target material. For velocities of the incoming particle greater than 3 km/sec the pit is usually glass-lined. Craters larger than 1 micron but less than 10 microns in diameter have morphology that is intermediate in properties, with a central glass-lined pit and a concentric zone surrounding the pit, from which sections of the impacted material have been ejected (a spallation zone). For craters larger than 10 microns the development of the spall zone is more complete, becoming more and more conspicuous for larger and larger particles. The exact amount of spalled material and the development of the spall zone also depend on the velocity, with the complete spallation only occurring for velocities greater than 5 km/sec.

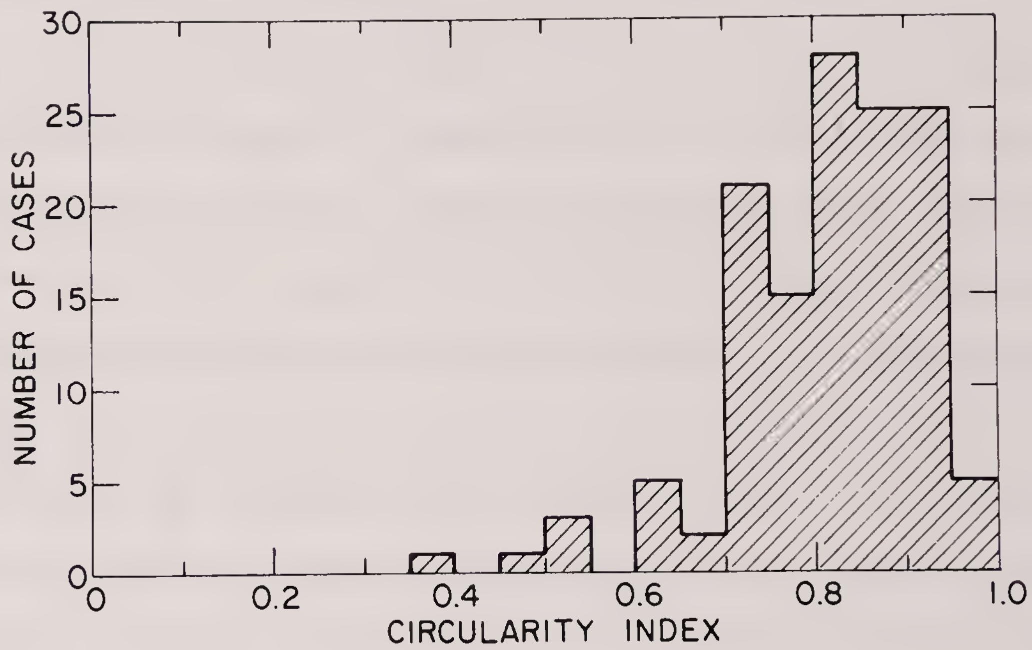

Figure 9-2. The circularity index for 131 lunar microcraters (from Brownlee et al., 1973).

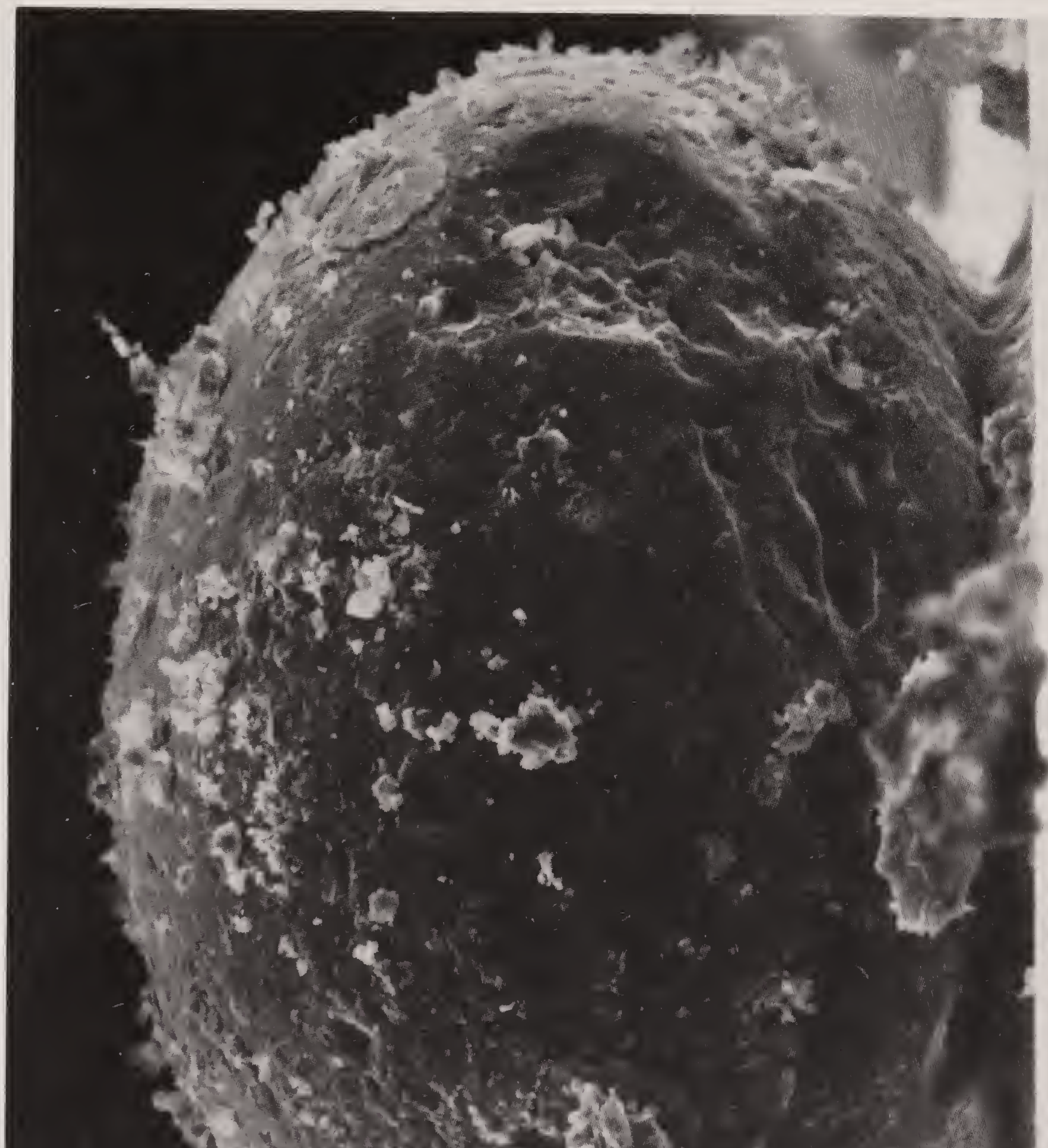

Figure 9-3. A lunar glass sphere, showing microcraters on its surface (courtesy D. Brownlee).

These laboratory results are found to be mimicked in the available shapes and relationships between shape parameters for the lunar microcraters, leading to the conclusion that not only are most of the lunar microcraters due to hypervelocity impact, but also that the particle properties are derivable from comparision with laboratory experiments.

One of the prime characteristics of a crater is its degree of circularity. A non-circular crater might be expected to be produced either by a highly irregular particle or by an oblique impact angle. The laboratory simulations with irregular projectiles (Kerridge and Vedder 1972) indicate that a crater resulting from a particle shaped like a rod or a plate tends to be deep and elongated, whereas a nearly spherical particle projected onto a surface at an oblique angle will produce an elongated crater that is shallow. From a large number of studies of shapes of lunar microcraters, Brownlee et al. (1973) established that the shape of almost all craters, of unknown incidence angle or particle shape, is very nearly circular. Figure 9-2 shows the "circularity index", defined at the ratio of the area measured by following the intersection of the target surface with the inside of the pit rim to the area of the smallest circle that just encloses this intersection. Thus a perfectly circular crater will have a circularity index of 1.0. The figure shows that most craters are very nearly circular. Highly non-circular pits are extremely rare and many of these are very shallow, indicating production by a particle coming in at an oblique angle. Brownlee et al. (1973) estimate that if dust grains are thought of as being approximated by a prolate ellipsoid, then the observations

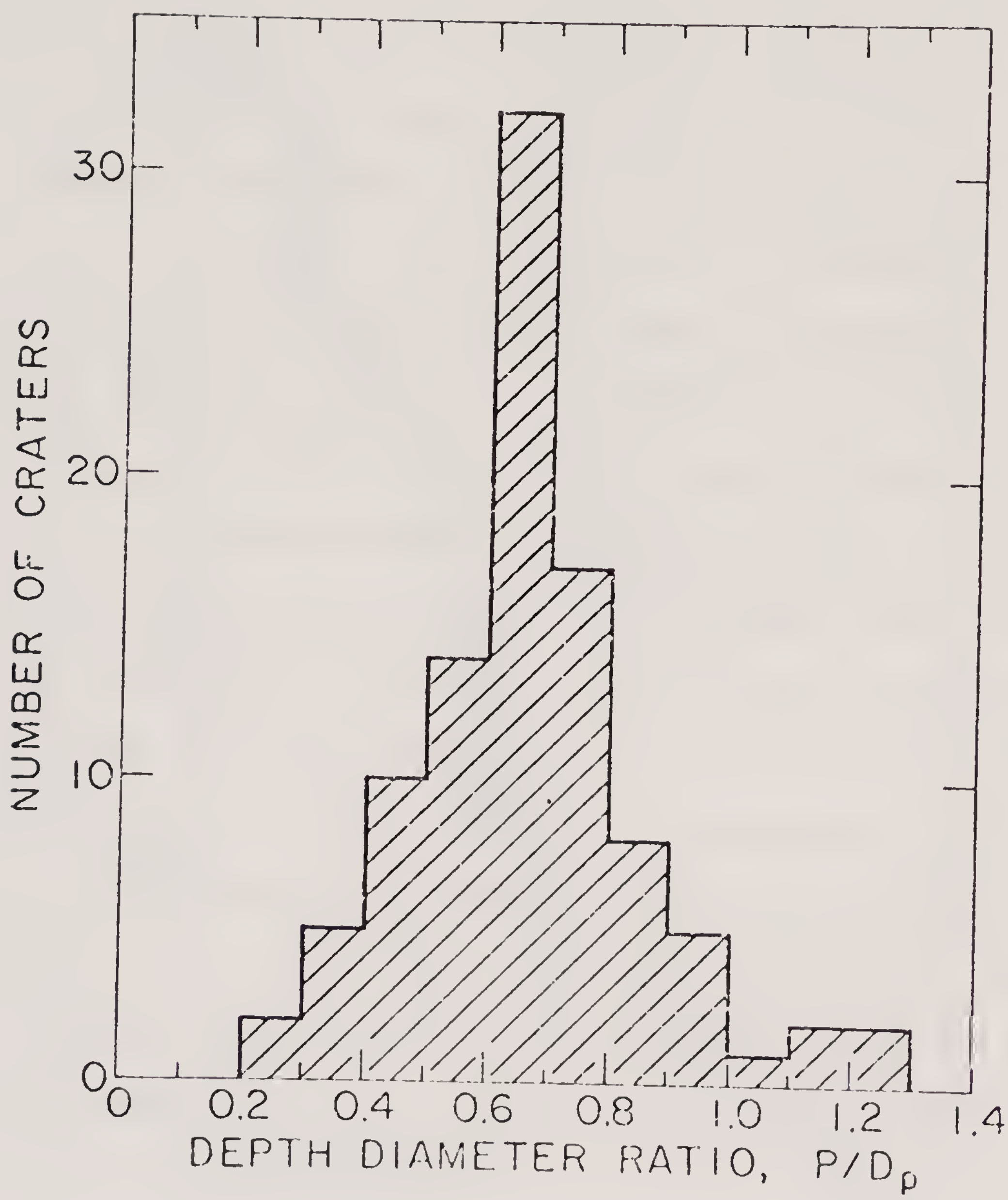

Figure 9-4. Depth-diameter ratios for 98 lunar microcraters (from Brownlee et al., 1975).

indicate that the average length to width ratio must be less than 2.

A second measurement of crater morphology has to do with the ratio of the depth of a crater to its diameter. Brownlee et al. (1973) measured the depth diameter ratio for 70 craters. Figure 9-4 shows the result, comparing it with laboratory results for particles of different densities (Vedder and Maneville 1973). In this figure the crater depth is determined as the maximum depth of the pit below the inferred original surface, while the diameter refers to the mean diameter of the inside of the rim of the pit. It is not possible to make specific determinations of densities of particles from these data because of the unknown velocity distribution for the incoming particles. Another uncertainty is caused by the fact that the laboratory data does not extend to large velocities. Nevertheless, it is possible to show that the mean densities of incoming particles cannot be very low. The fact that very few deep craters exists also seems to argue against there being large numbers of pure iron-nickel particles. Most are probably intermediate in density, with a mean value that is probably similar to that for carbonaceous chondrites or other low-density stoney meteorites. If an average impact velocity of 20 km/sec is assumed, the density range for particles smaller than 50 microns is estimated to be from 2 to 4 gm/cm^3.

About 10% of the craters in lunar samples appear to be interpretable as low velocity craters produced by secondary impacts. Hartung and Hörz (1972) suggest that these may, at least in part, be examples of structures for which the glass-lined pit has been spalled away. They could be primary craters produced by low density material. There is

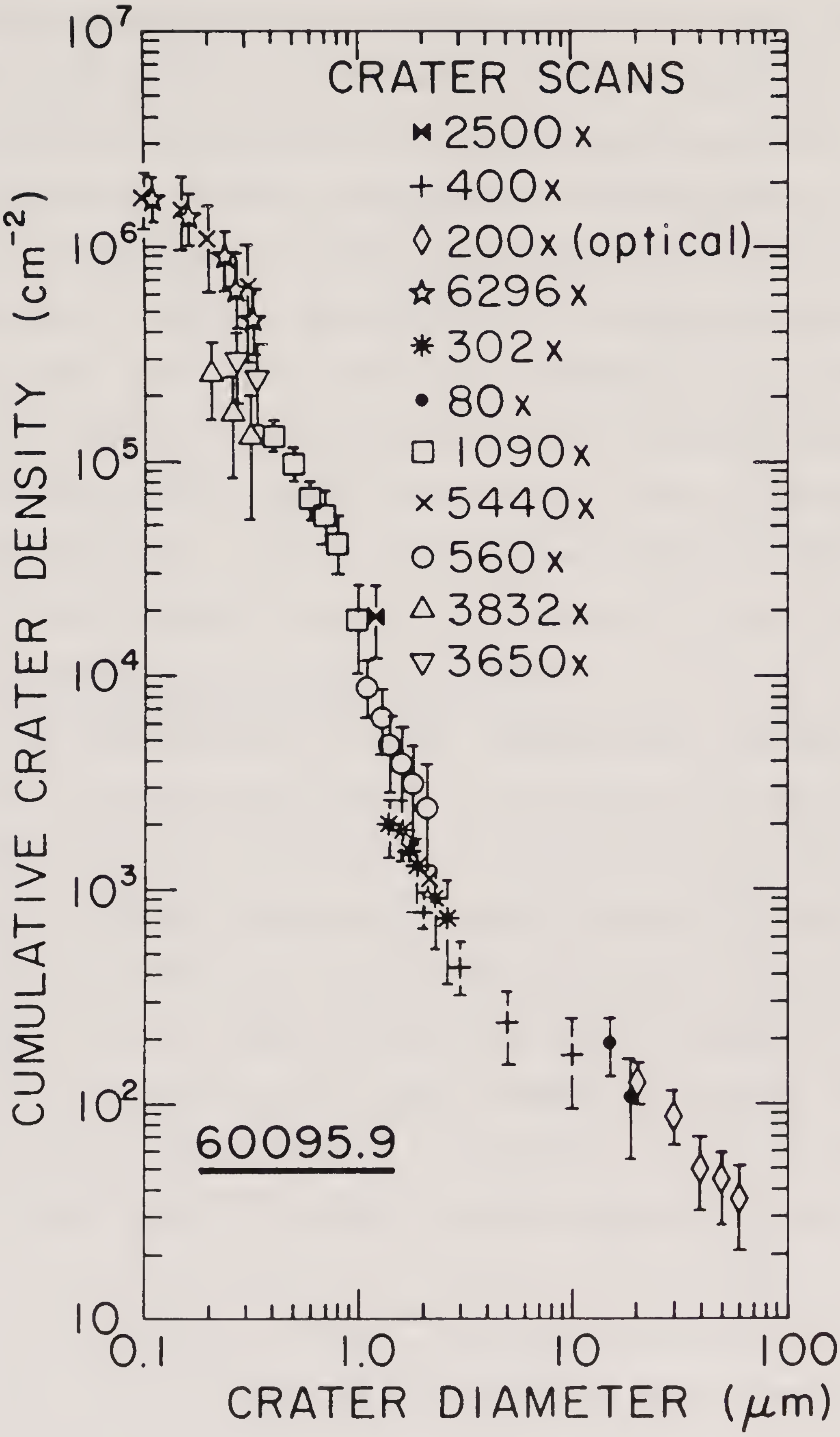

Figure 9-5. Crater frequency plot for a surface of a glass spherule from Apollo 16 (from Brownlee et al., 1975).

also evidence for a few examples of multiple craters that could have been produced by complex projectiles of highly irregular structure or of variable density distribution.

The size-frequency distribution of craters is shown in Figure 9-5. This figure is based on a count of craters by size on a 3 cm diameter glass sphere from the Apollo 16 samples, which showed 193 clear impact craters. Similar results have been obtained from other surfaces. The cumulative crater density at 0.1 micron size is on the order of $2x10^6$ craters per cm^2. It is important to note that there is no evidence for any small size turnover, implying that the frequency distribution of incoming projectiles continues to increase down to even these very small sizes. There are some samples, for example 15286, a rock from the Apollo 15 returns, that show a small-size turnover, but these are now believed to be caused by succeeding history in which the small-size features have been erased. The slope of the log cumulative density/log diameter relationship is very steep in the sub-micron range, on the order of -2.5. This slope has been an important element in the interpretation of the production processes for the small particles as well as an understanding of their dynamics (see Chapter 12).

I. Introduction

The zodiacal light, until recently, was our only source of information about the density of interplanetary dust in the solar system in general. As Chapter 2 describes, zodiacal light measurements have allowed the determination of models of variation of particle density with solar distance, but the correct power of r, the solar distance, in the equations is dependent upon the assumed particle properties. Thus this important relationship cannot be understood from zodiacal light data alone and the advent of interplanetary space exploration was a vital step in establishing the true facts of the matter.

II. Interplanetary Probes at 1 A.U.

Information on the 1 A.U. particle densities at significant distances from the earth-moon system has come from various interplanetary spacecraft, including both those with distant planetary missions (using data from the early parts of their missions) and from interplanetary probes with earth-like orbits. Among the former are Mariners 2 and 4, Mars 1, 2, and 3, Venus 2, and Pioneer 10 and 11. The latter include Pioneers 8 and 9.

Mariner 2 was launched towards Venus in 1962 and had on board a particle microphone sensor. Unfortunately, it only recorded two impacts, which, however, provided a datum point near 1 A.U. solar distance that agreed quite well with the distant earth-satellite curve (Fig. 10-1).

More complete information came from Mariner 4 (Alexander et al. 1965), which was launched toward Mars in 1964. Fig. 10-1 shows how the Mariner 4 data taken from the near-earth portion of the journey agree with other determinations of flux at 1 A.U. Both the Mariner 2 and Mariner 4

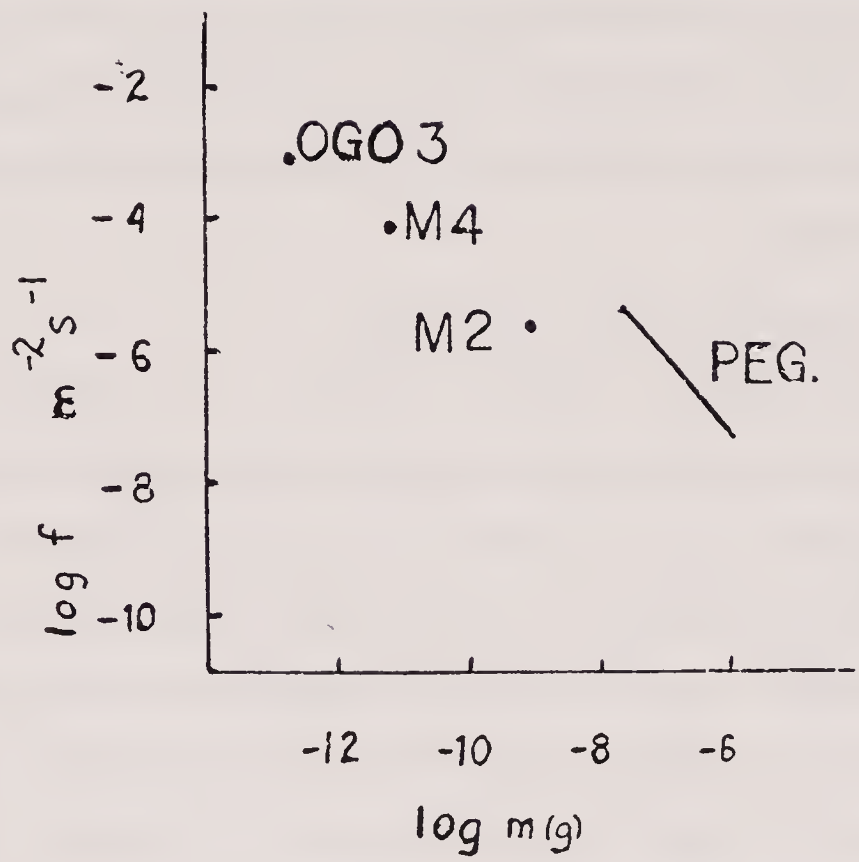

Fig. 10-1. Comparisons of near-earth fluxes determined by the Mariner 2 and 4 spacecraft with Pegasus and OGO 3 data.

experiments used microphone sensors, but it is probable that the data are not grossly affected by noise problems, as their environment was considerably quieter than that for near-earth orbiting satellites.

Pioneers 10 and 11, launched in 1972 and 1973, respectively, carried a variety of instruments to examine the meteoroid flux, particularly because these were the first spacecraft to penetrate the asteroid belt, which was expected to show a significant increase in particle density. In each case, the first portions of the data showed a particle density that was, within the uncertainties, the same as found from penetration detectors on earth satellites.

A far more comprehensive examination of the dust at 1 A.U. came from the long-range experiments carried on the interplanetary probes Pioneer 8 and 9 (Berg and Richardson 1969). Pioneer 8 was launched on December 13, 1967 into a nearly circular orbit, with perihelion and aphelion at 0.99 and 1.088 A.U., respectively. The particle detectors included plasma sensors and acoustical sensors (Fig. 10-2). The crucial orbital data was obtained from the part of the experiment package called the TOF (time-of-flight) sensor, which measured the time and location difference between a particle's penetration of a front film-grid array and a 5 cm distant back film-grid array. The particle velocity was measured by the separation in time of the two events and the orbital direction was measured by the coordinates of the events in the 16-frame front grid and 16-frame back grid. The attitude of the spacecraft was read out with respect to the solar direction at the time of each impact, so that the true direction of motion of each particle could be determined. Extensive calibrations of the experiments were carried out with a 2-million volt electrostatic accelerator,

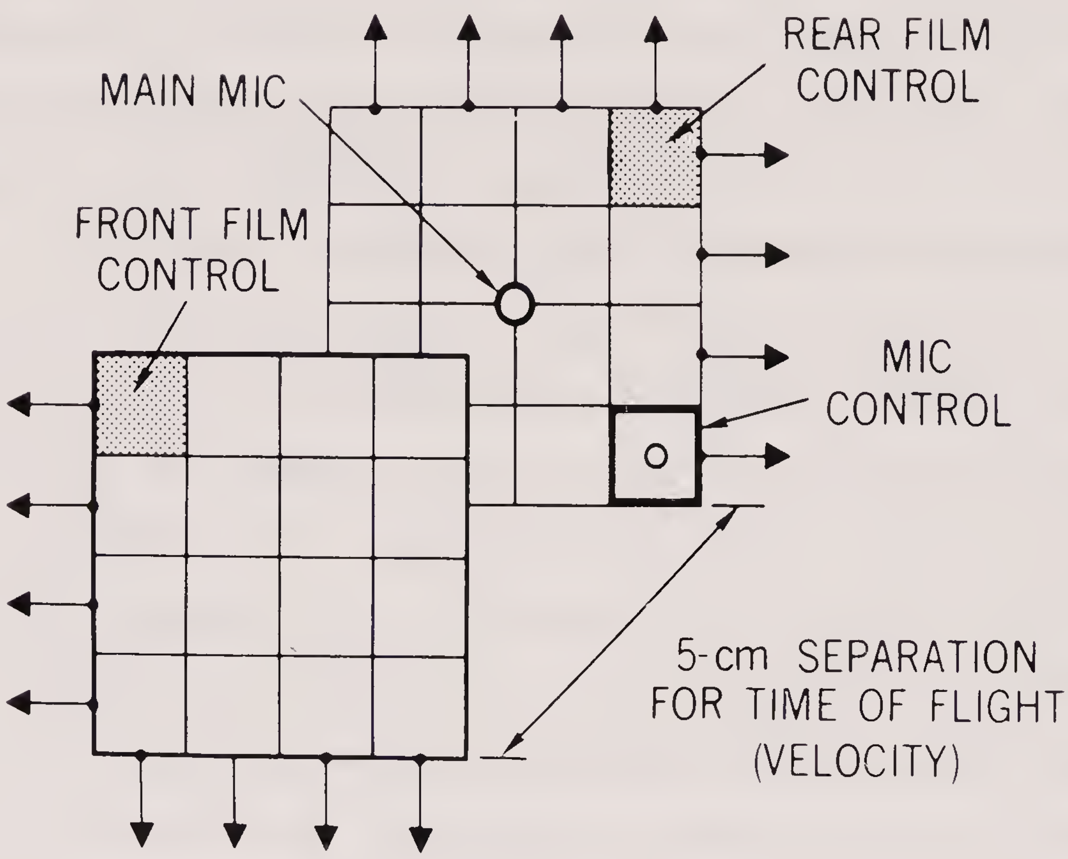

Figure 10-2. Pioneer 8 experiment design (from Berg and Grün 1973).

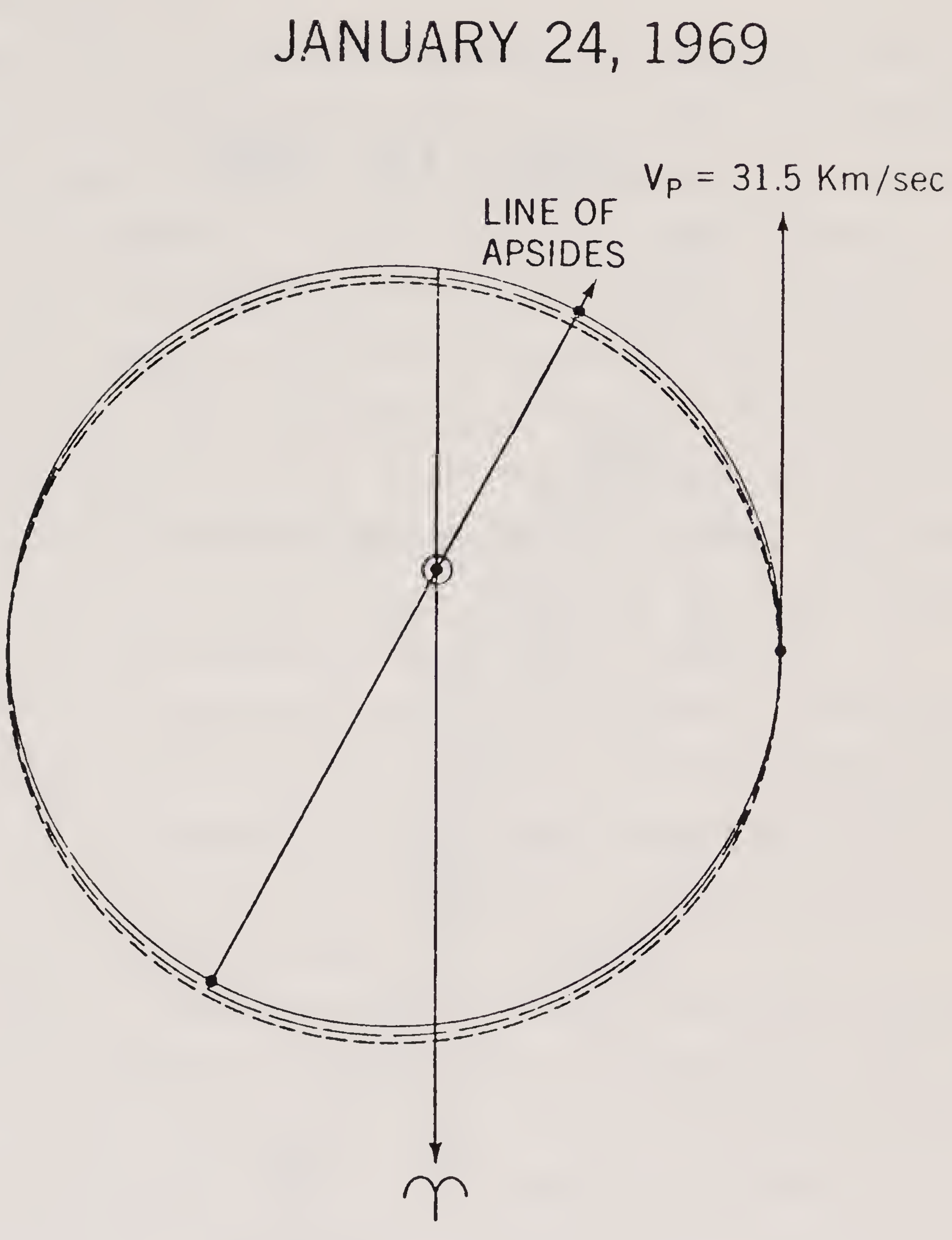

Figure 10-3. Orbit of a particle with a nearly circular orbit detected by Pioneer 8 on January 24, 1969. Dashed lines indicate limits allowed by experimental resolution (from Berg and Gerloff, 1971).

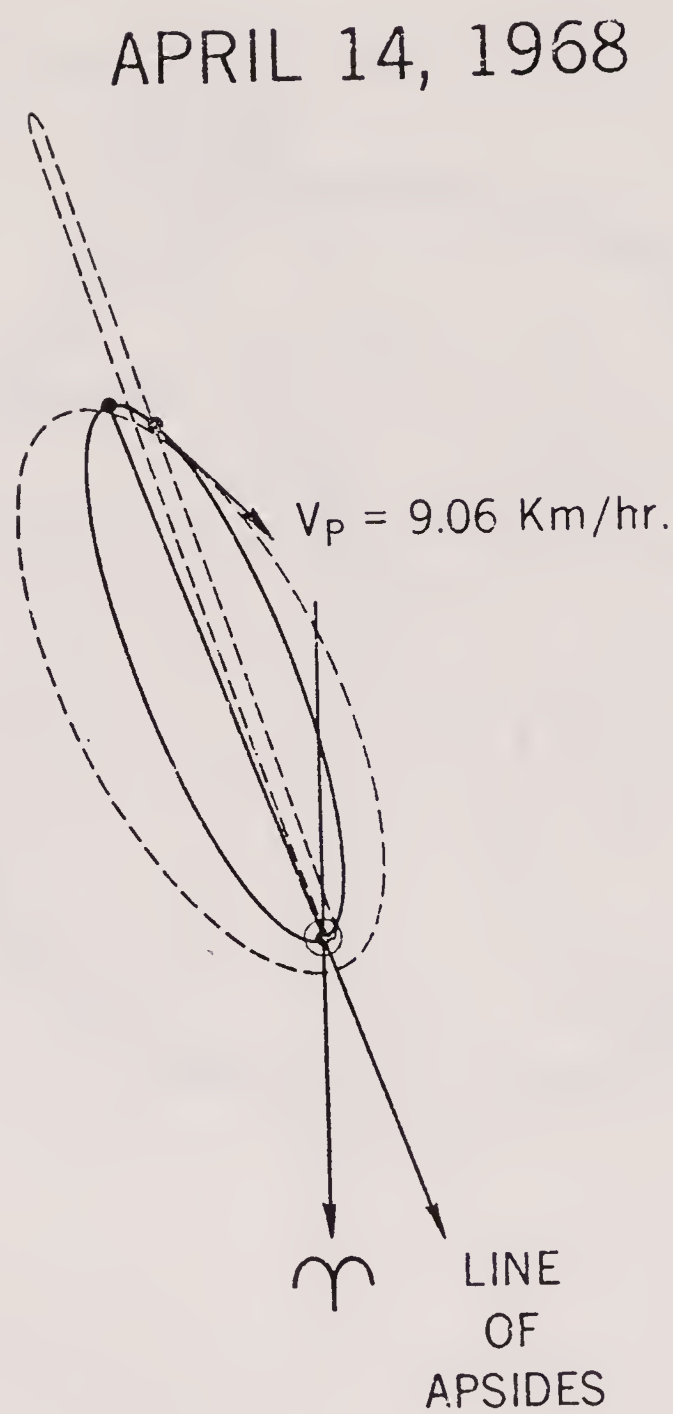

Figure 10-4. Orbit of a high-eccentricity particle detected by Pioneer 8 (from Berg and Gerloff 1971).

using iron pellets with impacting velocities in the range of 2 to 10 km/sec.

After only a few days' operation it was clear that Pioneer 8 was recording far fewer events than had been expected at the time of design of the experiments. In a similar, earlier TOF experiment on OGO 1 (Nilsson and Alexander, 1967) three events were detected in only four hours, while for the first entire year's operation of Pioneer 8 only six TOF events were recorded. This discrepancy, amounting to a factor of $4x10^4$, was apparently due to misidentification of noise in the OGO 1 instrument as real impact TOF events. The Pioneer 8 data rate did, in fact, agree well with the more reliable penetration earth satellite experiments' results.

Table 10-1 shows the results of orbital calculations for the first six Pioneer 8 TOF events (Berg and Gerloff (1971)). Two examples of orbits that include the limits of parameters allowed by the directional resolution of the experiment are shown in Figs. 10-3 and 10-4.

Pioneer 9, launched on Nov. 8, 1968, carried a system of particle sensors similar to that on Pioneer 8. Its orbit around the sun was similar, also, though slightly smaller (perihelion was at 0.75 A.U. and aphelion at 0.99 A.U.). As for Pioneer 8, events were recorded for the TOF experiment, for the rear-mounted acoustical microphone impacts, for front film only impacts, and for front film-grid coincident data.

The acoustical microphone data were not useful, as it was found that large numbers of spurious events occurred, many of which could be traced to solar proton events (Fig. 10-5). Additional evidence that the acoustical detections were spurious came from the use of a control microphone,

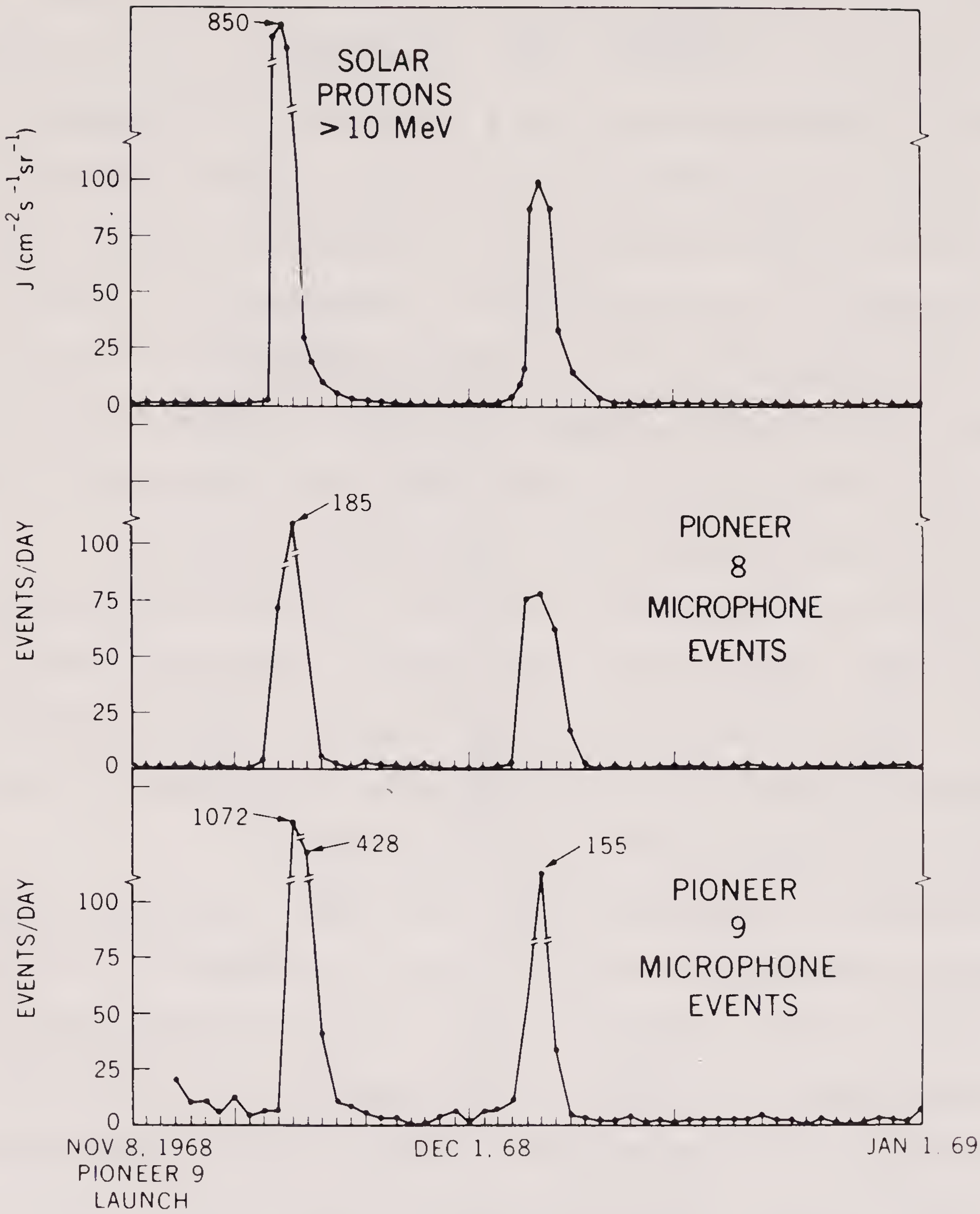

Figure 10-5. A comparison of the times of occurrence by solar proton events with microphone events on Pioneers 8 and 9 (from Berg and Grün 1973).

Table 10-1. Orbital Elements of Some TOF Event Particles from Pioneer 8 (from Berg and Gerloff 1971).

Date of Event	Measured Particle Velocity (km/sec)	True Particle Velocity (km/sec)	Particle Mass	a (AU)	e	q (AU)	ω	Ω	i	π
3/11/68	7.5	19.3	2.1	0.67	0.58	0.28	-	-	0°	339°
3/26/68	18.0	12.5	0.93	0.58	0.84	0.095	-	-	0°	7°
4/13/68	27.6	16.05	2.2	0.62	0.97	0.019	-	-	0°	24°
4/14/68	34.0	9.06	0.78	0.55	0.97	0.013	-	-	180°	17°
5/25/68	15.7	13.28	1.2	0.59	0.81	0.11	-	-	0°	50°
1/24/69	5.9	31.5	1.9	1.28	0.24	0.98	49.9	102°	5.9°	152°

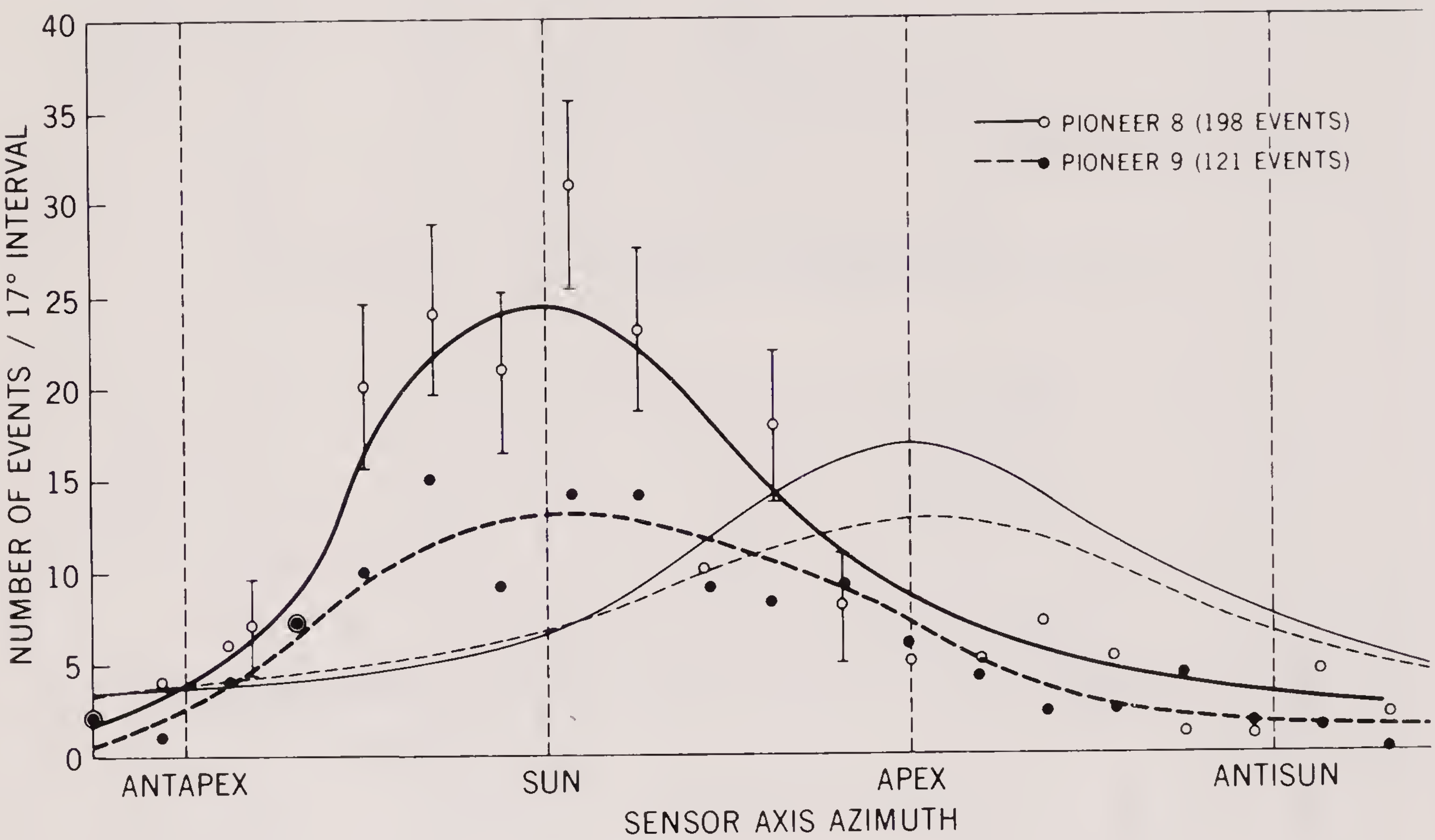

Figure 10-6. Pioneer 8 and 9 front film-grid events. The heavy lines are for the numbers of events and the thin lines show the average energy per event (from Berg and Grün 1973).

which recorded just as many events on both spacecraft as the experiment microphone.

In the Pioneer 8 and 9 experiments' combined exposure of over 7 years, there were a total of 20 TOF events (Wolf et al. 1976) and 319 FFG (front film-grid) events (Berg and Grün, 1973). The latter, which originally had been discounted as largely due to noise from solar particles and radiation, were later shown to be more likely primarily due to dust particles with hyperbolic orbits, emitted from the solar direction. It was suggested that the particles most likely are cometary fragments that spiraled in towards the sun under the Poynting-Robertson effect (Chapter 12) and then, when within a few solar radii of the sun, partly evaporated. The resulting smaller fragments had β parameters (Chapter 12) greater than 1, so that radiation pressure radially ejected them from the solar position. Most of these particles detected were inferred to be small, with masses $< 10^{-12}$ gm. Velocities, as judged from the TOF data, are very large for the smallest particles, perhaps reaching values > 100 km/sec for the solar radial particles. For masses $> 2x10^{-11}$ gm, the average velocity remains constant at about 20 km/sec, which agrees well with expectations if they are cometary debris.

III. Probes Into the Inner Solar System

Helios 1 provided the first reliable direct measurements of the meteoritic particle density in the inner parts of the solar system. With a perihelion distance of only 0.3 A.U., Helios 1 was equipped with two particle sensors, one facing towards the south ecliptic hemisphere and the other along the ecliptic plane. During the first two orbits, a total of 58 different particle impacts were recorded (Grün et al. 1978).

The inner solar system particle density was expected to be of interest for several reasons: the Poynting-Robertson effect should cause a steep increase in density near the sun (Briggs 1967); comets lose most of their mass near the sun; and particles collide with each other more frequently and with greater velocity in the inner solar system. All of these effects predict that the particle density should increase with decreasing solar distance, by an amount that depends on the particles' physical nature and on the cometary disintegration mechanism. For these reasons, the results of the Helios experiment were of great interest. Fig. 10-7 shows the radial dependence of the detected impact rate for the first two orbits, illustrating a clear increase in the rate for small solar distances. The rate at 0.3 A.U. was nearly twenty times higher than at 1 A.U. and the curve suggests a power law with exponent -2.5, with, of course, a large uncertainty. To translate these results into particle space densities requires certain assumptions to be made about their physical and kinematical properties. In particular, the impacting velocities are surely higher at small r because the orbital velocities of both particles and spacecraft are higher. The measured speeds for the Helios 1 impacts at 0.3 A.U. were ~ 2.5 times those at 1 A.U. This higher impact velocity means a lower detection threshold for particle masses, which, in turn, means a higher expected impact rate by an amount dependent on the mass distribution. Grün et al. (1978) suggest that these considerations imply that the Helios 1 results indicate an increase of particle space density at 0.3 A.U. on the order of four times that at 1 A.U., a result in good agreement with measurements, also made by Helios 1, of the zodiacal light (Link et al. 1976). The distribution of impacting directions was significantly asymmetrical, with

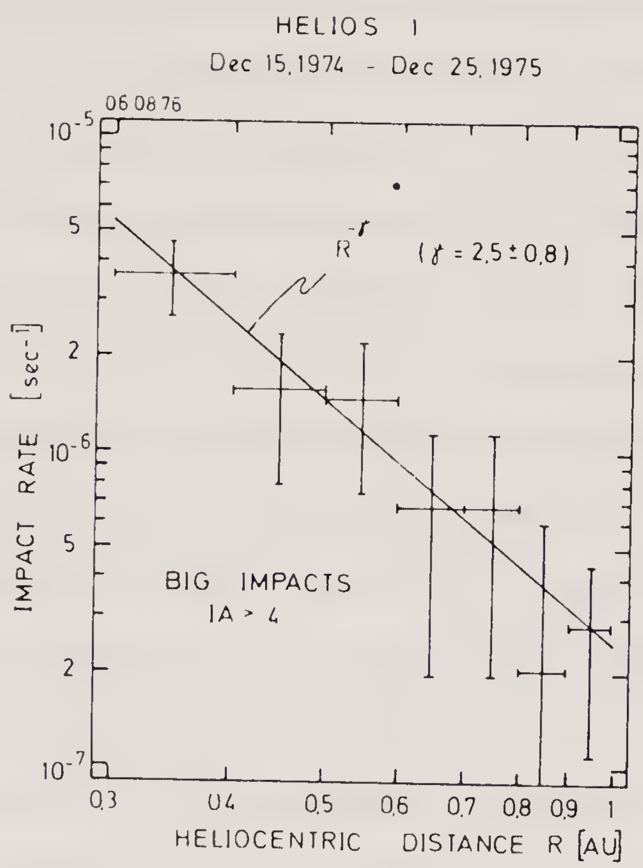

Figure 10-7. The impact rate encountered by Helios 1 during its first two orbits as a function of solar distance (after Grün et al. 1978).

enhancements along the ecliptic, in the direction of the spacecraft motion's apex, and in the solar direction. The latter seems to support, at least qualitatively, the Pioneer 8 and 9 results on solar hyperbolic particle orbits.

IV. Measurements Beyond the Earth's Distance From the Sun

Among the first attempts to penetrate the interplanetary medium of the outer solar system was the Mars 1 probe, which was launched by the USSR on September 1, 1962, and which carried microphonic dust sensors. It and the earth almost immediately passed through the Taurid meteor stream and Nazarova (1968) reported that a high incidence of events was detected between 6600 and 42000 km from the earth. She calculated a rate of 7×10^{-3} m^{-2} sec^{-1} for particles with masses $> 10^{-7}$ gm, which was 700 times the expected flux. However, since that time the microphone sensors have come into doubt (see Chapter 8) and thus this detection of the Taurid stream must be viewed with skepticism, as should the following data from Mars 1.

The Soviets' results for the density of particles in space beyond 1 A.U. were consistant with what they had found in earth orbital experiments: namely, there was a very uneven incidence of signals that suggested a highly non-uniform spatial density. A mean of approximately 10^{-6} m^{-3} was estimated for the density of 10^{-7} gm and larger particles just beyond the earth. In the distance range from the earth between 23 and 45×10^{6} km, an increased flux was recorded for about 4 hours. Nazarova interpreted this as due to an unknown meteor stream, with particle densities varying between 2×10^{-6} and 7×10^{-4} per cubic meter. The meteoritic particle experiment failed at that point and it was thus impossible to extend the sampling all the way to Mars.

Nazarova (1968) reported evidence that Mars 2 and 3 and Venus 2 had also encountered similar deep-space showers of particles, but this result is clouded by the same doubts that exist about microphone noise for other spacecraft. The failure of any clear confirmation of particle showers by detectors of different design has led to a general consensus that the showers were probably spurious.

Mariner IV, launched toward Mars in 1964, provided data from 1 A.U. to 1.6 A.U. (Alexander et al. 1965). A total of 241 events was recorded by the microphone sensor, but there were difficulties with the control, so that the results are still somewhat uncertain. Later analysis has suggested that the particle encounter rate was very roughly even, with some enhancement at around 1.4 A.U., and that the size distribution of particles changed significantly, having a steeper slope in the outer parts of the interval sampled (beyond 1.25 A.U.).

Of considerable interest because of the far greater distances achieved were the Pioneer 10 and 11 experiments. These spacecraft carried three different kinds of instruments designed to measure the properties of the interplanetary dust from ~ 1 to 5 A.U.: zodiacal light sensors, penetration detectors, and optical asteroid/meteoroid (AMD) telescopic detectors. The zodiacal light instruments detected a variety of particle sizes, weighted towards the 10^{-5} to 10^{-7} gm range (Chapter 2). The penetration detectors were tuned to detect primarily particles in the 10^{-9} gm range for Pioneer 10 and 10^{-8} gm for Pioneer 11, while the AMD telescopes detected much larger objects, in the 70μm - 20 cm size range.

Unfortunately, the three Pioneer 10-11 experiments did not agree on the implied radial dependence of particle space densities. The zodiacal light sensors showed a brightness

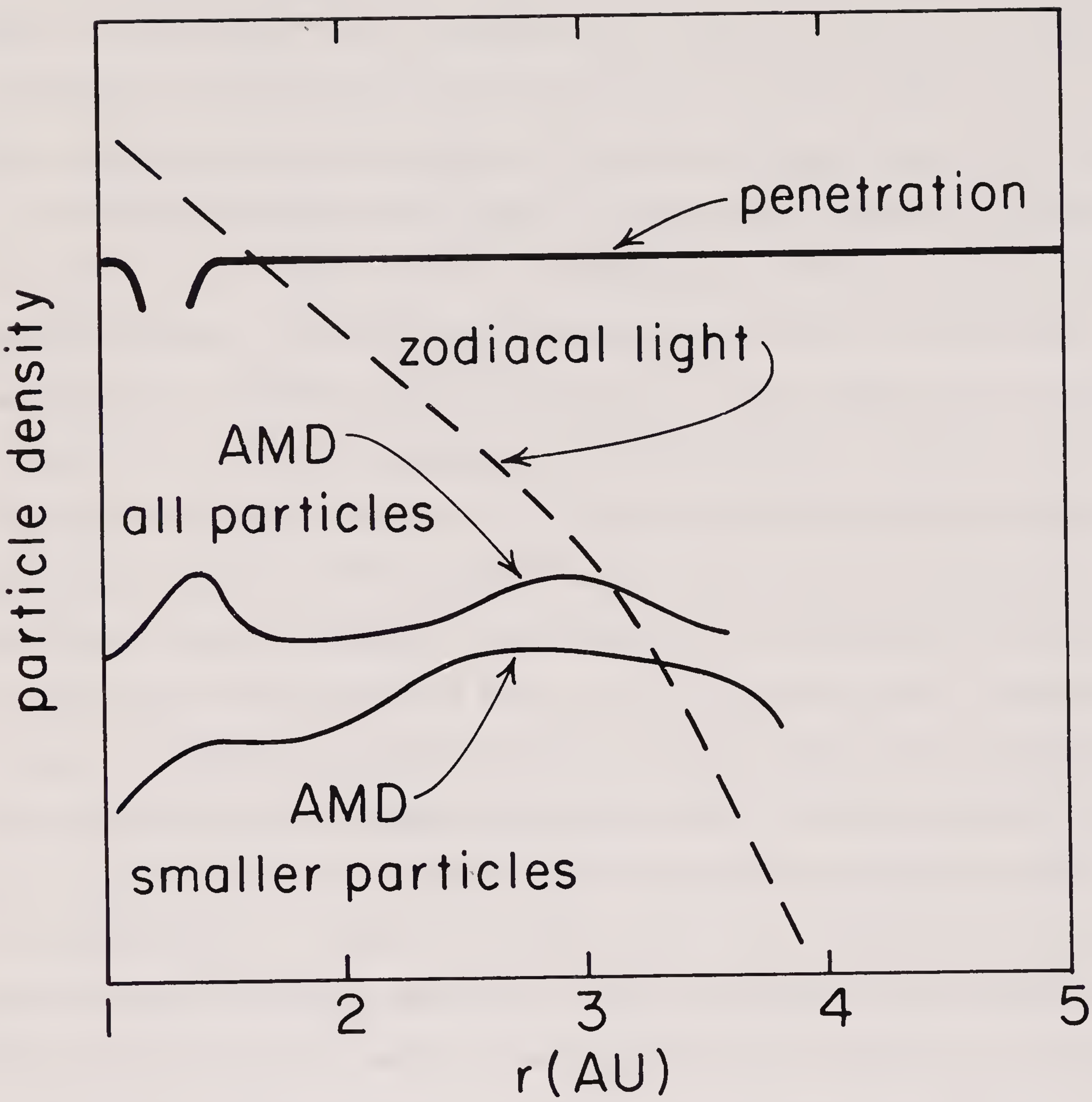

Figure 10-8. Relative particle concentrations for the three types of experiments on Pioneers 10 and 11, as a function of heliocentric distance (schematic).

decrease that was close to a r^{-3} dependence (where r is the distance from the sun), which implies a $r^{-1.5}$ dependence in the particle space density (Hanner, et al. 1974). The penetration sensors, on the other hand, showed a nearly constant space density from 1 to 5 A.U. with a possible mysterious gap in the range 1.15 - 1.34 A.U. that seems to show up for both spacecraft, though statistics are poor for the relatively less sensitive Pioneer 11 sensor (Kinard et al. 1974, Humes et al. 1975). A very considerable increase (~ 100X) in particle density was detected near Jupiter itself and the planets' gravitational focusing effect has been the accepted explanation of this observation. Finally, the AMD experiments found a gradual increase in the particle concentration with distance, between 1 A.U. and 3.5 A.U. (Soberman et al. 1974). This applied to the small particles, with radii less than 0.15 cm, and was a less clear trend for the data for all particles (Fig. 10-8).

The situation with respect to the interplanetary particle space density in the outer solar system remains unsatisfactory. Both theory (Briggs 1962) and the zodiacal light data indicate an $r^{-1.5}$ dependence, while the penetration data suggest an r^0 dependence. The AMD results suggest, on the other hand, that the space density increases with r, especially in the general area of the asteroid belt. Furthermore, the AMD telescopes give an order of magnitude higher value of density than the zodiacal light experiments. Further measures are needed before these remarkable discrepancies can be reconciled. As in other pioneering efforts in the meteoritic dust field, the Pioneer data remain at least partly suspect and the true radial dependence of particle densities in the outer solar system remains unknown.

I. Introduction

The term "micrometeorite" has held a variety of definitions during the past, but is now generally restricted to refer only to those objects that are sufficiently small that they can enter the earth's atmosphere at cosmic velocites without suffering ablation. Micrometeorites do not heat sufficiently to melt nor do they break up into fragments on impact with the atmosphere, and therefore after deceleration they gradually drift down to the surface of the earth in a relatively unaltered state.

The theory of micrometeorite entry into the atmosphere was first developed by Öpik in 1937. Some years later Whipple (1950, 1951) developed a detailed micrometeorite theory for an isothermal and non-isothermal atmosphere, in order to provide realistic estimates of the various size ranges available for different kinds of materials. The Whipple version of the theory was subsequently refined using a variety of modern atmospheric parameters by Cook (1968) and by Kornblum (1969). An extension of the modern version of the theory to specific kinds of meteoroid objects and a comparison of the theory with current micrometeorite influx estimates was published by Hodge and Wright (1969).

II. Basic Theory

Micrometeorite theory is based on the fact that at a certain size a small particle entering the atmosphere has a surface area to volume ratio sufficiently large that it can radiate away energy as fast as this energy is generated by collision with atmospheric molecules. In this way the melting temperature of the material is not reached and the particle remains unablated, basically in its pre-atmospheric state. Micrometeorites can include objects that have irregular shapes and that might suffer small amounts of spotty melting but that are primarily unchanged. The aim of the basic micrometoerite theory is to calculate the critical size below which ablation is unimportant, and to find the dependence of this size on such variables as the particle shape, particle composition, and incident angle.

The first step is to find the amount of energy contained in the air molecules that have been bombarded by the front of the meteoroidal particle as it passes rapidly through the atmosphere. This will give an expression for the increment of energy gained by the molecules. The mass of the air with which the body collides is

$$dm = A \rho V \, dt.$$

Where A is the cross sectional area of the body, ρ is the air density, and V is the meteoroidal velocity. Therefore, the molecules gain energy in the amount

$$dEg = \tfrac{1}{2} V^2 dm = \tfrac{1}{2} A \rho V^3 dt.$$

The next step, after calculation of the amount of energy gained, is to determine the means of dissipation for the energy. Almost all of the energy is transmitted directly to the incoming body and part of this is converted into heat, part is radiated away, part goes into dissociation, ionization, and excitation of the molecules and atoms, and finally part is involved in mechanical removal of material from the micrometeorite. As a first approximation, it is found that almost all of the energy is involved in radiation and therefore it is possible to use Stefan's Law to express the energy radiated

$$dE_r = a \sigma T^4 dt.$$

Where a is the surface area of the micrometeorite, σ is the Stefan-Boltzmann constant, and T is the temperature at the surface of the body. Making the assumption that the radiating area is approximately 4 times the cross-sectional area (A), the above equation can be written

$$dE_r = 4A\sigma\, T^4\, dt.$$

Assuming that the energy is primarily lost through radiation, it is possible now to equate the energy gained with the energy so lost, and the result from the above equations provides the following expression for the temperature

$$T^4 = \frac{\rho\ \ V^3}{8\sigma}.$$

It is next important to realize that the micrometeorite is experiencing a rapidly changing atmospheric density, and that therefore the velocity is decreasing. Meteor theory shows that the deceleration of a meteoroid depends on the mass, the density, the velocity, and the cross sectional area of an idealized body, with all of these quantities being related through a coefficient Γ, called the drag coefficient. Meteor theory's expression involving the drag coefficient and these parameters is as follows

$$mdV = -A\ \Gamma\rho\ \ V^2 dt.$$

Various experiments have shown that Γ is approximately equal to 1 for many bodies, and assuming this to be true for our micrometoerites and assuming that the particle density we are dealing with is approximately 3 gm cm^{-3}, then we find that the above equation can be written

$$dV = \frac{-\pi^{1/2}\ \rho\, V^2}{4A^{\frac{1}{2}}}\ dt.$$

The density of the atmosphere varies in a way that is well represented over most heights by the equation

$$\rho = \rho_o e^{-bh}.$$

Where ρ_0 is a constant and b is constant for the case of an isothermal atmosphere but otherwise varies. We now make the further simplifying assumption, only for the purposes of this chapter, of examining only the case of a semi-infinite atmosphere, with a zenith angle equal to zero (representing a micrometeorite that enters the atmosphere straight down). In that case,

$$dh = -Vdt.$$

Now putting the specific equation for the variable atmospheric density into the expression for the deceleration and writing it in terms of h, which is the height above sea level, the result is

$$\frac{dV}{V} = \frac{\pi^{\frac{1}{2}} \rho_o e^{-bh}}{4A^{\frac{1}{2}}} dh.$$

At a height h the velocity of the micrometeorite is V, smaller than the initial value outside the atmosphere, V_i. It is now possible to integrate the equation over the path from outside the atmosphere to height H as follows

$$\int_V^V \frac{dV}{V} = \frac{\pi^{\frac{1}{2}} \rho_o}{4A^{\frac{1}{2}}} \int_\infty^H e^{-bh} dh.$$

This gives

$$\log \frac{V}{V_i} = \frac{\pi^{\frac{1}{2}} \rho_o}{4A^{\frac{1}{2}} b} e^{-bh}.$$

And now rewriting this in terms of the variable density gives

$$\rho = -\frac{4A^{\frac{1}{2}} b}{\pi^{\frac{1}{2}}} \log \frac{V}{V_i}.$$

Now using the equation derived above for the temperature of the surface of the micrometeorite, and employing the above expression for , we find

$$T^4 = \frac{-A^{\frac{1}{2}} b V^3}{2\pi^{\frac{1}{2}} \sigma} \log \frac{V}{V_i}.$$

This is an expression for the temperature in terms of the velocity and size of the particle. It is now possible to rewrite this using a critical velocity V_c that corresponds to a temperature just below the melting temperature of the material. This is simply derived by differentiation of the above equation, thereby imposing a maximal condition on T and allowing us to find the value for V_c. Making the differential of the equation equal to zero, we find

$$V_c = \frac{V_i}{e^{\frac{1}{3}}} .$$

With this relationship between the initial velocity and the critical velocity, it is possible now to calculate the critical size above which melting will occur. Thus we calculate

$$T^4_{max} = \frac{A^{\frac{1}{2}} b V_i^3}{6 \pi^{\frac{1}{2}} \sigma e} .$$

For a particle that is roughly spherical, the cross-sectional area is related to the radius by the approximation

$$A \pi \approx r^2 .$$

So that the maximum critical radius of such a particle is given by the equation

$$r_c = \frac{6e \sigma T^4_{max}}{b V_i^3}$$

For most relevant materials the melting temperature of interest is on the order of 1500 K. Using a value for b of 1.1×10^{-6} cm^{-1} and a value for σ of 5.7×10^{-5} erg/cm^2 deg^4 sec, it is found that the critical radius can be calculated in terms of the initial velocity from the following simple formula (in cgs units):

$$r_c = \frac{4.2\text{x}10^{15}}{V_i^3} .$$

To show how the formula above relates to individual cases, we can examine the critical radius for a spherical particle of iron located just outside the atmosphere at rest, so that its initial velocity is vertical and equal to the escape velocity, 11.7 km per second. The above formula then will show that any particle 26 microns or less in radius will be a micrometeorite, never reaching a temperature high enough to cause ablation by melting.

III. Theoretical Refinements

Whipple's two papers deal with the physics in more detail than outlined above and make corrections in the micrometeorite theory for the variation of temperature in the atmosphere. These details will not be gone into here except to give the complete formula for an isothermal atmosphere and a table (Table 11-1).

$$r_c = \frac{9e\beta\sigma\Gamma(T_m^4 - T_o^4)}{\alpha\rho_s b(\cos Z)V_i^3}$$

where

β = gray emissivity coefficient

$\sigma = 5.7 \times 10^{15}$ erg/(cm^2)(deg^4)(sec)

Γ = drag coefficient, a function of V

T_m = melting temperature

T_o = temperature of the body outside the atmosphere

α = accommodation coefficient (fraction of molecular energy transferred to the micrometeorite)

ρ_s = density of particle

b = a parameter in the ρ_{air} formula which varies with air temperature

Z = zenith angle of the micrometeorite's path

V_i = velocity of the meteorite at the top of the atmosphere

Table 11-1 Numerical values for critical radii

V km/sec	
11.3	30
20.0	7
40.0	1
70.0	0.3

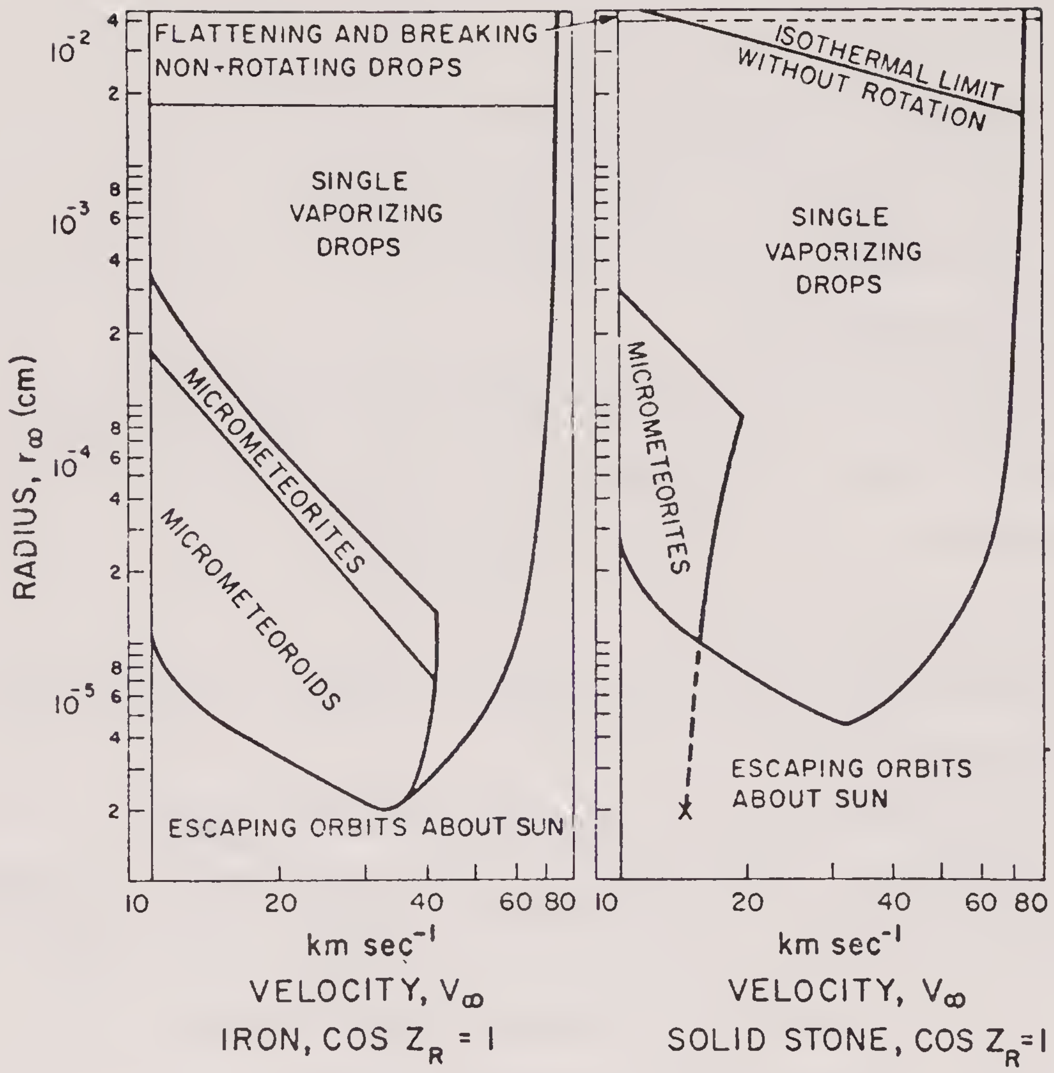

Fig. 11-1. Some of the modes of ablation analyzed by Cook (courtesy A.F. Cook).

Cook (1968) has further refined the theory to take into account the more recent developments in the theory of the interaction of the atmosphere with meteors and Kornblum (1969) has calculated with exhaustive computer simulations detailed results for particles of various kinds, shapes, and incident angles of approach to the atmosphere. In Cook's calculations he used a wide range of possible sizes for iron micrometeorites, taking into account both the upper size limits due to interaction with the atmosphere and the lower size limits due to escaping orbits about the sun. For stoney meteorites, Cook's analysis suggests that there would be a low rate of occurrence for all particles except for those with large zenith angles, a result somewhat at odds with Kornblum's calculations. Figure 11-1 is taken from Cook's paper.

IV. Comparison of Theory with Observation

Kornblum (1969) utilized his detailed calculations to examine the possibility that some of the particles collected up until then by various means in the atmosphere might be micrometeorites. The number that he calculated that should be expected turned out to be much smaller than the numbers collected, particularly in early rocket and balloon settling plate experiments.

Hodge and Wright (1969) did a similar analysis, comparing results with re-evaluations of the space density of interplanetary particles taken from spacecraft impact experiments. Those data had indicated several orders of magnitude fewer particles than had previously been calculated to exist in the earth's environment. Figure 11-2 shows the out-of-atmosphere particle fluxes at different masses that

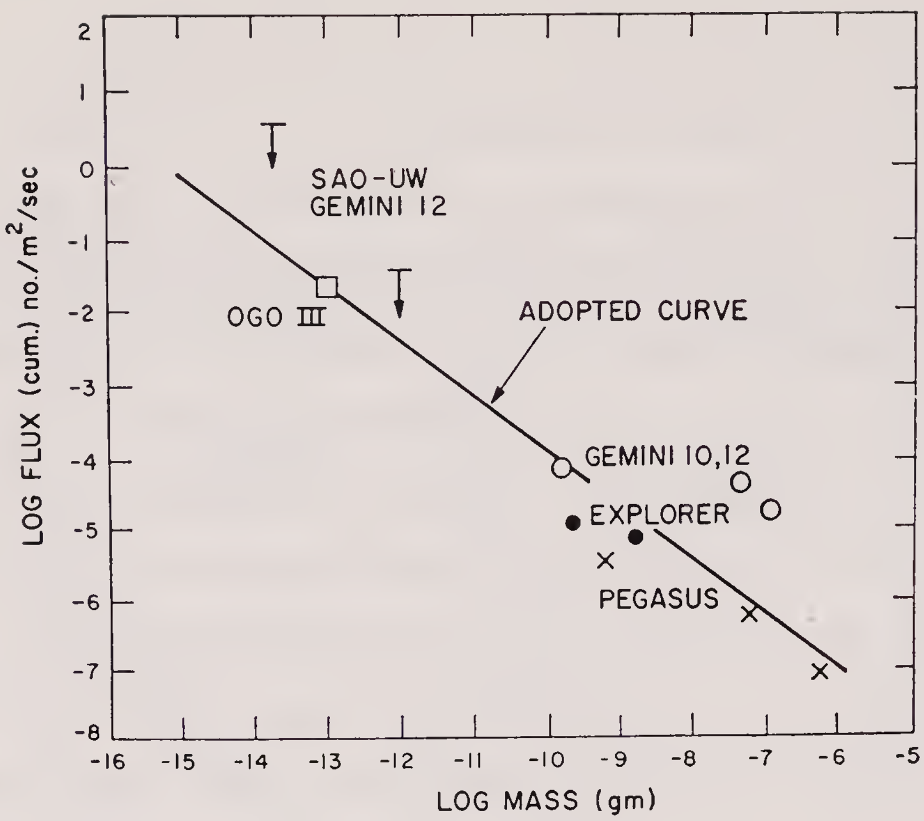

Fig. 11-2. Particle fluxes adopted for comparison with micrometeorite theory (from Hodge and Wright 1969).

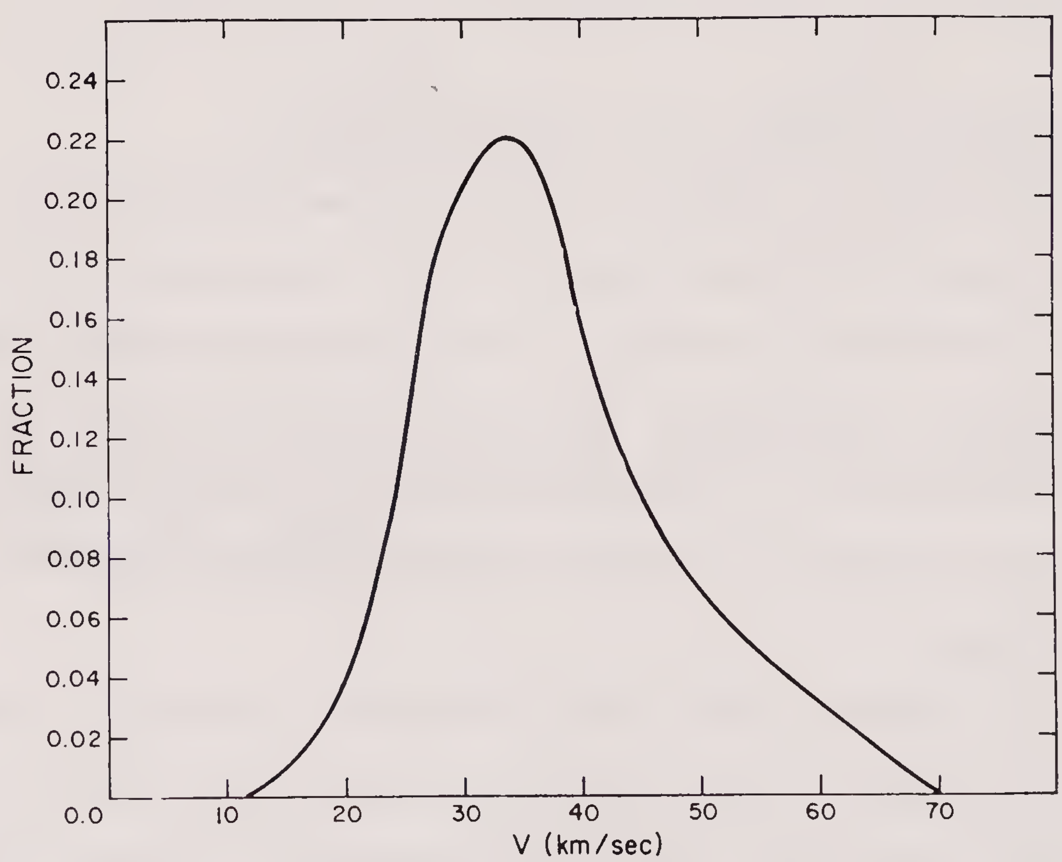

Fig. 11-3. Adopted velocity distribution of micrometeorites, based on radio meteor data (from Hodge and Wright 1969).

they adopted in their calculations. They calculated the expected number of micrometeorites at the surface of the earth using Cook's treatment of the basic micrometeorite theory, extending his results to all possible zenith angles. The true velocity distribution of interplanetary dust near the earth was estimated from radio meteor data, with the curve weighted somewhat towards the faintest meteors. Figure 11-3 gives the adopted velocity distribution so derived.

If the particles present an isotropic incidence on the atmosphere, then the probability, P, of the occurrence of zenith angle Z, is given by

$$\frac{dP}{dZ} = \sin 2Z.$$

This probability distribution was used in calculating the micrometeorite radius-velocity matrix for determining the flux at the surface of the earth. Figure 11-4 shows the result of this semi-empirical estimate of the micrometeorite flux for various particle sizes. The figure shows both the particle flux as it is in space and the flux of iron micrometeorites, calculated on the basis of the assumption that the iron micrometeorites make up approximately 7% of the total meteoroidal bodies in space, as seems to be the case for ponderable meteorite falls.

This result can be compared with the observed flux of microscopic bodies that had been identified as probable micrometeorites. From polar ice deposits, for example, Hodge, Wright and Langway (1964) identified two irregular particles with a nickel-iron ratio approximately that of iron meteorites. If both of these are assumed to be true nickel-iron micrometeorites, then it is possible to compare the resulting flux with the theoretical flux. They both

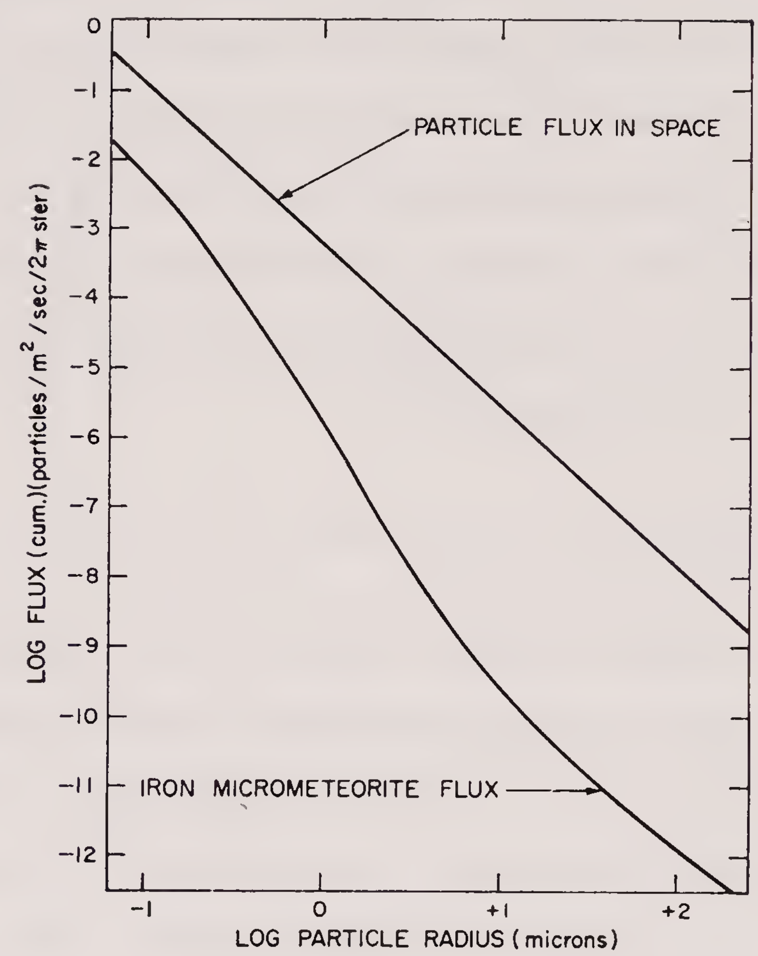

Fig. 11-4. A semi-empirical curve derived for the micrometeorite flux on the earth (from Hodge and Wright 1969).

come from ice at the South Pole, where the snow deposition rate is known. These are large particles, with an average diameter of 40 microns, and they lead to an estimated flux at the terrestrial surface of 10^{-6} particles m^{-2} sec^{-1}. From the theoretical curve, the expected flux at a radius of 20 microns is vastly smaller, on the order of $3x10^{-11}$ particles m^{-2} sec^{-1}. Therefore Hodge and Wright concluded that these particles are probably not micrometeorites as defined by Whipple.

In fact this comparison suggests that the chances of finding iron micrometeorites in polar ice deposits must be exceptionally low. The two particles mentioned above make up about 2% of the irregular particles that were analyzed, having been selected as probable candidates for being micrometeorites. The calculated flux of such irregular particles in the ice at the South Pole is approximately $2x10^{-4}$ irregular particles of all types with radii greater than 10 microns m^{-2} sec^{-1}. The theoretical flux of true iron micrometeorites in this size range, however, is only $3x10^{-10}$ m^{-2} sec^{-1}. Thus only about 1 in 1 million particles in this relatively pure environment can be a true iron-nickel micrometeorite.

Table 11-2 is taken from the study of Hodge and Wright (1969) and shows the calculated number of iron micrometeorites expected in various balloon sampling experiments. It is seen that it is far more effective to go to high altitudes and use high efficiency balloons or aircraft like those described in Chapter 5 to collect such objects than it is to look in sediments at the terrestrial surface. Of course, it must be emphasized that true micrometeorites represent a small fraction of the interplanetary material in the atmosphere and at the surface in the size range being discussed, most of the meteoritic material being ablation products (gas, spherules, fragments). Through the careful work of Brownlee and others, we now have hundreds of particles that are probably true micrometeorites collected from the stratosphere (Ch. 5).

Table 11-2. Number of Fe Micrometeorites Expected In Balloon Samples.

	Approximate number of micrometeorites expected per flight		
Type of collector	>5 μ in radius	>1 μ in radius	>0.1 μ in radius
Settling plate collector (10^h)	3×10^{-6}	2×10^{-3}	6
Rotating arm collector (10^h)	3×10^{-4}	0.2	600
Settling plate collector on circumnavigational super-pressure balloon (200^d)	10^{-3}	0.6	1800

I. Introduction

The problems of the dynamics of interplanetary dust particles can be approached from either of two points of view. First one can calculate various effects on the orbits' particles in the solar system. Included in the calculations are the effects of the sun's gravity, perturbations by the planets, collisions with other bodies, radiation pressure, the Poynting-Robertson effect, and interactions with the solar wind and magnetic field. An alternative and complementary approach is to use detection methods in space to assertain the velocities and directions of the interplanetary particles and from that to deduce the statistics of steady-state orbits. The final answer to questions about interplanetary dust particle dynamics comes from a comparison of these two approaches. Presently the understanding of both the physics and the experimental results is fairly far advanced and a fairly good accounting of particle orbits can now be deduced.

II. Gravitational Effects

To a first approximation it is expected that a dust particle in orbit in the solar system will move around the sun according to the Newtonian laws of gravitation:

$$(m + M)P^2 = \frac{4\pi^2}{G} a^3$$

where m is the mass of the particle, M is the mass of the sun, r is the distance between the particle and the sun, p is the period and G is the universal constant of gravitation. The path of the particle will obey Kepler's laws, which can be derived from Newton's laws, and will therefore have the form of conic sections with orbits that are in a plane that includes the sun. They will show a relationship between speed and distance from the sun called the law of areas (a radius vector drawn between the sun and the particle will sweep out equal areas in equal times) and will show a relationship between the period of the orbit and the semi-major axis of the form

$$\frac{P^2}{a^3} = \text{Constant}$$

The orbit itself will be described by the following equation

$$r = \frac{a(1-e^2)}{1+e\cos\theta}$$

where a is the semi-major axis, e is the eccentricity of the orbit and θ is the angle between the position of the particle and the position of the perihelion point in the orbit (the point nearest the sun).

Because of the presence in the solar system of bodies other than the sun, the actual gravitational behavior of individual particles is rather more complicated than would be indicated above. For one thing, the orbits of individual small bodies are influenced by close approaches to the planets, their satellites, and other more massive objects. The result is a greatly perturbed orbit, or in the extreme case, capture or collision. Gravitational focusing by a planet, for example, can pull in a large fraction of the particles near the planet that do not actually have intersecting orbits, causing a sweeping out of particles from a region in the solar system that has a larger cross sectional area than the planet itself sweeps out.

The focusing of particles on to a planet or other large body is dependent on the circumstances of the relative motions of the bodies as well as on their mass. A planet of mass m moving through a medium consisting of small particles of number density n at infinity, all of which have equal relative velocity (at infinity with respect to the planet) of v will experience a flux of particles onto the surface given by the equation

$$\text{flux} = nv\left(1+\frac{2Gm/r}{v^2}\right)$$

As this shows, the focusing effect, as measured by the flux of incoming particles, is dependent on the mass of the planet, the distance of the particle from the planet, and on their relative velocity. Particles with very large relative velocities experience a very small focusing factor, while those moving in orbits that are nearly identical to that of the planet, such that their relative velocities are near zero, are very highly susceptible to gravitational focusing and capture.

Considerations of the gravitational focusing effect for planets with satellites must take into account the multiple effect of two bodies on the path of the affected particle. Tomandl, for example, has calculated extensive orbital parameters for particles captured by the earth-moon system, in which the influence of the earth's gravity on the capture parameters of the moon are specifically determined. A large scale example of this kind of influence is given by the maria of the moon, which are almost exclusively limited to the earth side of that body because of these effects.

Another gravitational effect of interest in the consideration of interplanetary particles is the restricted three body problem involving the sun, the earth, and a small particle of negligible mass. When equipotential surfaces are calculated for such a configuration it is found that there are certain points in the space surrounding the two larger

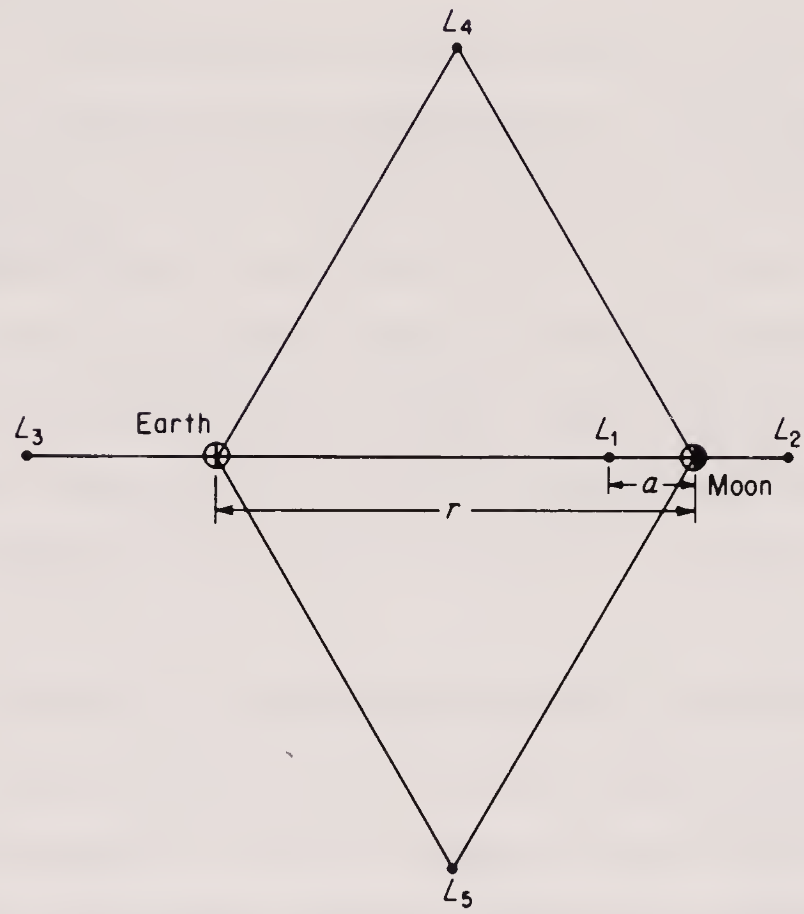

Figure 12-1. Lagrangian points of the earth-moon system.

objects where the potential is equal in all directions, that is, there is no acceleration in any direction felt at those points. At such a point, called a Lagrangian point, a small particle, experiencing no acceleration, could remain fixed relative to the planet and in the absence of any other influence.

There are five Lagrangian points in the restricted three-body problem, but only two of them are stable. That is, for only two of them is the particle able to remain if it is perturbed slightly in position. In the other three cases any slight movement of the particle away from the Lagrangian point will result in its escape. Figure 12-1 illustrates the five Lagrangian points for the earth-moon system. In this particular case, of course, none of the points is completely stable because of the interfering effect of a large third body, the sun. Therefore, the earth-moon system's Lagrangian points can only be temporary resting places of interplanetary dust. A great deal of observational effort has gone into attempts to detect any possible clouds of interplanetary particles at the L-4 and L-5 Lagrangian points of the earth-moon system, and although several detections have been reported at various times in the literature, none of these has been convincingly confirmed.

III. The Poynting-Robertson Effect

It's been known since 1903 that small particles in the solar system will gradually spiral into the sun under an effect that was first discussed by the physicist Poynting. He showed that the effects of absorbtion and re-emmission of light by a particle moving in an orbit around a radiating body will cause it to loose orbital angular momentum. The relativist, Robertson, later re-formulated the discussion of the problem in relativistic terms and applied his results to the question of the residence time for small bodies in the solar system. The equations of motion for a particle in orbit about the sun can be written

$$\ddot{r} - r\dot{\theta}^2 = -\frac{GM}{r^2} + \frac{\alpha c}{r^2} - \frac{2\alpha\dot{r}}{r^2}$$

and

$$\frac{1}{r}\frac{d}{dt}(r^2\dot{\theta}) = -\frac{\alpha\dot{\theta}}{r^2}$$

Where r, θ , G, and M are the distance from the sun, the position angle in the orbit, the constant of gravitation, and the mass of the sun respectively. The parameter α introduces the radiation pressure and it has a value that is equal to

$$\alpha = \frac{3.55 \times 10^{-8}}{s\rho} \quad (AU)^2/yr$$

where s is the radius of the particle and ρ is the density of the particle in cgs units. These equations ignore radiation pressure (Section 12-IV).

To calculate how long a particle will remain in orbit about the sun before it falls into the solar vicinity and is evaporated, one can use the above equations and integrate to find the time of fall. For a circular orbit, the equations give

$$\frac{da}{dt} = -\frac{2\alpha}{a}$$

which can be integrated to give the formula

$$-t = 7.0\times10^6 \; s\,\rho\,a^2 \text{ years}$$

Where a in this case is the initial distance of the particle in astronomical units and t is the time of fall into the sun

Table 12-1. Times of Fall for Particles with Various Initial Orbits

a, AU	e	$t/10^7$ yr x $s\rho$	Type of Orbit
3	0.0	6	Asteroidal
3	0.7	0.7	Asteroidal
1.4 (Geminids)	0.9	0.14	Meteor showers
3.5 (Bielids)	0.7	3	Meteor showers
10 (Leonids)	0.9	7	Meteor showers

expressed in years. Table 12-1 gives selected values for various initial orbits.

IV. Radiation Pressure

In the above section it is seen that small particles, on the order of 10 to 100 microns in radius, rapidly fall into the center of the solar system under the Poynting-Robertson effect. For smaller particles, however, an effect comes into play in the opposite direction, overwhelming the Poynting-Robertson effect and causing the propulsion of particles out from the sun with high efficiency.

The simple version of the theory of radiation pressure leads to a formula for the outward radial force due to this effect equal to

$$F_r = \frac{(\pi F)}{c} \pi s^2 Q(s)$$

where πF is the flux of the radiation in cgs units, c is the velocity of light, s is the particle's radius, and Q (s) is an efficiency factor for the particle's radiation pressure, figured in terms of the ratio of the effective cross-section for radiation to the geometrical cross section. This quantity depends upon a wide variety of physical parameters. Included are the optical properties of the particle itself, which if small enough is not infinitely optically thick so that internal refractions must be taken into account, as well as the optical effects depending on the surface characteristics. Defraction effects and interference effects can also enter in. The result of both experiments and detailed theoretical calculations indicate that this parameter is usually small and has a value near unity only at particle sizes that are near to the wavelength of the light. Thus particles of radius on the order of 5×10^{-4} cm will experience a strong outward pressure, while larger and smaller particles will experience a much lesser effect.

V. Solar Wind Interactions

The solar radiation is not the only source of complication due to the sun in the problems of the dynamics of interplanetary dust. Also eminating from the sun is a cloud of high velocity elementary particles, making up the solar wind. The velocity of these particles depends upon the position and the distance from the sun, but averages approximately 350 km per second. Because the speed is so much smaller than the velocity of light, the effect of the solar particles on the orbits of interplanetary dust is minor compared to the Poynting-Robertson effect. It has been shown that a roughly 25% increase in the amount of drag over the Poynting-Robertson effect on a typical particle might be expected, with a resulting longer time of fall (Whipple 1967). These calculations have to be tentative because of the generally uncertain optical properties of the particles and because of the varying velocity and direction of the solar wind, all of which affect the amount of drag.

VI. Residence Times

All of the above different effects on the dynamics of particles have an influence on the make-up of the interplanetary medium at any given time during the history of the solar system. Because interplanetary particles are apparently continually being produced in the solar system, there is at the present time a steady-state situation in which the loss of particles is balanced by their production. For any given particle the residence time in the solar system will be dependent upon its particular properties. Figure 12-2 is a composite diagram based on Dohnany's (1978) calculation of

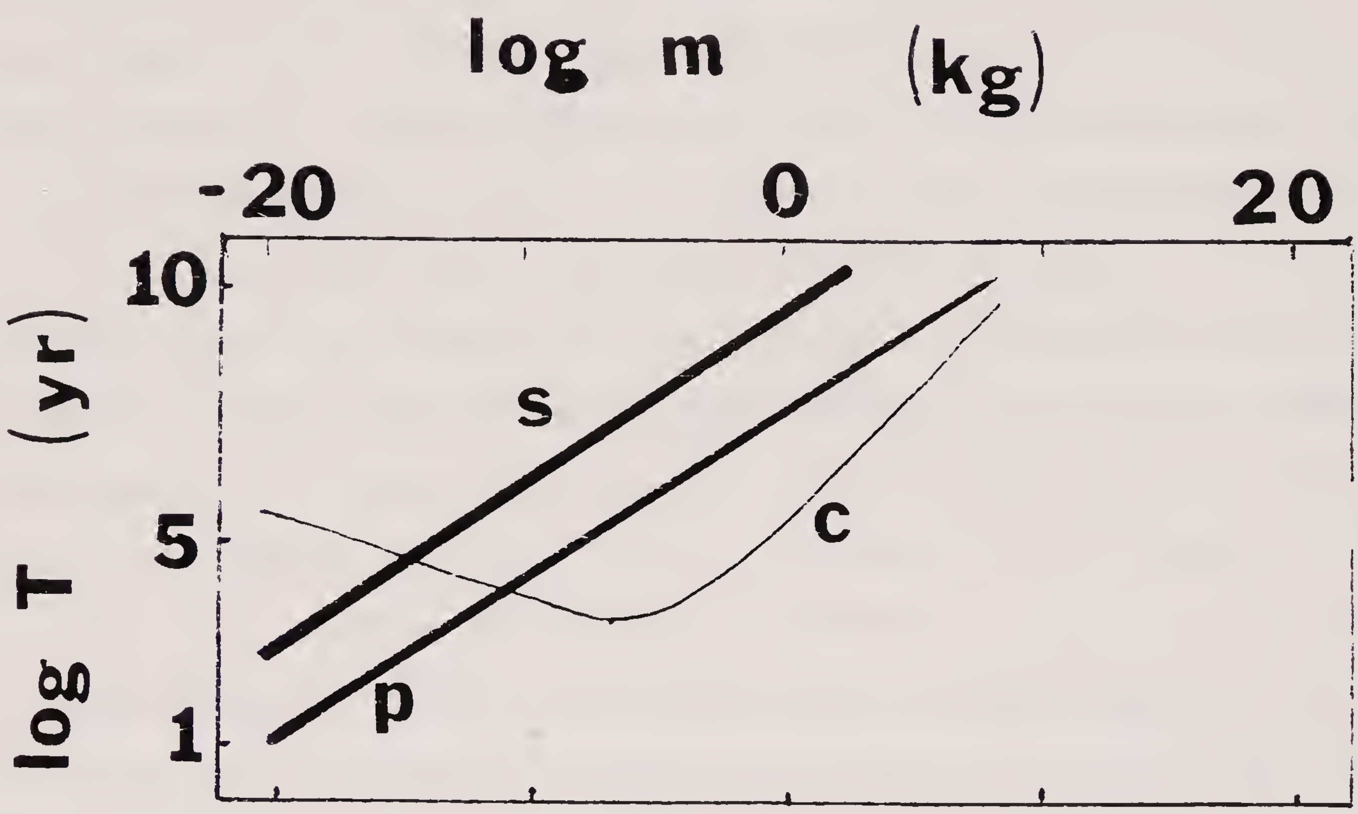

Fig. 12-2. Residence times for dust particles in the solar system, after Dohnany (1978). Curves are shown for the effects of sputtering (s), the Poynting-Robertson effect on a perfect absorber (p), and for catastrophic collisions (c).

the various effects described above, plus others. We see from those calculations that the residence time for the Poynting-Robertson effect for a perfectly absorbing particle ranges from 10^5 years down to 10 years for particles in the range of 10^{-4} down to 10^{-8} meters in radius. However, for a more realistic optical property, such as that calculated for obsidian, the particle residence time increases again for particles 10^{-6} to 10^{-7} meters in diameter and smaller, showing a minimum in that range of 5×10^3 years. Also shown in the diagram is the calculated residence time due to catastrophic collisions, which can move a particle away from the sun even after it has spiraled part way in. The upper curve is the time calculated for sputtering by solar wind particles.

Examples of comprehensive sets of calculations that attempt to take all of these effects into account are those carried out by Briggs (1962), who did the first thorough joining-together of meteor observations and theoretical modeling, and Dohnany (1976), who discussed the various sources of interplanetary dust and its evolution. Dohnany's earlier papers (1972, 1973) laid the ground work for his modeling of the disintegration of the larger interplanetary bodies that give rise to the interplanetary dust.

VII. Observed Dynamical Parameters

Chapter 8 described the measurements made so far of orbital parameters for particles near the earth. Particularly important for the interpretation of the importance of the various effects discussed in this chapter are the results from Pioneers 8 and 9 (Berg and Gerloff 1970, Berg and Grün 1973), which show that most of the orbits are probably direct (prograde), though the inferred distribution of orbital parameters is uncertain and still under discussion. A wide distribution of eccentricities and/or inclination angles is suggested. A significant fraction of the detected particles have hyperbolic orbits and are identified as particles that are being ejected from the solar system by radiation pressure. Their flux is consistant with the predicted effects on the general interplanetary medium, based on the theoretical considerations outlined in Section VI, above.

I. Introduction

Throughout the checkered history of the scientific study of interplanetary dust, scientists have speculated about its origin. At first, it was assumed that it all must be from the same extraterrestrial source as the meteorites. By the mid-twentieth century, this was recognized as implying that the dust is from the asteroidal belt, especially as meteorite orbits became determinable (Fig. 13-1). It was assumed that micrometeorites were merely the small-mass end of the mass spectrum of meteorites, formed by collisions among the asteroids. The spherules, on the other hand, were assumed to be ablation droplets from larger meteorites, which could be of any mass.

As the physical and orbital differences between meteors and meteorites became more clear, the origin of the dust became less so. Only the shape of the zodiacal light could be turned to for information on the dust particle orbits. The fact that the zodiacal light cloud seemed quite broad compared to the narrow confinement of asteroid orbits to the ecliptic was used to argue that the dust might be meteoric rather than meteoritic, as the meteors also showed a wide range of orbital inclination angles. Furthermore, as it became realized from their low density, their chemical composition as hinted at by spectra, and their orbital parameters (especially for showers), the meteors were clearly mostly cometary in origin, and thus by about 1960 most scientists thought that comets were the ultimate source of the zodiacal dust and of the detected and collected interplanetary dust particle candidates.

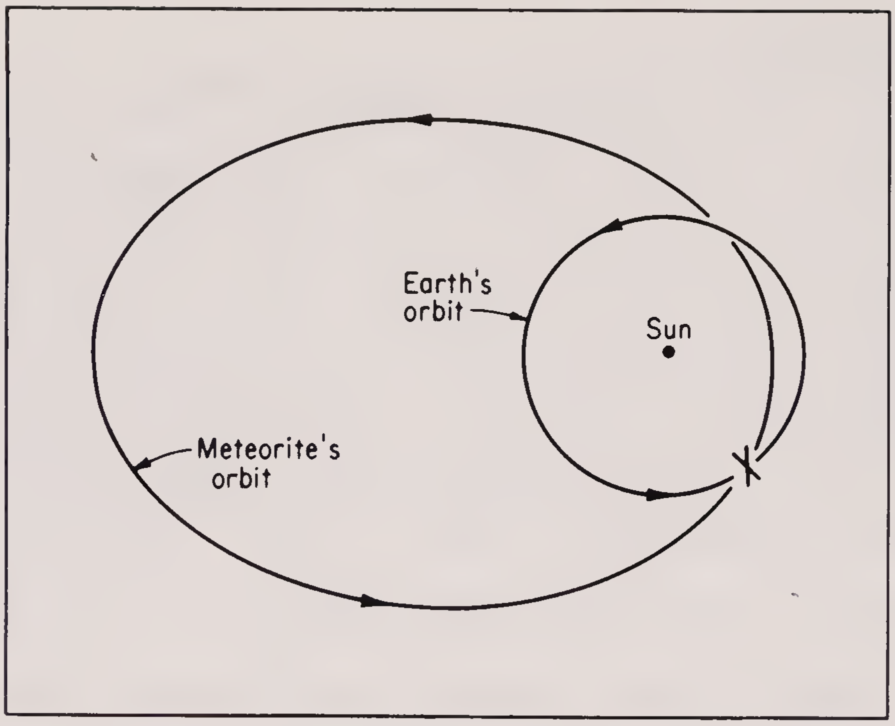

Figure 13-1. The orbit of the Luhy meteorite, the first to have an accurately-determined orbit (from Brandt and Hodge 1964, courtesy McGraw -Hill Book Co.).

Two other possible origins were considered, however. The interstellar medium includes significant amounts of dust and it was suggested that at least a small fraction of the local dust might be from beyond the solar system. Furthermore, it was suggested that the interplanetary dust might also include some left-over material from the period of solar system formation, particles that did not get captured by the forming protoplanets. Both of these sources of dust were (and still are) considered unlikely to be important, the first because the interstellar dust density is so low (about 2×10^{-13} particles per cm^3), and the second because of the various forces that tend to clean out the solar system of dust (Ch. 12).

Implications of the various modern measurements of the properties of interplanetary dust for understanding their origin have already been discussed in the preceding chapters where appropriate. Therefore, this chapter is primarily intended as a brief resumé of recent conclusions about the subject.

II. Orbital Evidence

The similarity of the width of the zodiacal cloud to that of the distribution of meteor and comet orbit inclination angles has been mentioned. This, however, is not direct evidence that the dust has a cometary origin, because the implied orbits for the zodiacal cloud particles are model-dependent and, in any case, the similarity, if it is true, is only circumstantial evidence of a common origin.

The best direct evidence, of course, is actual orbit determination, such as measured, for example, on Pioneers 8 and 9 (Chapter 10). Rhee, et al. (1974) examined the orbital parameters of fifteen dust particles intercepted by Pioneers 8 and 9 and speculated on their individual sources. Of the twenty particles studied, five had hyperbolic velocities and were among those hypothesized as having been ejected from the solar direction (Chapter 10), leaving the fifteen cases under discussion. Probable values for the orbital semi-major axes and eccentricities were derived for these. Table 13-1 gives representative values from the analysis of Rhee et al. (1974), where only one of three quoted possible sets of parameters has been taken from their paper. The uncertainties in the parameters are due to the known uncertainties in velocity and direction of the experiment.

As the table shows, the fifteen elliptical orbits are characterized by relatively small semi-major axes (the mean is ~ 0.77 A.U.) and moderate eccentricities (with a mean of ~ 0.67). Rhee et al. (1974) were able to identify eight

Table 13-1. Orbital Parameters for Pioneer 8 and 9 Dust Particles (from Rhee et al. 1974).

Particle No.	a	e	Probable Origin
1	0.86	0.23	asteroidal
2	0.62	0.73	asteroidal
3	0.79	0.85	?
4	0.56	0.99	?
5	0.67	0.63	asteroidal
6	1.01	0.09	asteroidal
7	0.98	0.26	asteroidal
8	0.83	0.54	asteroidal
10	0.54	0.99	cometary
12	1.13	0.59	asteroidal
13	0.55	0.99	?
14	0.96	0.80	?
15	0.54	0.99	cometary
17	0.72	0.86	?
19	0.74	0.52	asteroidal

particles as asteroidal and two as cometary on the basis of Whipple's (1954) criteria. The other five remain intermediate in character. They further conclude from the analysis that the particle orbits are like the Apollo group of asteroids because of their small semi-major axes (except for particle 14, which has possible values of a from 0.96 to 5.5 A.U.). These asteroids, furthermore, are thought (Opik 1963) to be the remains of now inactive (gas-less) short-period comets. Thus, the basic conclusion is that virtually all particles detected have a cometary origin, ultimately.

Confirmation of the hypothesis that the asteroid belt is not the place of origin for most of the dust came from the Pioneer 10 and 11 direct density measures made right in the asteroid belt (Chapter 10). No enhancement in particle density was encountered, though earlier NASA-generated models predicted a significant increase in density at about 3 A.U., in the main belt.

It should be mentioned also that, as Chapter 12 discusses, the orbits of particles in the solar system are constantly being altered by the Poynting-Robertson effect and radiation pressure, the former causing the semi-major axes and eccentricities to decrease with time and the latter causing ejection from the solar system. These effects depend on the size and other physical properties of the particles and therefore the steady-state assemblage of particle orbits for any hypothesized origin is dependent on assumptions (or, in some cases, measurements) about the physical properties of the particles.

III. Physical and Chemical Evidence

Most of our information on the physical and chemical properties of interplanetary dust particles comes from laboratory analysis of objects collected from the upper atmosphere (Chapter 5) and the deep sea (Chapter 6). Except in the cases of ablation spherules, which suffered physical and chemical alteration in the atmosphere, the properties of these particles provide a major source of evidence on their origin.

A thorough description of the analyzed micrometeorites has been published recently by Brownlee (1978). He had some 150 different particles, ranging from 3 to 40μm in diameter, for which detailed analyses were made. Three different groups were recognized as making up almost the entire sample (Brownlee et al. 1976). The most common chemical type, making up about 60 percent of the particles, had chondritic abundances. About 30 percent were called FSN particles because their major constituents were iron, sulphur, and

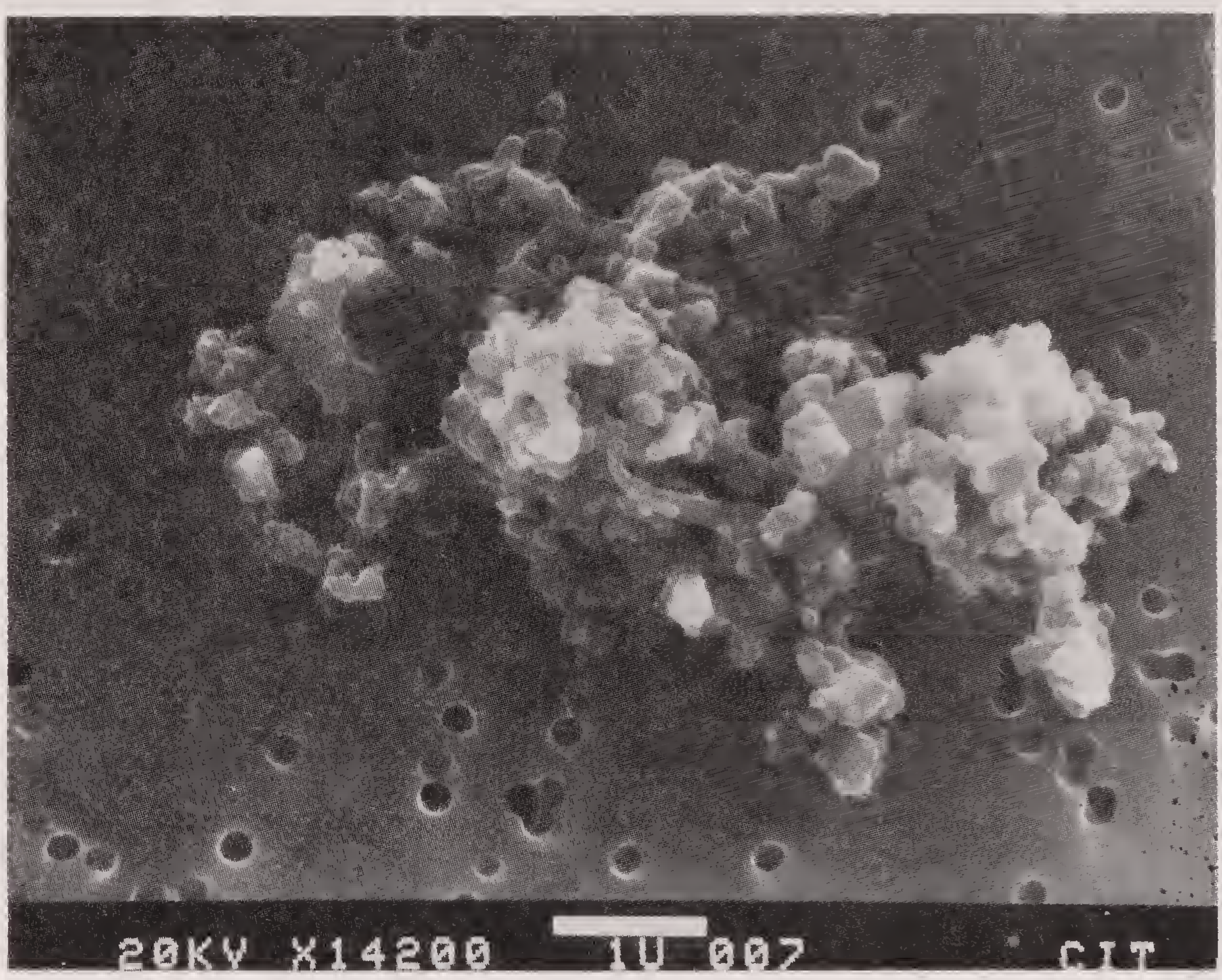

Figure 13-2. A chondritic aggregate particle (courtesy D. Brownlee).

nickel, while the remainder are primarily mafic silicates. Although distinct and separately recognizable, these particles were found imbedded in each other and adhering to each other in various combinations indicating that in space they were not separate, but fairly well-mixed within conglomerate parent bodies.

Most of the particles with chondritic compositions are found, when viewed under high magnification with a scanning electron microscope, to be aggregations of grains typically on the order 1000Å in size. For many of these the structure is very loose and porous, but most have a tightly-bound structure of grains. The average composition of the particles is similar to C1 and C2 carbonaceous chondrites, with Mg, Fe, Si, S, Ca and Ni abundances all within a factor of two of the average chondritic abundances, and data for the less-easily-detected elements Mn and Cr also in agreement. The carbon content is inferred to be fairly large. Most of the grains seem to have crystalline structure and several minerals (commonly Fe_3O_4 and Fe S) have been identified from X-ray diffraction analysis.

Brownlee et al. (1976) propose that these particles are representative of the matrix of meteoroidal bodies, in which inclusions of the kinds of material described below are located. Physically and chemically these objects strongly suggest a cometary origin, as the comets probably are made up of aggregates of pre-solar interstellar materials (Cameron 1973), which then eventually were compacted into the comet's nucleus by close perihelion passages. The C1 Chondrites may also have formed in this way out of pre-solar-formation grains.

The FSN particles are found in a variety of forms, with most being spherules, probably ablation products from the atmospheric encounter of C1-type meteoroids. The irregular FSN particles, on the other hand, are probably unaltered examples of inclusions from larger chondritic bodies. They can have the shape of single crystals, stacks of platelets, irregular assemblages, and aggregates. The shapes of some are quite similar to those of the magnetite inclusions found in C1 meteorites. Their abundances are similar to meteoritic troilite or pyrrhotite, and they may be like the poorly defined Fe-S-O and Fe-S-C phases found in C1 meteorites.

The third class of particle consists of iron-poor olivines and pyroxenes. Most are irregular in shape and frequently smaller chondritic particles are found adhering to their surfaces. Their chemical abundances are similar to forsterite and enstatite, and Brownlee et al. (1976) identify them as inclusions that were originally in larger, primarily chondritic bodies.

It should be mentioned that the spherical particles in the high altitude and deep sea deposits, which most scientists believe to be ablation products from the passage of meteoroids through the earth's atmosphere, have a different origin in at least one group's view (Parkin et al. 1980). They believe that the spherules were formed in the asteroid belt as a result of collisions between larger bodies and arrived at the earth in their present spherical shape.

Generally speaking, most present evidence, from the zodiacal light, from orbital data, and from physical and chemical studies, favors a cometary origin for most of the interplanetary dust. Most data is consistent with the picture of Apollo asteroids as burned-out comets, objects of a somewhat porous nature that produce the meteors and micrometeorites. They have typical cosmic abundances, similar to Cl chondrites, and are made up to a large extent of sub-micron pre-solar interstellar grains.

I. Introduction

In the last ten years or so scientists have made a great deal of progress in understanding some of the steps in the process of the origin of life on earth. Most of this work has dealt with possible ways by which earthly materials, obeying the laws of physics and chemistry and having plenty of time, could have evolved naturally from inanimate objects into living things. This involves intricate arguments and ingenious experiments in organic chemistry and biochemistry, and the astronomical input is only important at the beginning.

In the following paragraphs some of the ways by which life may have formed are reviewed. The geological evidence for the time scale of biogenisis is described, the see-sawing arguments about the earth's early atmosphere are outlined, and three possible sources of prebiotic organic molecules are given. The third suggested source, meteoritic dust, has only recently been realized to be a possibility.

II. The Geological Evidence

The earliest direct evidence about the origin of life on Earth comes from the record preserved in the oldest terrestrial rocks. Modern age-dating methods make it possible to establish ages for the rocks and rock formations involved and thus it is possible to have a reliable idea of how many years ago the beginnings of life occurred.

The oldest rocks found on the Earth are only 3 billion years old. This has been noted by some geologists as a rather curious fact, since the Earth is known to be considerably older, approximately 4.6 billion years old, which agrees with the ages of other objects in the solar system, such as the meteorites. It is not known whether the relatively young age for the oldest terrestrial rocks is due to a long period when the earth's crust was not stable and rocks could not persist or whether it is due to some other cause. It may be that we simply have not yet found older rocks, which may exist in some unexpected part of the Earth's surface, or there may be another, perhaps more surprising, explanation of this fact. It has been noted that the history of the Moon includes a sudden and as yet unexplained series of events about 3 billion years ago, events which produced the extensive volcanic flows of the lunar maria. Although probably merely a coincidence, the rough agreement in date between the lunar global upheavals and the oldest terrestrial rock formation may eventually be shown to have some common, perhaps cataclysmic, cause.

Among the earliest fossil evidences of the existence of life on the Earth are the small microscopic spheres found in the Figtree series of rocks of South Africa, which have been dated geologically as being about 3 billion years old. These objects are not clearly fossils of living organisms, but are believed by their discoverers, Barghoorn and Schopf, to be similar to the tiny proteinoid spheres produced and studied by Fox and Young. These artificial microspheres were produced in the laboratory under primitive conditions. In experiments with heated mixtures of various amino acids, they found that long chain peptides and dipeptides formed in time, and these fairly complex organic molecules appear to be chemically similar to proteins in living things. Furthermore they formed microscopic spherules that were the same size approximately as bacterial cells in living things. They showed properties that were almost like properties denoting life. Two could combine to form a single somewhat larger sphere or one of them could split apart. They showed the properties of osmosis and their size could be regulated by the amount of salt present in the solution. Although it is not known for certain that the fossil spheres are the same kinds of objects as those studied in the laboratory, their appearance is very suggestive.

The oldest clearly living fossils that are well established are from the Gunflint formation, an iron-rich rock found in Southern Ontario. Here the age is between 1.6 and 2 billion years and the fossil evidence of microscopic plant life is completely convincing. Both fungi and algae exist, and because algae operate by means of the complicated and late-developing process of photosynthesis, it is believed that primitive life must certainly have begun long before the flowering of the Gunflint flora.

III. The Earth's Primitive Atmosphere

Much of the presently believed theory for the development of life on the Earth depends critically on the chemical composition of the atmosphere of the Earth in its early history. It is generally believed by biologists that life could never have developed on the Earth if the atmosphere had always had the composition of the present terrestrial atmosphere. Specifically, the evidence indicates that naturally occurring events in the development of pre-biotic organic chemicals could never have occurred in the presence of free oxygen in the atmosphere. Of the hundreds of experiments in the early '50's, success in producing organic compounds out of simple elements has only been achieved in an atmosphere devoid of oxygen. Therefore it is believed that the predecessor molecules to life could not have formed in the presence of an oxygen atmosphere, and unless these molecules came from elsewhere, life could never have gotten started.

Abelson and others have shown that the early ocean and atmosphere must have both been reducing in their chemical properties so that free oxygen that might have existed, or might have formed for instance by photolytic dissociation, would be used up in combustion and oxidation of the reduced materials at the surface. There is no other source of oxygen. Free oxygen is not emitted from the interior of the earth in volcanic gases, which primarily include N_2, CO_2, H_2O, and H_2.

The astronomers Henry Norris Russell and Donald Menzel showed many years ago that the earth's atmosphere must have been completely lost in the early stages of the earth's development. This is based on the argument that in comparison with the Sun there are no noble gases, and if the abundances of the elements in the material forming the earth were similar to those in the sun, which otherwise is roughly the case, then these noble gases must have been lost at a time when the temperature was high, on the order of $5000\text{-}8000^{o}$ absolute.

By analogy with the major planets, Jupiter, Saturn, Uranus, and Neptune, it is believed that the primitive first atmosphere of the Earth must have been rich in hydrogen molecules, including molecular hydrogen, methane, and ammonia. This mixture also included appropriate amounts of the noble gases. From geological evidence it appears that any ammonium must have been very small in amount, because the oldest rocks on the earth of sedimentary origin are found in what geologists call chirts, which would not naturally form in the presence of ammonium. The environment in which these sedimentary rocks were laid down was highly acidic, and such conditions argue against anything more than very small amounts of ammonia either in the atmsophere or in the seas and oceans as early as 3.4 billion years ago. Thus, the primitive atmosphere, if it was indeed made up of hydrogen molecules and compounds as believed, must have been lost by the Earth before 3.4 billion years ago.

It is still uncertain whether the above facts are mutually consistent; it was apparently necessary to produce the early predecessors of living molecules in the presence of a reducing atmosphere which must contain hydrogen in molecular form. The hydrogen, however, must have left the Earth very quickly, because of its light weight and the relative warmth of the terrestrial position in the solar system. Whether enough hydrogen was left in the Earth's atmosphere for the pre-biotic molecules to form before the Earth's atmosphere changed from its primitive reducing nature to its secondary volcanic-gas composition is still unknown. It has been shown chemically that ammonium and methane are unstable without the presence of H_2, so whenever molecular hydrogen was lost, these compounds also must have left.

One final kind of evidence against the presence of oxygen throughout the early history of the Earth's atmosphere comes from biological evidence itself. The present way in which metabolism occurs in cells suggests that early simple organisms must have gone through their development without the benefit of free oxygen. They seem to have developed remarkable and ingenious ways of achieving metabolism without using oxygen and these ways continue to the present. Examples include fermentation, a pathway of metabolism called by biologists the hexosemonophosphate cycle, and photosynthesis. Particularly if oxygen were present, biologists argue that many of these pathways would not have been necessary. Respiration, which uses oxygen fully, must, in this view have been a much later development after sufficient oxygen existed in the atmosphere.

It has also been shown that if molecular hydrogen were present then the hexosemonophosphate cycle would not have developed. This apparent contradiction suggests that much of this early development of early energy-generating methods by life forms occurred after the hydrogen atmosphere of the earth was lost, but before oxygen was produced in significant quantities by life itself.

IV. Sources of Organic Molecules

In the modern view of the development of life, there were several stages of increasing complexity. First it was necessary for there to be simple organic molecules present in resonable abundance, and then various processes led to more and more lifelike objects.

Outline of Biogenisis

Biologists have shown that if simple organic molecules were available then under proper conditions and given long periods of time, they could have joined together to form very large macromolecules. Amino acids, simple carbohydrates, fatty acids, or hydrocarbon chains are the presumed starting molecules, and these are believed to have joined to form the more complicated peptides, glucose, and other sugar and starch molecules. In time these combined together to form what are called molecular aggragates, highly complex mixtures. At this time, as first proposed by A. I. Oparin, it is believed that the aggragates so formed developed simple membranes around them because of surface tension, which separated them from the liquid medium out of which they formed. One end of the fatty acid chain is attracted to water, and thus any fatty acids in a macromolecular aggragate could collect at the surface to produce such a membrane. Nucleic acids then began, somehow, to organize these aggragates, as they do now in life, and thus insured the ability of these aggregates to split into two similarly organized parts. Following this, evolution began and only those aggregates that could most efficiently use energy survived. It is believed that these objects depended on outside molecules as sources of energy, taking advantage of the energy available through electron transfer and carbohydrate breakdown and developing a means of storing energy in phosphate forms. These objects, depending on ready-made food in their environment, found as time went on their source of food diminishing, and therefore evolution is believed to have favored any ability to produce energy internally. Photosynthesis is such a process, and it is believed that it must have developed at this point. With the introduction of photosynthesis, life became independent of its surroundings to some extent, and large scale production of oxygen began. It should, of course, be remembered that much of this outline of the development of life is sketchy and details at several points are not yet understood completely.

Production in the Atmosphere

From the astronomical point of view, the most important question raised above is the question of the source of the organic molecules, which must have been present before life could form. There are three principle possibilities presently considered reasonable. The first and most generally accepted is that the organic molecules were formed in a primitive terrestrial atmosphere, out of which they accumulated in the oceans, and were perhaps concentrated in abnormally high densities on the beaches. Many experimenters, starting with Stanley Miller and Harold Urey in 1951, have shown that fairly complicated organic molecules may have been formed, including various amino acids, purines, sugars, lipids, and even some more complicated molecules.

Usually three molecules are prevalent, hydrogen cyanide, formate (COOH) and formaldyhyde. The most commonly assumed primitive atmosphere is one rich in methane, ammonia and hydrogen, but the geological evidence cited above raises the question of whether methane and ammonia were likely components of the earth's atmosphere. Scientists, however, have produced the same organic compounds by experimenting with an assumed atmosphere of carbon dioxide and nitrogen, as well as other mixtures of this sort, including water.

The simulation experiments involve the introduction of a source of energy into a mixture of gases in the laboratory. Included among different sources of energy in recent experiments have been heating, electric discharges, ultraviolet light, and X-rays. Almost without fail, the resulting mixture includes a reasonable number of organic molecules.

A second possible source of the organic molecules that preceded the formation of life is an extra-terrestrial one. This became realized as a possibility only after it was shown that the carbonaceous chondrites, until recently a little-known type of stony meteorite, were found to be much more common than originally thought. It is now quite possible that the carbonaceous chondrites are the most abundant type of meteorite in outer space, and only their fragile physical nature makes them rare on the earth. If they do not become completely destroyed by their passage through the atmosphere, which is probably usually the case, they are quickly broken down on the earth's surface and lost. If they are among the most abundant kinds of meteorites encountering earth, it is significant that they are rich in carbon and carbon compounds. In fact, recent research shows that the carbonaceous chondrites contain all of the more stable elements in the same proportions as in the Sun and about 6% of their cosmic proportion of carbon, making it an abundant component. Even more interesting is the fact that much of this carbon exists in compounds, some of which are complex organic compounds. A great deal of controversy once surrounded the subject of the organic molecules found in carbonaceous chondrites, but much of this controversy is now resolved. During the early 1960's there seemed to be evidence of life forms in the carbonaceous chondrites, but these were found to have been introduced from the earth after the meteorites had fallen. There is no controversy, however, about the presence of fairly complex organic molecules in freshly fallen carbonaceous chonrites, and these are generally recognized to be pre-biotic molecules that have no relationship to actual living organisms.

Carbonaceous chondrite meteorites usually contain several amino acids, and of those that have been studied in detail so far, many of these amino acids are common in proteins, including valine, alanine, glycine, proline, aspartic acid, and glutamic acid. But there are also many amino acids that do not occur in biological materials in large quantities. Besides these fairly common and relatively simple organic molecules, the carbonaceous chondrites also contain nitrogenous bases, such as purines and pyrimidines. These nitrogenous bases are not the ones that are common in biological samples, and it is curious to note that the laboratory experiments with primitive earth atmospheres have produced neither those common in biological samples nor those found in the carbonaceous chondrites.

It is also interesting that there are certain differences between the distribution of the different kinds of organic molecules found in the meteorites and those found in terrestrial life. It is not possible to say that the meteoritic compounds are all foreign to life, because many of them are not. Some are fairly common and others are found in low concentrations in living matter. However, the difference in general is quite striking. In life, there are approximately 20 amino acids that are common to proteins. All of these have one peculiarity in common. They are characterized by having an amino group and a carboxylic acid group attached to the same carbon atom. For those conditions, organic chemists call these alpha-amino acids. In the carbonaceous chondrites, especially the Murchison and Murray meteorites, which are among those most completely studied, the amino acids do not show this preponderance of alpha types. Instead, all possible isomers of amino acids are present that contain two or three carbon atoms. This feature suggests that the carbonaceous chondrites contain amino acids which were formed by a random and unbiased process, while those in life forms on earth have been formed selectively.

Another, rather similar difference between the meteorite compounds and those in terrestrial life have to do with the way in which the amino acids rotate plane polarized light. This in turn is the result of the preferential orientations of the individual parts of each, which can be either "left handed" or "right handed". In the meteorites, there is approximately an equal number of amino acids of one type or the other, but in life, amino acids are all of one orientation, called L-amino acids, because they are oriented in agreement with a standard chemical, L-glyceraldehyde.

A further difference between the organic compounds in life and in the meteorites has to do with the structure of hydrocarbons. Those in the Murchison carbonaceous chondrite, for example, are almost all double ring structures whereas in life, hydrocarbons are most often long, linear molecules. Organic chemists call the double ring structures of life bicyclic and the linear molecules isoprenoid.

These important differences between the meteorites and life might at first be considered evidence against the hypothesis that life originated from organic material brought from outer space in the meteorites. However, such a conclusion is unwarranted. In the first place, life has a very selective way of development, and it is unlikely that the raw materials, the pre-biotic organic molecules, would have been maintained in their original proportions through the long, selective process of biological evolution. In the second place, most of the differences between the meteoritic organic molecules and biological ones also exist between those organic molecules produced in experiments with primitive terrestrial atmospheres and biological materials. Therefore, neither hypothesis has preference over the other in this regard.

Interplanetary Dust

Finally, we come to consideration of a third possibility for the origin of the pre-biotic organic molecules, namely, the meteoritic dust encountered by the Earth. Recent experiments by Brownlee (Ch. 13) at the University of Washington and others have shown that much of the interplanetary dust may be chemically similar to the carbonaceous chondrites. If this is true, then the dust is a most likely extraterrestrial source of these compounds because there is a great deal more mass accumulated by the earth in the form of dust than in the form of large meteorites. The dust is acquired by the earth at a high rate and at high velocity. Much of it is ablated, melted and even evaporated in the process of its encounter with the upper atmosphere. Some of it is small enough to radiate away the energy of the encounter sufficiently fast that it does not reach the melting point. The latter are called micrometeorites (Ch. 11). For those particles that are heated up, small ablation droplets are formed and these plus any unablated fragments of the particle fall through the atmosphere, eventually reaching the surface. It is even possible that the energy involved in heating up the small particles may be sufficient to produce small amounts of more complicated carbon compounds out of the carbon-rich material of the dust.

To estimate the amount of organic molecules acquired by the earth from the interplanetary dust, we can note that the total flux of carbonaceous chondrite type particles encountered by the earth has been determined to be approximately 10^{-5} particles per square meter per second for sizes greater than 3 microns in radius. For particles of this size, the mass influx to the earth, therefore, is approximately $8x10^{7}$ grams per year for the entire earth. The influx of organic molecules would be on the order of 10^{5} grams per year for the earth. This means that in the first two billion years of the earth's existence, before biological processes started, the accumulated mass of organic molecules over the earth was approximately $2x10^{14}$ grams (200 million tons).

The above calculations suggest that significant amounts of organic molecules were introduced to the terrestrial environment from outside during its early period, and, for that matter, have been brought in up to the present. The calculations may have underestimated the amount accumulated in the early history of the earth if the evidence of Brownlee and Rajan is considered that suggests that the interplanetary dust density in the early years was approximately ten times greater than at the present (Brownlee and Rajan 196).

Nevertheless, even this adjustment does not change the calculations sufficiently to make it appear that organic molecules were highly concentrated anywhere on the earth from the extraterrestrial sources. In this sense, the large meteorites, though representing a much smaller total mass influx, do provide a concentration of organic molecules in one place. Such a concentration may have been important for the eventual development of life, because a sparse, evenly distributed sprinkling of organic molecules cannot lead to the spontaneous generation of the more complicated aggragates.

Biologists have suggested that the necessary concentration of molecules may have appeared on the beaches of the earth's primitive oceans. The hypothesis that the organic molecules were formed in the primitive atmosphere needs such a concentration process, just as does the hypothesis that they came in as dust from interplanetary space, and therefore, these two possibilities both require some process for concentration of the molecules in smaller areas, where their density can be sufficiently large for their coalescing into aggragates. It appears that at this time any of these sources of organic molecules might be considered equally likely, especially since we do not have good numerical information on the numbers of such molecules that might have been produced by ultraviolet light, X-rays, or discharges in the atmosphere. The primitive atmosphere hypothesis may turn out to be preferable from the point of view of the numbers of organic molecules that might have formed, but the interplanetary dust and meteorite hypotheses have the preference of being continuous sources that kept going on regardless of the constituents in the earth's atmosphere and regardless of other, perhaps inhospitable, conditions on its surface. It may turn out that these sources were all involved and it remains only to determine which was the most important.

This chapter has departed from the others in not giving detailed references. The literature is extensive and scattered, with several good books now available on both elementary and more advanced levels. Two recommended books that are listed in the Bibliography are that by Ponnamperuma (1972) and that by Miller and Orgel (1974).

I. Introduction

The study of meteoritic dust collected from the environments of meteorite craters has had important implications for several interesting problems. As shown particularly well in studies of recent craters produced in the Soviet Union (section II), these particles can come from various sources. They can consist of both ablation droplets produced in the atmosphere during the passage of the parent meteorite before its impact and particles (fragments and possibly also droplets) produced by the violent impact itself. Other possible sources of dust include recondensation droplets of meteorite vapor from the meteorite train as well as recondensation of vapor, apparently sometimes mixed meteoritic and terrestrial rock material, from the impact. The study of different kinds of particles produced in these various ways has made it possible to reconstruct some of the features of the violent event producing the crater, to gain insight into the kinds of particles produced by atmospheric ablation of meteorites, and even in some cases to learn about the conditions at the time of impact, for example the wind direction. A further motivation that has recently inspired most of the research on these objects is the analogy that is possible to be made between the formation of meteorite debris around craters on the earth and the processes responsible for what we observe on the lunar surface.

II. The Sikhote-Alin Crater Field

One of the most illuminating studies of the relationship between meteorite craters and the meteoritic material found in their surroundings has come from the exhaustive research of Soviet meteoriticists at the site of the Sikhote-Alin meteorite craters, formed in the far eastern part of the Soviet Union in 1947. Krinov has identified three different

Figure 15-1. A meteoritic dust particle extracted from the soil at the Sikhote-Alin Meteorite Shower site (from Krinov).

Figure 15-2. Meteoritic particles from the soil at the Sikhote--Alin crater field (from Krinov 1962).

kinds of particles from the soil at the Sikhote-Alin site. First are the iron oxide spheres which Krinov identifies on circumstantial evidence to have been formed by the atmospheric ablation of the skin of the iron meteorites before impact. He found similar iron oxide spheres, in some cases only half formed, on the surfaces of some of the large meteorite fragments at the site. Chemical analysis of one of these is reproduced in Table 15-1. A second type of particle found included fragments of iron oxides, either produced by the fragmentation process that occurred in the atmosphere in this case (the original iron meteorite apparently broke up into hundreds of pieces before landing on the Earth; there were 109 individual craters identified) or subsequently on impact. This type of particle is mostly iron oxide, with very little nickel present. The third type of particle is also angular, but of pure meteoritic material. The elemental abundances within them are the same as in the parent meteorite, and therefore they apparently formed by simple fragmentation without oxidation. Figs. 15-1 and 15-2 show examples of meteoritic particles extracted from the soil at the site of the craters (Krinov 1962).

III. Arizona Meteor Crater

The large meteorite crater in northern Arizona, sometimes called the Arizona Meteor Crater or the Barringer Crater, has been the subject of extensive study from many points of view. Nininger (1956) gives some historical review plus an account of his many research projects concerned with this crater, including the study of the small particles in the soil surrounding it. Nininger's work was primarily concerned with the location of the metallic spheroids found near the crater rim and with their bulk chemical properties and physical appearance. Table 15-2 lists some of the chemical results of his samples, showing that these particles, at least in bulk analysis, are primarily iron oxides like the impactite found in larger chunks near the crater.

Recently Nininger's pioneering research has been taken up by others, using more refined techniques. Mead, Litler, and Chao (1965) showed that the metallic spheroids from Meteor Crater had interesting chemical properties and were important clues to the understanding of the formation of the crater. In 1967, Brett published further studies of the metallic spherules found around the meteorite crater and was one of the first to show detailed evidence that the spheroids and the impactite metal are rich in nickel compared to the composition of the parent meteorite. Cobalt was also found to be enriched relative to iron, as shown by both Nininger's early bulk analysis and by more recent and detailed analysis of individual particles carried out by Blau, Axon, and Goldstein (1973). In some cases the enrichment is very large, Brett having found metallic particles containing up to 65% by weight nickel. It is not yet known whether the enrichment of nickel and cobalt with respect to iron can be explained as due to the preferential oxidation of iron during vaporization of the meteorite material or to shock-induced melting of sulfide rich areas in the meteorite. These areas are richer in nickel in the meteorite than the average. Brett has suggested that carbon dioxide and water in the rock sediments at the impact site may have helped the atmospheric oxygen to oxidize the iron.

The distribution of meteoritic dust around the crater has been studied in detail both by Nininger and by Rinehart. Whereas Nininger was primarily concerned with the areas within about a kilometer of the rim and concentrated more

Table 15-1. Abundances in Sikhote-Alin Ablation Sphere (Weight Percent)

Fe	55
Ni	2.5
Co	0.3
Si	0

Table 15-2. Abundances in the Arizona Crater Spheroids (from Nininger 1956) (Weight Percent)

Fe	54
Ni	9
Co	1.0
P	0.6
S	1.0
Ca	1.1

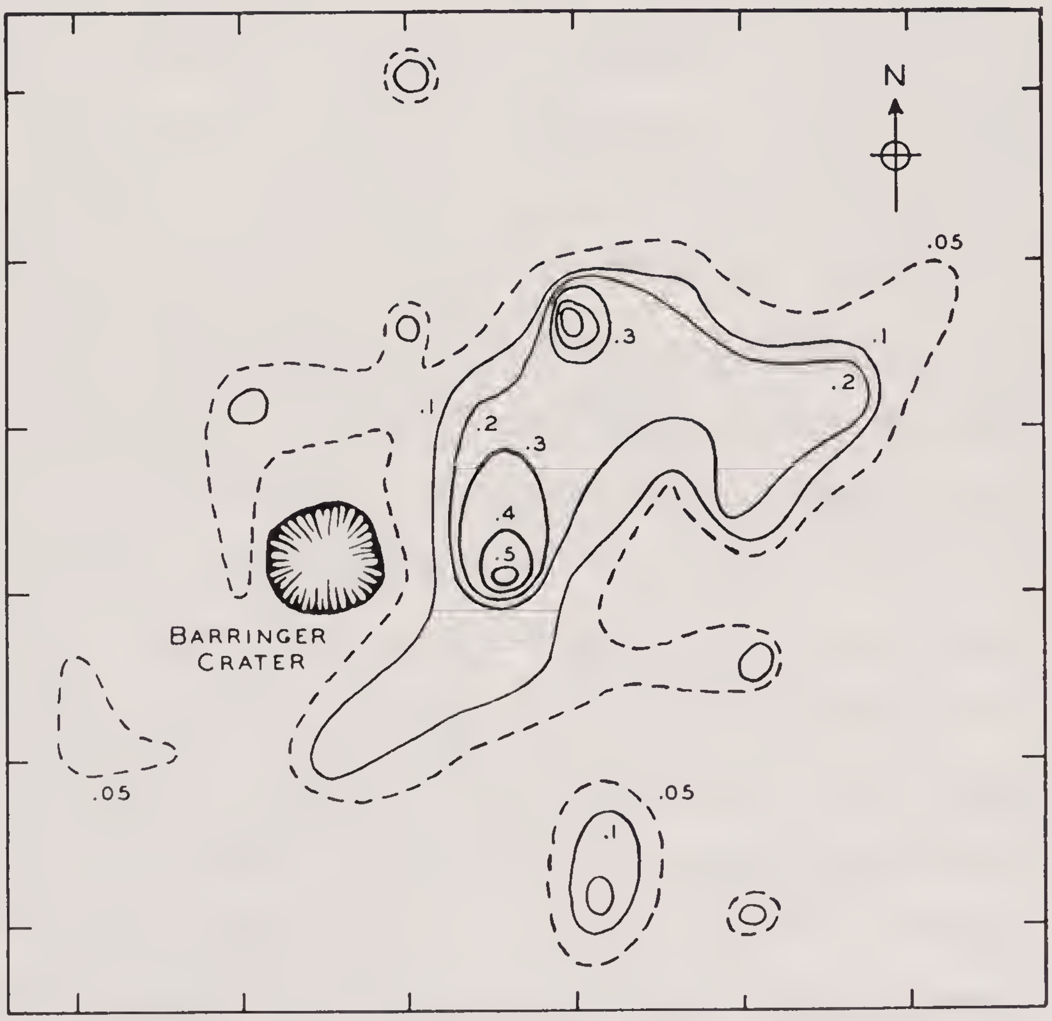

Figure 15-3. The distribution of small meteoritic particles around the Arizona crater (from Rinehart 1958).

on the particles on the order of a millimeter in size, Rinehart's survey went out to distances as large as 10 kilometers from the crater. He showed that particles existed out at least 6 kilometers from the crater center. He separated particles into various sizes and showed that the preponderant size for the meteoritic particles was much smaller than Nininger's collections. There has always been some uncertainty about the identification of particles and their separation from naturally-occurring iron rich particles in the soil. In Rinehart's case subsequent analyses of many of the particles have shown the presence of nickel and cobalt, though not all of the particles contained these elements. Figure 15-3 shows the distribution of small particles as plotted by Rinehart (1958).

The most recent chemical studies of metallic spheroids at the Arizona crater have been carried out by Kelly, Holdsworth and Moore at Arizona State University. Using atomic absorbtion analysis techniques and electron microprobe methods, these scientists studied 25 different metallic spheroids and 58 small impactite metallic particles from four different impact type samples. In agreement with others, they found nickel to be considerably enriched over the bulk analysis of the meteorite. The range for the spheroids was from 13 to 22% by weight nickel. The cobalt also was enriched, with the observed range being from 0.8 to 1.3%, also representing a two to three times enrichment factor. Copper, which is also a fairly good meteorite index, was also found to be enriched by about the same amount, the observed concentrations being between 260 and 430 micrograms per gram. They found that the cobalt to nickel and copper to nickel ratios in the spheroids were almost exactly the same as in the bulk analysis of the parent meteorite, suggesting that these spheroids must have been formed by preferential removal of iron by oxidation, leaving the other principle constituents relatively unchanged. Enrichments in the impactite metals were sometimes even greater, with nickel contents ranging up to 95% (Kelly et al., 1974).

Because of their importance to our understanding of the methods of formation of ablation products found in the atmosphere from interplanetary dust encounters, the spheroids at Meteor Crater are of particular concern to us here. Especially important is the question of whether they were formed during the passage of the meteorite through the atmosphere or whether instead they were formed as a result of the impact. Kelley and his coworkers have suggested that there can be four possible means of producing the chemical variations that are observed in these spheroids, listed as follows:

1. They can have been formed by condensation of a cloud of metallic gas which was produced by the explosive impact.
2. They may represent the volitalization of the meteorite, in which the iron is selectively vaporized far more rapidly than the nickel, cobalt and copper.
3. They could represent the shock melting of areas rich in sulfide in the meteorite, where the nickel, iron and copper are generally abnormally high in concentration compared to iron or
4. They could be the product of a process involving the preferential oxidation of iron from the meteorite mix.

Kelley and his colleagues believe that the first two of these possibilities are unlikely in view of the evidence produced by the recent analysis of nickel, cobalt and copper concentrations. Particularly important in this respect is the copper concentration, because, although cobalt and nickel have vapor pressures that are nearly equal, the vapor pressure of copper is very much higher; therefore, copper should not show a positive correlation with cobalt and nickel if vaporization or condensation were the mechanism involved. Similarly they argue that mechanism three is unlikely also in the face of this evidence. Particularly, they point out that the cobalt enrichment cannot be explained by this process, as the cobalt content of the nickel-rich minerals in the meteorite is low. Therefore, it seems that selective oxidation of iron is the most likely explanation of the particles' chemistry.

The above arguments seem to indicate that the meteoritic spheres found in the soil around the crater were oxidized by atmospheric oxygen either before the meteorite encountered the ground and impacted or, more likely, after impact when the droplets of melted meteoritic material were in flight away from the impact site. In either case, it seems reasonable to expect that the observed chemical proportions found in Meteor Crater spheroids are probably similar to what might be found from ablation products produced by smaller objects, interplanetary dust of iron meteorite composition, when they encounter the atmosphere.

IV. The Henbury Meteorite Craters

A group of 15 meteorite craters near the Henbury Station (ranch) in central Australia has revealed an unexplained pattern in striking contrast to the Arizona Meteor Crater in the properties of the meteoritic material in the soil surrounding it. The first study of the particles at Henbury was made by Spencer (1933), basing his analysis on the properties of metallic spheroids found in the impact glass brought back to him from the Henbury site. These were found to be nickel-iron in composition, with the nickel enriched relative to the average composition of the iron meteorite that formed the craters, as recently shown by El Goresy. The craters themselves have been described by Alderman, one of the first to explore them, by Milton, who made a detailed geological study of some of them, and by Hodge, who published an atlas on the craters (see refs. in Hodge, 1973).

A study of the meteoritic particles in the soil surrounding the Henbury craters, including detailed microprobe analysis of many of them, was published in 1971 by Hodge and Wright. They based their findings on a survey of the soil that reached out to distances of 1 kilometer from the center of the crater field. It was in that sense not an exhaustive survey, especially since they found evidence that the meteoritic particles probably continued considerably beyond that distance. Figure 15-4 shows the results of the samplings at Henbury and the outlines of the craters there.

The chemical analysis of the Henbury particles showed surprisingly different results from those of the Arizona meteor crater. Instead of a uniform group of iron-nickel spheroids, with nickel and other meteoritic elements enriched with respect to iron, they found three different kinds of particles each with iron enriched with respect to the nickel and cobalt, and each with different ratios of other elements, apparently derived from the soil. Table 15-3 summarizes the chemistry of these three types of particles. They were found from X-ray analysis to be mostly glass, with little if any raw metal. A study of the ratios of the elements in these three types showed that each represented a different discrete

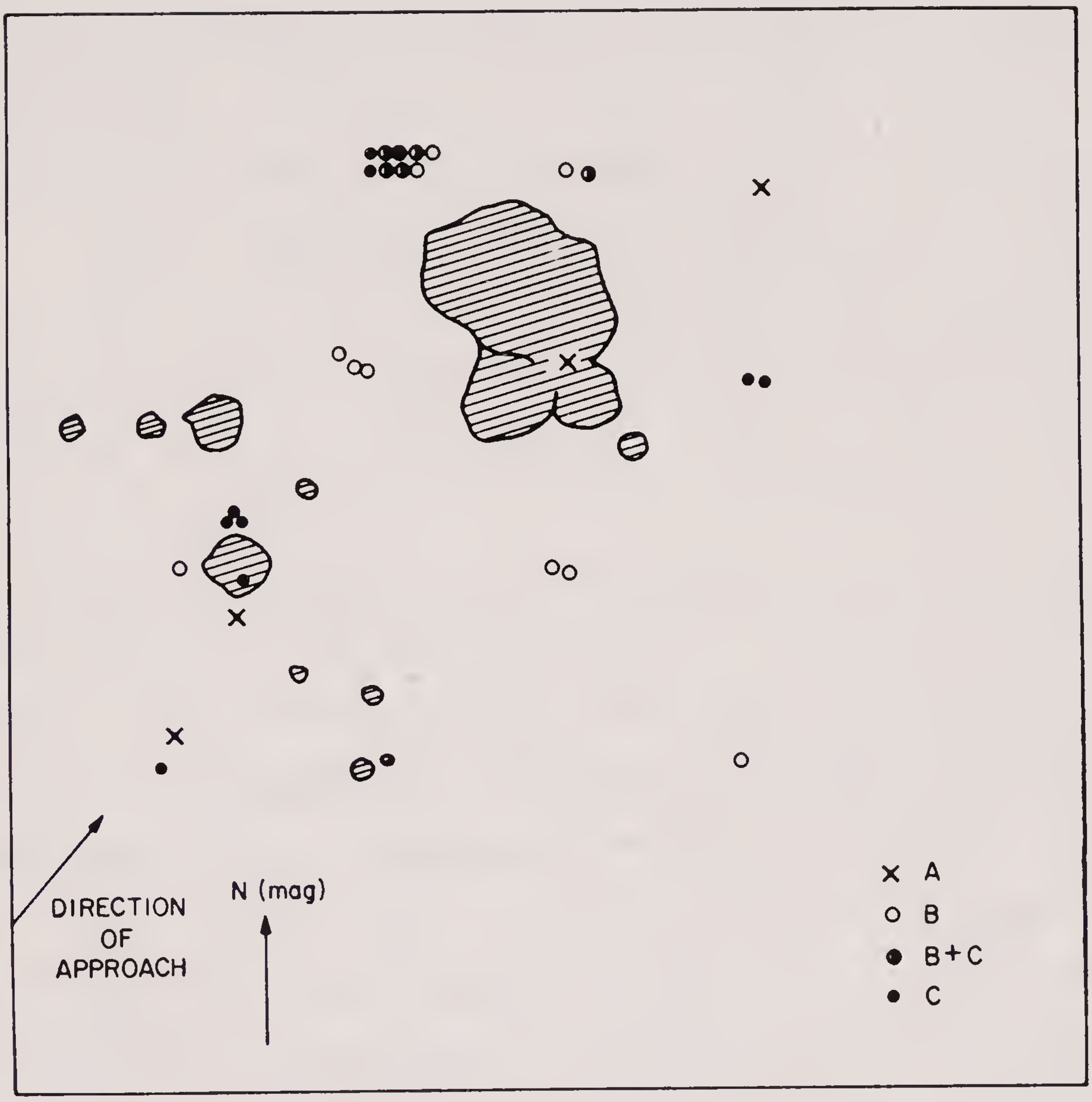

Figure 15-4. Locations of ablation spheres of different chemical families (see Table 15-3) around the Henbury meteorite craters (from Hodge and Wright 1971).

Table 15-3. Mean Properties of the Chemical Families of Henbury Spherules

	Composition, wt. %															Number of Particles
Family	O	Na	Mg	Al	Si	P	S	K	Ca	Ti	Cr	Mn	Fe	Co	Ni	
A	33	0	0.2	0.8	1.4		0	0	0.2	0.1		0	61	0.3	3.4	4
B	39	0.3	0.8	4.3	9	0.2	0.2	0.05	1.2	0.7	0	0.5	34	0.2	1.8	19
C	46	0.5	0.9	6	22		0	2.2	1.0	0.4	0	0.8	15	0.1	0.8	16

mix. The fact that these different mixes occurred widely at different places around the craters suggested that they were not produced by localized different conditions but rather are more likely the result of chemical and mineralogical differences. It was hypothesized that these different iron enriched globules were formed out of mixes of soil material and meteorite matter in a liquid form after impact, and were dispersed by the energy of impact. It is not known why there are no metallic particles in the spherules from Henbury, just as it is not known why there are no particles of the sort found at Henbury, involving a mixture of elements from the soil and from the meteorite, at the Arizona meteor crater. The principle differences between the two events are the size of the cratering event and the multiplicity of the Henbury craters, but as yet no hypothesis involving the differences has been worked out in detail to explain the differences in the meteoritic materials surrounding the craters.

From the survey, the total mass of particles in the case of Henbury was calculated to be approximately 10^9 grams. This is much less than that calculated for the Arizona meteorite crater by Rinehart, who estimated the total mass to be on the order of 10,000 metric tons (10^{13} grams).

V. The Boxhole Meteorite Crater

The Boxhole Meteorite Crater is located about 400 kilometers northeast of the Henbury craters in central Australia. The crater and its geological surroundings were explored by Madigan and Alderman in the late 1930's. It is 185 meters across and approximately 9 meters deep with a raised rim 3.5 meters above ground level. It shows the effects of erosion more than do either Henbury craters or Meteor Crater in Arizona, apparently because of the greater rainfall at the

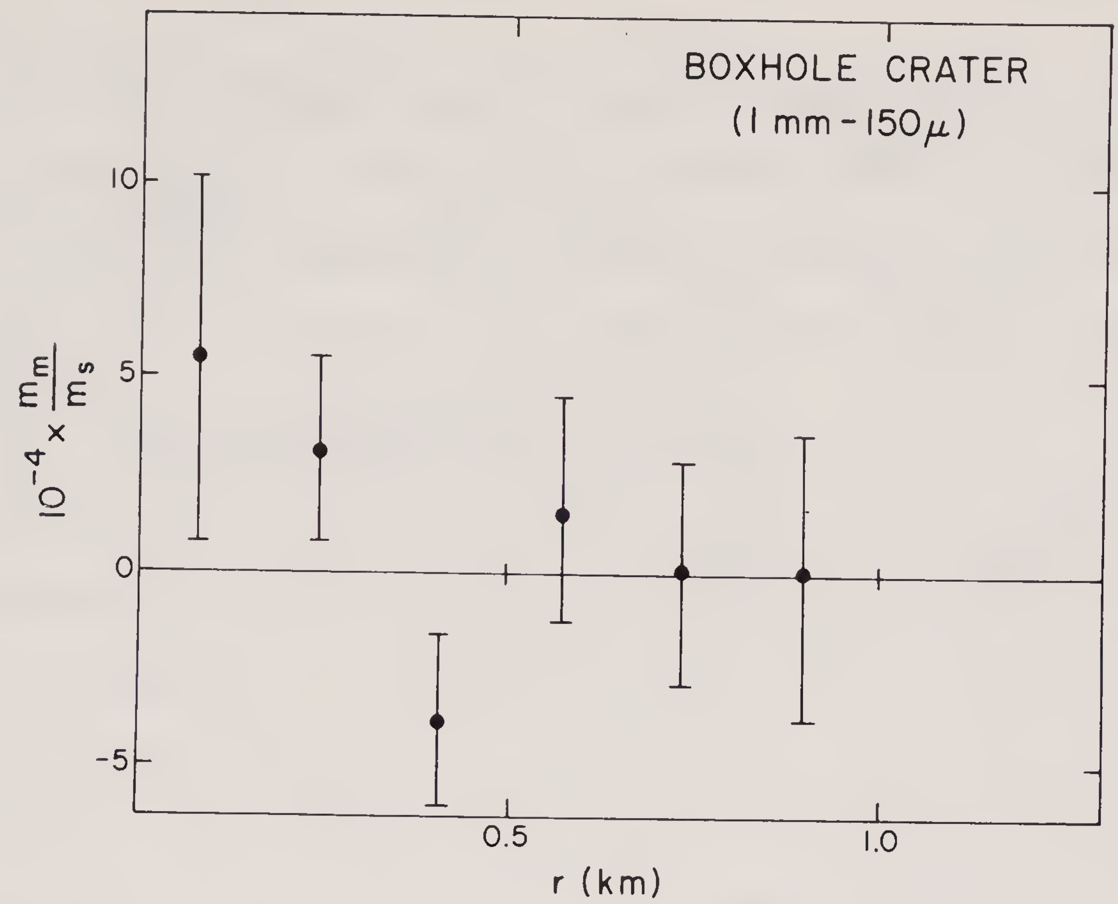

Figure 15-5. The Boxhole crater area showing the grid of collection points where the soil was searched for ablation spheres (from Hodge and Wright 1973).

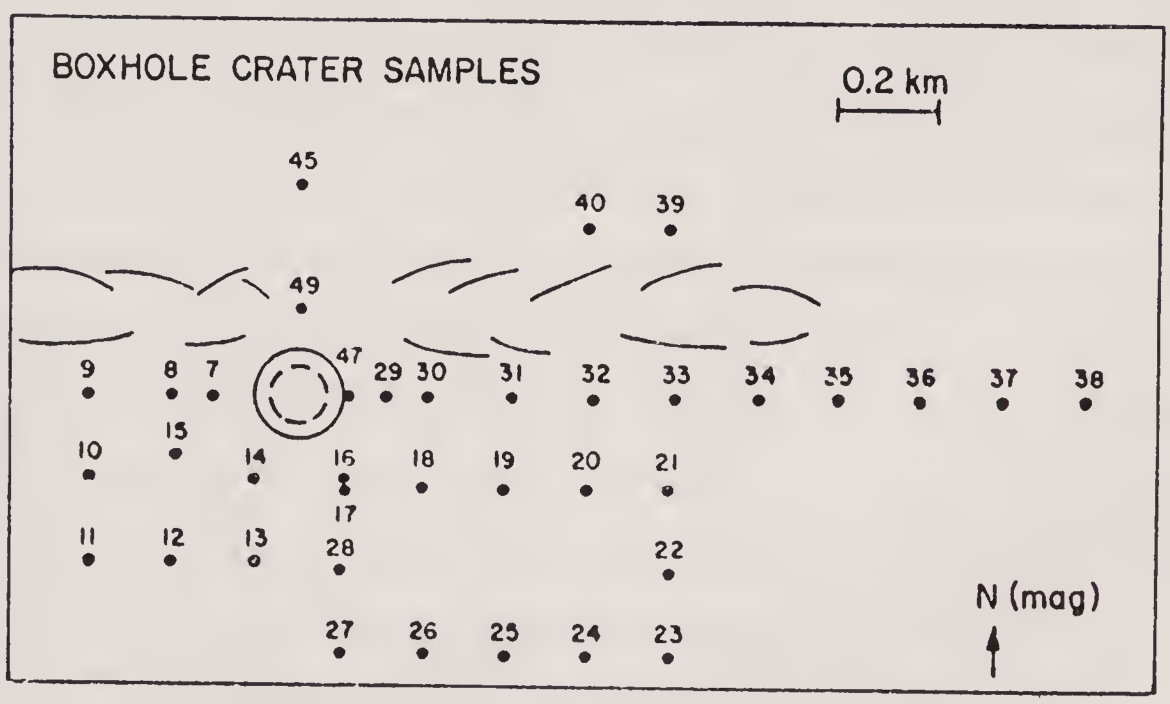

Figure 15-6. Radial distribution of magnetic particles extracted from the soil at the Boxhole crater.

Table 15-4. Spheroidal Particles Extracted From The Soil At The Boxhole Crater

Type of Particle	Composition	Number Analyzed
Meteoritic	Fe, Ni	2
Meteoritic plus soil	Fe, Ni, Al, Si, Mg	2
Spheroids	hematite and magnetite	23
Spheroids	ilmenite and titanomagnetite	23
Brown pellets	Si, Al, Fe	15
Glass spherules	SiO_2	4

Table 15-5. Compositions of Boxhole Crater Meteoritic Ablation Spherules (Weight Percent)

Element Size:	260μ	90μ	70μ	150μ
O	27	28	36	31
Na	0	0	0.1	0.2
Mg	0	0	6.2	0.5
Al	0.2	4.5	9.2	0.3
Si	0.1	0	10.0	0.2
K	0.05	0	0	0
Ca	0.08	0	0.5	0.03
Ti	0.4	0	0.1	1.03
Mn	0	0	0.1	0.2
Fe	66	62	19	45
Co	0.5	0.4	0.2	0.1
Ni	6.4	3.9	0.8	0.3
Total	100.7	99	82	79

location.

The only detailed study of the meteorite particles around the Boxhole Crater is that published by Hodge and Wright (1973). Figure 5-5 shows the collection grid, which was more limited than in the case of the Henbury or Arizona meteor craters.

The results of the soil sampling at the Boxhole crater showed that most of the metallic particles found in the soil were unrelated to the crater. Chemically most of them that could be separated by magnetic means were found to be iron oxides, including hematite, magnetite, ilmenite, and titano-magnetite. Of 62 particles analyzed by the microprobe, only four contained iron and nickel in anything like meteoritic ratios, the rest clearly belonging to the natural iron rich components of the soil. Figure 15-6 shows the radial distribution of the particles as a function of distance from the center of the crater and illustrates that little if any concentration exists at the crater itself. Table 15-4 gives a summary of the analyses of the various particles collected and found to have the shape typical of the expected meteoritic particles, and Table 15-5 gives the detailed analyses for those particles identified as having a meteoritic origin. Two of these were similar to the Arizona Meteor Crater particles, containing primarily iron oxide with copper and cobalt present in roughly meteoritic proportions; two were more similar to two of the classes of soil-meteorite mixture particles found at Henbury. Thus, Boxhole seems to provide an intermediate case between Henbury and the Arizona crater.

VI. The Odessa Crater

A soil survey of the environs of the meteorite crater near Odessa, Texas, was carried out several years ago by

Wright and Hodge, but the results have never been published. The task is a difficult one because of the extensive vestiges of civilization in the immediate vicinity of the crater, which is in the middle of a derick-filled oil field. Table 15-6 shows the results of analysis of one of the particles taken from the Odessa Crater environs. Generally, the spherules in the soil at Odessa are similar chemically to those at Meteor Crater in Arizona. None were found in this preliminary search that resemble the Henbury type particles, a soil-meteorite glass mixture.

VII. The Tunguska Event

The collision of an object with the earth in 1907 in Siberia near the Tungus River has been identified as having been caused by a comet, which broke up at an altitide of about 8 kilometers (Fesenkov 1969). Several expeditions into the area have been carried out by Soviet meteoritists for the purpose of identifying extraterrestrial material in the environs. No ponderable meteoritic fragments have been found and the circular depressions originally thought to be meteorite craters have been identified as natural terrestrial features having nothing to do with the Tunguska event itself. Maskelova and Teskovich, from extensive analysis of soil taken from the area where the forest was destroyed, concluded that the fairly common occurrence of small black magnetic spheres could be ascribed to material formed by the event. Chemically these objects are similar to those from Meteor Crater.

VIII. The Wabar Crater Particles

The craters at Wabar, Arabia, have not been found as yet to be surrounded by large amounts of nickel-iron

Table 15-6. Composition Of a Spherule From The Odessa Crater Soil Samples

Element	Abundance (Weight Percent)
Fe	61
Ni	5.5
Co	0.5
Si	0

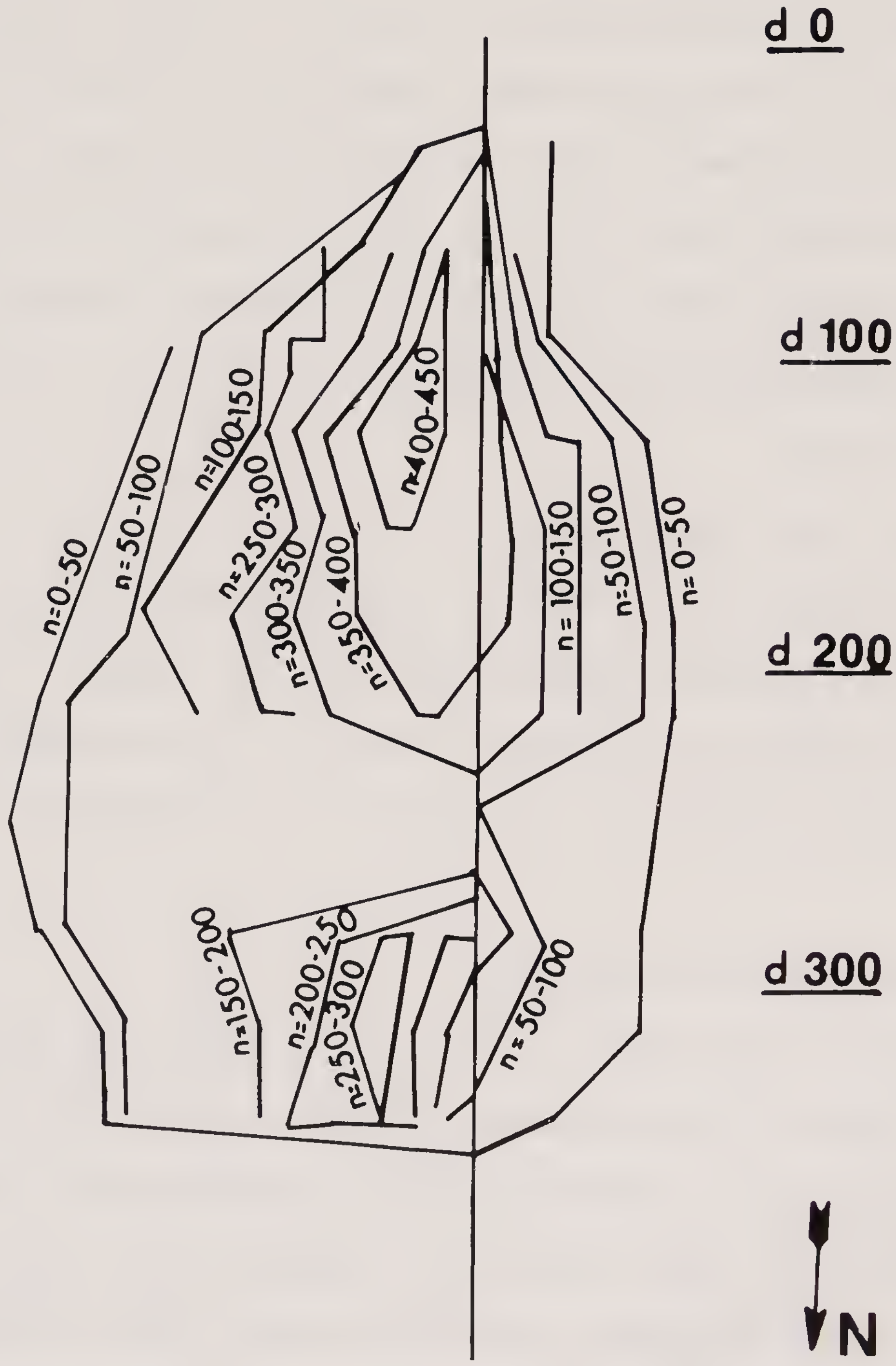

Fig. 15-7. Lines of equal density for suspected meteoritic particles found in the soil surrounding the Morasko craters (from Korpikiewicz 1978).

particles in the soil, but such nickel-iron spheres are found in the glass impactite bombs that have been studied in some detail from these craters. Spencer (1933) first described the Wabar glass and many others have studied it in recent years (e.g., see Brett 1967). The spherules are primarily nickel-iron in metallic form locked in impactite. They contain some 8 to 70% nickel, whereas the parent meteorites all have approximately 7% nickel. This suggests that the spherules in the glass were partially oxidized before or during their involvement with the impactite glass. The glass is also abnormally rich in iron, and therefore it is suggested that the nickel-free iron oxide may have diffused into the glass, thus depleting the spherules of iron and enriching the glass in iron.

IX. The Lonar Lake Particles

Fredrickeson et al. (1973) reported on the discovery of glass particles surrounding Lonar Lake in India. This lake is now established as an impact crater. The glasses are similar in their chemical and physical properties to those at Henbury.

X. The Morasko Crater Spheres

The Morasko Meteorite Craters lie near the outskirts of Poznán, Poland (Korpikiewicz 1978). Eight craters have been recognized and studied and large numbers of particles from the soil have been separated magnetically and counted. Isopleths for the magnetic particles are shown in Fig. 15-7, and it is this distribution that lead to the conclusion that the particles <u>and</u> the craters are meteoritic in origin.

Studies such as these will continue to be needed, both as more meteoritic craters are recognized and as more techniques are developed that might throw light on the formation mechanisms for ablation spheres. And, as the space program progresses, we hope one day to be able to examine similar debris about the craters on other planets, especially Mars, Venus, and Mercury, to study the effects of different atmospheric conditions on the mode of formation of the spheres.

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INTERPLANETARY DUST
P. W. Hodge

Interplanetary dust was until recently one of the least understood components of the solar system. This book relates its somewhat checkered early history as a discipline, explains the many difficulties that faced interpreting even modern rocket and satellite experiments, and gives a detailed account of how the many highly divergent results of the 1960's were finally reconciled and understood in the 1970's. The spatial density, size distribution, orbital characteristics, and physical and chemical nature of the dust is now known and probable sources of the dust have been established. Its relation to the question of the origin of life on the earth is discussed and the book also describes research on meteoritic dust that is associated with terrestrial and lunar meteorite craters.

Contents

The quest for cosmic dust. The zodiacal light. Fossil dust collections. Surface collections. Aircraft and balloon collections. Deep sea collections. Rocket collections. Measurements from earth satellites. Lunar microcraters. Deep space measurements. Micrometeorites. Dynamics. Origin of the dust. Meteoritic dust and the influx of organic molecules. Meteoritic dust particles around meteorite craters.

Professor Hodge, presently in the Astronomy Department of the University of Washington, did his first research on interplanetary dust when he was an undergraduate at Yale University, where he developed a global year-long particle collection program to explore the universality of the fall to earth of suspected extraterrestrial dust. Continuing work along these lines at Harvard University and the Smithsonian Astrophysical Observatory, he developed high-altitude aircraft collections and balloon techniques. At the University of Washington he established the Meteoritic Dust Laboratory, where he and his colleague and former student Donald Brownlee have expanded the realms of particle research to spacecraft, the moon, and deep sea deposits.

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