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A SURVEY OF DATA ON MICROSCOPIC EXTRATERRESTRIAL PARTICLES

(Revised June 1964)

by Richard A. Schmidt

Ames Research Center

Moffett Field, Calif.

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PREFACE

The problems of conducting a literature survey are many and varied. A major consideration is, of course, assembling pertinent books, reports, articles, and research notes dealing with the subject. In assembling the first edition of this work, the writer was ably assisted by Mrs. Elizabeth Boardman, Librarian of the Geophysical and Polar Research Center at the University of Wisconsin. Her untiring efforts and active interest in this project were of great value. With that strong foundation, the task of revising the work was lessened considerably.

Rapid recent progress in the study of microscopic extraterrestrial particles necessitated a complete revision of the 1963 survey. In many places, new data afford better understanding of problems encountered in the earlier work. Moreover, the new results suggest areas for further study to answer questions they raise about the nature and origin of the particles.

Many people contributed to this task, and their assistance is gratefully acknowledged. Rough drafts of the text were reviewed by many investigators working on the same general topic. Their many comments, criticisms, and suggestions were of great value in preparing the final draft, although the responsibility for its contents is the writer's.

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INTRODUCTION

Microscopic particles are the least understood of all materials that reach the Earth from outer space. Indeed, for much of the time since their discovery about a century ago, they were regarded merely as geological curiosities. Although usually mentioned in Earth science textbooks as an exótic source of material for oceanic sedimentation, little was known about the nature of the particles, their origin, or how they came to be deposited at the Earth's surface. The small size of the particles and the difficulty in obtaining samples free from terrestrial contaminants thwarted many early attempts to unlock their mysteries, and few data were available until recently.

Space exploration provided the impetus for renewed efforts to determine the composition, characteristics, occurrence, and origin of microscopic extraterrestrial particles, because they occupy a position of critical importance to better understanding the space environment of our planet. These data are essential to comprehensive planning of space research, and especially to the design and construction of successful, manned space vehicles. Problems of obtaining quantitative data for such particles are no longer severe because of advances in instrumentation. Furthermore, modern efforts to study the particles are commonly coordinated and complementary, unlike many conducted in the past. To evaluate the present research properly, however, knowledge of previous studies is essential.

A survey of data on microscopic extraterrestrial particles was undertaken to provide an up-to-date compilation of existing information on the subject as a reference for new research in progress at Ames Research Center. The present survey is a revision of an earlier version (Schmidt, Jan. 1963), which has been expanded to include most recent studies. The objective of the survey is to bring together as much available data as possible. Principal attention was devoted to the following categories: particle description, size, physical properties, chemical composition, occurrence, location of samples, annual deposit, space concentration, and theories of origin.

Many sources of information were employed in this effort; all are listed in alphabetical order in the bibliography. A few works, however, were relied upon more extensively and deserve special mention. The studies of Buddhue from 1940 to 1948 produced a classic paper on "meteoritic dust," published in 1950. This research, an important contribution in its own right, served to arouse new interest in the study of such particles, which had been virtually neglected since the time of Murray (1883). Shortly after Buddhue's monograph was published, several more reports of studies of dust particles appeared. Another valuable source of articles on "cosmic dust" and "interplanetary dust" was the annotated bibliography of Hoffleit (1952), expanded by Hodge, Wright, and Hoffleit (1961). Still other papers were located through bibliographies compiled by Magnolia (1962, 1963, 1964). Finally, the bibliographies of Salisbury and Salisbury (1961), Salisbury, Van Tassel, and Adler (1962), and Salisbury, Van Tassel, Adler, and Dodd (1963) were also of considerable value. It is no exaggeration to say that without such useful and current bibliographical aids, a survey of the present type would be infinitely more difficult. The authors of these works are performing a real service to those studying interplanetary matter. The remainder of the data summarized here was taken from works referenced by several authors and from the current literature.

Many investigators have studied the occurrence and characteristics of microscopic extraterrestrial particles. Short descriptions of works completed prior to 1950 were presented in chronological order by Buddhue (1950). This novel and interesting practice provided valuable insight into the development of the science of particle study. Available works completed since then were briefly summarized, in the same manner, in the appendix to allow this presentation to be employed as an extension of Buddhue's review to the present day.

DEFINITIONS

The material treated in this survey is known by many names, among which are cosmic dust, cosmic spherules, caudaites, meteoritic dust, meteoric dust, micrometeorites, nanometeorites, interplanetary dust, interstellar dust, primordial dust, zodiacal dust, galactic dust, cometary debris, planetary debris, and asteroidal fragments. It is clear that these diverse terms, often used by different workers to describe the same matter, can be confusing. In an attempt to reduce such confusion, definitions of each are presented below. The first four subsections describe materials collected at the surface of the Earth. In the strictest sence, these classes of particles are meteorites because of their occurrence. However, the particles have in the past been designated by different terms to provide insight into their origin, and this practice is adopted here. The fifth subsection considers particles occurring in space, and the final subsection presents a summary of preferred terminology.

Cosmic Dust

The term was coined by Murray (1883) to denote all classes of extraterrestrial particles discovered in ocean sediments sampled during the HMS Challenger expedition. Cosmic dust included metallic spherules as well as siliceous particles. All particles, which ranged in size from about 10 microns to 250 microns, occurred in both recent and ancient sediments located in the deep ocean basin, far from land and from possible sources of industrial contamination (which might well have been a much less serious problem at that time than at present). Furthermore, Murray and Renard (1883, p. 490) noted that the form and character of the spherules were "essentially different" from those collected near manufacturing centers. The metallic particles (also known as cosmic spherules) were black, and were coated with a magnetic iron oxide covering an inner portion which gave positive chemical tests for metallic iron, cobalt, and nickel. These elements are rather rare in terrestrial materials, but are common to meteorites. Therefore, Murray and Renard (1883) postulated an extraterrestrial or cosmic origin for such particles. They suggested that the dust particles represented fragments of meteorites which disintegrated upon entering the Earth's atmosphere. Unfortunately, Buddhue's definition of meteoritic dust (see below) is identical to this usage of cosmic dust, and these apparent synonyms have been used indisciminately by many workers. The writer finds this practice confusing, particularly because reference to original usage of the terms is commonly omitted. Brunn, et al. (1955) proposed to call such particles caudaites to distinguish them from other cosmic bodies, but this term did not gain acceptance.

Recently, Krinov (1961) suggested that the term cosmic dust be restricted to those particles sufficiently small to settle on the Earth's surface without undergoing melting by atmospheric friction. The particles would thus be essentially unchanged from their form in space, and could be considered as samples of interplanetary dust (see below). To accomplish unaltered entry into the atmosphere, iron particles must be less than 5 microns diameter, while glassy particles must be smaller than 10 microns diameter. Krinov's definition of cosmic dust clearly departs from Murray's original usage of the term, and is identical with Whipple's usage of "micrometeorite" (see below).

Over the years Murray's use of cosmic dust was not followed with care by subsequent workers. The result was that, while many papers referred to cosmic dust, entirely different material was often described. It is therefore proper at the present to redefine cosmic dust to conform to modern usage. The writer prefers Krinov's definition of cosmic dust, limiting this term to the smaller particles encountered by the Earth. In a clear, descriptive manner, it summarizes the nature of the smaller particles and presents what can be inferred about their origin.

The smallest particles yet recovered (about 0.01 micron diameter) were designated nanometeorites by Hemenway, et al. (1961). The writer regards these particles as a type of cosmic dust, although so little is known about them that future work may require revision of this categorization.

Meteoritic Dust

This term was employed by Buddhue (1950) to describe spherical particles composed of both metal and glass, cindery fragments, and angular grains. It implied that such material originated from disintegration and/or partial fusion of meteoroids during their passage through the Earth's atmosphere. The similarity of this definition of meteoritic dust with Murray's usage of cosmic dust is apparent. However, the writer does not favor use of two names for the same material.

Krinov (1959) suggested that meteoritic dust be redefined as the globules and angular, deformed, particulate matter which occurs at the sites of larger meteoritic falls. This definition is preferred by the writer.

Micrometeorite

This term was coined by Whipple (1949) to describe very small meteoroids which radiate energy fast enough that upon entering the Earth's atmosphere they do not reach their melting point. Micrometeorites would be iron particles less than 5 microns diameter and stony particles less than 10 microns diameter, which could survive entry into the atmosphere at vertical incidence velocities (Whipple, 1950, 1951). It may be presumed that larger particles could survive atmospheric entry at lower velocities and/or angles of incidence.

Unfortunately, micrometeorite was used by Vedder (1961), among others, to denote solid particles encountered by space vehicles. Newspaper accounts of space research are particularly guilty of this improper usage, which became popular in spite of the fact that material must reach the Earth in order to be considered a meteorite. As Goettleman, et al. (1961) pointed out, the term "micrometeoroid" should be used instead to describe particles found in space. In connection with that incorrect usage of Whipple's term, current practice by many workers expanded it to include all sorts of microscopic extraterrestrial particles, not just the smallest as Whipple intended. Engineering considerations of spacecraft design led to still other usages, such as that of Bradford and Dycus (1964), in which micrometeorite was defined as a particle with mass less than 10^{-4} gm. It is regrettable that the original definition of micrometeorite should have become so clouded in such a short time. However, because of this confusion, the writer prefers the term cosmic dust for such small particles, as discussed above.

In an attempt to conform to present usage, Krinov (1959) suggested that micrometeorite be restricted to small particles having the basic properties of meteorites (i.e., fusion crust, flow marks, etc.). To possess these features the particles must necessarily be larger than about 10 microns in diameter. The writer recommends that this definition be adopted; it is precisely implied by the components of the term.

Meteoric Dust

Krinov (1959) coined this term to denote material resulting from melting of a cometary meteor in the earth's atmosphere. Some of the particles resulting from this process are spheriodal, while others are irrgular flakes. They have an entirely different chemical and mineralogical composition from the bodies that produced them because of oxidation during flight. Meteors are quite distinct from meteorites, and apparently have had a different origin (Mason, 1962).

The writer has encountered this term rarely in his literature survey. It is a relatively new one, which may account for its limited adoption. A primary reason for its infrequent use may be the difficulty in recognizing the source of particles, so critical to the definition of this term. The parent material of meteors apparently disintegrates in the atmosphere and is either lost or extremely difficult to distinguish from meteorites. Still, the writer regards meteoric dust as a useful term, and recommends its adoption. Perhaps the metallic flakes with amorphous (organic?) attachments that Parkin, et al. (1962) recovered are meteoric dust; they appear to be associated with principal meteor showers (Parkin and Hunter, 1962). It is difficult, however, to understand how such large flakes (often several hundred microns long) could have escaped melting during entry into the atmosphere. Designation of these materials as extraterrestrial in origin should be deferred until conclusive proof is obtained.

Interplanetary Dust

Solid particles of microscopic size occurring in space outside of planetary or solar atmospheres are known by many names. Recent efforts in space research have contributed to this proliferation of terms. The occurrence of such material in space is suggested by the names interstellar dust (Herzberg, 1954); interplanetary dust (Minneart, 1954); galatic dust (Inglis, 1961); primordial dust (Öpik, 1954); zodiacal dust (Kallman, 1954); and zodiacal particles (Whipple, 1954). What can be inferred about the origin of the particles is indicated by the terms cometary debris, planetary debris, asteroidal fragments, and micrometeoroids.

Probably, particles from many sources comprise the interplanetary dust cloud, but present knowledge of solid particles occurring in space is fragmentary and incomplete. The writer prefers a descriptive term, one which informs the reader of particle character and occurrence, but which does not impose an assumption about particle origin, and recommends that interplanetary dust be adopted for this purpose.

Summary of Preferred Terminology

The writer prefers the following terms to denote microscopic extraterrestrial particles which occur at the surface of the Earth or in the Earth's atmosphere.

Cosmic dust: microscopic particles small enough to settle on the Earth's surface without undergoing melting by atmospheric friction (less than about 10 microns diameter for particles at vertical incidence velocities).

Meteoritic dust: microscopic particles which occur at the sites of larger meteorite falls.

Micrometeorite: microscopic particles having the basic properties of meteorites, including fusion crusts and flow markings, but which do not occur at places of larger meteorite falls.

Meteoric dust: microscopic particles resulting from evaporation and/or disintegration of a cometary meteor in the Earth's atmosphere or in the vicinity of the Earth.

The writer prefers the term interplanetary dust to denote microscopic particles occurring in space outside the practical limits of the Earth's atmosphere.

DESCRIPTION OF PARTICLES

Identification of microscopic extraterrestrial particles is a difficult task, principally because some terrestrial geological processes and industrial activities can produce material generally similar in appearance. Volcanic eruptions, such as that of Krakatoa in 1883, spewed large amounts of dust and ash into the Earth's atmosphere. Fredriksson and Martin (1963) showed that some volcanic particles were similar in appearance to those of extraterrestrial origin, differing primarily in chemical composition and expecially in nickel content. Hodge and Wright (1964) reported that particles of volcanic origin were compositionally distinct from those thought to be of extraterrestrial origin. They found, moreover, that volcanic particles rarely occurred as spheroids, unlike the extraterrestrial material which commonly were spherules. Industrial particles may also be confused with those from space. Handy and Davidson (1953) showed that the particles Thomsen (1953) recovered from Iowa snows and believed to be of meteoritic origin were probably from a nearby manufacturing center. It is apparent that contamination hazards must be considered in each collection of extraterrestrial particles in order to obtain meaningful results. Unfortunately, precautions employed to eliminate or control contamination have not been standard throughout the history of this work. The reader is urged to keep this in mind as he considers the following review of particle descriptions.

Microscopic extraterrestrial particles are represented by several different types, as recognized in previous studies. These are described in table I, which contains eight different classifications of such material taken from the literature. The table shows that most of the particles are spherical in shape, and that their most common constituents are metallic (iron and nickel) and glassy (siliceous). The predominance of spherical particles in these classifications is striking, expecially among the varied material of Buddhue's (1950) listing. It is reasonable to suspect that the cause of this superabundance of spherical particles is their ease of recognition. A smooth, spherical grain is conspicuous in any assemblage of normal, subangular to subrounded rock fragments, and can be readily distinguished as distinctly different from its neighbors. Moreover, terrestrial geological processes so rarely produce spherical forms that an extraterrestrial origin for such particles is a real possibility. Recognition of nonspherical extraterrestrial particles in juxtaposition with terrestrial rock fragments is many times more difficult, and it is likely that this accounts for the paucity of data for them. In fact, Murray's original classification was limited entirely to spherical particles, as were more recent ones by Skolnick (1961) and Utech (1962). Examples of particles generally assumed to be of extraterrestrial origin are shown in figures 1 and 2.

The several classifications of microscopic extraterrestrial particles, each useful separately in their present forms were employed in the construction of a comprehensive classification of such particles. This is shown in table II. It was thought that in this way the present investigation could most effectively benefit from the knowledge attained by the previous workers. The aggregate classification is viewed as a working model, which will probably require revision during present research.

The writer classifies most of this material as micrometeorites. The majority of particles are too large to be cosmic dust. Most samples are from localities far removed from known meteorite falls or were collected from air and not related to meteorite passage, therefore, not satisfying the preferred definition of meteoritic dust. The few coated particles may be samples of meteoric dust. Except where specifically noted, however, all material in the comprehensive classification given in table II is regarded as a type of micrometeorite.

SIZE

The sizes of known microscopic extraterrestrial particles vary over a considerable range. The smallest (cosmic dust) particles collected are 0.01 micron in diameter (Hemenway, 1961), while the largest (micrometeorites) are 850 microns in diameter (Skolnick, 1961). These are the extremes of particle sizes investigated. Most particles, however, are less than 250 microns in diameter, and the most frequently occurring sizes are in the narrow range from 1 micron to 60 microns in diameter. A listing of size determinations is presented in table III.

Graphical representations of size distributions and abundances of particles are shown in figures 3 and 4. Figure 3 is a compilation of data from eight surface-based studies of micrometeorites (metallic spherules). While it is apparent that not every investigation of metallic spherules considered particles in the same size group, the particle size distribution found in these studies was of similar character. Each investigator found that the bulk of his sample consisted of smaller particles, with larger particles occuring rarely. This appears to be in general agreement with the theoretical relation proposed by Laevastu and Mellis (1961), which is

$$V_1N_1 = V_2N_2$$

where V is the volume or mass of a single spherule in a given size group or diameter interval; and N is the number of spherules in this size group.

It is interesting to note the similarity in abundances of particles resulting from studies in the same size range. Hodge and Wildt (1958), Hodge (1960), and Crozier (1960) found similar values for particles from 3 to about 30 microns in diameter. Buddhue (1950), Laevastu and Mellis (1955), Hunter and Parkin (1960), Thiel and Schmidt (1961), Langway (1963), Mutch (1963), and Schmidt (1963) found similar abundances for particles from 10 to about 200 microns in diameter. Slight disagreements between these studies will probably be resolved by current research.

Figure 4 shows a compilation of size distributions for glassy particles, compiled from three surface-based studies. In general, abundances of glassy particles are similar to those of metallic spherules, but the data are too limited to permit further comparisons at this time. Parkin and Hunter (1962) found two size groups for "stony" spherules. The smaller particles, less than 60 microns in diameter, were thought to be derived from the breakup of larger spherules due to aerodynamic forces. Whether a similar explanation can be applied to small, metallic spherules remains to be demonstrated.

PHYSICAL PROPERTIES

The small size of microscopic extraterrestrial particles has made determinations of their physical properties quite difficult. What little is know or inferred about these properties is summarized in table IV. These data present only a general idea of the physical character of micrometeorites. Furthermore, it is difficult to compare values obtained by different workers, for often the methods used and error limits of the values obtained were not reported. The data suggest, however, that the density and refractive indices of the glassy particles place them in the realm of rock-forming minerals and meteorites. The metallic spherules are most similar to metallic meteorites. Glassy particles appear similar to natural silica-rich glasses and may be akin to tektites.

CHEMICAL COMPOSITION

Relatively few chemical analyses of microscopic extraterrestrial particles have been performed. It is likely that the small size of the particles hindered progress in this direction. However, even in the earliest studies, bulk gravitational chemical analyses of particle aggregates were reported which indicated a similarity of particles to meteoritic matter. Many qualitative analyses were done as a part of earlier works, and still are performed today (Grjebine, Lalou, Ros, and Capitant, 1963). It is difficult to see any advantage in further qualitative analyses as compared to reliable, quantitative data in providing information necessary to resolve questions of particle origin. With the development of the electron microprobe, it became possible to obtain quantitative analyses of individual particles. Care must be exercised in this work, however. Data of analyses of particle surfaces were reported by Riggs, Wright, and Hodge (1962); Wright, Hodge, and Langway

(1963); Langway (1963); Langway and Marvin (1963); Schmidt (1963); Hodge and Wright (1964); and Hodge, Wright, and Langway (1964). More than 1200 particles were examined in this way, but only few have surface compositions indicative of meteoritic materials, including samples from known meteorite falls such as Meteor Crater, Arizona and Sikhote-Alin, USSR. An explanation for these curious results was offered through a study by Schmidt and Keil (1964). Particles were examined in cross section (fig. 5), revealing a terrestrial alteration zone at the surface which often masked a variable internal texture and meteoritic composition. Consequently, the surface analyses could not be representative of entire particles. It is unfortunate that the surface analyses which exist are of limited value, although some problems of interpretation of those data are now alleviated. A sampling of available analyses is presented in table V.

OCCURRENCE

Locations where microscopic extraterrestrial particles were collected on the Earth are listed in the appendix and are shown in figure 6. It can be seen that they were recovered from positions which differ widely in latitude and longitude. In fact, particles were found literally around the world and almost from pole to pole. Therefore, many workers assumed that the particles fell uniformly over the surface of the Earth. This assumption may require review, but existing information is insufficient for a critical evaluation. Sites from which particles were obtained are badly scattered over great distances. Few data are available on the character of particle occurrence over a regional area. A first attempt to define particle occurrence on a regional basis was made for the Antarctic Peninsula Traverse area by Schmidt (1963). That work showed a strong meteorological effect upon particle occurrence, with a direct relation between frequency of particle occurrence and annual snow accumulation (fig. 7). It was postulated that particles were swept out of the atmosphere by the falling snow. However, no correlations of particle occurrence in snow layers representing the same year at different stations were observed. Surface winds produced rapid changes in snow surface which made correlation impossible. As a result, Marshall's (1959, 1963) suggestion that particulate matter can be used as a quantitative stratigraphic parameter for correlation of glaciological measurements over broad areas of polar ice caps appears to be a forlorn hope.

Relationships of extraterrestrial particles to precipitation were also proposed by Bowen (1956), in a hypothesis which he was later to describe wryly as "well-known but widely ignored." Noting that periods of heavy rainfall occurred about 30 days after principal meteor swarms, he suggested that the particles required this amount of time to fall through the atmosphere to the level where they could influence precipitation by acting as condensation nuclei for moisture. This view was challenged by many workers. One of these was Fletcher (1961) who pointed out that meteoric particles have low activity as condensation nuclei and would be insufficient to make Bowen's mechanism operate. Another objection was the length of time of particle fall through the atmosphere. Collections of Parkin and Hunter (1962) suggested that meteoric particles fell through the atmosphere in a few days, not the month which Bowen required. Calculations by Thiel and Schmidt (1961) supported that view, although an idealized case was considered.

Bowen (1963) recently modified his hypothesis to include an apparent relationship of rainfall, freezing nuclei, and meteor showers with lunar phase. Brierley and Davies (1963) concurred in that view, although Ellyett and Keay (1964) reported that the existence of any lunar influence on meteor rate data was doubtful.

Support for Bowen's view was found by Rosinski and Pierrard (1964) in a study of noctilucent clouds, tenuous clouds observed at twilight in summer at high latitudes. It was suggested that condensation of moisture on meteoric particles were responsible for the clouds. Collections of particles from noctilucent clouds by Soberman, et al. (1963) were consistent with this view, as Fe and Ni particles with ice coatings were recovered.

Whether or not Bowen's hypothesis is proved correct, it served a real purpose in forcing students of micrometeorites and cosmic dust to take atmospheric and meteorlogical effects into account. The theoretical treatments of deceleration of particles upon atmospheric entry formulated by Gazely (1957) can be used to show that most particles less than 10 microns in diameter reach maximum deceleration at altitudes of the order of 100 to 200 km. Large particles are decelerated at slightly deeper levels in the atmosphere, so that an effective filtration of particles by size (and probably strength) occurs. Fiocco and Colombo (1964) described radar meteor observations which support this view. A radar scattering layer found between 110 and 140 km altitude was attributed to fragmentation of meteoric particles. Progressive fragmentation in the atmosphere was postulated, so that the average size of particles and mass flux would vary with altitude.

From the altitude of maximum deceleration, particles fall to Earth at terminal velocity under the Earth's gravitational field. In this condition of fall the particles are subject to meteorological influences which may be expected to affect the occurrence of particles at the surface of the Earth. It would be valuable to achieve an understanding of particle influx if future collections of particles could be directed at obtaining representation of particle occurrence over regional areas.

On the basis of astronomical observations, the presence of solid particles in interplanetary space was suspected for some time. Many studies of the character of solar light suggested that bands of "obscuring matter" or dust particles may occur in scattered localities throughout our galaxy. Light absorption studies showed that interplanetary dust is indeed present in space, and that it tends to be concentrated in the plane defined by the Sun and the orbits of the planets. The reflection of sunlight from such particles was postulated as the cause of the zodiacal light, hence the name zodiacal dust was applied to these particles.

Recently, rocket and satellite observations suggested that interplanetary dust occurs in rather high concentrations in the space near the Earth.

Beard (1959, 1963) noted that interplanetary dust is distributed in space as the inverse three-halves power of its distance from the Sun. He further stated that all particles in the vicinity of the Earth will have their orbits materially affected by the Earth's gravitational field, forming a dust blanket around the Earth. The particle concentration in the dust blanket was estimated to be 10^3 times greater than the deep space value. A similar gravitational mechanism was proposed by Kaiser (1963), but it was extended to account for particle deposition on the Earth. Gravitationally concentrated particles near the Earth were thought to eventually encounter the Earth's atmosphere where they would be decelerated as described above and deposited. Dole (1962) suggested that gravitational concentration of low-velocity particles could maintain a steady-state dust cloud near the Earth. This view was challenged by Southworth (1963), who showed that Dole's mechanism would, by itself, be a negligible contribution to the Earth's dust cloud.

Whipple (1961), while agreeing that a high concentration of interplanetary dust occurs near the Earth, suggested that the concentration falls off roughly as the inverse 1.4 power of the distance from the Earth's surface to a distance of approximately 100,000 km. Dole's (1962) calculations suggested that concentration decreases as the inverse 1.66 power of the distance from Earth.

Goettleman, et al. (1961) apparently held a view similar to Whipple's. They postulated the existence of a meteoroid halo or belt of relatively high, constant particle density surrounding the Earth, but extending only to an altitude about 4000 km above its surface. Beyond that level they envisioned a region of lower particle density.

Another view is held by Singer (1961), who proposed that there is a maximum in dust concentration at about 2000 to 3000 km above the Earth's surface, giving rise to a dust shell. Mirtov (1962) also postulated a dust shell, but placed the maximum at only 100-200 km above the Earth's surface. The increase was thought to amount to only a few times the value of the dust concentration in interplanetary space, rather than the factor of 1000 given by Beard (1959).

The work of McCracken, Alexander, and Dubin (1961) does not support the dust cloud or dust shell interpretations cited above. They maintained that there is no discernible dependence of the spatial density of dust particles on altitude. Further, they stated that if a high concentration of dust particles exist, measurements of dust concentrations at very large distances from the Earth would be necessary to confirm its presence. In other words, they maintained that the limited data currently available do not permit recognition of a dust cloud or dust shell around the Earth.

Recently, however, Alexander (1962) reported measurements of interplanetary dust conducted by the Mariner II space probe. These indicated that 10^4 times fewer particles were encountered in space between Earth and Venus than were detected by satellites nearer the Earth. The preliminary data thus suggested that there is a concentration of interplanetary dust near the vicinity of Earth. Its exact character is still unknown.

Ingham (1963) suggested that the gegenschein (counter glow), a diffuse light observed on the opposite side of the Earth from the Sun, was produced by reflection of sunlight from particles in the Earth's dust cloud. Work by Dycus, et al. (1964) is consistent with this suggestion; a concentration of penetration - size dust particles was computed to occur in this region (fig. 8).

A compilation of several estimates of the concentration of interplanetary dust in space is given in table VI. The table shows that most workers consider interplanetary dust to be present in space in concentrations ranging from 10^{-20} gm/cm^3 to 10^{-24} gm/cm^3. Fewer values are available for the concentration of particles in space near the Earth, and these are in less close agreement, ranging from 10^{-14}gm/cm^3 to 10^{-22} gm/cm^3. A representation of near Earth and space concentration of particulate matter presented by D'Aiutolo (1963) is shown in figure 9.

ANNUAL DEPOSIT

Microscopic extraterrestrial particles were collected from sediments (including ice) and from rocks of many different geological ages. It would appear that virtually the entire Earth received deposits of such material from the present day back through geological time to the Precambrian era, more than 500 million years ago (Mutch, 1964, personal communication). It may be suspected that particle deposits occurred even earlier in the Earth's history. Possible, but yet to be proved, is the suggestion that dust particles similar to those observed today played some role in the origin of the Earth through accretion of dust particles.

Many terrestrial studies of the rate of spherule deposition were conducted. Each estimate, however, is subject to errors in extrapolation of particle occurrence over a small area to the surface of the Earth, assuming uniform deposition. Furthermore, the assumed uniformity of particle distribution remains to be demonstrated. The reader is cautioned to keep these facts in mind as he considers the data of particle deposit.

Knowledge of the amounts of sediment and snow which are deposited in 1 year, together with determinations of mass of particles occurring in annual layers, were used by previous workers in estimating the annual deposit of particles on the Earth. Most data are available for black, magnetic spherules, and only these will be considered. Resulting estimates, listed in table VII vary widely, from 8 metric tons per year (Buddhue, 1950) to 2.4×10^9 metric tons per year (Grjebine, 1963). Part of this enormous disparity in values may be traced to the fact that not all estimates were based on studies of the same types of particles. For example, one value may be obtained from study of metallic spherules (Bruun, et al., 1955), another from the total influx of all dust particles (Öpik, 1956). Still, serious disagreement exists among estimates of deposit for supposedly identical material. For example, estimates of the influx rate of black, magnetic spherules differ by as much as a factor of 10^9 (Buddhue vs Grjebine). In the writer's opinion, the large estimates of annual deposit of black spherules by Thomsen (1953;

2×10^6 metric tons per year); Kreiken (1959; 3.1×10^6 metric tons per year): and Grjebine (1963; 2.4×10^9 metric tons per year) represent contaminated samples. Handy and Davidson (1953) showed that Thomsen's particles were probably industrial fly ash. Kreiken's samples were taken in Ankara, Turkey and probably reflect industrial products; even he suggested that the results were rather large. Grjebine, et al. (1963) reported qualitative analyses of particles collected from metropolitan France which cannot be ascribed to meteoric matter. Deletion of these large estimates lowers the range of values to only about 6 orders of magnitude. We may reduce the range still further by recalling that Buddhue's (1950) value cited as the lowest estimate was for a special, limited case. If that is omitted from consideration, we are left with estimates of annual deposit for black, magnetic spherules which range from 10^2 to 10^5 metric tons per year.

The values still are spread out over a considerable range. However, recent estimates of the deposit of black, magnetic spherules appear to be in reasonably close agreement. Although slightly different sizes of particles were examined, Crozier (1961, 1962); Fireman and Kistner (1961); Thiel and Schmidt (1961); Wright and Hodge (1962); Langway (1963); Schmidt (1963); and Utech (1963) each estimated the annual deposit of black spherules to be some integer times 10^5 metric tons per year. At the present stage of investigation the slight disagreements among these workers should not be discouraging. As pointed out earlier, little is known about influences upon spherule deposit on the Earth. The apparent disagreement may be a clue that some force is acting to produce variation in spherule deposit. Schmidt and Cohen (1964) considered this possibility, and found an apparent relationship of annual deposit estimates with geomagnetic latitude of the collecting site. It was suggested that some of the scatter in estimates could be caused by the Earth's magnetic field (fig. 10). On the other hand, Öpik (1956) concluded that an electrically charged dust particle in space would be unaffected by the terrestrial or solar magnetic field, particularly at meteoric speeds. Singer (1958), however, suggested that the geomagnetic field may influence particle occurrence. Parkin and Hunter (1962) pointed out that the presence of ionized interplanetary gas would produce strong interactions with fine particles. The particles would be brought to rest with respect to the gas, drift with it, and would, perhaps, thus be concentrated at the auroral zones. This process would be enhanced if the particles were traveling at low velocities. It is interesting to note that Hawkins (1963) reported radar meteor observations suggesting low velocities for smaller particles. At present the data are incomplete, and in order to verify or disprove the hypothesis much work remains to be done.

The cumulative rate of particle deposition is greatest for smaller particles, decreasing sharply for larger materials. This facet of the problem was considered by many workers. Particle collections by Crozier (1961, 1962); Schmidt (1963); and Hodge, Wright, and Langway (1964) led to definition of the relationship for micron-sized particles, shown in figure 11. Slight disagreement exist among the different studies, but these can be accounted for by local conditions at the collecting sites. Measurements of particle flux by satellites led to a wider distribution, shown in figure 12 (Alexander, et al., 1962). The total flux of extraterrestrial objects was examined by

Hawkins (1963), as shown in figure 13. These data clearly show that microscopic particles are by far the most abundant extraterrestrial matter in the vicinity of the Earth.

An apparent seasonal variation in the deposition of black, magnetic spherules was observed. Kizilirmak (1954) noted that fewer particles were deposited in Ankara, Turkey in the month of February, while maximum numbers of particles were recovered in July. His work was continued by Süslü (1956), who observed similar variations and found much greater numbers of particles than were collected in the earlier study. Kreiken (1959) summarized the earlier Turkish observations, and suggested that the numbers of particles collected were related to periods of meteoric activity, but that they lagged about one month behind that phenomenon. Parkin and Hunter (1962) reported a much shorter lag relationship of particle occurrence to meteor showers. Maximum particle occurrences were observed only a few days after meteor showers. Crozier (1962) reported that, in general, maximum numbers of spherules were collected in spring and summer months. Both Crozier's New Mexico station and the site of Turkish observations are situated on about the same latitude, although on opposite sides of the globe. The fact that similar effects were observed at each place suggests that their cause may have been world-wide. Parkin, et al. (1962) also noted greater amounts of particles in the summer months. Hasegawa (1959) reported that Japanese workers found conflicting seasonal variations of particle deposition. Morikubo found largest numbers of particles during August and September, as did the workers cited above. On the other hand, Yamada found largest numbers of particles in January and February, when all other workers reported fewest particles. This disagreement in Japanese data is difficult to explain, unless it has been caused by proximity to nearby industrial centers as appears likely.

All sites where seasonal variations in particle deposition were observed are located in the northern hemisphere. It would be valuable to know whether similar seasonal variations in particle deposition occur in the southern hemisphere. In particular, it would be important to determine whether or not any seasonal variations in the southern hemisphere occur at the same time of year as those observed in the northern hemisphere. In view of the following, one would expect southern hemisphere variations to occur 6 months later than in the northern hemisphere.

Insight into the seasonal variation is offered by the radar meteor observations of Keay (1963). Radar meteors are small particles on the order of those collected by the workers cited above. Consequently, variations in radar meteor flux is important to consider in this context. Keay found a high flux in the northern hemisphere during June, July, and August, the same time when largest numbers of particles were collected (fig. 14). In the southern hemisphere, greater fluxes were observed during December, January, and February, almost exactly out of phase with northern hemisphere data. Maxima of radar meteor flux occurred during summer in each hemisphere. It is known that the inclination of the Earth's axis to the orbital plane alternately presents each hemisphere more directly to the Sun every 6 months. The fact that greater numbers of particles are collected and/or detected during these times suggests that the Sun may exert an influence on particle deposit.

What follows is speculation. During summer when one hemisphere of the Earth is facing the Sun more directly, perhaps the solar wind is more effective in "blowing" particles onto the Earth, producing the variations in particle influx observed. Should this be the case, one might expect to find greater numbers of particles deposited during periods of intense solar activity such as sunspot maxima. The writer observed apparent correlation of particle frequency with periods of sunspot maxima in yet-to-be-published work on Antarctic particles, but the relationships are not clear cut. It is hoped that other students of extraterrestrial particles will also consider this problem so that more and better data will be obtained.

Earlier workers suggested that the seasonal variations in particle deposition was related to principal meteor showers. While this may account for part of the variation, it seems incapable of explaining the similar but out-of-phase results for the different hemisphers.

Measurements of microscopic extraterrestrial particles *in situ* by artificial Earth satellites were conducted from the beginning of the space age. These studies also yielded estimates of annual particle deposition on the Earth. However, the devices employed on satellites to detect particles were unable to differentiate between compositional types, and the values for annual deposit represent the total influx of all particles to the Earth. As table VII shows, the satellite results are in remarkable agreement, indicating that slightly more than 10^6 metric tons of microscopic particles of all types are deposited on the Earth each year. Part of the agreement may be apparent, produced by common assumptioms of particle velocity, density, and strength essential to interpret data from impact on satellites. Furthermore, as Crozier (1961) and Alexander (1963) cautioned, a large fraction of particles encountered by satellites may be in long-lived orbits around the Earth, and may not be deposited. Still, it is interesting that the annual deposit of black, metallic spherules is about 10 percent of the total particle influx as suggested by satellite measurements. The significance of this percentage is that it is in excellent agreement with the abundance of macroscopic metallic meteorites; Krinov (1961) noted that only about 6 percent of known falls of large meteorites were metallic. The apparent analogy in abundance is another similarity between metallic particles and metallic meteorites.

THEORIES OF ORIGIN

The data suggest that many microscopic, extraterrestrial particles are similar to larger meteorites in appearance, physical properties, chemical composition, and abundance. These relationships have weighted heavily upon theories of particle origin.

Murray and Renard (1883) suggested that the black, metallic spherules they recovered from oceanic sediments were produced by "combustion" and "fragmentation" of metallic meteorites during their passage through the Earth's atmosphere. Buddhue (1950) proposed a similar hypothesis. He reasoned that the spherical shapes and highly polished surfaces indicated that the particles had been melted and suggested that meteorite ablation yielded metallic micrometeorites. The writer interprets Buddhue's remarks on particle origin as including siliceous spherules, although they were not specifically mentioned. However, Bruun, et al. (1955) held a similar view, and suggested that silicate spherules were produced by ablation of stony meteorites. Castaing and Fredriksson (1958) adopted the ablation hypothesis as an explanation of the oxidized particle rim and distribution of iron and nickel in the particles. The argument is impressively supported by the data of quenching experiments which Bruun, et al. (1955) conducted with artificial iron-nickel-carbon melts. Molten metal was poured into a container of water from a height of about one meter, and black spherules identical to those found in oceanic sediments were produced. Clearly, the experimental work suggested that spherules could be produced through meteorite ablation. However, it was shown that even if the entire mass of each meteorite entering the Earth's atmosphere were converted to spherules, this amount would be insufficient to produce the number of spherules thought to fall to Earth each year (Parkin and Hunter, 1962). It would appear that this hypothesis is unable to account for the majority of spherules. Only those particles which occur at the places of fall of known meteorites such as Sikhote-Alin, Canyon Diablo, and others can be unequivocally explained by atmospheric ablation of a larger body. The writer therefore adopts this mechanism for the production of meteoritic dust.

Whipple (1950, 1951) and Öpik (1956) showed that microscopic particles larger than about 5 microns diameter would be heated to the melting point upon entering the atmosphere. Depending on entry angle, velocity, and materials comprising the particles, temperatures sufficient to produce thorough melting could be achieved. In this way, spherules could be produced from angular particles. (It is difficult to comprehend how Parkin and Hunter's flakes survived entry.) Alternatively, pre-existing spherules would undergo melting at least on surface layers to produce the oxidation zones noted. This mechanism appears capable of explaining the presence of spherules removed from the places of larger meteorite falls, and the writer proposes that micrometeorites are formed in this manner.

The origin of meteoric dust is probably related to ablation of cometary meteors in the Earth's atmosphere. Whipple (1950, 1955) regards comets as a conglomeration of ices of water, ammonia, methane, and carbon dioxide together with solid debris of a meteoritic nature. Friction with the Earth's atmosphere would cause the volatile ices to evaporate, freeing the solid particles to fall to Earth. Perhaps the amorphous coatings on metallic flakes represent samples of the cometary ices. This hypothesis may be supported by the work of Parkin and Hunter (1962), who found that metallic flakes were apparently related to meteoric activity; greater numbers of metallic flakes were collected following meteor showers. They suggested that the metallic flakes were embedded in a mass of oils or waxes of low volatility, which evaporate and cool the flakes during retardation in the Earth's atmosphere. As the waxes melt the metallic flakes would be freed in the meteoric wake. This hypothesis, however, remains to be proved since the origin of metallic flakes is in question.

The production of cosmic dust and interplanetary dust is more speculative than the apparent origins of the above materials. Probably, evaporation of cometary nuclei as they approach the Sun releases solid particles into space. Whipple (1955) estimated that about 30 tons per second of meteoritic material is continuously contributed to space by this mechanism. However, only about 3.5 tons of the total are added effectively to space, because many particles are lost through the actions of the interstellar wind, collisional destruction, attraction by Jupiter, and by the Poynting-Robertson effect. The latter is a retardation of the orbital motion of particles by the "braking" effect of solar radiation, which causes a slow, secular decrease in the semi-major orbital axis of any small body, and, ultimately, fall into the Sun.

Whipple's icy comet hypothesis appears to avoid the difficulty posed by the Poynting-Robertson effect, among the others, by suggesting a continuous source of interplanetary dust particles. In other words, at least as much solid material (interplanetary dust) is thought to be added to interplanetary space by the evaporation and/or disintegration of cometary nuclei as is lost to the Sun by the action of the Poynting-Robertson effect, and by other processes mentioned which might cause a decrease in its concentration.

Similar views are held by van de Hulst (1955). He estimated that interplanetary dust particles are at low temperature (10° to 40° K), and that they consist of ices of water, ammonia, methane, and metal impurities.

Along the same lines Squires and Beard (1960) noted that surface evaporation of comets takes place as these bodies approach the Sun. The material present is thus lost from the comet, and presumably forms its tail. Comets are though to lose a considerable fraction of their mass during one flight. The formation of the dust particles themselves, however, is poorly understood at present.

At least part of interplanetary dust may originate in the asteroidal belt through collisions between asteroids, meteoroids, and sporadic bodies. The asteroidal belt is a region of space between the orbits of Mars and Jupiter in which several hundred solid bodies of varying size are situated. Many believe that these were produced through the explosive breakup of a former planet (Ringwood, 1961). Internal collisions among the resulting fragments could be a continuous source of dust particles (Piotrowski, 1953). However, Harwit (1963) argued that most of the debris would be produced in very rare collisions between the largest asteroids, and that the dust cloud supplied by this means would be highly variable. It was concluded that no theory is capable of accounting for a steady cloud. Harwit suggested that a possible solution might be found in a process which would counter the Poynting-Robertson drag and permit grains to have longer lives in space. If that were possible, the comet dust supply would then be adequate to account for a steady-state dust cloud.

In addition to internal collisions in the asteroidal belt, it is possible that some dust particles may represent fragments of the lunar surface, dislodged by meteoroid or cometary impact (Gault, 1962; O'Keefe, 1962, personal communication). However, the character of such material and the amount contributed from this source are imperfectly known.

It was once thought that interplanetary dust particles were remnants of the original dust cloud from which our solar system originated. However, it has been shown by Öpik (1955) and by Wyatt and Whipple (1950) that even if our solar system did originate in this way, most smaller particles would have been swept into the Sun by the Poynting-Robertson effect. It thus appears unlikely that interplanetary dust particles encountered by contemporary space vehicles could represent original galactic dust.

Another source of interplanetary dust might be intergalactic clouds of dust encountered periodically by our solar system as it drifts through space (Best, 1960). The existence of such clouds in intergalactic space has been postulated because astronomical studies of the light emitted by stars and by the Sun show that it has been scattered, absorbed, and polarized. While the possibility that such material may contribute to the interplanetary dust content of our solar system cannot be ignored, present information is too limited to permit serious evaluation of the proportion of interplanetary dust which might be supplied by this source.

The ultimate origin of particles in space was examined by Cassidy (1963). It was suggested that, on the basis of chemical phase relationships at sufficiently high temperatures, it was possible for particles to form by sublimation from a supersaturated, primordial gas. Donn and Sears (1963) also considered the ultimate origin of particles. Crystal nucleation from a supersaturated, primordial solar nebula was proposed. Subsequent aggregation of crystals into larger bodies was proposed to account for the development of comets, planets, and other units. With the limited data available at present, however, it is difficult to evaluate these proposals properly.

A summary of the sources of microscopic, extraterrestrial particles as indicated by the above discussion is presented in table VIII. Robey's (1959) general scheme was adopted in constructing this table, although it was altered somewhat from the original form to include the preferred terminology used in this survey. The conclusions about particle origin which this table presents are tentative, however, and subject to revision. More definitive hypotheses can be formulated only when the results of quantitative chemical and physical studies of the particles become available.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., Oct. 7, 1964

APPENDIX

CHRONOLOGICAL RÉSUMÉ OF PREVIOUS WORK ON MICROSCOPIC EXTRATERRESTRIAL PARTICLES (SINCE 1945)

A brief chronological résumé of previous work on microscopic extraterrestrial particles since 1945 is presented below. The date 1945 was chosen as a limit for the present historical review of studies on such particles because Buddhue's (1950) monograph contains a survey of nearly all such research before that time. To allow this presentation to be employed as an extension of Buddhue's review to the present day, the form which he established will be observed.

1945 V'iunov discussed the role of meteor streams in the causation of magnetic storms and polar aurorae. He concluded that cosmic dust may cause disturbances of the terrestrial magnetic field. The greatest magnetic storm and auroral acitivity was in March and in September-October, coinciding with the periods of meteor showers.

1947 Landsberg reported collections of atmospheric dust collections at Mt. Weather and Arlington, Virginia. He described 25 opaque, magnetic particles, ranging in size from 0.005 mm to 0.1 mm diameter. He though the magnetic particles were related to the Giacobinid meteor shower, as no magnetic particles were recovered in the week before that event.

1949 Fesenkov discussed the brightness of the zodiacal band and the total mass of asteroidal matter. The total mass of asteroidal material that produces the phenomenon of the zodiacal light is proportional to the minimum size of particles. It was concluded that the transition between the asteroids and small fragments of matter is not continuous. Fairly large bodies, measured in kilometers, add nothing to the brightness of the zodiacal belt. Rather, it is produced by smaller, secondary material which originated as a result of continuous fragmentation in the region of the asteroidal ring.

Norris and Hogg reported collections of magnetic dust particles from the air. Contamination from local sources was found, but many particles gave positive tests for nickel and were considered of meteoritic origin.

Whipple defined the term micrometeorite as an extraterrestrial body that is sufficiently small to enter the Earth's atmosphere without being damaged by encounter with the atmosphere. The limiting circumstance arises when the micrometeorite radiates energy rapidly enough that its temperature remains below its melting point as its motion is retarded by the atmosphere. The limiting radius for a spherical micrometeorite varies approximately as the fourth power of the melting temperature, the inverse cube of the velocity, the inverse logarithmic density gradient at the point of maximum temperature, and the secant of zenith distance; it is about 3 to 5 microns. Larger particles (20-40 microns) may have been partially vaporized.

1950 In this year Buddhue published a monograph on "meteoritic dust." This valuable work contains a chronological survey of studies of such particles. Buddhue collected cosmic dust from the air in cans and on sticky slides, and to a lesser extent, from rain and snow. His work produced a valuable classification of such material, which is presented in an earlier section of this survey. The bulk of particles collected had physical properties and chemical compositions most closely akin to those of magnetite than to other known minerals. On the basis of measurements of grams of dust per centimeter of rainfall, the annual deposit of cosmic dust was estimated to be from 8 metric tons per year to 126,000 metric tons per year over the entire Earth. The particles examined were thought to have been formed by ablation of meteorites during their passage through the Earth's atmosphere.

Link suggested that there is a layer of dust particles in the Earth's atmosphere in order to explain light absorption observed during lunar eclipses.

Pettersson and Rotschi described analyses of sediment cores from the Pacific Ocean, in which unusually high amounts of Ni were found. The NiO content of the samples was roughly in inverse proportion to the rate of sedimentation. The origin of nickel in the sediments could have been from (1) sea water, (2) submarine vulcanism, or (3) cosmic dust. A cosmic origin was favored.

Whipple proposed his "icy comet" hypothesis, in which the cometary nucleus is thought to consist of a conglomerate of ices in which solid dust particles are embedded. Vaporization of the ices by externally applied solar radiation frees the dust particles, which are then distributed along the comet's path through space.

Wyatt and Whipple discussed the Poynting-Robertson effect on small particles occurring in the solar system. They noted that the Poynting-Robertson effect will operate to sweep small particles of the solar system into the Sun at a cosmically rapid rate. Because of this, they viewed meteor showers as originating from comets.

1951 Blanco reported collections of micrometeorites from rainwater and balloons in Puerto Rico. Several magnetic particles were obtained.

Ovenden reviewed the meteor hazards to space travel. Heavily armoured hulls or "meteor bumpers" were recommended for long-lived space stations.

Struve discussed in general the nature and occurrence of dust in our solar system.

Whipple discussed the theory of micrometeorites - small particles which can radiate energy fast enough that they do not suffer melting by atmospheric friction - in heterothermal atmospheres. A rigorous mathematical treatment of the problem was presented.

1952 Beals discussed the materials of interstellar space, thought to be parts of the process of star formation. Gases and dust particles and clouds were viewed as especially important for this process.

Gold showed that the dynamical interaction between galactic gas and those dust particles which are elongated will lead to a partial alinement of the particles under certain circumstances. The direction of alinement is that of the relative velocity between gas and dust.

Hoffleit compiled an annoted bibliography on meteoritic dust. A total of 505 references were listed.

Krinov and Fonton detected cosmic dust at the place of the fall of the Sikhote-Alin iron meteorite shower in the Soviet Union. They found traces of melted matter on the surfaces of these meteorites, and postulated that the dust particles were swept from the melting surfaces of meteoric bodies during passage through the Earth's atmosphere.

Millman surveyed data on meteor astronomy. The daily accretion of meteoritic material by the Earth was estimated to range from 10^3 to 10^4 tons.

Nininger discussed micrometeorites in a general description of meteorites and their occurrence in North America.

In this year Pettersson reported that the nickel content in most sediment cores from the central Pacific Ocean was much higher than the average value for normal continental rocks and sediments. It was suggested that this high nickel content may be caused by the presence of cosmic dust particles in the sediments.

Dalton suggested that meteoritic material encountered by the Earth may represent fragments resulting from destruction of a planet between the orbits of Mars and Jupiter. This was offered in exploration of the object responsible for Meteor Crater, Arizona.

Thomsen collected magnetic spherules in Iowa City, Iowa on March 14, 1951 following a heavy snowfall. Gravimetric analysis showed Fe_2O_3, 72 percent, SiO_2, 28 percent, with the presence of Ni doubtful. The magnetic spherules ranged from 0.008 mm to 0.08 mm in diameter. The annual deposit of such material over the entire Earth was calculated at 2,000,000 metric tons per year, with the adopted density of particles as 4.

1953 In the same year Handy and Davidson noted that industrial fly-ash, produced in quantity in the midwestern United States, has essentially the same composition as the "meteoritic dust" particles reported by Thomsen. They noted that "from a spectroscopic analysis Thomsen reported nickel as 'doubtful' in his samples; the authors believe that the identical adjective applies to the meteoritic origin of at least a part of his samples (for this reason)."

1954 Ahnert also doubted whether Thomsen's metallic spherules are of meteoritic origin. He noted that similar nickel-free dust was collected near factories.

Herzberg described studies of the spectra of interstellar material. Diffuse interstellar spectral lines were not considered as due to absorption by atoms of the Fe group embedded in interstellar grains. Rather, they were attributed to transitions of negative atomic ions (O^-, C^-, N^-, etc.) from their ground states to preionized states, corresponding to excitation of an inner electron.

Kaiser and Seaton discussed the relation of interplanetary dust to the physical processes in the upper atmosphere of the earth. It was concluded that the density of such particles is too low to play any significant role.

In this year Kizilirmak recovered metallic spherules from snow in and around Ankara, Turkey. The spherules contained iron, but no nickel, cobalt, or magnesium. More particles appear to have been recovered in the summer months; he noted a steady increase of particles until a maximum was reached at the beginning of July, afterwards a slow decrease occurred in the number of particles collected.

Svestka examined Link's (1954) proposal that there is a layer of dust particles in the atmosphere and concluded that particles larger than one micron cannot produce the absorption observed, and micrometeorites were probably formed from smaller particles on the order of 10^{-5} to 10^{-6} cm.

1955 Bowen examined rainfall figures for many sites, and discovered that there is a tendency for more rain to fall on certain dates than on others. A close correspondence between the dates of rainfall maxima were found for both northern and southern hemispheres. The rainfall peaks occurred approximately 30 days after prominent meteor showers, and it was suggested that they were due to the nucleating effect of micrometeorites falling into cloud systems in the lower atmosphere, the time difference being accounted for by the rate of fall through the atmosphere.

Bruun, Langer, and Pauly collected magnetic spherules from the deep ocean bottom with a magnetic rake. Several types of particles were recovered, some of which contained iron and nickel. Other particles had a silicate groundmass "loaded with magnetic crystallites." It was proposed that atmospheric ablation of stony meteorites may be responsible for the formation of such particles. Ablation of iron meteorites was viewed as a likely cause of formation of the metallic spherules. Quenching experiments with iron-nickel-carbon melts showed that spherules very similar in every detail to ocean-bottom particles can be artificially produced by rapid cooling of liquid metal. This evidence appears to support the hypothesis that these particles were formed by meteoritic ablation. The annual deposit was estimated to be about 30 metric tons.

1955 Buddhue reported a collection of micrometeorites from the Geminid shower of 1949. A total of 477 meteoritic spherules were collected on one slide; of these, 326 were black, 139 were siliceous, and 12 were metallic.

deJager stated that "the observed deposit of extraterrestrial dust on the Earth is by a factor of about 1000 greater than the deposit computed on the basis of observed meteor frequencies." Dust particles were thought to be captured in satellite orbits around the Earth, and drawn closer to its surface by the influence of solar radiation (Poynting-Robertson effect). It takes only a short time for the particles to fall to Earth, from the continuous supply furnished by this effect. The daily deposit of dust was estimated to be between 1.6 billion grams and 9 billion grams.

Heard reported that more spherules were recovered from air sampling over industrial centers (Windsor, Ontario, Canada) than in the Arctic. "No bright metallic spherules were found, and the particles that were are probably not meteoritic."

Kallmann has compared micrometeorites with interplanetary (zodiacal) dust in the size range 0.5 mm to 0.002 mm. It was found that there were two categories of dust particles in space; dense, fast moving meteoric particles "in all probability of cometary origin," and less dense, slower moving quiescent dust particles which are more abundant than the meteoroids and "whose origin might be connected with the origin of the planets."

Laevastu and Mellis studied material described by Pettersson (1952). They adopted a density of 5.2 for the spherules, and estimated that about 125 tons per year of black cosmic spherules ranging in diameter from 0.01 mm to 0.23 mm reach the Earth. It was noted that the high nickel content of sediment cores reported by Pettersson is too great to be accounted for by the cosmic spherules. Instead, it was suggested that the iron and nickel appear to be derived in part from coprecipitation from sea water.

Lebedinsky stated that "stars are originating as a result of gravitational condensation of diffuse matter (presumably dust). Diffuse matter is used up in formation of stars, but this is compensated by the ejection of matter from stars, creating a steady state system."

Levin found that the spatial density of dust particles decreased by a factor of 1/R with increased distance from the Sun. (The same relation was reported by others around this time also). In the vicinity of Earth, the density of particles was calculated to be about 10-23 g/cc.

Minneart noted that information on interplanetary dust may be obtained from (1) the zodiacal light, (2) the solar corona, and (3) meteors. He notes that methods (1) and (2) provide more information on the particles than can be inferred from meteors. Dust particles were found to occur in the ecliptic plane, increasing in concentration as the Sun is approached. The total mass of interplanetary dust was estimated at 10^{18} g. The interplanetary dust was thought to originate from meteoroid bombardment or from comets in such a way as to replenish the dust lost to the Sun by the Poynting-Robertson effect.

1955 Oört noted that interplanetary dust is absent in elliptical galactic systems and certain nebulae, but is quite common in spiral nebulae. He attributed an important function to the interplanetary gas in which the dust particles occur, viz, they are produced by condensation of the gas, and represent condensation nuclei.

Öpik suggested that the unusually high nickel content of deep-sea deposits of the Pacific Ocean were due to concentrations of nickel-bearing cosmic dust, along the same lines as Pettersson (1952). This was proposed following examination of some of Pettersson's samples.

Öpik noted that data on observational meteors indicated that they were a spongy, dust-ball type of much lower average density than that of the minerals of which they consist. They seemed to "decompose" (pulverize) from aerodynamic pressure, along the lines of Whipple's comet model.

In another paper of this year, Öpik found that the major fraction of space density (and from 30 to 40 percent of the recorded meteor numbers), belong to the class of zodiacal particles. The distribution of heliocentric motions of this material was concentrated in the plane of the ecliptic.

Stromgen noted that interplanetary dust particles contributed only about 1 to 2 percent of the total mass in space. The heavy element content of interstellar matter was about equally divided between the gaseous component and the dust particles; its total abundance was about 3 percent. The diffusion of interstellar dust particles through the interstellar gas under the influence of radiation pressure was slow, and the distribution of interstellar gas and dust was "generally identical." Dust and gas clouds were present in "dark nebulae." Large agglomerations of interstellar matter have been viewed as the place of star formation, but evidence from chemical compositions was "definitely against any mechanism of star formation that is characterized by concentration of the dust component relative to the gas component of interstellar matter."

van de Hulst reviewed the status of data on the likely properties of interplanetary dust particles. He estimated that the particles were at low temperature (10^{o} to 40^{o} K); probably composed of ices of water, ammonia, methane, and metal impurities less than 1 micron in diameter, that is, smaller than expected (some process is thought to limit their rate of growth); shaped like needles of flakes; and concentrated on the order of 10-13 particles per cc near the ecliptic plane. The dust particles were though to act on the interplanetary (solar?) gas, cooling it and also absorbing radiation.

Whipple discussed the amount of material added to the solar system by comets. "Some 30 tons/second of meteoritic material are contributed continuously in typical comet orbits..." However, most of this (all but about 3.5 tons/second) is lost by the effects of interstellar wind, collison, and Poynting-Robertson effect.

1956 Berg and Meredith discussed results of a high altitude rocket experiment in which an impact detector was flown to measure micrometeorite flux. Almost all recorded impacts occurred at altitudes greater than 85 km, and it was suggested that they were caused by meteoroids.

Bracewell measured the freezing nucleus concentration at Palo Alto, California daily during the month of January, 1956. Maxima were discovered on dates corresponding to meteor showers.

Burgess reviewed apparatus used in high altitude experiments, and described measurements of micrometeorites conducted by means of microphone detectors. No altitude dependence was shown by the impacts recorded, and it is possible that terrestrial dusts were encountered.

Crozier collected magnetic spherules from the air in New Mexico. He found that the rate of deposit of these particles might be correlated with meteor showers.

Dubin described an experiment for the detection of meteoric particles by means of an artificial satellite. A brief review of the subject, together with description of an acoustical particle detector for satellites, was presented.

Fredriksson found "several hundred black spherules, greater than 35 microns diameter, from different layers in the cores" taken by the Swedish Deep-Sea Expedition. These particles were composed of metallic iron nuclei surrounded by magnetite. The spherules were thought to be of Tertiary age, and the depth of their occurrence precludes any industrial contamination. They were thought to be of "cosmic" origin.

Griffith, Nordberg, and Stroud reviewed available data on the environment of an Earth satellite. One section of this review dealt with meteorites and micrometeorites.

Mayne examined the problem of the origin of helium in the Earth's atmosphere. As a result of this work, it was proposed that helium may be produced in extraterrestrial dust by cosmic radiation, and that dust particles contribute helium to the atmosphere as they encounter the Earth. It was estimated that about 5000 tons of dust particles are deposited over the Earth's surface each day.

Öpik reviewed the properties, amount, and terrestrial accretion of interplanetary dust.

Solid particles in interplanetary space will carry an electrostatic charge of the order of 200 volts, caused by photoelectric effects of radiation from the solar corona. The lower limit of radius of metallic particles in space is 7.2×10^{-6} cm as determined by radiation pressure, and 1.9×10^{-5} cm for compact stone fragments as shown by the disruptive force of electrostatic charge. The actual radii of "dust ball" grains are probably about 0.02 to 0.03 cm.

Particles above the minimum size limit, when charged to 200 volts, are not influenced appreciably in their motion by the terrestrial or solar magnetic fields, but are controlled by gravitational forces. The electrostatic charge is of primary importance in the interaction of solid particles with interplanetary gas. A quiescent, rotating cloud of zodiacal gas is incompatible with the data. Fast corpuscular radiation cannot be present in space with an average density of more than 5 atoms per cm^3, otherwise sputtering effects would destroy even meteorites. Only soft, corpuscular radiation is compatible with observations. At the upper limit of radiation intensity, drag of the corpuscular radiation on dust particles could exceed the Poynting-Robertson effect several hundred times.

Zodiacal dust consists of particles from 10^{-4} to 0.03 cm radius, frequency varying about as the inverse 2.8 power of radius. A mean space density is estimated at 2×10^{-21} gm cm^{-3}. The particles have low reflecting power. The zodiacal dust is the main source of terrestrial accretion, all other meteoric or meteoritic sources together accounting for less than 1 percent of the total.

Three processes of accretion may occur: (1) accretion by direct collision, (2) accretion through the gravitational lens effect, and (3) two-stage accretion through decaying satellite orbits. It was estimated that 2.5×10^5 metric tons of meteoric dust per year are deposited on Earth. Particles were thought to have velocities only slightly in excess of escape velocity from the Earth.

Plavec discussed the evolution of meteor showers. He noted that "although a relationship of several showers to the minor planets (asteroids) cannot be excluded, the majority of the streams no doubt are of cometary origin." Ejections from comets by internal forces appeared to be the main causes of meteor streams.

Singer reviewed knowledge about interplanetary dust particles, and presented a preliminary account of a simple charged-dust theory. These considerations were then applied to possible satellite experiments.

Stoiber, Lyons, Elberty, and McCrehan found magnetic (magnetite) spherules ranging in size from 0.005 mm to 0.1 mm in deep cores on Arctic ice island T-3. They thought them to be "probably extraterrestrial."

Süslü collected iron dust from the air at Ankara, Turkey. He noted that "it is probable that the iron particles are related to meteorites which are visually observed," although they did not contain any nickel.

Hecht and Patzak reported chemical analyses of cosmic spherules recovered by the Swedish Deep-Sea Expedition. They found compositional similarity with meteorites for Fe, Ni, and Co. They proposed a meteoritic origin.

1957 Dufay postulated that "dust particles (are) formed by condensation of intergalactic gas."

1957 Hoenig reviewed the hazards of meteoroids for space flight and concluded that for short periods of time, hazards were regarded negligible.

Kizilirmak described an objective method for measuring the fall of micrometeorites.

Ludlam reviewed knowledge on noctilucent clouds. These are thin cirrostratus-like clouds visible about an hour after sunset. They occur between altitudes of about 78 to 89 km, and are illuminated by the Sun's rays from beyond the horizon. The clouds occur mainly after mid-summer and are restricted to north latitudes between 55° and 70°. Particles in the clouds were estimated to be less than 1 micron in diameter, with concentrations of 10^{-16} g/cc. Noctilucent clouds may be composed of ice particles, volcanic dust, meteoritic dust, or interplanetary dust. The clouds are most likely composed of small solid particles, which may originate from terrestrial volcanic eruptions or from meteors.

Stephenson reviewed the nature of interstellar dust, and especially the problem of whether it could be accreted through interaction with interstellar gas. He concluded that such interaction cannot compensate for the influence of radiation pressure.

Yavnel reported nickel-iron particles 0.03 mm to 0.06 mm in diameter occurring in soil samples at the place of the fall of the Tunguska meteorite in the Soviet Union. He concluded that these particles were part of the meteorite.

1958 Astapovich concluded from a study of work on micrometeorites and cosmic dust in the Earth's atmosphere that more than 16,000 tons fell on the Earth each year.

Castaing and Fredriksson analyzed cosmic spherules from the Pacific Ocean with the X-ray microanalyzer. They found nickel to be present, and in greatest abundance (up to 31.6 percent) in the metallic nuclei of iron-nickel spherules. They considered it "most probable" that the spherules formed as drops drawn off bigger meteorites by friction against the atmosphere.

Hodge and Rinehart collected dust from high altitudes using high flying jet aircraft. "Some dark, shiny metallic particles may be extraterrestrial, since their abundance does not change rapidly with altitude, as with particles of terrestrial origin."

Hodge and Wildt collected opaque, shiny spherules less than 0.015 mm diameter on sticky slides. They thought them to be of meteoritic origin, in that the rate of fall and frequency distribution of particle sizes was the same at several widely separated stations. Assuming that the density of the counted particles was that of magnetite, they estimated the annual accretion for the entire Earth to be 500,000 metric tons.

1958 Kolomensky and Yudin discovered spherical particles in the fusion crust of the Sikhote-Alin meteorite. This appeared to support an origin of such material by ablation of iron meteorites during passage through the Earth's atmosphere.

Pettersson and Fredriksson described a study of cosmic spherules in sediment cores from the Pacific Ocean. The number of spherules was determined in various sediment fractions of several drill cores, but no correlation of spherule maxima between cores was possible. Spherules were found to occur in Tertiary sediments, refuting the hypothesis that meteoritic falls were limited to the last 25,000 years. However, there were strong indications that the frequency of spherules deposited in recent times was greater than in the past. (Or are the rocks just less perfectly compacted?) It was estimated that from 2,400 metric tons to 5,000 metric tons of spherules are deposited on the Earth annually.

Rinehart described the distribution of meteoritic debris about the Arizona meteorite crater. He employed a systematic sampling program and magnetic separation of meteoritic matter. He estimated that slightly less than 12,000 tons of finely divided meteoritic material is present in the soil about the crater. He noted a concentration of material to the east of the crater. The distribution is not smooth, but contains several areas where the density of meteoritic material is high. He postulated that the meteorite struck from the southwest, and sprayed fragments to their present position to the east of the crater.

Smales, Mapper, and Wood analyzed some of the spherules collected by Pettersson, using radioactivation methods. They found that the spherules contained from 0.03 to 3.9 micrograms Ni, 0.01 to 0.3 micrograms Co, 0.0006 to 0.53 micrograms Cu. They concluded that deep-sea spherules are closely similar to the iron meteorites.

1959 Barber and Sweitzer conducted a literature search of material on micrometeorites and related phenomena. They listed a total of 282 articles in an annotated bibliography.

Deirmendjian and Vestine described the nature of light from noctilucent clouds. The spectra may be explained in terms of primary scattering of direct sunlight by dielectric spheres with a maximum radius of 0.4 microns, and certain night sky emissions. They found the possibility of an ice composition of the clouds formed by condensation of terrestrial water vapor unjustified on physical grounds. They favored a siliceous composition and an interplanetary origin for the cloud particles.

Dubin reviewed the nature of cosmic debris in interplanetary space, and described measurements of these particles conducted by satellites. The daily mass accretion rate of such particles to the Earth, as determined by the Explorer I satellite, was 8.8×10^3 metric tons per day for all interplanetary materials.

1959 Fessenkov discussed the nature of the zodiacal light, and concluded that its properties can be accounted for by scattering of solar light by fine interplanetary dust particles. He suggested that the dust particles originated from the periodic comets without any appreciable velocity at their disintegration.

Gazley, Kellogg, and Vestine reviewed available data on meteoroids in connection with a general discussion of the space environment.

Hasegawa presented a discussion on collecting dust particles, together with an examination of theories of origin. The most common collecting method used by Japanese workers was vaseline-coated slides exposed to the air. He summarized Japanese work on these particles. Most dust particles collected in Japan range from 5 to 50 microns in diameter. They contained iron and nickel, and it was estimated that 0.9×10^{-1} particles fell per cm^2 of the Earth each day. The origin of particles was reviewed, and meteorite disintegration, meteor showers, and interplanetary dust were discussed as sources. The influence of meteorological variations on seasonal variations in dust occurrence was thought to be great. Most particles were thought to be due to meteorite disintegration.

Komissarov, et al. discussed a micrometeorite detector used on Soviet rockets and satellites.

Kreiken summarized work on the fallout of meteoritic iron particles at Ankara, Turkey. The number of particles appeared to be strongly affected by climatological conditions, and few particles were recovered following rainfall. The number of particles collected varied with the seasons: fewest particles were obtained in September, October, and November. It was estimated that 3,100,000 metric tons of iron particles fell on the Earth annually. This appears to be one of the highest estimates of the annual deposit of micrometeorites on record.

Krinov discussed nonterrestrial dust particles. Meteoric dust results from melting of a meteor in the Earth's atmosphere; the particles are spherical and have an entirely different chemical and mineralogical composition from the bodies that produce them, because the particles are oxidized in the air. Meteoritic dust is produced when meteorites strike the ground and has the same composition as the parent bodies. Cosmic dust enters the atmosphere directly from interplanetary space and is similar in composition to meteors. Micrometeorites are small particles with the basic properties of meteorites.

Lovering estimated that the influx rate of meteor particles during meteor showers may be as much as five orders of magnitude greater than the background rates given by satellite measurements.

Manring discussed results of micrometeorite measurements on 1958 alpha and gamma satellites. A maximum in flux rate of particles 10 microns in diameter or larger was obtained from 1 February to 7 May 1958. Unfortunately, the detector was apparently damaged by a meteor shower.

1959 Marshall suggested that particulate matter in polar ice caps could be used as a stratigraphic tool. He described a method for investigating this possibility.

Nishibori and Ishizaki described samples of micrometeorites recovered from snow at Syowa Base, Antarctica. The particle-size ranged from 5 to 60 microns.

Parkin and Hunter reported collections of particles from the atmosphere. They observed black, magnetic spherules ranging from 5 to 35 microns and found one needle 240 microns by 20 microns. They also obtained coated metallic flakes in which they detected nickel.

Redman discussed results of studies of the zodiacal light and solar corona, and their bearing on interplanetary dust. Particles influencing optical measurements were about 2×10^{-3} cm diameter, and had a space density of about 1 particle per cubic kilometer.

Robey presented a general discussion of micrometeorites. He thought siliceous and magnetic spherules originated from vaporized meteorites at high altitudes in the Earth's atmosphere. He believed a large quantity of smaller-sized dust to be cometary, either arriving directly from comets or indirectly from exploding or disintegrating meteoroids. The possibility that a portion of the influx of meteoroids may contain a sizable percentage of frozen molecular fragments has influenced the results. A diagrammatic presentation of the sources of interplanetary debris was presented.

Whipple reviewed available data on solid particles in the solar system as a part of a symposium on space exploration. He offered suggestions for studying these particles.

Yagoda obtained dust particles on plastic surfaces during stratospheric balloon flights. Positive nickel tests were found for material "presumably formed by the disintegration of larger units entering the top of the atmosphere."

1960 Best reviewed the works of several investigators on the accretion of micrometeorites by the Earth. He noted that by far the most numerous particles are of small size, 10 microns in diameter or less. He discussed several possible sources of meteoritic dust. These are (1) galactic dust outside the orbit of Jupiter which is attracted by the Sun's gravitational pull; (2) asteroidal belt dust; (3) fragments of meteors; (4) cometary ablation; and (5) interstellar dust clouds encountered by our entire galaxy.

Briggs computed the space density of dust particles at many points in the solar system. The formula assumes the distribution of dust particles to have rotational symmetry about an axis through the Sun which is normal to the ecliptic and also to have plane symmetry about the ecliptic. He concluded that there was a strong concentration of dust particles in the plane of the ecliptic with a sharp maximum at a distance of 0.06 a.u. from the Sun.

1960 Brown estimated, from data on observed meteorite falls in selected areas, that about 480 meteorites per year strike the Earth. He calculated the space density of meteoritic bodies weighing one gram and more to be 10^{-12} particle par cubic kilometer.

Buck described development of techniques for acoustic detection of meteoric particles. He presected specific details of electronic devices employed and rocket experimentation.

Crozier recovered magnetic spherules from sediments ranging in age from Recent to Ordovician. He estimated that about 150,000 metric tons of such spherules fall to Earth each year.

Dmitriev, Mishina, Mikirov, and Cherenkova investigated the influence of cosmic dust on the intensity of radiation passed through the atmosphere. They observed a weakening of solar radiation during the period of major meteor showers.

Dokuchayev considered the electrical change produced during passage of meteors through the Earth's atmosphere. The passage of a meteor through the upper layers of the Earth's atmosphere is accompanied by the formation of a strongly ionized trail consisting largely of electrons and ions of the meteor material. He considered therefore, that the meteoric particle may leave behind it a cloud of well conducting gas, surrounded by a gas having a considerably lower conductivity. The luminous aureole surrounding a moving meteor was thus due to a corona discharge in the front part of the ionized trail.

Dubin compared the results of particle measurements by satellites 1958 Alpha and Pioneer I. These measurements indicated a daily accretion rate for all types of interplanetary dust of 10^4 tons. This is equivalent to 3,650,000 tons per year for the entire surface of the Earth. If the particles are assumed to move with a velocity of 30 km per second, the density of interplanetary matter at the position of the Earth's orbit was 5×10^{-22} g/cc. There were indications, however, that the particles may move with a lower velocity relative to the Earth. High impact rates on one portion of the orbit of satellite 1958 Alpha were attributed to a meteor shower. Data from Pioneer I suggested that the particles are concentrated in the plane of the ecliptic. A daily variation in the number of particles impacting was noted, probably because of the heliocentric motion of the Earth.

Feller-Kniepmeier and Uhlig described electron-probe microanalyzer analyses of metallic meteorites. They studied macroscopic meteorites, not micrometeorites, but included a valuable description of experimental procedure and sample preparation.

Fesenkov reviewed present knowledge on the occurrence, characteristics, and origin of both interplanetary dust and meteoritic dust. Primary emphasis was placed on Soviet work.

1960 Gallagher and Eshelman discussed radar measurements which suggested that the conventional view of a few streams of meteor particles plus a large background of independently travelling sporadic particles is no longer valid. Instead, most of the background activity is caused by particles concentrated into numerous shower orbits. The concentrations of particles are very small, and it was estimated that there must be millions of shower orbits which intersect the orbit of the Earth. The number of independent shower orbits is so great, and the Earth encounters a given grouping so rarely, that is would be practically impossible to predict the occurrence of particular showers. The observed particle groupings, as most meteoric material in the solar system was believed to be associated with past or present comets, may indicate the presence of a large number of very small, subvisible comets.

Hawkins discussed asteroidal fragments and large meteorites. If the influx of such objects has been constant, the Earth has collected the equivalent of an asteroid 14 km in diameter during the last 5×10^9 yrs. It was estimated that the asteroids consist of 16.7 percent Ni-Fe, indicating a primary object that before breakup was intermediate in size between the Moon and Mars. The space density of meteorites was shown to vary as $(\text{radius})^{-4}$ and the total mass of meteorites with radius between 1 cm and 1 km was at least 5.6×10^{-24} g cm^{-3}. The size distribution of particles produced by the crushing of rock was similar to that found for meteorites and suggests that meteorites undergo a considerable number of collisions in space.

Hodge conducted a study of meteoritic particles from the Arizona meteorite crater, and estimated that the total mass of the original meteoritic material represented by these particles was about 12,300 short tons. This work also included atmospheric dust collected by high-flying vehicles. It was found that the amount of terrestrial dust at heights of 50,000 feet or more is greater than commonly believed. The influx of meteoritic particles into the Earth's atmosphere was less than generally quoted, only 28 particles per cubic meter of air, most in the size range from 3 microns to 6 microns in diameter.

Hunter and Parkin described studies of cosmic spherules collected from surface sediments of the Atlantic and Pacific Oceans. Three types of spherules were recognized: stones, stony iron, and iron. The stones ranged in size from 15-500 microns, the stony irons from 20-100 microns, and the irons from 20-384 microns. More spherules were found in the Pacific sample than in the Atlantic ones. The irons were blacker, smoother, and more rounded than the stones, which were quite gray and rough by comparison. Iron spherules contain up to 70 percent Ni in their center, but only about 1 percent in their oxidized shell. Stony spherules were less regular in form, often having craters on the surface. Creamy-white to pale yellow-green colorations were seen at the base of craters. The majority of stony spherules were solid gray-black throughout. The stones were a magnesium-rich, fine-grained olivine, and contained nickel. The origin of the particles were probably from meteorites or from the zodiacal cloud.

Jonah reviewed the physical properties of solid debris in space in connection with the design of space vehicles. He examined the mass, density, and total number of particles. He concluded that if the density of meteors were taken as 0.3 gm/cm^3, a zero magnitude meteor of the dust ball type would be about 5 cm in diameter, and would contain about one million particles with an average density of about 4 gm/cm^3.

1960 Krinov discussed microscopic dust particles from the Sikhote-Alin meteorite shower. He believes that meteorite showers are usually caused by fragmentation of one large meteorite as it passes through the atmosphere. In the process, many microscopic dust particles become separated from the main meteorite mass. These have the fusion crust and morphology of meteorites, and differ from cosmic dust that enters the atmosphere directly from space in that cosmic dust particles are practically unaltered by impact with the atmosphere.

Krzeminski briefly described the matter occurring in space between the Earth and Sun. His article is a review of earlier work.

LaGow and Alexander studied direct measurements of particles by instruments on satellite 1958 Alpha and 1959 Eta. Assuming that a significant number of meteoritic particles were not in orbit around the Earth, they suggested the daily influx of interplanetary matter on the Earth (particles between mass 1.2×10^{-8} g and 1.2×10^{-10} g) is approximately 10^4 tons per day. They discovered a daily variation in the dust particle density near the Earth.

Liller examined the tails of comets 1956h and 1957d photoelectrically. His studies showed that, at a solar distance of about two-thirds at an a.u., most of the radiation between λ 3400 and λ 6400 was of a continuous nature and redder than sunlight. This strongly suggested that spherules of iron in the comet tails, with an average diameter of 0.6 micron and mass of 8×10^{-13} gm, produced this radiation.

Lovering, Parry, and Jaeger studied temperature and mass losses by iron meteorites during ablation in the Earth's atmosphere. Temperature gradients were studied by examination of thermal alteration rims. The base of the thermal alteration rim indicates the depth to which a certain temperature penetrated. For a large meteorite, the temperature is given by

$$t = t_o \exp(-Ux/K)$$

where

t initial temperature

t_o melting temperature

U rate of ablation

x distance

k thermal diffusivity, $K/\rho c$

K thermal conductivity

ρ density

c specific heat

Surface ablation and heat alteration as described by the equation are not significantly affected by the size of the meteorite because heat penetration is negligible. Preheating does not affect the establishment of a steady-state condition. From ablation rates and time of flight through the atmosphere, it was estimated that two ataxites each lost about 27 percent by ablation.

Maringer and Manning discussed metallographic examination of the heat-affected surface zone of the Grant meteorite. This zone serves as a record of the thermal gradient which caused it during aerodynamic heating as it fell to Earth. The average rate of ablation was of the order of 1 to 2 mm per sec. If the meteorite spent 20 or 30 sec in passing through the atmosphere, the estimated total amount of ablation would be of the order of 2 to 6 cm, less than predicted by earlier workers.

Nazarova reported the results of "meteoritic dust" impacts on Soviet satellites and rockets. The density of meteoric matter in space near the Earth was found to vary in time and with position. High counting rates on May 15, 1958 (four orders of magnitude greater than other values) suggested that the satellite encountered a meteor shower.

Neugebauer compiled an annotated bibliography of articles dealing with the space environment of the Earth.

Pettersson presented a popular account of his 1958 work.

Shaw reviewed data on solid particles in interplanetary space as a part of a larger work on the natural environment of space. He presented a comprehensive compilation of existing information and current thoughts on the asteroids, comets, meteors, and interplanetary dust. He included a valuable bibliography.

Squires and Beard noted that surface evaporation of comets takes place as these bodies approach the Sun. The side facing the Sun is warmed, and the material present there is lost from the comet, presumably forming its tail. Comets lost a considerable fraction of their mass during one flight. Calculations suggested that an average comet nuclear radius could be as little as 300 meters if the material density is as much as 0.005 g/cc. The comet temperatures varied less than 25° from an average value of 165° K throughout their visible flight. Solar heating and evaporation were believed to be responsible for considerable changes in the cometary orbit. The material lost from the comet may have some sort of significance in connection with interplanetary dust.

1961 Alexander described micrometeorite studies from Earth satellites. He estimated the amoung of material falling to Earth to be about 10^4 tons per day.

1961 Alexander, McCracken, and LaGow reported exceptionally high interplanetary dust particle activity on satellite 1959 Eta at the time of the Leonid meteor shower. Many impacts of particles up to about 0.014 mm in diameter were recorded in a very short time.

Bain considered possible effects on magnetic field alinement on meteoric ionization. Field alinement of ionization along the Earth's magnetic lines results in enhanced scattering efficiencies. The magnetic field can maintain such a field alinement on ionization produced by a meteor trail, perhaps explaining the long duration of some meteor trails. Both overdense and underdense meteors would have long duration; however, underdense meteors would be detectable only on radar.

A considerable daylight radiant activity in the summer months was observed in Manchester, England, where these radiants lie very close to the plane of the ecliptic. This configuration placed the radiants within a few degrees of being parallel to the lines of force of the Earth's magnetic field. Thus, any general concentration of sporadic meteors would manifest itself as an increase in activity in the summer months.

Beard noted that planetary and solar gravitational attractions, together with angular momentum considerations, would tend to concentrate interplanetary dust in the plane of the ecliptic. This concentration varies as the inverse three-halves power of the solar distance, according to Beard. Observations of the dust-scattered light in the solar corona showed that the concentration of dust in interplanetary space was 10^{-14} to 10^{-15} particles per cc at the position of the Earth's orbit. However, space vehicle observations gave a flux density of 10^{-12} particles per cc at a height of 3000 km above the Earth. These observations were taken to indicate the presence of a dust blanket about the planets.

Bjork summarized current knowledge on the flux rate, mass, velocity, and density of meteoroids to assess their effects on space vehicles. He examined and tabulated the probability of meteoroid puncture as a function of vehicle area, exposure time, and skin thickness so that armor required to protect space vehicles could be determined.

Brandt and Hodge discussed the origin of the gegenschein. They believe it was thought that this effect is produced as a result of sunlight on a dust tail behind the Earth. They consider the Moon to be the source of the dust.

Brown revised his earlier estimate of the total fall of meteorites upon the Earth to 560 per year.

Cohen described measurements of the flux of small extraterrestrial particles using wire grids and microphones mounted on rockets and satellites. The mean influx of particles large enough to break the grid wires was likely to be less than 1.7×10^{-3} particles/m^2/sec, with short periods where the influx rates are greater. The average influx of particles on microphone detectors was 5.7×10^{-3} particles/m^2/sec. The mass distribution of particulate influx was most similar to that found for large meteor(ite)s.

1961 Crozier compared the annual mass accretion of particles to the Earth as determined by satellites (390,000 metric tons) with that of ground level studies of magnetic spherules (90,000 metric tons). He regarded the satellite data as uncertain because of the possibility that many of the particles encountered may be in orbit around the Earth.

Dauvillier presented a discussion about cosmic dust. He described the evolution, distribution, and nature of cosmic dust as related to comets, asteroids, meteors, and meteorites.

Davison and Winslow described the hazards to space vehicles resulting from natural space debris. They reviewed briefly the several types of materials which may be encountered in space and listed a total of 78 references.

Dingle argued that meteorite fall and dust influx is greater now than in the past.

Dubin described the instrumentation on the Explorer I satellite for detecting particulate matter in space. He showed a diurnal dependence by pointing out that 90 percent of the impacts occurred on the dawn side of the Earth between the hours of midnight and noon. He ascribed higher impacts registered over short times to meteor showers. He estimated that 10^4 tons of interplanetary matter are deposited on the Earth each day.

Eichelberger and Gehring discussed the effects of meteoroid impacts on space vehicles. They described the mechanism of crater formation by hypervelocity impact and applied it to various models of the behavior of materials and to the design of spacecraft.

Ericson, Ewing, Wollin, and Heezen noted the presence of "cosmic spherules" in abyssal sediments taken from the Atlantic Ocean.

Fesenkov reviewed investigations of meteorites and micrometeorites conducted by earlier workers.

Fireman and Kistner collected dust from altitudes greater than 40,000 feet using airplanes and balloons. The chemical composition of this material was very different from that of the deep-sea spherules. Fewer than 10 percent of the high altitude particles contained Fe, Ni, and Co in meteoritic proportions. The spatial density of opaque dust particles at high altitudes varied considerably, suggesting the existence of dust clouds. Their data indicated that about 30,000 metric tons of material with Fe/Ni ratios similar to that of meteorites fell to Earth each year.

Fisher discussed the erosion of iron meteorites in space. He estimated the maximum erosion rate to be approximately 1.1×10^{-8} cm per year, suggesting that previous erosion estimates were at least an order of magnitude too large.

Fletcher reviewed Bowen's (1955) hypothesis that meteoritic dust particles serve as freezing nuclei for rainfall, citing arguments in favor of the hypothesis, as well as presenting criticisms of the theory. The principal objection to the postulated explanation was that no simple mechanism for limiting the size range of efficient nuclei or transporting agency has yet been discovered.

Fredriksson described work on spherules collected in Hawaii. While these were similar to cosmic spherules, their composition and structure are different. They were deficient in nickel and were usually thin, empty, fragile shells. These were thought to be of volcanic origin.

Fremlin suggested that the concentration of dust in the space near the Earth was caused by ablation of meteorites which graze the outer portion of the Earth's atmosphere.

Goettleman, et al. reviewed data of meteor flux and mass obtained by terrestrial observations. They found that this information encompasses only the larger particles which may be encountered by a space vehicle. However, calculations of zodiacal light scattering have produced estimates of the character and size of interplanetary dust particles. Four classes of material were postulated; (1) high density spheres about 20 microns in diameter, (2) low density particles less than 20 microns in diameter, (3) solid, high density particles about 1 micron diameter, and (4) original galactic dust less than 1 micron diameter.

Satellite data showed that at some times meteoroid impacts were higher than at others. These were ascribed to many meteor shower orbits which intersect the orbit of the Earth. Characteristic dimensions of these particle concentrations might be about 10^9 meters, since the intersection of a meteor stream with the Earth might last from a few hours to a day. In addition, the measurements may indicate the presence of a number of very small, subvisual comets.

From this information, three theoretical models of meteoroid occurrence in space were examined. These were: (1) a continuous particle field, with no variation in the meteoroid flux with time; (2) meteoroid clouds in which the particle concentration varies with position in the cloud away from a center of highest particle density; and (3) an altitude-dependent version of the continuous particle field model in which a meteoroid halo or belt surrounds the Earth to an altitude of about 4000 km.

Goldmann and Hollister compiled an annotated bibliography on effects of micrometeorites on space vehicles. It included a total of 116 references.

Hagihara discussed gaps in the distribution of asteroids, and concluded that these result from the accumulated effects of disturbing actions by small masses passing close by.

Hart reviewed data on micrometeoroids in relation to simulation studies for spacecraft design.

Hemenway, Fullam, and Phillips collected large quantities of very small, high density particles approximately 75 Å in size on high altitude aircraft flights over Antarctica. The composition of these particles was similar to that of meteorites. Because of their small size, they were named nanometeorites.

1961 Hibbs concluded from particle impacts on sensors aboard satellite 1958 Alpha that the particles were traveling in closed orbits around the Earth, without sufficient energy to escape from the Earth's gravitational field. He found no apparent correlation between satellite position (relative to the Earth's motion around the Sun) and average particle impact rate. A decreasing impact rate with altitude was suggested by the data.

Hodge and Wright collected particulate matter from the upper atmosphere between 50,000 and 90,000 feet during aircraft flights. They estimated the average space density of particles larger than 3 microns in diameter to be 150 per cubic meter, but the space density varied considerably from place to place. They believed only a small percentage of these particles was to be of possible extraterrestrial origin. An upper limit for the space density of dust was from 10 to 20 particles larger than 3 microns diameter per cubic meter, and an upper limit to the influx rate of meteoritic material was approximately one million tons per day. Two-thirds of all particles were between 3 and 6 microns in diameter.

Hodge, Wright, and Hoffleit compiled an annotated bibliography on interplanetary dust with 205 references, including many on particles designated here as micrometeorites.

Hunter and Parkin found the remains of cosmic spherules in tertiary rock from Barbados. The metallic nuclei of the spherules had been removed by weathering, leaving only the iron oxide outer shell. Density and X-ray data showed this material to be magnetite.

Ingham examined the nature and distribution of interplanetary dust by observing light in high altitude experiments. He estimated smallest particles in space to be 0.2 to 0.3 micron in diameter. The mass density of particles in interplanetary space near the plane of the ecliptic was estimated to be about 10^{-24} gm cm^{-3}.

Isakovich and Roy discussed the acoustic method of detecting particles by Earth satellites. They stressed that careful calibration of piezoelectric elements is essential for obtaining usable data.

Jacchia and Whipple noted that meteors of interstellar origin would move in hyperbolic orbits around the Sun. These were thought to be gravitational members of the solar system. The vast majority (more than 99 percent) "must be cometary in origin." The number of meteoroids produced by the encounter of meteorites with the Moon was viewed as quite insignificant, and comets "seen to supply essentially all the visual meteors and probably also smaller meteoroids."

Jones and others reviewed data on meteoroids as a part of a study to develop techniques for simulating the natural environment of interplanetary space.

1961 Kaiser reviewed several methods for studying interplanetary dust. Among them are optical meteors, radio meteors, light scattering, accretion by the Earth, rocket and satellite experiments, and atmospheric studies. He summarized the results obtained by each method.

Keay and Ellyett described the latitude dependence of radar meteor showers. At a given observing station they found meteor rates to depend very strongly on the geographical location of the station.

Komissarov, et al. described apparatus employed in measuring the "solid component of interplanetary matter" on Soviet Earth satellites. This consisted of a ballistic-sensitive plate, which when displaced by particle impact yielded an electronic signal proportional to the particle's energy. Particles with mass from 8×10^{-9} to 2.65×10^{-8} g were encountered with an average frequency of 10^{-4} impacts/m^2/sec. A sharp increase in the number of impacts was registered on May 5, 1958.

Laevastu and Mellis studied the size distribution of cosmic spherules found in sediments and concluded that "the mass of particles in equal size (diameter) intervals remains constant, in accord with the relation

$$V_1N_1 = V_2N_2$$

where

V volume or mass of a single spherule in a given size group or diameter interval

N number of spherules in this size group"

LaGow, Schaefer, and Schaffert described equipment used on U. S. satellites to detect particulate matter in space with an average flux of 3.6×10^{-2} impacts/m^2/sec. The mean daily number of meteoric particles striking the Earth was estimated to be 4.0×10^{18} collisions/day.

Manring discussed the nature of interplanetary matter, and reviewed the progress made in study of these particles, including descriptions of spaceborne micrometeoroid detectors. He offered suggestions for future studies of such materials and suggested techniques for determing particle mass, density, diameter, and composition from space vehicles.

McCoy reviewed the space environment as a part of a study of hyper-environment simulation for spacecraft design. He devoted particular attention to particle impacts on materials likely to be used in spacecraft.

Öpik calculated the probabilities of collision, ejection, and orbital change in random close encounters of stray bodies with the planets.

Rasool examined the effect of major meteoric showers on the densities of the upper atmosphere. He concluded that with a daily accretion of 10^6 g of interplanetary dust, density will increase 5 to 8 percent at 344 and 660 km altitudes during major meteor showers.

1961 Rosinski and Snow calculated the size distribution of secondary particulate matter formed from condensing vapors in meteoric trains. They found the diameters of the particles to be approximately proportional to the size of the meteor and calculated the particles to be smaller than 100μ in diameter. They found the average concentration of secondary particles to be higher than that of sporadic meteors and suggested that Bowen's rainfall-hypothesis should be re-examined in light of these data.

Salisbury and Salisbury compiled an extensive annotated bibliography of lunar and planetary research.

Singer pointed out that rather than there being a "dust belt" about the Earth, there is in reality a "modest dust shell." He postulated a continuous increase in dust concentration to a maximum at about 2000 to 3000 km above sea level. This was only a few times the value of dust concentration in interplanetary space, not the factor of 1000 as given by Beard.

Skolnick examined magnetic spherules in well cuttings and cores of sedimentary rocks of Cretaceous, Miocene, and Pleistocene ages from central California. He postulated that this material was dominantly meteoritic in origin and that the Earth had been subjected to the fall of meteorite showers since at least late Cretaceous time.

Soberman, et al. described experiments with the "Venus Fly-Trap," micrometeorite collector rocket. In this work specially prepared particle collectors were exposed on an Aerobee rocket flight at altitudes between 88 and 168 km above the Earth and were successfully recovered. Three types of particles believed to be of extraterrestrial origin were identified. These were (1) dense spheres, 16 percent of the total; (2) irregular submicron particles similar in appearance to meteorites, 72 percent of the total; and (3) extremely irregular ("fluffy") particles, 12 percent of the total. The particles ranged from 0.1 to 1.0 micron in diameter, most having the smaller sizes. Electron diffraction studies were inconclusive, and the writers "... are beginning to suspect that micrometeorite particles do not have a crystal structure or that any original crystal structure has been scrambled by cosmic ray bombardment." The study indicated that (1) submicron particles are present in the region of space adjacent to the Earth; (2) the particles had low impact velocities upon the detectors and may have been in orbit around the Earth; and (3) an unexpectedly large number of particles were collected, suggesting the possibility of a meteorite shower.

Thiel and Schmidt reported the occurrence of metallic spherules in Antarctic ice cores. From data on the particle size, number, and annual accumulation of snow at collecting sites, the annual deposit of spherules was estimated to be 184,000 metric tons.

Utech described cosmic spherules from the New Red Sandstone. He recognized three types of hollow spherules: (1) rough, gray, Fe-Si spherules; (2) smooth, black Fe-Si spherules; and (3) rough, gray spherules up to 1.5 mm in diameter, Fe-Si, with a variety of shape modifications. He concluded that the spherules had a cosmic origin.

1961 Whipple studied acoustical impacts of micrometeoroids on sensors carried on rockets and satellites, and these data "... show clearly that a high concentration of interplanetary dust occurs near the Earth." He thought the concentration of interplanetary dust decreased roughly as the inverse 1.4 power of the distance from the Earth's surface, out to about 100,000 km, where it approximates the concentration of the zodiacal dust cloud. He found the dust in the vicinity of the Earth to be between 100 and 1000 times more concentrated than in the zodiacal cloud.

In another paper, Whipple stated that the "small, particulate matter of the solar system can be viewed as originating primarily in comets, distributed originally from typical comet orbits, with a considerable concentration toward the plane of the ecliptic." He discussed the physical properties of the dust, and also meteoritic etching rates in space.

Wiederhorn reviewed the meteoroid environment in connection with a study of effects of the space environment on liquid propellants and their storage systems.

Wright, Hodge, and Fireman reviewed the status of studies of micrometeorites, and described particles from the Earth's atmosphere, collected by high altitude aircraft. The average space density of particles greater than 3 microns diameter was 250 particles per cubic meter at 50,000 feet altitude. This value increased greatly for lower altitudes and appeared to decrease slowly for higher altitudes. Most of particles were transparent or semitransparent, with only about 1 percent resembling meteoritic material in appearance. These few particles led to an upper limit for the influx rate of meteoritic material of less than 10^6 tons per day.

Zaslow and Kellogg analyzed metallic spheroids from Meteor Crater, Arizona, using X-ray methods. Positive identification of kamacite, taenite, quartz, and magnetite were made. The existence of quartz in the spheroids was not thought to be inconsistent with an origin of the particles from a metallic vapor cloud.

1962 Alexander described cosmic dust experiments conducted by the Mariner II Venus probe. If the flux of dust particles in interplanetary space were assumed to be omnidirectional, about 10^4 times as many particles would be encountered by satellites near the Earth as were measured by Mariner II. Previous studies of dust particles in interplanetary space indicated a flux 10^2 times greater than the preliminary Mariner II value.

Alexander, McCracken, Secretan, and Berg reviewed rocket, satellite, and space-probe measurements of interplanetary dust. They described and tabulated measurements from microphone systems, photomultiplier and rocket collection systems, and fracture experiments. They used these data for estimating the cumulative mass distribution of the particles in the vicinity of the Earth and the annual mass accretion rate (10^4 tons per day). The fluctuations of the influx rate, however, suggested that the dust particles are not in long-lived orbits around the Earth. They estimated the average mass density of all particles to be approximately 1 g/cm^3.

1962 Briggs described a model for the distribution of interplanetary meteoric particles based on orbital data from observed meteors and the zodiacal light. He derived a steady-state distribution of orbits from these considerations as modified by the Poynting-Robertson effect.

Carleton studied the experiments of Volz and Goody (1962), and concluded that interplanetary dust particles must be essentially in orbit about the Earth. He further concluded that their contribution to the total mass accretion was "not overwhelming," and any effects of ionization or excitation were negligible. The dust cloud about the Earth was an adequate source of atmospheric dust, and about 260 metric tons per day are deposited on the Earth.

Carlson reviewed the space environment as a part of a study of the simulation of effects of meteoroids on space vehicles.

Caylor surveyed the effects of meteoroids on space vehicles. After making a general review of natural space debris, he devoted particular attention to meteoroid flux and penetration.

Crozier described studies on black, magnetic spherules collected from the atmosphere in New Mexico over a five year period. The average numerical rate of deposition for spherules larger than 5 microns diameter was 2.8×10^{-3} particles/m^2/sec. The average rate of mass accretion to the Earth was 1.6×10^5 metric tons/yr. The deposition rate dropped rapidly as diameters exceed 40 microns. Generally, the maximum spherule deposition occurred in the spring and summer months.

Dole demonstrated that the thin cloud of dust particles concentrated in the space near the Earth may be due entirely to the gravitational attraction of the Earth. The velocities of most of the dust particles in space that are eventually captured by the Earth were shown to be relatively low, permitting such concentration. Such particles, initially moving around the Sun on direct orbits in the plane of the ecliptic can produce a steady-state dust cloud about the Earth. The calculated particle flux was found to vary with the 1.66 power of the distance from the Earth's center, agreeing with satellite observations. Individual dust particles were continually entering and leaving the dust cloud, but the concentrations remained constant over time.

Dubin and McCracken presented a summary of measurements of interplanetary dust. The cumulative distribution curve of the influx rate of dust particles as a function of particle mass may be described approximately by the equation

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

where I is the influx rate in particles m^{-2} sec^{-1} and m is the mass in grams in the range from 10^{-10} g $< M < 10^{-6}$ g. The spatial density of particles was estimated at 1×10^{-20} g cm^{-1}. The spatial density of dust particles near the Earth was approximately 10^3 times greater than in interplanetary space. The accretion rate of interplanetary dust particles was about 5×10^4 tons per day.

1962 Fesenkov described direct methods for determining the density of cosmic matter in interplanetary space. He obtained a higher value than that suggested by studies of the zodiacal light. He suggested that the dust cloud around the Earth augments the influx of cosmic matter, and that the gegenschein phenomenon may be a manifestation of this cloud.

Gallant argues that there is no reason not to suppose the meteorites fell on the Earth before the "late Quaternary period," contrary to the views of Dingle (1961).

Harwit showed that radiation pressures in space can account for the formation of certain groups of stars, and for the acceleration of interstellar clouds in the vicinity of hot stars and galactic nuclei.

Hodge discussed the interactions of the planet Mercury with interplanetary material. The space density of material at Mercury's distance from the Sun is about three times that at the Earth's distance (1A.U.). He adopted particle orbits near Mercury of low inclination, low eccentricity, and primarily direct motion. He found about 10^3 times the mass of incident material to be displaced by impact, and concluded that Mercury has been severely eroded by interplanetary material. It is probably dust covered. If Mercury is assumed to have no appreciable atmosphere, about 10^4 g/sec of dust is ejected from the planet, and should form a faint tail opposite the Sun.

Hruška described the motion of a small meteoric particle in the atmosphere. Even if irregular, vertical motions of the air are present, the actual time of fall is not significantly different from that calculated under the assumption of a stagnant atmosphere.

Krivetsky, Bauer, Loucks, Padlog, Robinson, and Walters discussed micrometeorites as a part of a review of the space invironment in connection with zero-gravity expulsion techniques.

Kurt and Moroz examined the potential of a metal sphere in interplanetary space. The potential was shown to be within the limits -2.5 to +4 volts, assuming an interplanetary gas temperature of $10^{4\circ}$ K. Appreciable negative potentials (up to kilovolts) are possible in the outer radiation belt.

Levin maintained that the magnitude distribution of meteors is strongly influenced by fragmentation, so that estimates of mass distribution of meteors must be revised.

Magnolia compiled an extensive annotated bibliography on interplanetary matter of all types. He lists a total of 1650 references.

Mar described meteoroid puncture experiments on the first Canadian satellite. He concluded that during the first year of operation, there was only a 15 percent chance that one meteoroid would penetrate the inner payload. Exposed components, however, are susceptible to reasonable probability of penetration.

1962 Mason presented a general review of micrometeorites as part of a discussion of the entire subject of meteorites.

McCrosky and Soberman described experiments with an artificial iron meteoroid. A small, stainless steel pellet was accelerated from the nose of a high-speed reentry rocket. The purpose of the experiment was to determine the efficiency with which the kinetic energy of a meteoroid is transformed into luminous energy in the photographic region. The beginning of luminosity is accompanied by vaporization from the surface of the pellet or by vaporization from small droplets thrown off from it. They deduced that initial mass loss was due to melting and spraying.

Mrkos collected particulate matter from the snow at Vostok Station, Antarctica. He described spectral analyses and reported iron, nickel, and cobalt, but gave no data. He concluded that many of the particles were of cosmic origin.

Mirtov summarized Soviet research on "solid interplanetary matter in its finely dispersed form (micrometeorites)." The Soviets have recorded collisions of satellites with particles of mass 10^{-7} g to 10^{-9} g, and have derived estimates of 5000 to 10,000 tons per day. They believe a dust cloud exists around Earth, increasing in density toward its surface. They estimated the maximum concentration of dust particles to be at a distance of about 100 to 200 km from the Earth's surface.

Neugebauer compiled references published since her earlier review.

New briefly summarized knowledge on micrometeorites and micrometeoroids as a part of a survey on the dynamic environment of space.

Newkirk and Eddy presented data obtained during high-altitude coronagraph observations.

Newkirk and Eddy investigated the influx of meteor particles in the upper atmosphere by stratospheric coronagraph observations. They confirmed the existence of an aerosol layer at approximately 65,000 feet. Most of these particles are probably terrestrial in origin. Above this layer, the particle concentration drops sharply, and it is assumed that a steady state occurs.

Newkirk and Eddy, in another paper, gave a more general account of their high-altitude coronagraph experiments and an excellent description of the equipment and techniques used.

Parkin, Hunter, and Brownlow described collections of atmospheric dust on the Isles of Scilly during 1961. The concentration of metallic iron varied, and showed three main peaks. These may be correlated with the Arietids, B-Taurids, and Perseids meteor showers if the dust is allowed a delay of about 3 weeks in falling from the upper atmosphere. This was in accord with Bowen's (1953) rainfall hypothesis. Iron-nickel and even pure nickel particles were observed. Attachments were sometimes found adhering to the metal particles. These were frothy cream color, with transparent nodular excrescences sprouting from the surface. In the dry state it gave no indication of the Ni metal flake embedded in it. Refractive index of the transparent, amorphous material was 1.547 to 1.540. This amorphous material might be partly organic, and where not charred by impinging on the atmosphere at high speed, may represent cosmic dust in its original state. A very nickel-rich flake of metal embedded in an amorphous material which had a refractive index of 1.549 was found in Antarctic melt water. In transmitted light it was a pale yellowish green, and in reflected light is appeared a frothy white or cream.

1962 Parkin and Hunter reviewed the salient facts about meteorites in connection with a study of extraterrestrial dust particles. They concluded that the dust particles were either meteoritic or meteoric in origin. They thought meteoritic particles originated from planetary destruction followed by subsequent internal collisions among the fragments and ascribed meteoric particles to ablation of cometary meteors, especially principal meteor showers.

Parkin and Hunter described the apparatus and techniques employed in collecting iron dust from the air, and presented the results of initial experiments. They found that the accretion rate of iron dust varies with meteoric activity, and that the particles fell to Earth shortly after meteor showers. This does not support Bowen's rainfall hypothesis, which requires a larger time for particles to settle.

Spherical particles were shown to be produced by the melting of minute meteoritic fragments (and thus should be classed as micrometeorites). Ablation of meteorites, once thought to be the cause of spherules, cannot produce sufficient material to account for the annual spherule deposit.

The iron flakes collected were thought to originate through the evaporation of volatile ices from cometary meteors, freeing the flakes to the meteor wake.

While in space, the particles would be electrically charged which would inhibit any influence upon the path of the particles by the Earth's magnetic field. This would be especially true if the particles were traveling at meteoric speeds. However, if ionized interplanetary gas exists, there would be strong interaction between the gas and the particles. The particles would be brought to rest with respect to the gas, and drift with it, perhaps becoming concentrated over the auroral zones of the Earth. (This process would be aided if the particles traveled more slowly than at meteoric velocities.)

Pskovski reviewed knowledge of dust in circumterrestrial space.

Riggs, Wright, and Hodge reported chemical analyses of particles collected by high-altitude aircraft and balloons. They used an electron-probe X-ray microanalyzer. Unfortunately, only a few particles are thought to be of meteoric origin; most are apparently of artificial origin.

Ruskol discussed the origin of the concentration of dust around the Earth, based on satellite measurements. The concentration near the Earth was found to be 10^5 times larger than the zodiacal cloud concentration. Most particles are thought to be in orbit about the Earth. Whipple's suggestion that particles are contributed by impacts on the Moon was discounted. Two mechanisms for concentration of dust particles near the Earth are proposed: neutral inelastic collisions and atmospheric deceleration. Neutral inelastic collisions among dust particles causes loss of velocity by transfer of kinetic energy into heat and deformation. This would account for the concentration at 500 to 1000 km altitude. Atmospheric decelerations cause dust velocities to decrease, causing the particles to fall to Earth. Maximum deceleration will occur in the region 100-300 km above the Earth's surface; explaning the concentration of dust particles observed there.

1962 Salisbury, Van Tassel, and Adler compiled a bibliography of lunar and planetary research published in 1961. A total of 265 references were included.

Shoemaker suggested that the particles discovered by Kordylewski near the Earth-Moon triangular Lagrangian points may be ejecta from hypervelocity impact on the Moon.

Singer investigated the effects of solar radiation pressure and solar corpuscular drag on zodiacal dust. Solar radiation pressure produces a force opposed to solar gravity, which leads to an appreciably lower circular orbital velocity. A pronounced anisotropy in density distribution about the earth is produced; should be higher in the evening. The solar corpuscular drag leads to a spiraling of dust particles toward the Sun if the interplanetary gas is streaming outward from the Sun. If a gas cloud rotated with solar angular velocity, the effect is in the opposite direction, and particles would spiral outward.

Smith considered the problem of deposition in atmospheric diffusion of particulate matter. He presented a mathematical development of the problem.

Storebø suggested that meteor particles down to 10 microns diameter could initiate raindrops by colliding with cloud droplets.

Utech reported cosmic spherules from lower Triassic sediments. The main components of these particles were magnetite and olivine or bronzite. These are thus older than the late Quaternary, contrary to the work of Dingle (1961).

Valley reviewed data on space and planetary environment. Micrometeorites which he mentioned only briefly will be the subject of a later survey.

Volz and Goody conducted measurements of the absolute intensity of twilight in an attempt to derive quantitative data on dust concentrations in the upper atmosphere. They found maximum dust concentrations near 20 km elevation, fewer amounts at higher altitudes, and a seasonal maximum during winter months.

Wright and Hodge reported collections of extraterrestrial particles by high-flying aircraft. The mean space density of particles greater than 3 microns diameter was 4,000 per m^3 at 40,000 ft, and decreased to 1,000 per m^3 at 87,000 ft. The space density of small spherical particles (cosmic dust) was 3 per m^3 at 45,000 ft. The rate of fall of these particles was 0.3 spherule/an^2/day. About 2×10^8 kg of this kind of particle fell to the Earth each year.

1963 Alexander reported on studies of interplanetary dust in the triennium (1960-1963) report to the International Union of Geodesy and Geophysics. He summarized both direct and indirect measurements bearing on particle composition, dynamic properties, and origin.

Alexander and McCracken reviewed dust particle fluxes as determined by satellite measurements.

Alexander, McCracken, Secretan, and Berg reviewed direct measurements of interplanetary dust from satellites and probes. They established a cumulative influx curve for particles between 10^{-6} and 10^{-13} g. The accretion of interplanetary matter by the Earth is dominated by small particles with masses less than 10^{-6} g. A conservative estimate of the accretion rate is 10^4 tons per day. The influx rates undergo large fluctuations, and some were correlated with meteor showers. The fluctuations suggest that dust particles are not predominantly in long-lived orbits about the Earth.

Ali reviewed information available on meteoroids, giving particular attention to the meteoroid hazard to spacecraft.

Baker described research into the velocity of faint meteors. A real seasonal variation in the observed velocity distribution of faint meteors was discovered. Despite this seasonal effect, the observations still seem to indicate a decrease in average velocity with magnitude.

Beard reviewed data on comets and cometary debris in the solar system. Comets were described as icy conglomerates with low structural strength and density. As they approach the Sun, gases and dust are released, and the comets become visible. Most cometary major axes are probably very much less than those assumed to move in simple Keplerian orbits. On the average, about 30 tons of cometary debris are ejected into the solar system each second; when this material encounters the earth's atmosphere, meteors are produced. Much of this debris is removed by perturbing forces such as solar radiation pressure. The Fraunhofer component of the solar corona is a result of light diffraction by micron-sized particles occurring in space. The concentration of particles in space near the Earth was estimated to be 10^{-15} particles cm^{-3}. Gravitational attractions result in an enhancement of dust in the region of the planets.

Black surveyed the space debris environment and hazards to spacecraft from that source.

Bowen reported that the radar meteor rate, rainfall, and freezing nucleus count all vary in a similar way with lunar phase.

Boyle and Orrok considered the problem of penetration of spacecraft on the lunar surface by lunar secondary meteoroids. They concluded that particles of the lunar surface dislodged by meteoroid impact have a low probability of penetration of spacecraft.

1963 Brierley and Davies reported radar meteor rates which suggested a relationship with lunar phase, similar to that found by Bowen (1963).

Cassidy reported on radioactivation analyses of cosmic dust. Only iron was detected, with the exception of one glassy spherule which gave a remarkable similarity to average tektite composition.

Cassidy described experimental data bearing on questions of cosmic dust genesis. From consideration of a part of the Fe-Mg-Si-O system, it was concluded that a wide range of compositions in the Fe-FeO-MgO-SiO_2 subsystem would split into three mutually immiscible liquids at temperatures greater than 1681° C $\pm 2^\circ$. For an appreciable range of composition three-liquid immiscibility may exist up to vaporous temperatures. Initial chemical segregation during condensation of cosmic dust could be extreme.

D'Aiutolo described results of meteoroid penetration experiments with Explorer XVI. The data indicated that for thin metal sheets, meteoroid penetration may occur 10 to 100 times less frequently than has been assumed.

D'Aiutolo described satellite measurements of the meteoroid environment, as determined by Explorer XVI. The flux estimated as a result of penetrations in thin metallic sheets was much less than other satellite flux measurements.

D'Aiutolo reviewed the meteoroid environment based on satellite measurements with Explorers XIII and XVI. These spacecraft carried several impact and penetration detectors to record encounters with meteoroids. On the Explorer XVI, 10^{-2} cm thick aluminium had about 10^{-6} penetrations m^{-2} sec^{-1}. This rate was greater than that estimated by Watson-Bjork but less than estimated by Whipple or Charters and Summers. Explorer XVI data indicated a lower dust frequency near Earth than reported by earlier workers. These results indicated a penetration frequency essentially identical with estimates of particle concentration in interplanetary space. It may be possible to design spacecraft with less shielding against meteoroid impact.

Davidson and Herbach considered the dispersion of clusters of particles in the atmosphere. They reported that two important physical processes contribute to separation, turbulence, and varying terminal velocities. They found deposition to be dependent only on the logarithm of the ratio of the median terminal velocity to the friction velocity, and on the coefficient of variation of the terminal velocity distribution.

Donn and Sears applied crystal growth theory to the formation of particles from the primordial solar nebula. The particles are expected to grow as filaments and thin platelets. Such particles, upon collision, would form loosely packed "fairy castle" or "lint ball" structures of low density. Such particles would facilitate successive aggregation into planets, comets, and asteroids. The difficulties associated with the aggregation of spherical smoke particles would be avoided.

1963 Donn discussed the origin and nature of solid particles in space. He reviewed the paper by Donn and Sears, on the origin of particles in space and compared the source and sample material to direct sampling programs for these materials.

Dubin examined the effects of meteoroid impacts on space exploration. Following a review of data on meteoroids and cosmic dust, he presented estimates of expected impact rates as a function of mass. For a density of 2 g cm^{-3} and velocity of 30 km sec^{-1}, he calculated an "effective expectation of impact frequency" by meteoroids. This shows that the flux of meteoroids which could prove a hazard to spacecraft is considerably less than early estimates. Relatively long exposure times over extended surface areas would be required to obtain experimental data in the space environment.

Dubin, Alexander, and Berg described satellite measurements of cosmic dust which indicate large fluctuations in flux. In addition to daily variations, periods of greater flux appear to be associated with cosmic dust streams. A stream was detected beginning February 2, 1958, although it does not correspond to any known annual meteor shower. A second dust stream was apparently related to the Leonid meteor shower.

Fechtig and Utech reported on X-ray and laboratory experiments with micrometeorites and meteoritic iron. They examined spherules from the Albatross expedition and German oil wells and prepared samples of meteoritic iron and artificial Ni-Fe alloy which showed oxidation zones similar to those shown by the natural spherules.

Fechtig and Utech described spherules recovered from sediments collected during the Albatross Expedition. They examined polished surfaces of spherules, and discovered that some had an acentrally located nickel-rich "core," surrounded by iron oxide (magnetite). Many spherules had no cores, and they postulated that the cores had been dissolved. They concluded that spherules need not contain nickel to be considered cosmic in origin. An experiment with an iron meteorite yielded apparent concentration of nickel toward the interior of the body. They concluded that the smaller a meteorite gets by ablation, the higher its concentration of nickel. Furthermore, they regarded the nucleii of spherules as a birth scar or navel with which the spherules had been connected to its mother substance until final separation.

Fredriksson and Gowdy reported studies of meteoritic debris from the Southern California desert. Electron probe analyses of many spherules revealed two of probable meteoritic origin. These were attributed to a cosmic origin.

Fredriksson and Martin discussed the origin of black, magnetic spherules from various sources. On the basis of electron probe analyses of polished surfaces of spherules they concluded that many particles found in deep sea sediments and on Pacific islands may be of volcanic origin. The particles gave positive results for Fe, Ti, and Mn, but showed little or no Ni or Co. Estimates of the accretion rate of cosmic particles derived by counting black spherules are likely to be uncertain, because of the difficiency in nickel of many particles. Hollow spherules are likely to be of volcanic origin.

1963 Fesenkov studied the fragments resulting from the 1908 impact of the Tungus meteorite in Siberia. The retrograde motion of the body, the strong aerial explosion, wide distribution of debris, lack of fragments or craters at the site of explosion, and anomalous light scattering shortly following the event suggest that it was a small comet rather than a meteorite.

Gault described hypervelocity impact experiments which indicate that interplanetary debris impacting on the Moon causes lunar material to be injected into space. Trajectories indicate that much material escaping the lunar gravitational field is hurled into geocentric orbits; this material presumably contributes to the Earth's dust cloud and eventually may be deposited on the Earth's surface. Terrestrial accretion of lunar material appears to be a continuous process and a means of obtaining lunar samples from the Earth.

Giese reviewed models of interplanetary matter derived from scattering of the zodiacal light. A model for light scattering by small ($<$ 0.2 microns), spherical solid particles by Rayleigh-like scattering and without contributions from electons accounts for both the brightness and polarization observed in zodiacal light. Further models describing scattering functions of nonspherical particles, similar to those collected by sounding rockets, are needed to provide additional information on the problem.

Graziano and McCormick compiled an annotated bibliography on the meteoroid hazard to space vehicles and listed a total of 78 references.

Greenberg reviewed data on interstellar grains which were obtained from astronomical or astrophysical sources.

Greenman described heat annealing experiments on Venus Fly-Trap particles. Diffraction spots distinct from the substrate and likely contamination appeared after heat treatment.

Grjebine reported on collections of dust particles made by means of radioactive fallout detectors in metropolitan France. It was estimated that 2.4×10^9 metric tons of such dust are deposited on the Earth each year. If this rate had continued for 3×10^9 years, a layer about 7 km thick would have been deposited, which is about the depth of the Mohorovicic discontinuity beneath the oceans.

Grjebine reported on collections of dust particles made in France by radioactive debris collectors and air filters. If the average iron content is assumed constant for all cosmic dust samples, cosmic dust can be detected by a "magnetic weight" method. This method yielded an estimate for annual accretion of 2.4×10^9 metric tons per year. Relatively uniform results were found for several sites in a large network. Possible sample contamination from eolian pollution and industrial sources was considered negligible. The density of cosmic dust in the air is variable, and higher concentrations were found by ocean ships than land stations. The rate of fall of particles through the atmosphere is so fast that no transport of dust is likely. The similarity in peaks of particle influx observed at the same time at several places, by different investigators suggests that dust is introduced to the atmosphere on a world-wide scale.

1963 Grjebine, Lalou, Ros, and Capitaut studied magnetic spherules from sediments of the Mediterranean Sea. The particles were magnetically separated from dispersed sediment and examined microscopically. Several types of particles were recognized: shiny black spherules, slaggy black spherules, two types of brown spherules, transparent spherules, and white spherules. Some hollow spherules were found, as well as some which had a "shiny nucleus." In general, fewer spherules were found in coarser sediments. There was no systematic correlation between the occurrence of spherules and amounts of Fe, Ni, and Mn in the sediment. They reported qualitative electron microprobe analyses and concluded that the particles are of cosmic origin.

Harwit discussed the origins of the zodiacal dust cloud. Much of the dust emitted by comets was shown to be soon lost because the Sun's radiation pressure pushes the grains out of the solar system. The adequacy of present models of the zodiacal cloud to explain the observed concentration of dust was examined. Comets are unlikely to provide dust at a rate comparable to Poynting-Robertson losses. Asteroids may supply dust, but the supply must be highly variable, and the zodiacal cloud cannot be in a steady state. The present epoch would then have to be one of unusually high dust density.

Harwit examined the possible origins of interplanetary dust. An asteroidal origin was found to be incompatible with a steady-state interplanetary cloud. Interstellar dust could be captured by the solar system from accretion or by solar radiation pressure. Neither of these mechanisms could be important at the Sun's present speed with respect to the interstellar medium.

Hastings described the Explorer XVI micrometeoroid satellite, which carried several different experiments, including pressurized cells, wire grids, cadmium sulfide detectors, and sounding boards.

Hastings gave preliminary results for the Explorer XVI satellite. Data indicated that the rate of puncture was intermediate between the lowest and highest estimated rates. Solar cells were degraded by space erosion less than 14 percent.

Hastings reported on continued micrometeorite experiments with Explorer XVI. The puncture rates remained the same as in the previous period.

Hawkins discussed meteorite impacts on the Earth and Moon. Although 9 out 10 meteorites are stony, the larger objects which collide with the Earth may be predominantly iron. It was assumed that rates for the surface of the Moon are 1/2 of the rates for the Earth. He concluded that the near-approaching asteroids are iron objects, although the bulk of material in the asteroid zone may be nonmetallic. The maximum size of object to collide with the Earth was estimated at 10^{17} kg; for the Moon, 10^{16} kg.

1963 Hawkins, Lindblad, and Southworth described radar meteor results bearing on the velocity of faint meteors. They found a systematic change in average velocity which depends on magnitude and thus on size. Smaller particles have lower velocities. There were indications that the change becomes more pronounced for the fainter meteors. The average decrease was about 5 km sec^{-1} for 3 magnitudes. The effect was attributed to the difference in orbits between the various meteor populations.

Hawkins reviewed principal facts about "the meteor population." Although average-sized meteorites are usually stones, very large meteorites are usually irons. The distribution laws for each are consistent with the hypothesis that meteorites are asteroidal fragments. Particles with mass between 10^{-12} and 10^{2} g are predominantly derived from the icy nucleus of a comet. About 50 percent of the meteor flux comes from major streams, the rest from sporadic meteors. Cometary meteors are extremely fragile, and small particles investigated by radar techniques show fragmentation. In general, smaller particles suggest lower velocity. No evidence was found to support the myriad showers postulated by Eshelman and Gallagher (1962). Micrometeorites have a maximum diameter of about 40 microns at 15 km sec^{-1} velocity and an over-all density of 3 g cm^{-3}. The probability of particles impacting with spacecraft is "trivially small."

Equations for mass distribution of the several-sized particles were developed.

1. Stone meteorites:

$$\log_{10} N = -0.73 - \log_{10} m$$

2. Iron meteorites:

$$\log_{10} N = -3.51 - 0.7 \log_{10} m$$

3. Cometary meteors:

$$\log_{10} N = 0.41 - 1.34 \log_{10} m$$

4. Micrometeorites:

$$\log_{10} N = 12.43 - 0.39 \log_{10} m$$

where N = number; m = mass.

Hawkins and Southworth described the physical characteristics of meteors as determined by the Harvard radio meteor project: A progressive change in the physical characteristics occurs from brighter to fainter objects. Bright objects are probably solid fragments, while faint objects are thought to have low strength and density. A direct relation of mean height to velocity of radar meteors was discovered. The height decreases for faint meteors. The relationship was interpreted as follows: bright meteors continuously shed fragments as they pass through the atmosphere, and behave somewhat as a single body. Larger meteoroids are fragile, and particles are given off early in the trajectory. Fainter meteors, however, disintegrate completely at the beginning of the trajectory, possibly because these meteoroids are so small. The number of fragments is almost independent of the mass of meteoroid, suggesting that the fragments may be unequal in size, and many smaller fragments do not contribute to total ionization.

1963 Hemenway, Soberman, and Witt described collections of particles from noctilucent clouds. This short note was a preliminary account of the investigation.

Ingham reviewed knowledge of interplanetary matter. Most of interplanetary matter was considered to be particles of about 0.3 microns radius and 3g cm^{-3} density. The zodiacal light was assumed to be caused by the scattering of sunlight by dust particles. Many smaller particles were thought to be involved in light scattering, rather than few larger ones. While spherical particles were assumed in calculations, many grains are probably irregular. The Earth's dust cloud may be comprised of particles too small to survive the forces of radiation pressure in interplanetary space. The gegenschein was thought to be caused by reflection of sunlight from dust particles in the Earth's cloud being drawn out in a tail opposite the Sun. Dust particles in space may be of cometary and/or asteroidal origin.

Jacchia discussed the interrelationships between meteors, meteorites, and comets. He reviewed the history of research in this area and described the "present-day picture:" Meteor streams are formed by particles ejected along comet orbits. Meteor streams are dispersed by a number of perturbing forces: gravitational attractions, Poynting-Robertson effect, solar radiation, and drag from interplanetary medium. Physical characteristics of meteor showers suggest that the meteors are fragile, and that strength is relatable to orbital character and age of the stream. Brighter meteors are caused, at least in part, by asteroidal fragments.

Jiusto and Eadie examined the terminal fall velocity of radar chaff. They presented a theoretical development of forces on such particles, based on a circular cylinder. Terminal velocity was found to be approximately

$$V_t \approx \frac{\left[\left(\frac{\pi}{21}\right) \rho_c g\right]^{0.73} d^{1.19}}{\mu^{0.46} \, \rho a^{0.27}}$$

where

ρ_c cylinder density

ρa air density

d cylinder diameter

g gravitational acceleration

μ dynamic viscosity

Graphs of this function versus height were given.

1963 Kaiser examined the distribution of interplanetary particles: Satellite data yield a different distribution function than meteor, accretion, and zodiacal light data, and suggest higher spatial densities of smaller particles. A cloud of particles in geocentric orbits, probably resulting by capture from the zodiacal cloud, is postulated.

Kaiser reviewed data on meteors and the abundance of interplanetary matter. Photographic and radar observations of meteors were described. Photographic data suggest that there is a maximum meteor rate in the morning, and, in the northern hemisphere, at the autumnal equinox. Radio studies suggest that the faint shower meteors are "swamped" by the sporadic background. Particles small enough to radiate energy rapidly enough to prevent atmospheric ablation can survive to settle on the Earth. In addition, ablation products of larger bodies may also settle on the Earth. Studies of this material provide insight into the character of interplanetary dust. Estimated influx rates are greater than would be expected if all particles came from fragmentation of meteoroids. The maximum temperature attained by a dust particle in traversing the atmosphere is given by

$$r\rho \cos x \simeq 49 \frac{\Gamma H \sigma T_m^4}{\Lambda v_\infty^3}$$

where

r	particle radius
ρ	density
$\cos x$	zenith angle of trajectory
Γ	drag coefficient (~1)
H	scale height (~7 km)
σ	Stefan's constant
T_m	maximum temperature (Kelvin)
Λ	accommodation coefficient (~1)
v_∞	initial velocity

Particle temperatures of about 1700° K for iron particles 7 microns in diameter traveling at about 14 km sec^{-1} were obtained. Size distributions of collected particles are in accord with gravitational attraction and atmospheric deceleration. Particles probably are responsible for the zodiacal light. Rocket and satellite measurements of solid particles yielded estimates of the flux and space density of interplanetary dust. Bright meteors are produced by conglomerate meteoroids somewhat less than 1 mm in diameter. Fainter telescopic and radar meteoroids are produced by compact particles. Particles less than 0.3 micron radius are removed from the solar system by radiation pressure. The evidence is in favor of a dust cloud about the Earth.

1963 Keay described a radar survey of meteoric activity in New Zealand. It was confirmed that the spatial density of small, meteoric matter is greater along the Earth's orbit during the latter half of the year. The effect was found to be exactly out of phase with northern and southern hemisphere stations. In other words, northern hemisphere stations showed a maximum of meteor rates in the summer months (June, July, August) while southern hemisphere stations showed a maximum in the winter months (December, January). The combined effects of the Earth's axial tilt and the asymmetrical meteor distribution along the Earth's orbit are apparently responsible for the observed effects.

LaGow and Secretan presented the results of micrometeoroid experiments on the Explorer VII satellite. It was concluded that one penetration through one cell occurred, and that it was caused by a particle approximately 10 microns in diameter.

Langway investigated extraterrestrial dust in snow deposits at Camp Century, Greenland. Although perfect spheres were most common in the smaller size ranges (< 40 microns), droplet and oval forms were present, particularly in the larger particles. A large proportion of the spherules were hollow. Translucent and transparent spherules were also present, but most attention was devoted to black spherules. Surface features of these ranged from smooth and shiny to rough and dull. Density determinations revealed that most spherules were hollow; density ranged from 4.27 to 5.90 g cm^{-3}. Spherules size ranged from 5 to 160 microns in diameter. Electron probe analyses of particle surfaces revealed two class s of particles; iron-rich and silicon-rich particles. The data suggest a possible correlation between variations in spherule occurrence with yearly snow layers.

Langway and Marvin compared the chemical and physical properties of black spherules collected from the Greenland ice sheet with industrial weld spatter particles. Diameters of the Greenland spherules range from 5 to 230 microns. The spherules lacked an obvious tarnish or oxidized crust. Weld spatter spherules had many morphological similarities with the Greenland spherules. Electron probe analyses of spherule surfaces show the Greenland spherules contain mainly Fe, Mn, and Si. Weld spatter spherules showed a wide range in composition. Mineralogical studies and density measurements were also performed. The composition and density of weld spatter particles was distinct from spherules. Although the Greenland spherules did not appear to contain Ni, it was felt that they are of cosmic origin.

Larson, Dwornik, and Adler described electron probe analyses of cosmic dust from several sources.

Lazarus and Hawkins examined the ionizing probability for sodium atoms evaporated from the surface of a meteoroid entering the Earth's atmosphere. The estimated meteor mass suggested an upward revision of the meteor mass scale. The lower limit of mass for a zero-magnitude Geminid meteor incedent at 45° was found to be 6.86 g, and a Perseid meteor was 2.35 g.

1963 Magnolia compiled a supplement to his 1962 bibliography on interplanetary matter, including a total of 567 annotated references.

Marmo and Brown described a model which assumed that vaporization of meteoritic debris provides a constant source of sodium atoms at 105 km. Above the source altitude, the debris is controlled by molecular diffusion and by subsequent loss by escape above 500 km. Predictions of the model are in harmony with the observed data for the sodium content in the Earth's atmosphere.

Marshall investigated the stratigraphic distribution of particulate matter smaller than 15 microns diameter in snow from Byrd Station, Antarctica. Preliminary results suggested that fewer particles were found in winter layers than in summer layers, and that the particle deposition rate varied throughout a year. He suggested that the study of particulate matter throughout the Antarctic ice sheet would make stratigraphic correlation between widely varying environments possible.

McCracken and Alexander compared direct measurements of small interplanetary dust particles with new data from sensors on satellite 1960 Xi. The newer data agreed with previous work, and from this an average distribution curve for small interplanetary dust particles in the vicinity of Earth was established. This showed "no discernible dependence on altitude of the spatial density of dust particles," and the postulated "dust belt" around the Earth was not supported by this work. The accretion rate of these particles on Earth was estimated to be about 10,000 tons per day.

McCracken and Dubin discussed dust bombardment on the lunar surface. Following a review of observational data available for the vicinity of the Earth and for interplanetary space, they estimated the flux of dust particles on the Moon. An accretion rate of 1 g cm^{-2} for particles with masses less than 10^4 g impacting on the Moon was adopted. A porous, low-density surface layer 10 cm to 1 m thick was assumed to exist on the Moon. This would act as a protective covering against impacts of small dust particles, and inhibit production of high-speed spray particles which could escape from the Moon. The surface layer thus consists of a mixture of lunar and interplanetary material.

Mead, Chao, and Littler gave results of a study of the mineralogy, texture, and chemical composition of metallic spheroids from Meteor Crater, Arizona. Some spheroids had a kamacite core, commonly intergrown and surrounded with goethite, while others consisted of alternating bands of goethite and maghemite. Electron probe analyses showed the following:

Mineral	Ni, percent	Fe, percent
Kamacite	2-25	72-97
Maghemite	4-7	60-67
Goethite	2-2	52-60

The wide range of nickel content , the fine-grained texture, and the siliceous glass coating suggested that the spheroids probably condensed from a vapor or melt produced during impact of the meteorite.

1963 Melton described collections of particles from the upper atmosphere. A DC-8 aircraft was employed for collecting particles from 36,000 to 41,000 feet. Preliminary results indicated that some particles appeared to be of meteoritic origin.

Merrihue analyzed rare gases from dust particles in Pacific red clay. He detected He^3 and argon of cosmic origin in the magnetic separate, indicating an extraterrestrial origin for probably less than 1 percent of this material. It is possible that the solar wind could have implanted the cosmic gases in grains of cosmic dust; they were not of cosmogenic origin.

Millard developed a model for meteorite recovery based on known falls and population data. He concluded that the average minimum meteorite flux density for 1810-1950 was about 1.1 ±0.4 falls per 10^6 km^2 per year, and that the average distance between the point of fall and the person who eventually picked up the meteorite was 0.12 km. He estimated an approximate yearly value of 15 falls per 10^6 km^2.

Millard and Brown investigated yearly and monthly time-of-fall patterns for all meteorite falls. The number of falls have three and possibly four maxima. Monthly fall patterns for veined olivine-hypersthene chondrites appear to be nonrandom. The study of meteoric time-of-fall patterns resulted in no definite conclusions as to the types of orbits followed by meteorites, and their origins are no less secure.

Mitler examined the amount of He^3 in planetesimals (solid, homogeneous spheres of ice and silicate). He calculated the production and concentration of He^3 resulting from bombardment by prehistoric solar protons. He found that the presently observed terrestrial isotopic ratios can be obtained only if the He^3 concentration in the "skin" of planetesimals never rose above 6600 per 10^6 silicon atoms. The maximum found was about 500.

Moroz discussed the Earth's dust envelope. He reviewed the observational data, and described the apparent decrease in dust concentration with distance from the Earth. He examined several hypotheses for the origin of the dust concentration but perferred to believe that particles originate by fragmentation of larger bodies "by some mechanism which has not yet been identified."

Mutch collected dust particles from Paleozoic salts. He found several types of particles, one of which appeared likely to be meteoritic, by X-ray and ore microscopy.

Mutch collected magnetic spherules of extraterrestrial origin from Silurian rock salt from New York. The majority of spherules had a slightly roughened brownish surface. Others were black, perfectly spherical, had a metallic luster, and were composed principally of magnetite. Sizes ranged from 5 to 250 microns.

1963 Nazarova described experiments to detect dust with satellites. She summarized both American and Soviet data, which suggest that dust is concentrated at heights of 100 to 300 km above the Earth's surface.

Nazarova, Bektabegov, and Komissarov described detection of meteoric material on the Mars 1 probe. The probe encountered the Taurid meteor stream, which yielded an average frequency of impacts at 7×10^{-3} m^{-2} sec^{-1}, an unusually high rate. The space density of meteoric bodies in the stream was extremely uneven. Few impacts were received at about 23 million km from the Earth. However, from 23-45 million km from the earth, a high density of meteoric matter was again encountered. It was proposed that this was a meteor stream which has not yet been identified. Again, the distribution of meteoroids was uneven.

Park and Reid made a comparative study of metallic spherules. They analyzed material from the Arizona meteor crater, Pacific Ocean sediment, Gulf of Mexico sediment, and a variety of slags. Spherules from deep sea sediments were oxidized and contained less than 1 percent nickel. Gulf of Mexico spherules were thought to be terrestrial. No nickel was found in slag material.

Peterson discussed further thermal radiation from interplanetary dust. The infrared emission spectral distributions of the interplanetary dust cloud were considered according to several models. The gradient of emitted intensity provided no clear means of discriminating between space density laws if large albedos are considered.

Peterson described a model for the emission of thermal radiation by the interplanetary dust, and its possible role in the phenomenon of reddening of the solar corona. Inclusion of a thermal emission component in coronal intensity brings observed and predicted reddening into good agreement for all observations. Thermal radiation intensities from interplanetary dust are predicted to exceed the scattered radiation intensities in the near infrared. He suggested experiments to verify the existence of this thermal component in the solar corona.

Ray described the motion of charged particles in the geomagnetic field. The treatment is essentially that of Störmer (1955), with the innovation that the field not be required to have axial symmetry in order for the Störmer integral to be exact. The treatment was used to obtain results for trapped particles and cosmic rays, but can be adapted to other situations.

Ruskol discussed the origin of the interplanetary dust cloud around the Earth. Rocket and satellite measurements indicate a concentration of dust particles in the space near the Earth. In particular, the concentration from 100-300 km is more than 10^5 times greater than the zodiacal cloud. He argued that these particles could not come from the Moon as Whipple suggested. Inelastic collisions between particles cause them to be captured by the Earth. Atmospheric decelerations also contribute to the concentration.

Safronov formulated a restricted solution to the accretion equation. He concluded that one half the mass of the Earth during the final stage of its growth was contributed by bodies larger than the Moon. However, fragmentation of colliding bodies leads to an increase in the mass contributed by small particles.

1963 Salisbury, Van Tassel, Adler, and Dodd compiled a bibliography of lunar and planetary research published during 1962. They listed a total of 450 references.

Sauval discussed the consequences of collisions between West Ford needles and micrometeorites. While uncertainties are present, the data suggest that each needle will be struck more than once by a micrometeoroid and will break at least once during the initially predicted eight year lifetime of the belt of needles.

Sauval reported on the belt of West Ford needles. He described the West Ford needles, belts of orbiting dipoles used as passive communication satellites, in relation to other types of cummunication satellites and presents their advantages. In an extensive, comprehensive report he described the formation of the belt of dipoles by dispersion from a satellite, functioning of the belt for communication, effects of the dipoles on other scientific activities (negligible), perturbations of the belt, and preliminary results of the experiment.

Schaeffer, Thompson, and Megrue described experiments to test the presence of cosmogenic nuclides in ocean sediments. Analyses of ocean cores for Cl^{36}, He^{3}, Ne^{21}, and Ar^{38} were made, with negative results, which places an upper limit on the rate of accumulation of extraterrestrial material in the deep ocean basins.

Schmidt compiled a survey of data on microscopic extraterrestrial particles. It included works published up to the end of 1962.

Schmidt described dust particles collected from snows of the Antarctic Peninsula. He found both metallic and glassy particles. The metallic particles consisted of magnetite, primarily; the glassy particles were somewhat akin to tektites. The frequency of occurrence was directly related to snow accumulation, and spherule size was inversely related to accumulation. He found no correlation of spherules in annual layers among stations. He estimated the annual mass accretion to be about 1×10^{5} metric tons for the entire Earth.

Schmidt, Venkataraman, Jackson, and Woollard examined the surface features of metallic spherules with an electron microscope. They found three types of particles: smooth particles, pitted particles, and "ridged and furrowed" particles. The latter two types were thought to have resulted from space erosion, the surface features being preserved by atmospheric entry at low angles of incidence and/or low velocity.

Shapiro described a new method for investigating micrometeoroid fluxes: Several long, thin, metallic wires would be orbited and monitored by radar. Dust particle fluxes would be determined from the increase in the number of separate fragments.

1963 Shapiro, Lautman, and Colombo investigated a mechanism for capturing cosmic dust into long-lifetime Earth orbits: Particles approaching the Earth on hyperbolic paths with small impact parameters pass through the atmosphere and lose enough energy to be captured. If the approach trajectories are suitably oriented, then sunlight pressure increases perigees of captured particles to allow survival up to thousands of revolutions. The number of trapped particles can be increased by the drag, which may cause fragile particles to break up. The capture mechanism is effective mainly for velocities "at infinity" between 0 and 5 km sec^{-1} and for initial closest approach altitudes of between 150 and 250 km.

Shapiro, Maron, and Kraft described an experimental study of charge drag on orbiting dipoles. Charge drag has not produced a decrease in mean altitude at an average rate greater than 0.3 km/yr and may be actually less. An upper limit of 0.6 volt for average electrostatic potential of the dipoles was established by making assumptions about the nature of the plasma.

Shelton discussed factors influencing the rate of meteoroid impact on a satellite.

Shelton, Stern, and Hale considered the isotropy of the meteoroid distribution in the vicinity of the Earth in relation to the impact rate on spacecraft. Flux was defined as the total particle path length traced out through a unit volume at the point of interest, during unit time. Application of the Liouville theorem to the problem of focusing of meteoroids by the Earth provided a mathematical basis for treatment of meteoroid distribution.

Singer discussed the distribution of dust in cislunar space: The gravitational field leads to a modest increase in dust concentration near the Earth, but to an increase in flux of 2 to 3 orders of magnitude. A dust belt is formed with a maximum at 21 km.

Singer discussed forces on dust and needles in the magnetosphere of the Earth: Small bodies moving in the magntosphere are affected by minor forces, radiation pressure and coulomb drag. These forces can cause important orbit perturbations. For large area to mass ratios, radiation pressure will distort the orbits of incoming interplanetary dust and create a diurnal asymmetry. Radiation pressure will seriously affect lifetime in a satellite orbit through a "resonance effect." If electric charge is large, then resonance is spoiled by coulomb drag.

Soberman discussed noctilucent clouds, and described the apparatus and techniques for sampling particles in the clouds.

Soberman and Della Lucca studied particulate impacts upon detectors carried on satellite 1960 Zeta I. Most of the particles were found to be about 5 microns in diameter. Apparently, no particles larger than 10 microns were detected. The data suggested that there is a geocentric variation in the micrometeorite flux.

1963 Soberman and Skrivanek described particle collections from noctilucent clouds. Particle counts 2 to 3 orders of magnitude greater were found by a rocket which penetrated a cloud than by one which did not. The particles from the cloud appeared to be surrounded by a ring of structure which suggested that the particles were ice coated.

Southworth commented on Dole's paper, which concluded that particles would be gravitationally concentrated by the Earth. He pointed out that Dole's mechanism does not enhance the particle density near the Earth by more than 12 percent in the most favorable case. Only 0.5 percent of photographic meteors and less than 0.5 percent of smaller particles are amenable to the gravitational process. He concluded that the effect of gravitational concentration is negligible.

Southworth discussed the size distribution of zodiacal particles. Solar radiation will destroy particles less than about 0.1 A.U. from the sun. The density of the zodiacal cloud will vary roughly as r^{-1} from $r \approx 0.1$ to $r = 0.5$ for comets or $r \sim 3$ for asteroids. The Fraunhofer corona (light diffracted by small particles between the Earth and the Sun) is redder than the Sun. Adopting these space density distributions, the average particle radius (weighted by particle area) is 15 microns or more. Approximately 99 percent of all cometary particles have radius × density exceeding 0.001 g cm^{-2}.

Utech described the occurrence of cosmic spherules in rock salt and sediment cores. He compared the concentration of spherules larger than 75 μ-diameter in 100 gram increments of sample with a broad picture of the lithographic character of individual sediment layers. Assuming that sediments of different type formed at different rates, he concluded that the fall of cosmic spherules upon the Earth was constant over a long period of time. He suggested that spherule concentration in sediments could be used to determine rates of sedimentation, as a "natural clock."

Utech and Fechtig gave an interpretation of the mechanics of origin of cosmic spherules. They favored an origin by ablation of iron meteorites. Terrestrial weathering removes nickel-iron nuclei from spherules deposited on the Earth in pretertiary times, while recent spherules show such nuclei. Thus, they thought the presence or absence of nickel was not indicative of origin. Similar spherules were obtained in laboratory experiments with artificial materials.

Wasson considered the radioactivity in interplanetary dust in terms of production, astrophysical relationships, geophysical relationships, sampling, and measurement. The most abundant radioactivities in the dust are produced by solar protons. Low-energy proton reactions on highly abundant target nuclides such as Si^{28} and Fe^{56} account for most radioactivities. The most abundant radioactive nuclides having half-lives longer than a few hours in dust of chondritic composition are Co^{56}, Fe^{55}, Al^{26}, Mn^{53}, Co^{55}, C^{14}, Na^{22}, and Co^{57}. He proposed measuring the ratios of artificial and natural radioactivities to determine dust parameters. Poynting-Robertson and corpuscular drag forces could be determined by measuring nuclide ratios in various size fractions of the dust. The fraction of dust vaporized during atmospheric entry could be estimated by nuclide ratios. He proposed that Al^{26} and Mn^{53} be measured in dust from ocean sediment and polar ice samples.

1963 Whipple described the erosion rates on the surfaces of meteoroids in space. Based on photographic meteor studies and cosmic ray ages, the upper limit of the erosion rate of nickel-iron meteorites in space was estimated at 1.2×10^{-7} cm yr^{-1}. The similar value for stony meteorites was 1.7×10^{-6} cm yr^{-1}. The rate for photographic meteoroids was $2.3\times10^{-5}/\rho$ cm yr^{-1}. Erosion rate was thought to depend in some inverse fashion upon the strength or brittleness of the materials, which would be expected if erosion were produced by impacts with interplanetary dust. The mean space density was estimated at roughly 10^{-21} g cm^{-3}. The Poynting-Robertson effect can cause only the very smallest cometary meteoroids to spiral into the Sun if the present argument is valid. The dust concentration near the Earth suggests that erosion rates may be greater there than in deep space.

Whipple revised his 1957 estimate of meteoroid penetration of space vehicles. He directed attention to photographic meteors, "which certainly must be of cometary origin." He adopted a meteoroid density of 0.44 g cm^{-3} and a mass of 1 g for zero-magnitude visual meteor of velocity 30 km sec^{-1}. He estimated meteor influx as a function of mass to correspond to the relation

$$\log N = -1.34 \log m + 2.68 \log(0.44/\rho) - 14.48$$

where N is the cumulative number of meteoroids per second striking a surface of 1m^2, randomly oriented in space near the Earth, m is mass, and ρ is density. Only smallest particles were thought to be appreciably concentrated in the space near the Earth. He adopted a mean velocity of 22 km sec^{-1}, although he pointed out that mean velocity probably decreases with decreased meteoroid mass. He reduced the calculated perforation rate on a 0.1 cm thick Al plate in the Earth's neighborhood by a factor of more than 3000 from his 1957 estimate. Possibly an unobserved, large flux rate in the mass range 10^{-3} to 10^{-7} gram may exist.

Witt, Hemenway, and Soberman reported on particles collected from the mesopause (75-95 km) by sounding rockets: Particle counts were two to three orders of magnitude greater associated with the presence of noctilucent clouds. Electron microprobe analyses gave evidence of particles containing both Fe and Ni. The numbers of particles per unit area and the size distributions were in agreement with observed light scattering properties of noctilucent clouds.

Wood reviewed the state of knowledge on the physics and chemistry of meteorites. He presented an extensive summary of data on the physical properties, chemical composition, mineralogy, petrography, and metallography, classification, and origin of meteorites.

Wright, Hodge, and Langway reported electron probe analyses of the surfaces of 118 extraterrestrial particles. Eight types of particles were recognized from their shapes and composition: iron-rich spherules with nickel; iron-rich spherules without nickel; silicon-rich spherules; other spherules; iron-rich irregular particles with nickel; iron-rich irregular particles without nickel; iron-rich irregular particles; other irregular particles. Nickel-iron, iron particles in which iron content greatly exceeds silicon, and some siliceous particles were thought to be of cosmic origin. They estimated that some 2×10^5 metric tons of black spherules are deposited on the Earth annually and that about 10^6 tons of all particles are accumulated.

1963 Wright and Hodge studied the composition of extraterrestrial particles and concluded from comparison of these objects with similar material of known origin that they are probably meteoroid ablation droplets.

Wright and Hodge also analyzed material from the stratosphere, polar ice caps, and from ancient sediments. Their surface analyses were made with an electron probe.

1964 Bradford and Dycus reviewed the meteoroid environment in cislunar space and on the lunar surface. They defined a micrometeoroid as less than 10^{-4} grams in mass.

Dycus, Luebbe, and Bradford investigated the problem of meteoroid flux in cislunar space. Their attention was devoted primarily to the effect of the Earth's gravitational field on the meteoroid flux, assuming the meteoroids to be influenced only by the Earth's central force field. They found the flux to be a minimum just above the sensible atmosphere, increasing gradually to a maximum at less than 7 Earth radii, then decreasing slowly to the deep space value. The region of enhanced flux lies in the antapex direction of the Earth (following the Earth in its orbit).

Ellyett and Keay analyzed the meteor rate obtained at Christchurch, New Zealand. They found that the relation of meteor rate to lunar cycle suggested by Bowen (1963) was doubtful.

Fiocco and Colombo reported optical radar experiments using a ruby laser. They discovered a scattering layer at an altitude between 110 and 140 km. They assumed that the radar echoes were produced by meteoroids undergoing progressive fragmentation during their flight through the atmosphere. The atmosphere apparently acts as a filter, with the size distribution of particles varying as a function of altitude. They estimated a total influx of the order of 6×10^4 tons per day. The mass flux of extraterrestrial material is critically dependent on the height of which it is evaluated.

Hodge and Wright compared the compositions of spherules of meteoritic and volcanic origin. In the 10 to 100 micron size range, only about 2×10^{-5} of volcanic particles are spheroids. They found the typical surface composition of volcanic ash to be 40 percent Fe, 20 percent Si, 10 percent Al, 3 percent Ti, and 1 percent K, distinctly different from particles from polar ice caps and favor a meteoroidal origin for particles from polar ice caps.

Hodge, Wright, and Langway analyzed dust particles from polar ice deposits. They analyzed particle surfaces with an electron probe and found several particles with nickel-iron ratios indicative of a meteoric origin, others to be of cosmic origin. They found the rate of deposit of opaque spherules on the Earth was found to be nearly the same at all geographical locations samples.

1964 Honda and Arnold discussed the effects of cosmic rays on meteorites, which offer the opportunity for an extended study of the fossil record of cosmic radiation.

Lebedinets discussed the density of meteoric matter in the vicinity of the Earth's orbit as determined from radar meteor observations. He argued that meteoroids vaporize in the narrow range of heights from 100-110 km. Ionized meteor trails were thought to expand greatly so that observation would be difficult. He estimated that from 10^4 to 2×10^5 tons of meteoric matter are deposited on the Earth each year.

Magnolia compiled a second supplement to his earlier bibliography on interplanetary matter and included a total of 662 references.

Parker described the perturbation of interplanetary dust grains by the solar wind. He expected that photoelectric emission from dust grains would lead to a positive charge of the order of 10 volts on each grain. Assuming that the sign of the interplanetary magnetic field reverses every few days, he showed that the orbital inclination of particles with radii equal to or smaller than 1×10^{-4} cm at the orbit of the Earth is greatly increased by Lorentz forces exerted on the charged particles by magnetic fields carrried in the solar wind.

Rosinski and Pierrard examined the relation of condensation of meteor vapors and their connection with noctilucent clouds and rainfall anomalies. The size of secondary particles formed by coagulation is dependent upon the mass of meteor vapors produced by a meteor shower. The variable component in Bowen's hypothesis can be attributed to variations in vertical transport through the 80-40 km layer. They assumed the primary mechanism of transport to be settling of coagulating particles in the gravitational field of the Earth. Changes in the density of the atmosphere versus height increase residence time of settling particles in the vicinity of 80 km, so that enhanced coagulation can take place. Relatively large particles are formed in this way, accounting for those present in noctilucent clouds. Absorption of water vapor on the surface of an hydrous particles induces adsorption of nitrogen (II) oxide, promoting formation of positively charged particles. These charged particles are subject to a converging horizontal Lorentz force, causing the accumulation of secondary particles and the formation of noctilucent clouds.

Schmidt and Asthana collected particulate matter from snows of Roosevelt Island, Antarctica.

Schmidt and Cohen studied reported accretion rates for metallic spherules of cosmic origin. The data suggested that accretion rates increase with increasing geomagnetic latitude of the collecting site. An attempt to account for the latitude variation in the framework of classical theory for the motion of a charged particle in the Earth's magnetic field. However, preliminary calculations suggested that only charged, microscopic particles on the order of the smallest found to date could impinge preferentially at high latitudes. An integrated, mean accretion rate of metallic spherules was about 7×10^4 metric tons yr^{-1}, or approximately 10 percent of the total particle influx as indicated by satellite data.

1964 Schmidt, Giovinetto, and Asthana studied particulate matter from Camp Michigan, Antarctica.

Schmidt, Giovinetto, and Asthana studied the occurrence of particulate matter in four centuries of snow deposits at the South Pole.

Schmidt and Keil studied polished sections of spherules from Atlantic Ocean sediments. The results indicated that these spherules were meteoritic in origin, formed by ablation of meteorites upon atmospheric entry. Subsequent terrestrial alteration significantly modified spherules surfaces so that analyses limited to surfaces cannot be regarded as representative of their composition.

Surdin studied the distribution of interplanetary dust as a function of mass, from a theoretical point of view. The lowest distribution obtained was

$$df = \frac{1}{m_o} e^{-\frac{m}{m_o}} dm$$

where df is the number of dust particles between m and dm, and m_o is the average mass.

Thompson and Schaeffer investigated the chlorine 36 content of Pacific Ocean red clays. Chlorine 36, a cosmic-ray-induced nuclide, offers the possibility of characterizing extraterrestrial dust and measuring its influx to the Earth. If the sediment accumulation rate is assumed to be 1 mm per 1000 years and the chlorine 36 content of extraterrestrial dust is 200 dpm-kg, the upper limit of chlorine 36 observed in the sediment indicates that less than 10^6 tons of extraterrestrial are contributed to red clays annually, on a worldwide basis.

Vronskiy and Florenskiy reviewed the problem of cosmic dust and its relation to the origin of the Earth. They surveyed and reported results from terrestrial, rocket, and airplane collections of cosmic dust and summarized satellite measurements of particle flux.

Zaslavaskaya, Zotkin, and Kirova described the size distribution of cosmic balls collected from the region of the Tungusska meteorite fall. A variety of spheres 10 to 200 microns diameter was present; porous, hollow, and more rarely, compact varieties. Silicate balls of the same dimensions were encountered. The distribution number of particles as a function of diameter D was found to have the relation

$$N(D) = \frac{N(1)}{D^K}$$

where K equals 1.5. The mass distribution had the relation

$$n(M) = \frac{1}{M^S}$$

where S equals 1.2.

TABLE I.- CLASSIFICATIONS OF MICROSCOPIC EXTRATERRESTRIAL PARTICLES

Murray and Renard (1883)	Size, microns
Black, magnetic spherules ± metallic nucleus	60-200
Brown-colored spherules, resembling chondrules, with a crystalline surface	60-500
Yellowish or brown spherules, with bronze luster ± opaque inclusions of magnetite	<500
Jung (1883)	
Irregular, amorphous grayish fragments	100-200
Mammillated particles, black and opaque (clusters of minute spheres)	100-200
Fibrous particles	100-200
Black, opaque corpuscles	10-20
Hollow spheres with a tiny, vase-like neck	?
Buddhue (1950)	
Irregular, angular fragments	---
Scoriaceous or cindery particles	---
Rounded grains resembling fine black sand (probably terrestrial magnetite)	---
Smooth, black, highly polished perfect spheres of widely varying diameter	20 (mean)
Larger black spheres with less luster and often roughened or pitted	100 (mean)
Silicate spheres which are white, gray, yellowish, brown, and sometimes black. Some are transparent and these usually show bubles and dark inclusions	---
Hybrid spheres which are mostly type 4, but also include visible areas of glass which is often semi-transparent.	---
Bruun, Langer, and Pauly (1955)	
Reniform, slag-like grayish to grayish brown	100-200
Grayish to grayish brown spheres	100 (mean)
Shiny, black spheres	100-500
Light metallic gray spheres	200-500
Hunter and Parkin (1960)	
Smooth, black, iron-nickel spherules	20-384
Rough, gray, stony spherules	15-500
Stony-iron spherules	20-100

TABLE I.- CLASSIFICATIONS OF MICROSCOPIC EXTRATERRESTRIAL PARTICLES - Concluded

Skolnick (1961)

Color	Esterior	Magnetic attraction	Wall	Core
Black	Smooth, faceted, dull, shiny	Weak to strong	Thick	Yes
Steel gray	Smooth, burnished, reticulate	Strong	Thin	None
Mottled black, steel gray	Faceted, intergrown	Strong	Thick	None
Brown to black	Smooth, rare bubbles	Nonmagnetic	Thick	None

Hemenway, et al. (1961)	Size, microns
Black spherules	0.01-1
Irregular particles	0.1-1
Fluffy particles (cosmic dust)	0.1-1
Parkin, Hunter, and Brownlow (1962)	
Metallic flakes and particles with yellowish, amorphous (organic?) attachments (meteoric dust)	70×400
Utech (1961)	
Steel gray, rough surfaced spherules	80-120
Black, smooth, shiny spherules	80-120
Steel gray spherules	<1500

TABLE II.- COMPREHENSIVE CLASSIFICATION OF MICROSCOPIC EXTRATERRESTRIAL PARTICLES

Description	Size, microns	Source
Black, magnetic spherules with or without metallic nuclei	200	Murray and Renard (1883)
Black, smooth, highly polished perfect spheres	200	Buddhue (1950) Jung (1883) Skolnick (1961)
	20-38	Hunter and Parkin (1960)
Black, smooth spheres of COSMIC DUST	0.01-1	Hemenway (1961) Jung (1883)
Shiny, black, hollow spheres with or without vase-like neck	100-500	Bruun, et al. (1955) Fredriksson (1961) Skolnick (1961)
Larger black spheres with less luster, often roughened or pitted, light metallic gray color	100	Buddhue (1950) Bruun, et al. (1955) Skolnick (1961)
Mammillated particles, black and opaque clusters of minute spheres	100-200	Jung (1883)
Mottled black, steel gray, faceted intergrown	?	Skolnick (1961)
Silicate spheres which are white, gray, yellowish, brown, and sometimes black. Some transparent, usually with bubbles and dark inclusions (magnetite or metallic iron)	70-500	Murray and Renard (1876) Buddhue (1950) Bruun, et al. (1955) Skolnick (1961)
Hybrid spherules: part semi-transparent glass, part metallic	100 20-100	Buddhue (1950) Hunter and Parkin (1960)
Irregular, angular fragments	100-200	Jung (1883) Buddhue (1950)
Irregular fragments of COSMIC DUST	0.1-1	Hemenway (1961)
Stony spherules	15-500	Hunter and Parkin (1960)
Scoriaceous or cindery particles	100	Buddhue (1950)
Reniform, slag-like grayish to grayish brown particles	100-200	Bruun, et al. (1955)
Fibrous particles	100-200	Bruun, et al. (1955)
Metallic particles with amorphous (organic?) coatings (METEORIC DUST)	70x400	Parkin, Hunter and Brownlow (1962)
Fluffy particles of COSMIC DUST	0.1-1	Hemenway (1961)

TABLE III.- SIZE OF MICROSCOPIC EXTRATERRESTRIAL PARTICLES

(After Buddhue (1950) and Hodge, *et al.* (1961))

Investigator	Date	Size, microns	Source
Nordenskiold	1874	250	Snow
Murray	1883	200-500	Deep sea sediments
Silvestvi	1880	80-100	"Dust fall"
Wulfing	1890	100-200	Snow
Jung	1883	100-200	Snow
Nininger	1941	90	Rain
Landsberg	1947	---	Air
Buddhue	1950	1-120	Rain
Thomsen	1953	8-80	Snow
Ahnert	1954	100-200	Rain
Kizilirmak	1954	1-100	Rain
Bruun, *et al.*	1955	200-500	Deep sea sediments
de Jager	1955	10	Zodiacal light
Kallman	1955	1-10	Zodiacal light
Laevastu and Mellis	1955	10-230	Air
Levin	1955	10	Meteor astronomy
Minneart	1955	<350	Zodiacal light
Stromgren	1955	1-10	Light scattering
van de Hulst	1955	0.8-1	Light scattering
Whipple	1955	0.1	Meteor astronomy
Fredriksson	1956	35	Air
Stoiber	1956	10-340	Ice Island T-3
Yavnel	1957	30-60	Meteorite impacts
Hodge and Wildt	1958	3-15	Air
Kolomensky and Yudin	1958	40-200	Meteorite crust
Beard	1959	1-5	Meteor astronomy
Hasegawa	1959	5-50	Air
Hibbs	1959	"several microns"	---
Nishibori and Ishizaki	1959	5-60	Antarctic ice
Parkin and Hunter	1959	5-35	Air
Yagoda	1959	20-40	Air
Best	1960	10-100	Light scattering
Crozier	1960	5-35	Sediments
Krinov	1960	3-800	Air, snow, sediments
Hunter and Parkin	1960	15-500	Ocean sediments
Pettersson	1960	30-250	Deep sea sediments
Fredriksson	1961	30-100	Air
Hemenway, *et al.*	1961	0.01-1	High altitude balloons
Hodge	1961	3-30	Air
Hunter and Parkin	1961	14-650	Tertiary rock
Skolnick	1961	50-850	Sedimentary rock
Soberman, *et al.*	1961	0.1-1	High altitude rockets

TABLE III.- SIZE OF MICROSCOPIC EXTRATERRESTRIAL PARTICLES - Concluded

(After Buddhuė (1950) and Hodge, et al. (1961))

Investigator	Date	Size, microns	Source
Thiel and Schmidt	1961	15-180	Antarctic snow
Utech	1961	80-500	Sediments
Crozier	1962	5-60	Air
Langway	1962	5-60	Greenland snow
Newkirk and Eddy	1962	0.1-3	High altitude coronagraph
Langway	1963	5-160	Greenland snow
Langway and Marvin	1963	5-230	Greenland snow
Mutch	1963	5-250	Silurian rock salt
Schmidt	1963	10-170	Antarctic snow
Soberman	1963	0.01-5	Air
Schmidt and Asthana	1964	5-80	Antarctic snow

TABLE IV.- PHYSICAL PROPERTIES OF MICROSCOPIC EXTRATERRESTRIAL PARTICLES

Investigator	Date	Particle type	Density	Refractive index	Magnetic attraction
Nordenskiold	1870	Glassy	2.63	--	--
Silvestri	1880	Yellow spherule	2.92	--	--
Buddhue	1950	Metallic spherules	4.422-5.535	--	--
Buddhue	1950	Glassy spherules	--	1.524-1.560	--
Buddhue	1950	Glassy spherules	--	1.530-	--
Thomsen	1953	Metallic spherules	4*	--	--
Laevastu and Mellis	1955	Metallic spherules	5.2*	--	--
Bruun, *et al.*	1955	Silicate spherules	--	1.63-1.66	--
Hodge and Wildt	1958	Metallic spherules	4*	--	--
Hasegawa	1959	Metallic silicate	4.42 av	1.524-1.560	Present
Skolnick	1961	Metallic spherules	--	--	Strong
Thiel and Schmidt	1961	Metallic spherules	5.18*	--	--
Parkin, Hunter and Brownlow	1962	Amorphous coating	--	1.540-1.549	--
Langway	1963	Metallic spherules	4.27-5.90	--	--

*Adopted density

TABLE IV.- PHYSICAL PROPERTIES OF MICROSCOPIC EXTRATERRESTRIAL PARTICLES - Concluded

Investigator	Date	Particle type	Density	Refractive index	Magnetic attraction
Schmidt	1963	Metallic spherules	4.7-7.1 (mean = 5.1)	--	Moderate to strong
		Glassy spherules	1.9-2.5 (mean = 2.3)	1.48-1.52	--
Hawkins	1963	"Micro-meteorites"	3*	--	--

*Adopted density

TABLE V.- CHEMICAL ANALYSES OF MICROSCOPIC EXTRATERRESTRIAL PARTICLES

Investigator	Date	Percent by weight									
		Fe	Ni	Si	Co	Al	Mg	Mn	Cr	Ti	Ca
Herman	1825	90	-	-	-	-	-	-	-	-	-
Nordenskiold	1883	92	8	-	-	-	-	-	-	-	-
Buddhue*	1950	72	tr	-	-	-	-	-	-	-	-
		62	tr	-	-	-	-	-	-	-	-
		61	tr	-	-	-	-	-	-	-	-
Thomsen*	1953	50	-	14	-	-	-	-	-	-	-
Hasegawa*	1956	62	tr	-	-	-	-	-	-	-	-
Smales, *et al.**	1958	90	5	-	tr	-	-	-	-	-	-
Castaing and Fredriksson	1958a	69	30	-	1.5	-	-	-	-	-	-
	b	44	54	-	1.8	-	-	-	-	-	-
center	c	57	20	-	-	-	-	-	-	-	-
rim		75	0.5	-	-	-	-	-	-	-	-
center	d	40	24	-	-	-	-	-	-	-	-
rim		70	1	-	-	-	-	-	-	-	-
Yagoda	1959	+	+	-	-	-	-	-	-	-	-
Hunter and Parkin	1960	+	70	-	-	-	-	-	-	-	-
Fireman and Kistner	1961	90	tr	-	-	-	-	-	-	-	-
Fredriksson	1961	55	0.2	-	-	-	-	-	-	-	-
Riggs, *et al.*	1962	+	+	-	-	-	-	-	-	-	-
Utech	1961	+	+	+	-	+	+	+	+	-	-
Mrkos	1962	+	+	+	-	-	-	-	-	-	-
Fechtig and Utech	1963										
center		83	20	-	-	-	-	-	-	-	-
rim		67	tr	-	tr	-	-	-	-	-	-
Fredriksson and Gowdy	1963										
center		31	68	-	1	-	-	-	-	-	-
rim		72	0.2	-	-	-	-	-	-	-	-
Fredriksson and Martin	1963	55	0.2	-	0.2	-	-	0.5	-	5-10	-
Grjebine, *et al.*	1963					(qualitative)					
Witt, *et al.*	1963	+	+	-	-	-	-	-	-	-	-
Wright, *et al.*	1963										
I		63	11	3	-	-	-	-	-	-	5
II		73	-	1	-	-	-	4	2	-	-
III		1	-	45	-	25	-	-	-	-	-
IV		1	-	1	-	13	-	-	-	2	2
V		57	2	2	-	-	-	-	-	-	tr
VI		63	-	11	-	-	-	3	-	-	tr
VII		20	-	60	3	3	-	-	10	0.5	18
VIII		23	-	6	-	-	28	-	23	tr	0.5

TABLE V.- CHEMICAL ANALYSES OF MICROSCOPIC EXTRATERRESTRIAL PARTICLES - Concluded

Investigator	Date	Fe	Ni	Si	Co	Al	Mg	Mn	Cr	Ti	Ca

Percent by weight: Fe, Ni, Si, Co, Al, Mg, Mn, Cr, Ti, Ca

Key
- I = iron-rich spherules with nickel
- II = iron-rich spherules without nickel
- III = silicon-rich spherules
- IV = other spherules
- V = iron-rich irregular particles with nickel
- VI = iron-rich irregular particles without nickel
- VII = silicon-rich irregular particles
- VIII = other irregular particles

*Analysis recalculated
+Qualitative analysis, element present
-Element not detected

TABLE VI.- ESTIMATES OF THE CONCENTRATION OF INTERPLANETARY DUST IN OUTER SPACE

Investigator	Concentration (g/cm^3)	Remarks
Greenstein (1937)	10^{-21}	Near ecliptic plane
Allen (1947)	10^{-23}	Space near Earth
van de Hulst (1947)	10^{-21}	Spectral studies
Buddhue (1950)	10^{-28}	Space
Pettersson and Rotschi	10^{-21}	Ocean sediments
Lebidinsky (1955)	10^{-22}	Space
Levin (1955)	10^{-23}	Space
Minneart (1955)	10^{-15}	Near Earth
Siedentopf (1955)	10^{-20} to 22	Space
Stromgren (1955)	10^{-26}	Space
van de Hulst (1955)	10^{-21}	Near ecliptic plane
Öpik	10^{-21}	Mean
Beard (1959)	10^{-15}	Near Earth
Best (1960)	10^{-27}	Zodiacal dust
Hibbs (1959)	10^{-10} to -11	Near Earth
Brown (1960)	10^{-17}	Near Earth
Dubin (1960)	10^{-20} to 22	Near Earth
Hawkins (1960)	10^{-24}	Space
Whipple (1960)	10^{-20}	Near Earth
Beard (1961)	10^{-18}	Space
Beard (1961)	10^{-15}	Near Earth
Singer (1961)	10^{-21}	Near Earth
Dubin and McCracken (1962)	10^{-20}	Near Earth
Beard (1963)	10^{-15} particles cm^{-3}	Near Earth
Ruskol (1963)	Near Earth 10^5 times greater than deep space	
Whipple (1963)	10^{-21}	Mean deep space

TABLE VII.- ESTIMATES OF THE ANNUAL DEPOSIT OF MICROSCOPIC EXTRATERRESTRIAL PARTICLES

Investigator	Annual deposit (metric tons)	Source
Wylie (1935)	1560-3120	Meteor astronomy
Watson (1939)	10,000	Meteor astronomy
Watson (1941)	560	Meteor astronomy
Buddhue (1950)	8-129,000	Black spherules
Laevastu and Mellis (1953)	125	Deep sea spherules, adopted density 5.2
Thomsen (1953)	2,000,000	Spherules from air, adopted density 4
Bruun, *et al*. (1955)	30	Deep sea spherules
de Jager (1955)	10^3 tons/day (365,000 tons/yr)	Zodiacal cloud
Mayne (1956)	1,825,000	He measurements
Öpik (1956)	170	From Laevastu and Mellis (1953), assuming density 7.8
Öpik (1956)	250,000	Total dust influx
Astapovich (1958)	16,000	"Meteoritic dust"
Hodge and Wildt (1958)	500,000	Black spherules, adopted density 4
Pettersson and Fredriksson (1958)	2,400-5,000	Deep sea spherules, adopted density 5
Kreiken (1959)	3,100,000	Black spherules
Best (1960)	7,300	Meteors 70.1 mm
Crozier (1960)	150,000	Black spherules
Dubin (1960)	10^4 tons/day (3,650,000 tons/yr)	Satellite 1958 Alpha
Fesenkov (1960)	3,650	Zodiacal light
Fesenkov (1960)	365,000	"Micrometeorites"
LaGow and Alexander (1960)	10^4 tons/day (3,650,000 tons/yr)	Satellites 1958 Alpha, 1959 Eta

TABLE VII.- ESTIMATES OF THE ANNUAL DEPOSIT OF MICROSCOPIC EXTRATERRESTRIAL PARTICLES - Concluded

Investigator	Annual deposit (metric tons)	Source
Pettersson (1960)	3,300	Mediterranean sediments
Whipple (1960)	10^4 tons/day (3,650,000 tons/yr)	
Alexander (1961)	10^4 tons/day (3,650,000 tons/yr)	Satellite
Crozier (1961)	90,000	Magnetic spherules
McCracken and Alexander (1961)	10^4 tons/day (3,650,000 tons/yr)	Satellite 1960 Xi
Thiel and Schmidt (1961)	184,000	Antarctic spherules, adopted density 5.18 (> 15 microns)
Mirtov (1962)	5,000-10,000 tons/day (1,825,000-3,650,000 tons/yr)	Soviet satellites
Wright and Hodge (1962)	200,000	Spherules from air
Alexander, *et al*. (1963)	10^4 tons/day (3,650,000 tons/yr)	Satellites
Langway (1963)	910,000	Spherules from Greenland snow
Grjebine (1963)	2,400,000,000	Particles from air
Schmidt (1963)	120,000	Spherules from Antarctic snow
Fiocco and Colombo (1964)	6×10^4 tons/day (22,000,000, tons/yr)	Radar meteors
Lebedints (1964)	10,000-100,000	Radar meteors
Schmidt and Cohen (1964)	70,000	Mean black spherules

TABLE VIII.- SOURCES OF MICROSCOPIC EXTRATERRESTRIAL PARTICLES
(after Robey, 1959)

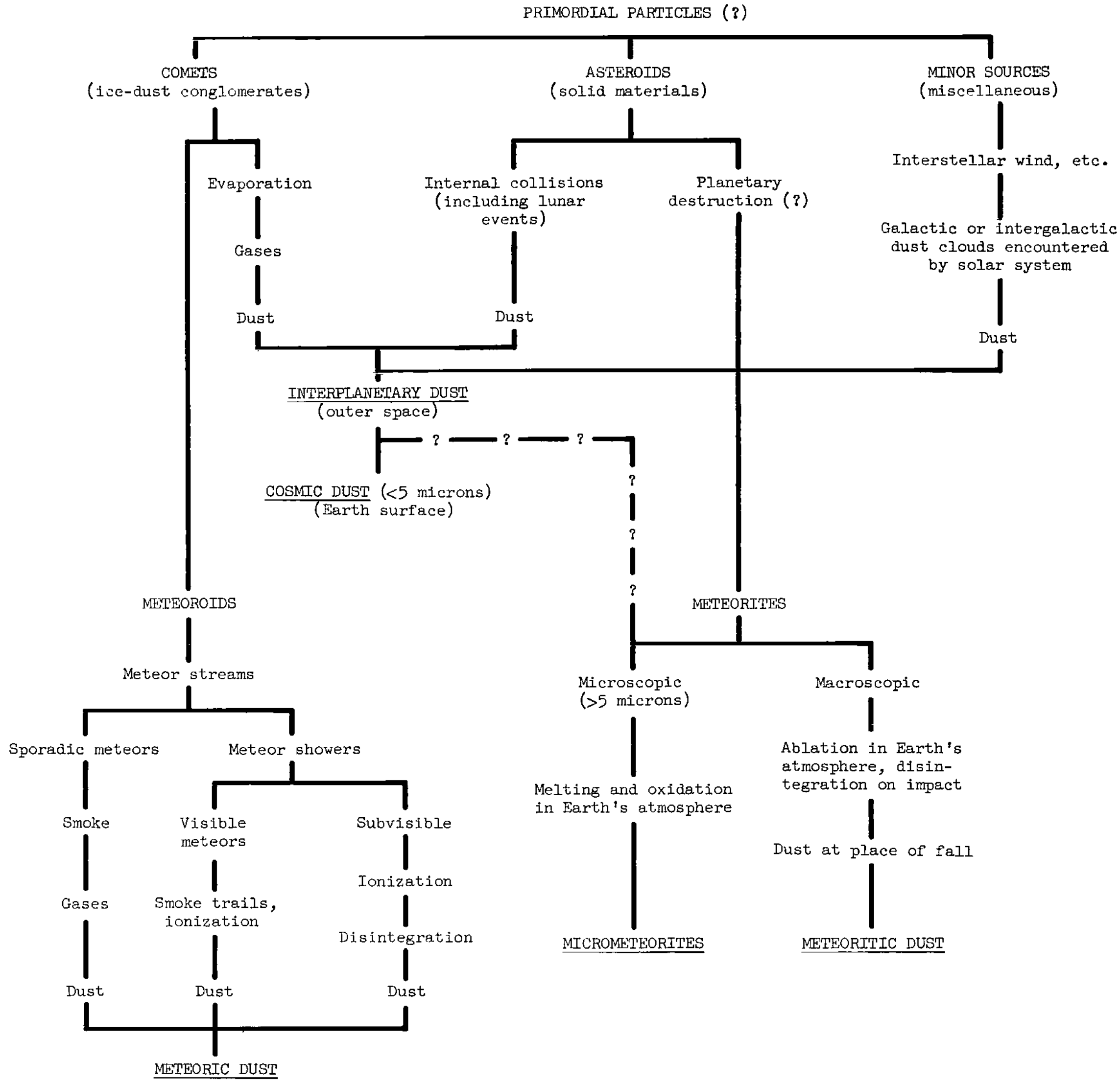

TABLE IX.- LOCATIONS OF MICROSCOPIC EXTRATERRESTRIAL PARTICLE COLLECTIONS ON THE EARTH'S SURFACE
(Expanded from Buddhue (1950) and Hodge, *et al*. (1961))

Investigator	Date	Location		Remarks
Mayer and Van Stoop	1819	Flanders		"Red rain"
Pictet	6-21-1821	Majo, Spain		Iron particles in hailstones
Eversmann	6-11-1825	Sterlitamak, Siberia		Iron and sulfur in hailstone
Cozari	8-26-1834	Padua, Italy		Iron particles in hailstones
Ehrenberg	2-7-1839	Baku, USSR		"Black, polished hollow kernels"
von Reichenbach	1859	10°38'S Lat.; 117°49'E Long.		Shower of "bird-shot"-like black particles on ship
Ehrenberg	1-25-1859	Indian Ocean		Fine metallic dust
Nordenskiold	7-19-1870	Greenland		Fine metallic dust in snow
Nordenskiold	12, 1871	Stockholm, Sweden		Black metallic particles in snow
Nordenskiold	3-13-1872	Evoia, Finland		Soot-like metallic iron particles in snow
Arctic Exped. 1872	8-8-1872	80°N Lat.; 13°E Long.		Small, black metallic iron particles on snow
Arctic Exped. 1872	9-2-1872	80°N Lat.; 15°E Long.		0.1-1.0 mg/m^3 black metallic iron particles in snow (0.25 mm diam.)
Nordenskiold	Fall 1873	Stockholm		Metallic iron in hail
Tissandier	1873	St. Marie du Mont, France		124 mg of magnetic material from rain
		Latitude	Longitude	
Murray	1876	42°42'S	134°10'E	Magnetic spherules
		11°24'N	143°16'E	225 bronzite spherules
		35°41'N	157°42'E	241 ?
		35°22'N	169°53'E	244 cosmic spherules
		37°52'N	160°17'W	252 cosmic spherules
		12°42'N	152° 1'W	265 magnetic spherules
		7°25'S	152°15'W	274 magnetic spherules
		13°28'S	149°30'W	276 magnetic spherules
		32°36'S	137°43'W	285 cosmic spherules
		33°29'S	133°22'W	286 magnetic spherules
		36°32'S	132°52'W	287 magnetic spherules
		36°48'S	42°45'W	327 magnetic spherules
		21°15'S	14° 2'W	338 magnetic and bronze spherules

TABLE IX.- LOCATIONS OF MICROSCOPIC EXTRATERRESTRIAL PARTICLE COLLECTIONS ON THE EARTH'S SURFACE
(Expanded from Buddhue (1950) and Hodge, *et al*. (1961)) - Continued

Investigator	Date	Location		Remarks
		Latitude	Longitude	
Murray	1876	$2^{\circ}42'$S	$14^{\circ}41'$W	346 magnetic and bronze spherules
		$0^{\circ}15'$S	$14^{\circ}25'$W	347 magnetic and bronze spherules
Vega Exped.	8-13-1878	Taimyr Pen., Siberia		Oldhamite (?) xls in snow
Silvestri	3-29-1880	Catania, Sicily		Yellow dust containing steel gray metallic spherules + Ni
Lasaulx	1880	Kiel, Germany		Metallic iron particles in snow
Nordenskiold	1883	San Fernando, Chile		Red-brn spherules in snow + Ni
Jung	1883	Montreux (L. Geneva) Switzerland		Iron particles in snow
		St. Bernard, Switz.		Iron particles in snow
Batchelder	1885	Pelham, N.H., USA		Iron dust from rain
Kammerman	11-27-1885	Gent, Belgium		'Meteoritic particles'
Hartley and Ramage	11-16-1897	London, England (?)		Magnetic spherules
Palmieri	3-10-1901	Africa		Magnetic particles
Meunier	5-27-1903	$64^{\circ}54'$N Lat.; $13^{\circ}40'$E Long.		Black spherules, glassy globules
?	1924	Washington, D.C., USA		Transparent glassy spheres + mineral grains
Rudaux	1927-1933	Donville, Mandie, France		Magnetic particles from rain, air
Rudaux	9-1927	Donville, Mandie, France		Particles associated w/ fall of fireball
Rudaux	10-9-1933	Donville, Mandie, France		Particles associated w/ Draconid meteor shower
Rudaux	1927-1933	Pyrenees Mts.		Magnetic particles from snow
Makemson	1931-1932	Winter Park, Fla., USA		Clear, fragile globular particles
Spencer	1933	Henbury, Aus. and Wabar, Arabia		Meteoric iron and glass
Schloss	1935	Lake Obalski (300 kms)		Magnetic particles
?	1939	James Bay, Canada		Magnetic particles and qtz, feld
Nininger	1940	SW USA		Magnetic particles from rainwater + Ni
Revelle	1944	$29^{\circ}21'$N Lat.; $132^{\circ}20'$W Long.		1 magnetic spherule

TABLE IX.- LOCATIONS OF MICROSCOPIC EXTRATERRESTRIAL PARTICLE COLLECTIONS ON THE EARTH'S SURFACE (Expanded from Buddhue (1950) and Hodge, et al. (1961)) - Continued.

Investigator	Date	Location	Remarks
Landsberg	11-16-1946	Mt. Westner, Va., USA	Black magnetic spherules from rain w/ Draconid meteor shower? 0.022 mm
Norris and Hogg	Summer 1948	Haliburton, NWT Canada	Magnetic spherules from air + Ni
	Winter 1948	Ft. Smith, NWT Canada	
Divari	1948	Tian-Shan, China	Snow-no cosmic dust
Malyuga	1948	Alma Ata., USSR	Dust in snow (probably terrestrial)
Phipson	9-1948	?	Black, angular particles w/ Perseid meteors?
Buddhue	1950	Pasadena, Calif.	Meteoritic dust
Krinov and Fonton	1952	Russia	Metallic spherules
Pettersson	1952	Central Pacific (?)	Ni, Fe, Mn in sediments
Thomsen	1953	Iowa City, Iowa, USA	Magnetic spherules (no Ni)
	1953	Iowa City, Iowa, USA	Thomsen's material was terrestrial
Ahnert	1954	Germany?	Magnetic and nonmagnetic spherules
Kizilirmak	1954	Ankara, Turkey	Irregular magnetic dust
Heard	1955	Arctic?	Magnetic spherules
Öpik	1955	Ocean (from Pettersson)	Ni-dust
Laevastu and Mellis	1955	7°38'S Lat.; 152°53'W Long.	Black spherules
Smales, et al.	1955	Ocean sediments	Magnetic spherules
Bruun, Langer and Pauly	1955	3°54'N Lat.; 8°22'W Long.	
		0°42'N Lat.; 5°59'W Long.	1°00'S Lat. 76°17'E Long.
		2°17'S Lat,; 8°10'E Long.	12°47'N Lat. 116°24'E Long.
		35°00'S Lat.; 27°22'E Long.	35°00'S Lat. 39°45'S Long.
		35°12'S Lat.; 27°35'E Long.	45°47'S Lat. 164°39'E Long.
		34°56'S Lat.; 36°31'E Long.	
		8°52'S Lat.; 49°25'E Long.	
		7°24'S Lat.; 48°24'E Long.	
Crozier	1956	N. Mexico, USA	Black magnetic spherules
Fredriksson	1956	Pacific Ocean	Black spherules
Hasegawa	1956	Japan	Black spherules, silicate spherules

TABLE IX.- LOCATIONS OF MICROSCOPIC EXTRATERRESTRIAL PARTICLE COLLECTIONS ON THE EARTH'S SURFACE (Expanded from Buddhue (1950) and Hodge, *et al*. (1961)) - Continued.

Investigator	Date	Location	Remarks
Stoiber, *et al*.	1956	Arctic Ice Island T-3	Magnetic spherules
Suslu	1956	Ankara, Turkey	Metallic spherules
Rinehart	1957	Meteor Crater, Am USA	Metallic spherules
Yavnel	1957	Tunguska Meteorite USSR	Black, shiny globules
Astapovich	1958	USSR	Meteoric spherules and dust
Hodge and Wildt	1958	48°00'N Lat.; 122°22'W Long. 46°50'N Lat.; 121°45'W Long. 34°30'N Lat.; 117°30'W Long. 65°N Lat.; 148°W Long. 75°N Lat.; 95°W Long.	Opaque shiny spherules
Kolomensky and Yudin	1958	USSR	Crust of Sikhote-Alin meteorite
Pettersson and Fredriksson	1958	7°38'S Lat.; 152°53'W Long. 3°21'S Lat.; 174°12'E Long. 3°21'S Lat.; 174°12'E Long. 1°20'S Lat.; 167°23'E Long. 11°33'S Lat.; 91°26'E Long. 33°59'N Lat.; 31°02'E Long. 43°28'N Lat.; 7°22'E Long. 41°29'N Lat.; 5°51'E Long. 2°23'N Lat.; 173°50'W Long. 2°48'S Lat.; 178°57'W Long.	Magnetic spherules
Smales, *et al*.	1958	Pettersson's samples	Ni-bearing magnetic spherules
Kreiken	1959	Ankara, Turkey	Iron particles and meteoritic origin
Nishibori and Ishizaki	1959	69°00'S Lat.; 39°35'E Long.	Black spherules
Hunter and Parkin	1959	34°11'N Lat.; 52°32'W Long. 24°30'N Lat.; 64°47'W Long. 27°07'S Lat.; 115°10'W Long.	Spherules
Yagoda	1959	Crosby, Minn. Holloman AFB, N. Mex.	Ni-bearing dust
Crozier	1960	Carthage, N. Mex. Glendale, Canada Big Bend, Texas	Black, magnetic spherules

TABLE IX.- LOCATIONS OF MICROSCOPIC EXTRATERRESTRIAL PARTICLE COLLECTIONS ON THE EARTH'S SURFACE
(Expanded from Buddhue (1950) and Hodge, *et al.* (1961)) - Continued

Investigator	Date	Location	Remarks
Crozier	1960	42°43'N Lat.; 142°13'W Long.	Black, magnetic spherules
		44°31'S Lat.; 127°14'W Long.	
		Lake Chicago, Wisconsin	
Krinov	1960	USSR	Metallic spherules
Pettersson	1960	Hawaii	Metallic spherules
		Mediterranean	
		Central Pacific	
Crozier	1961	Socorro, N. Mex., USA	Magnetic spherules
Fredriksson	1961	Hawaii	Metallic spherules
Hunter and Parkin	1961	Barbados	Metallic spherules
Skolnick	1961	S. California, USA	Magnetic spherules
Thiel and Schmidt	1961	90°S	Metallic spherules in Actarctic
		80°S Lat.; 120°W Long.	Ice
		80°26'S Lat.; 169°35'E Long.	Black spherules
Utech	1961	N.W. Germany	Black spherules from sediments
Crozier	1962	Magdalena and Mt. Withington, New Mexico	Black spherules
Langway	1962	Greenland	Black spherules
Mrkos	1962	79°S 103°E	Spherules from Antarctic snow
Parkin, Hunter and Brownlow	1962	England - Scilly Is.	Coated spherules
Wright and Hodge	1962	U.S.	Black spheres from air
Grjebine	1963	41°58'N 7°05'E	Mediterranean sediments
		41°24'N 7°05'E	
		43°12'N 7°02'E	
Schmidt	1963	74°14'S Lat.; 84°46'W Long.	Micrometeorites from snow
		74°03'S 80°32'W	
		74°56'S 76°01'W	
		74°52'S 71°28'W	
		74°50'S 71°43'W	
		74°16'S 70°10'W	
		73°33'S 68°38'W	
		74°04'S 66°35'W	

TABLE IX.- LOCATIONS OF MICROSCOPIC EXTRATERRESTRIAL PARTICLE COLLECTIONS ON THE EARTH'S SURFACE
(Expanded from Buddhue (1950) and Hodge, *et al*. (1961)) - Concluded

Investigator	Date	Location	Remarks
Schmidt	1963	74°58'S Lat.; 68°12'W Long. 75°27'S 72°21'W 75°22'S 74°56'W	Micrometeorites from snow
Langway	1963	77°N	Greenland snow
Langway and Marvin	1963	77°N	Greenland snow
Melton	1963	West Coast of U.S.	Air
Schmidt, Giovinetto, and Asthana	1964	79°S 165°W	Antarctic snow
Schmidt and Asthana	1964	78°S 164°W	Antarctic snow
Schmidt, Giovinetto, and Asthana	1964	90°S	Antarctic snow

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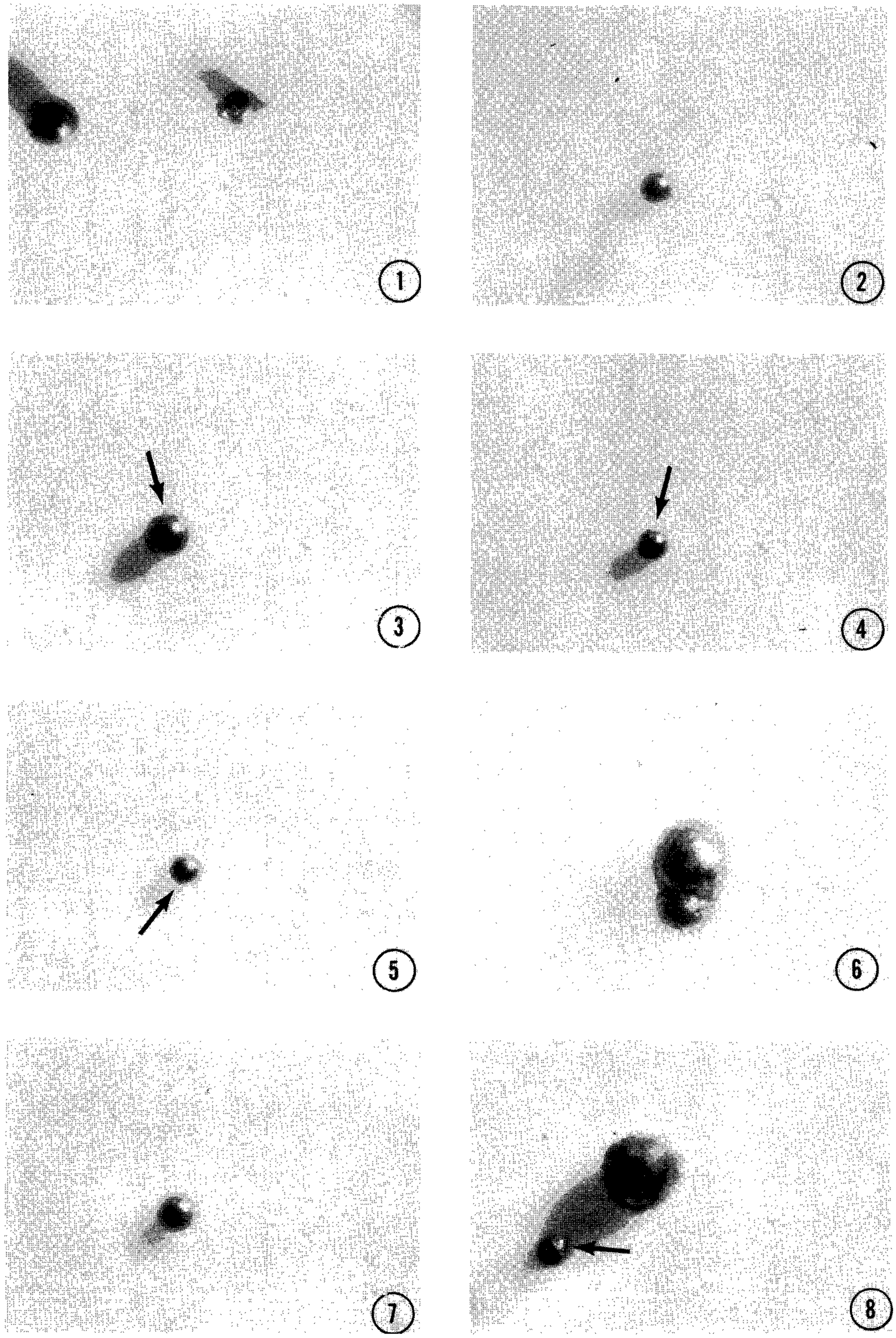

Figure 1.- Typical black, metallic spherules (after Schmidt, 1963).

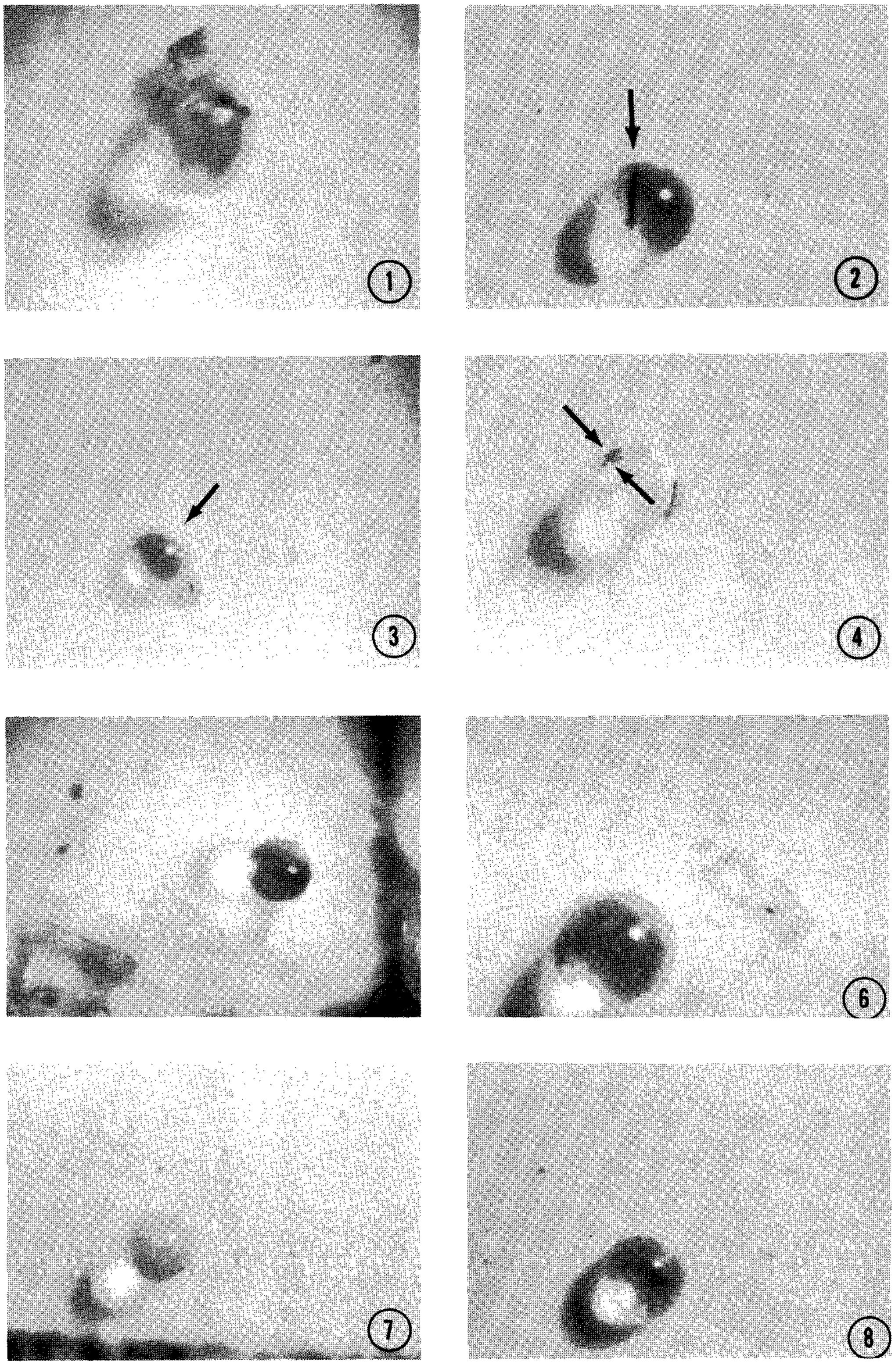

Figure 2.- Typical glassy spherules (after Schmidt, 1963).

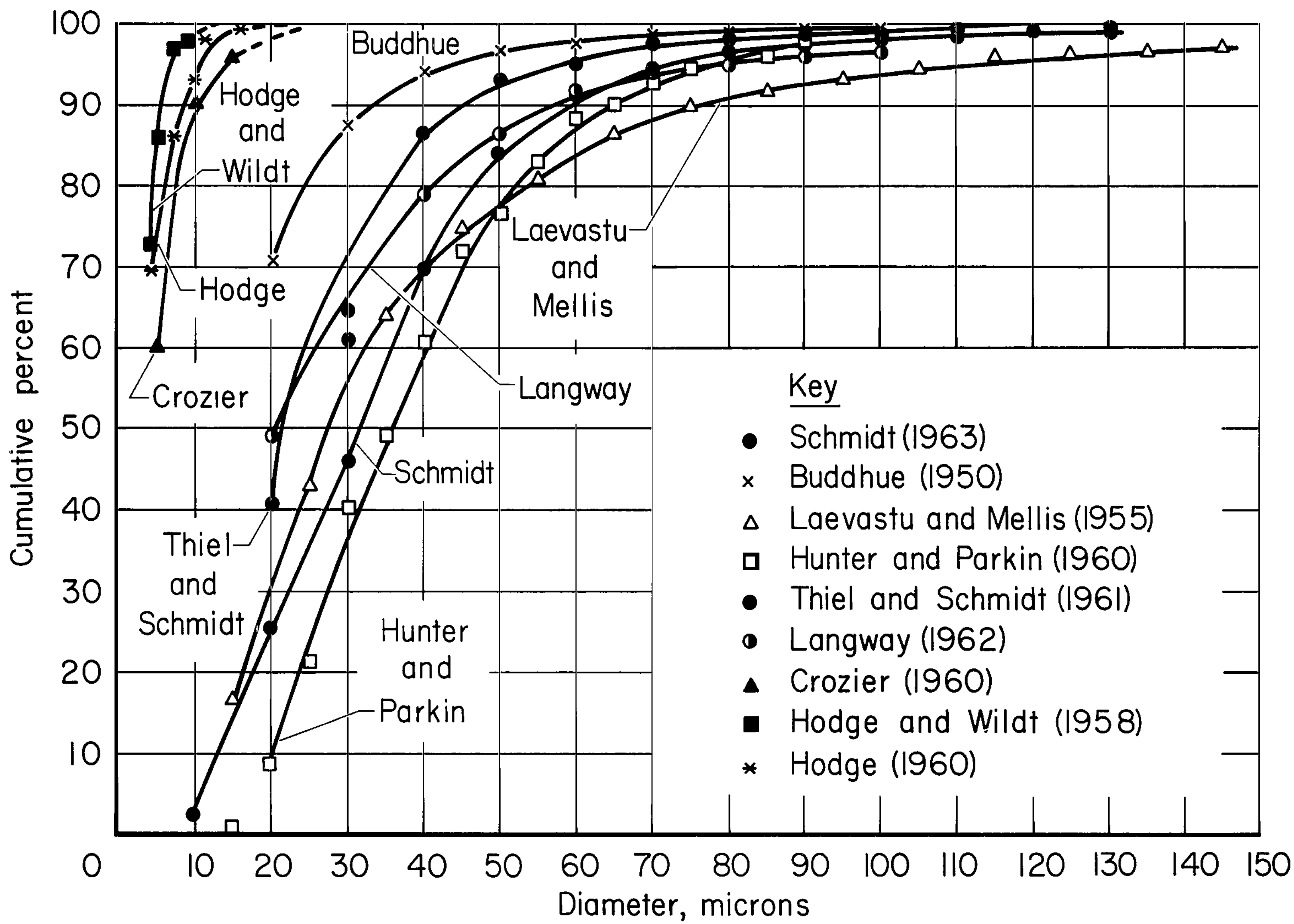

Figure 3.- Size distribution of metallic particles as indicated by surface-based studies.

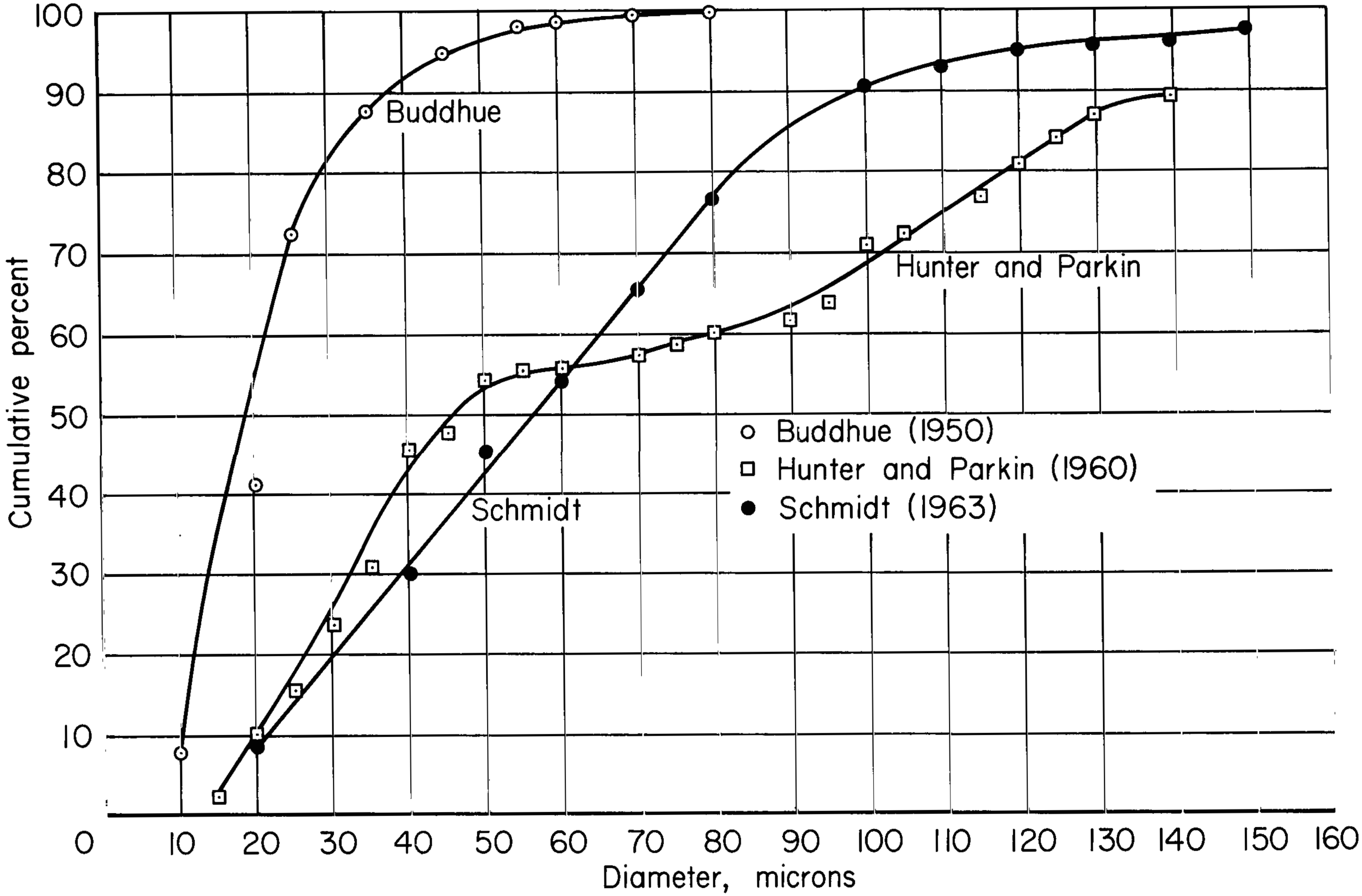

Figure 4.- Size distribution of glassy particles as indicated by surface-based studies.

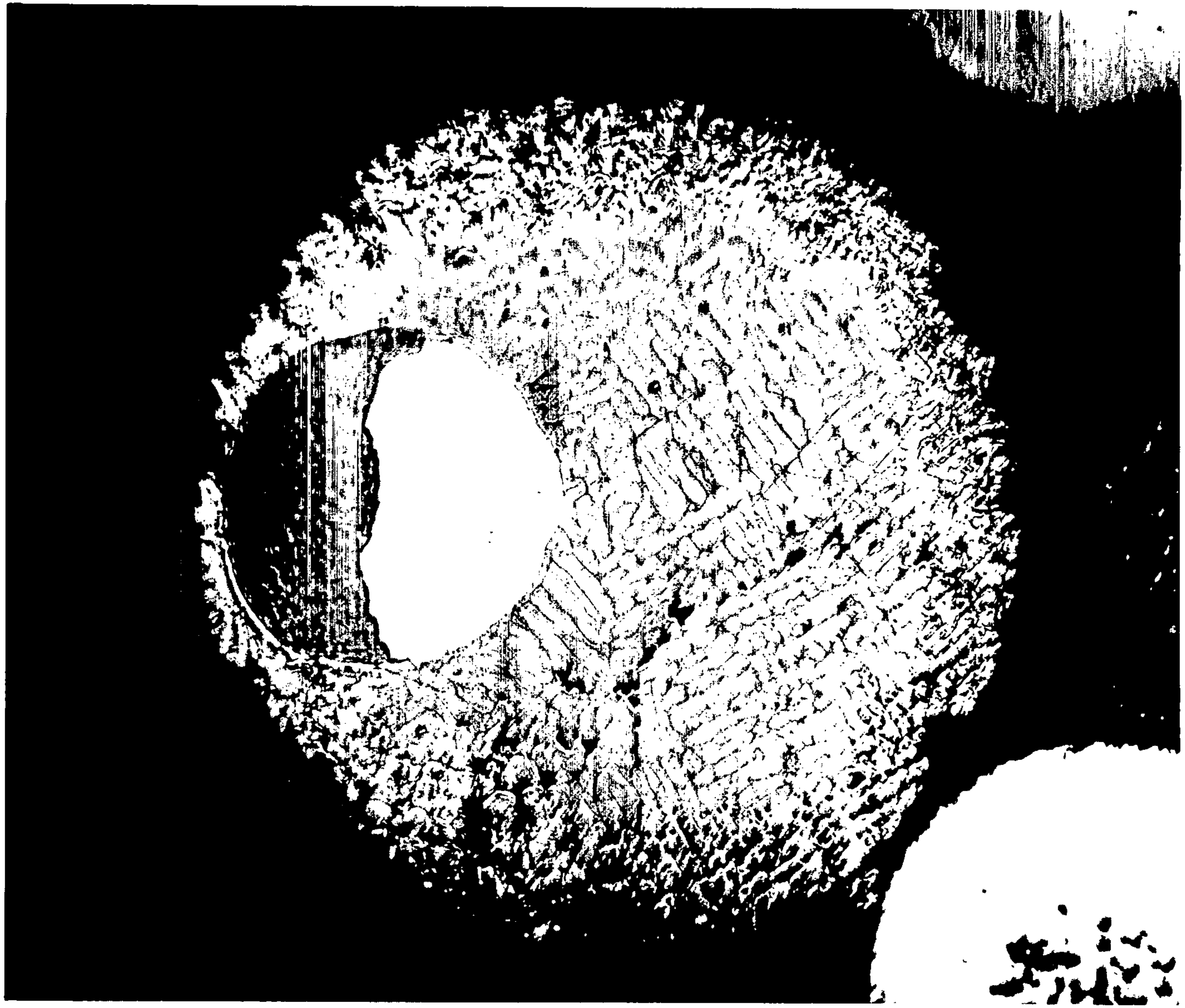

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Figure 5.- Polished section of metallic spherule (after Schmidt and Keil, 1964).

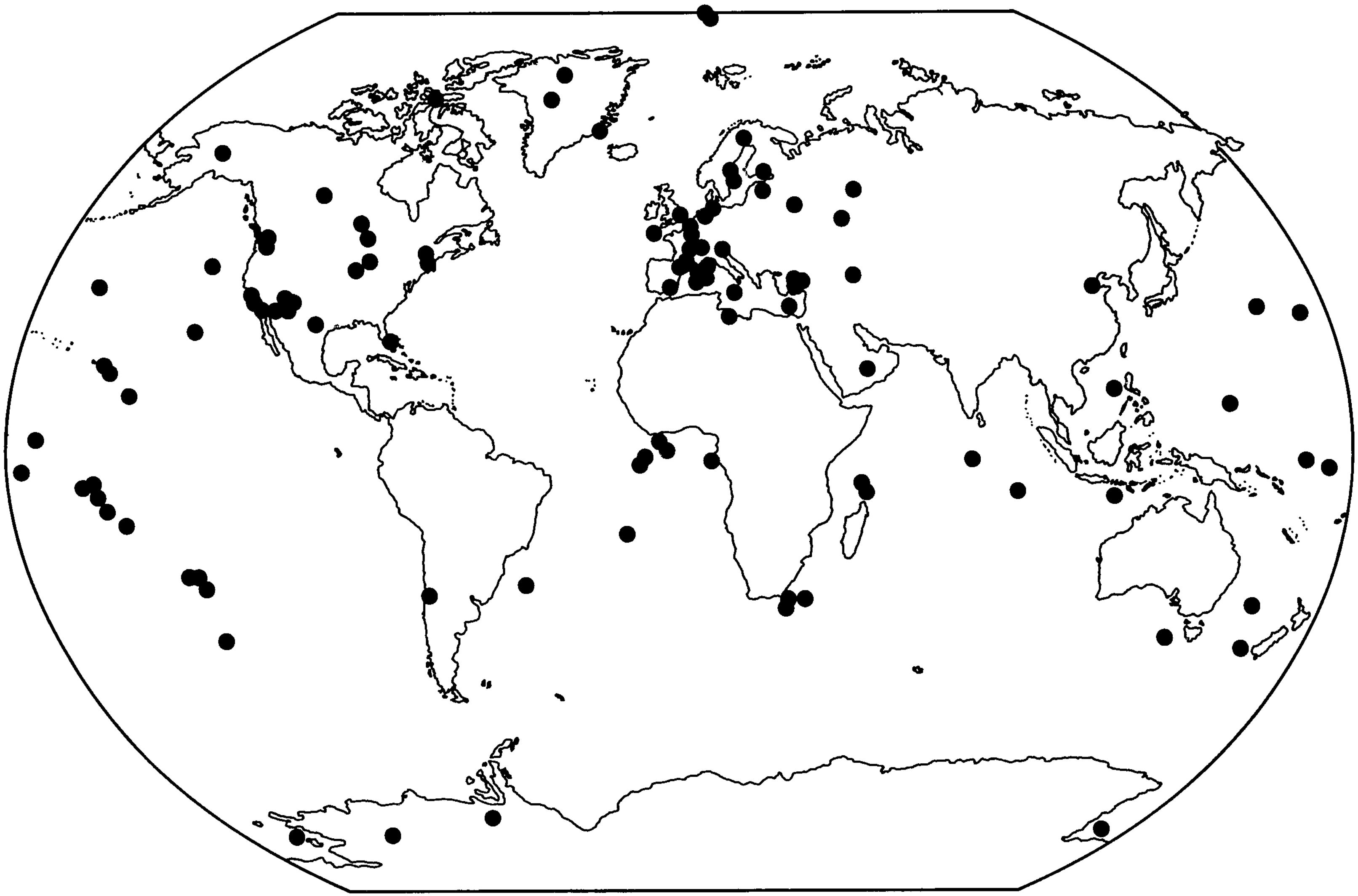

Figure 6.- Locations of collections of microscopic extraterrestrial particles.

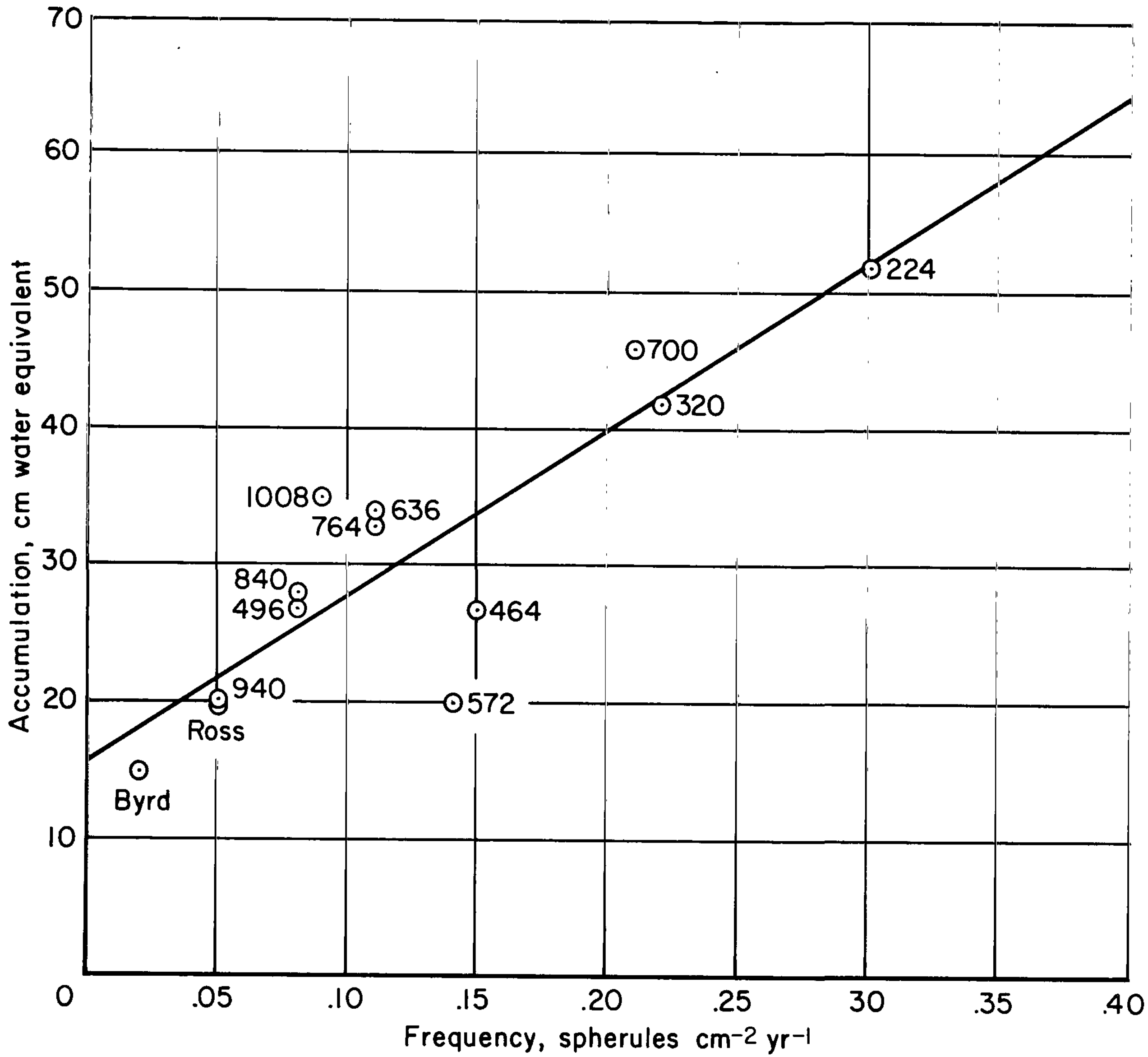

Figure 7.- Frequency of spherule occurrence as related to snow accumulation (after Schmidt, 1963).

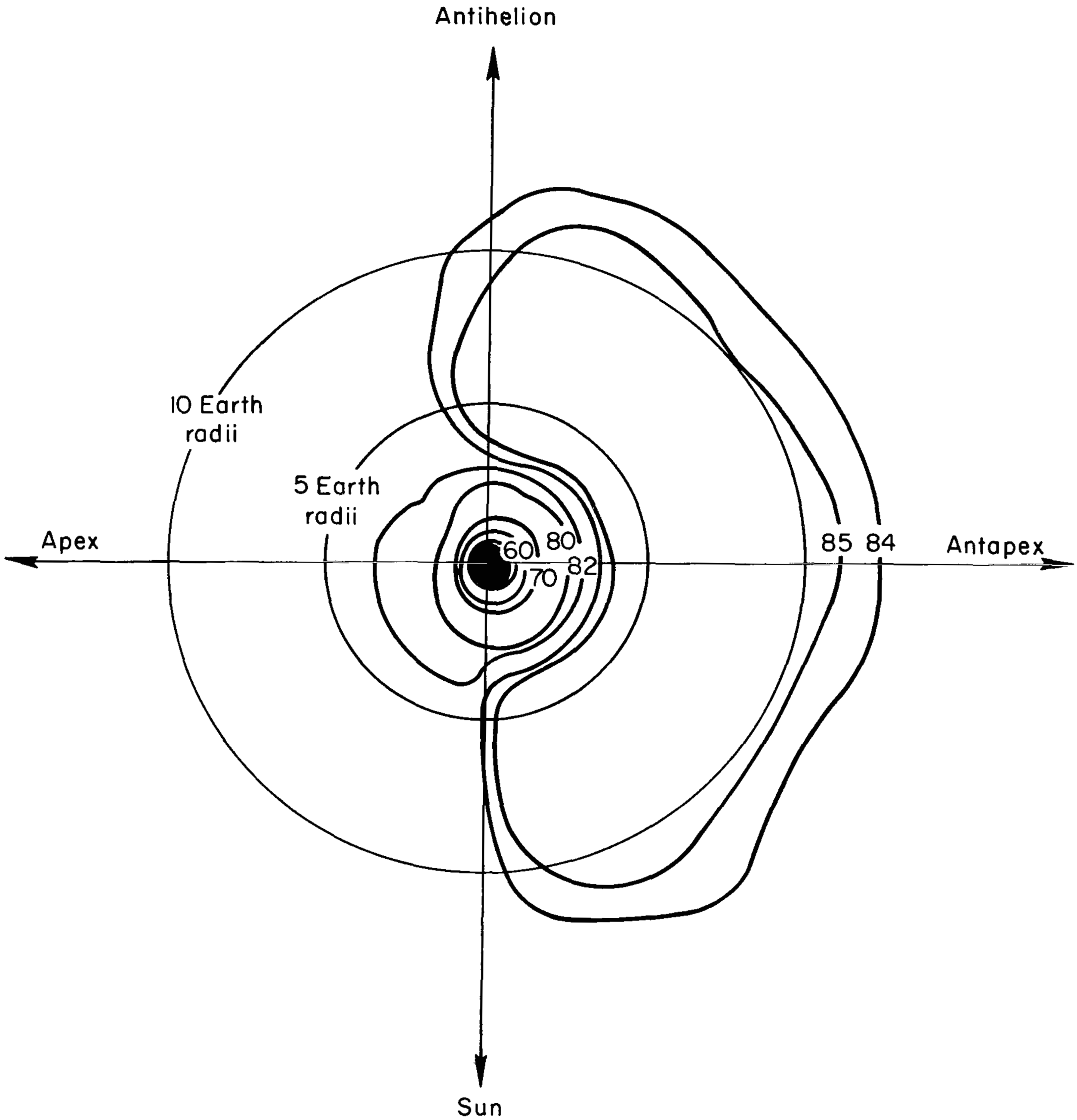

Figure 8.- Concentration of penetration-sized meteoroids (after Dycus, Luebbe, and Bradford, 1964).

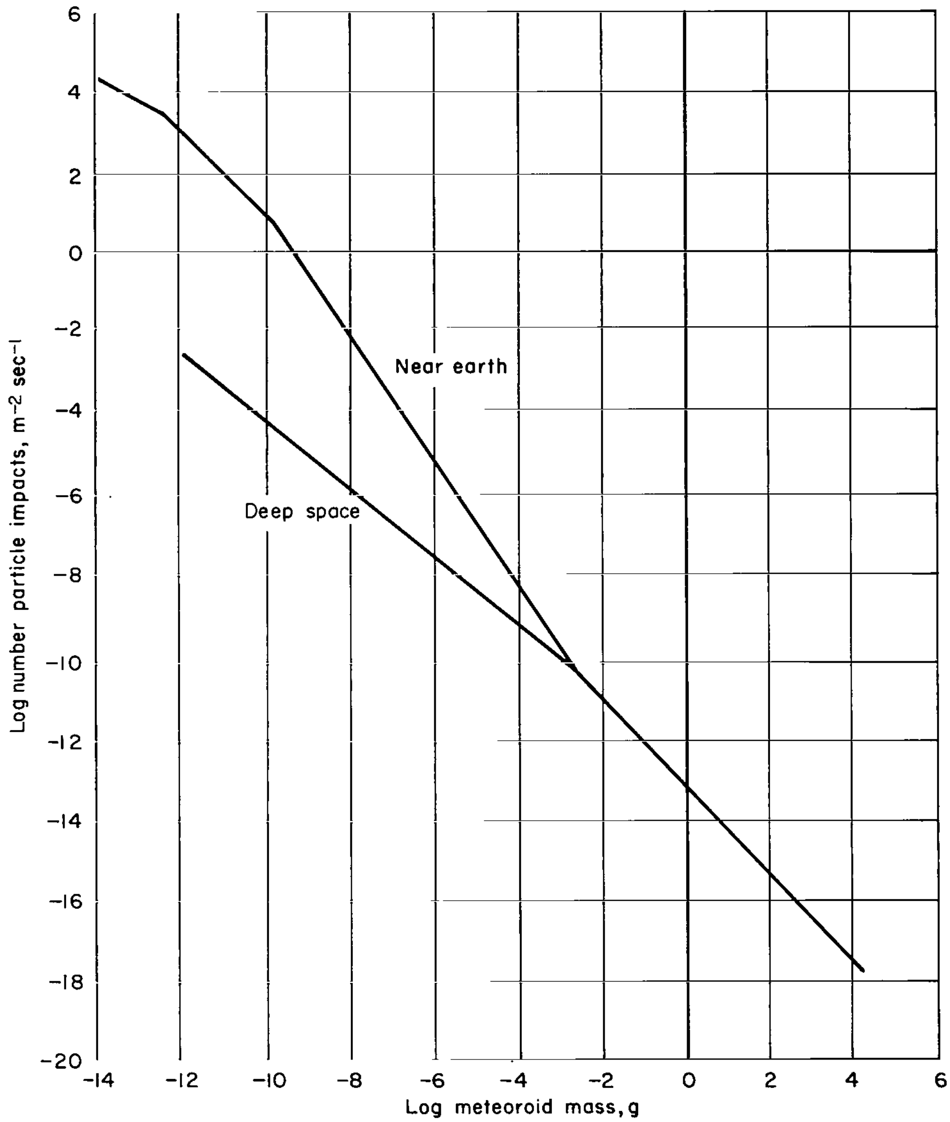

Figure 9.- Average cumulative meteoroid impact rates (after D'Aiutolo, 1963).

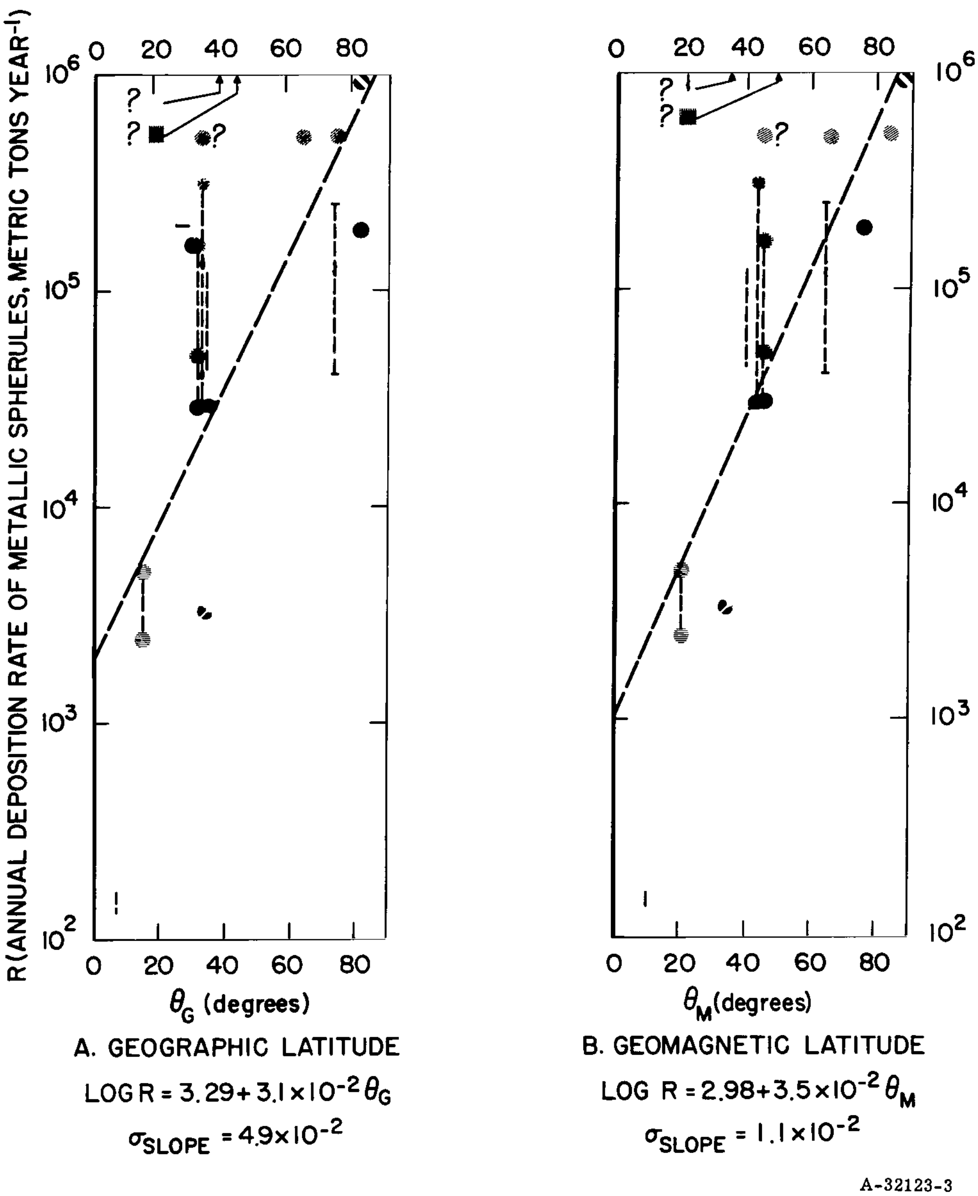

Figure 10.- Variation of particle accretion rates with latitude (after Schmidt and Cohen, 1964).

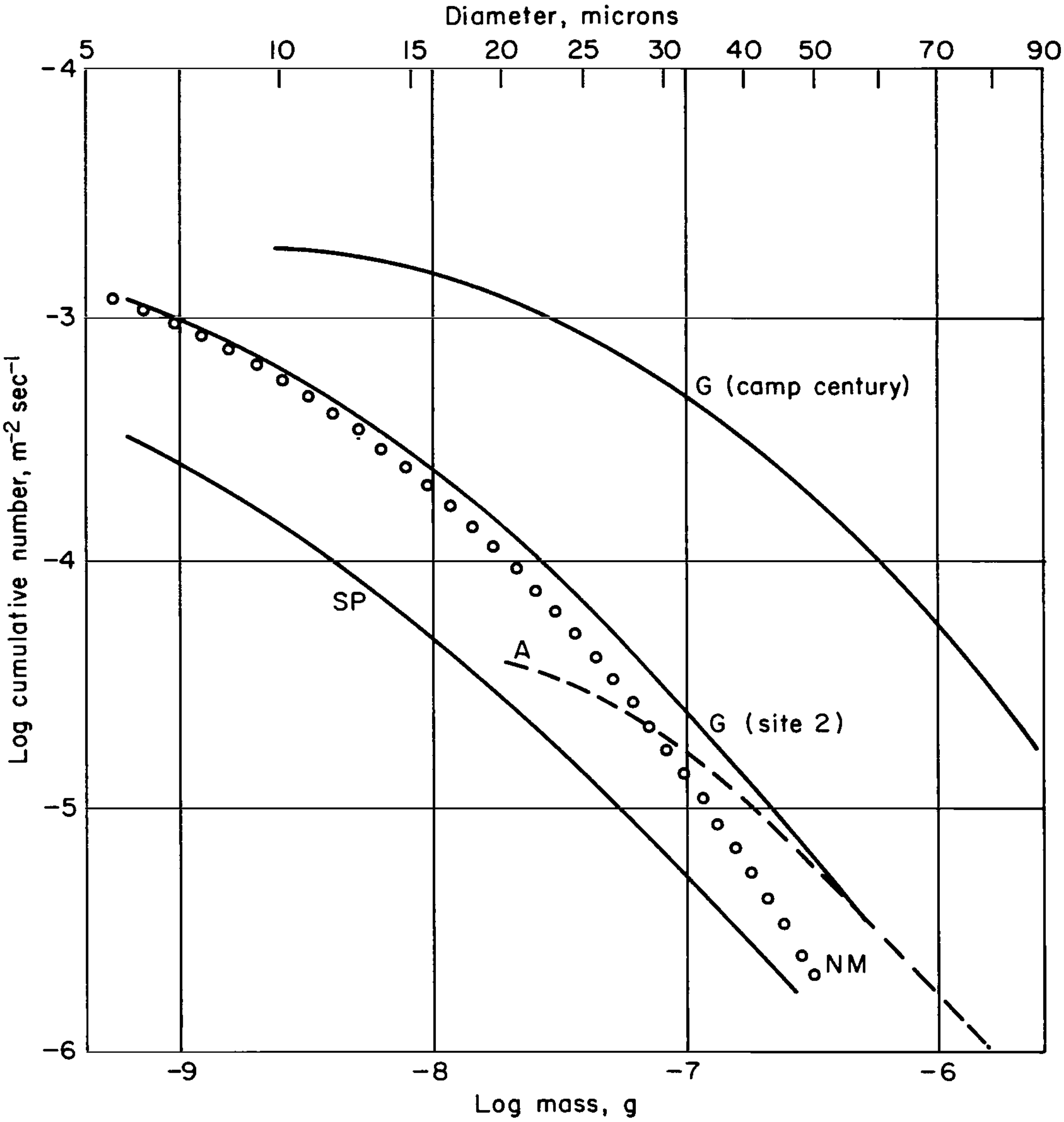

Figure 11.- Cumulative size distributions of numerical rates of spherule deposition (after Hodge, Wright, and Langway, 1964).

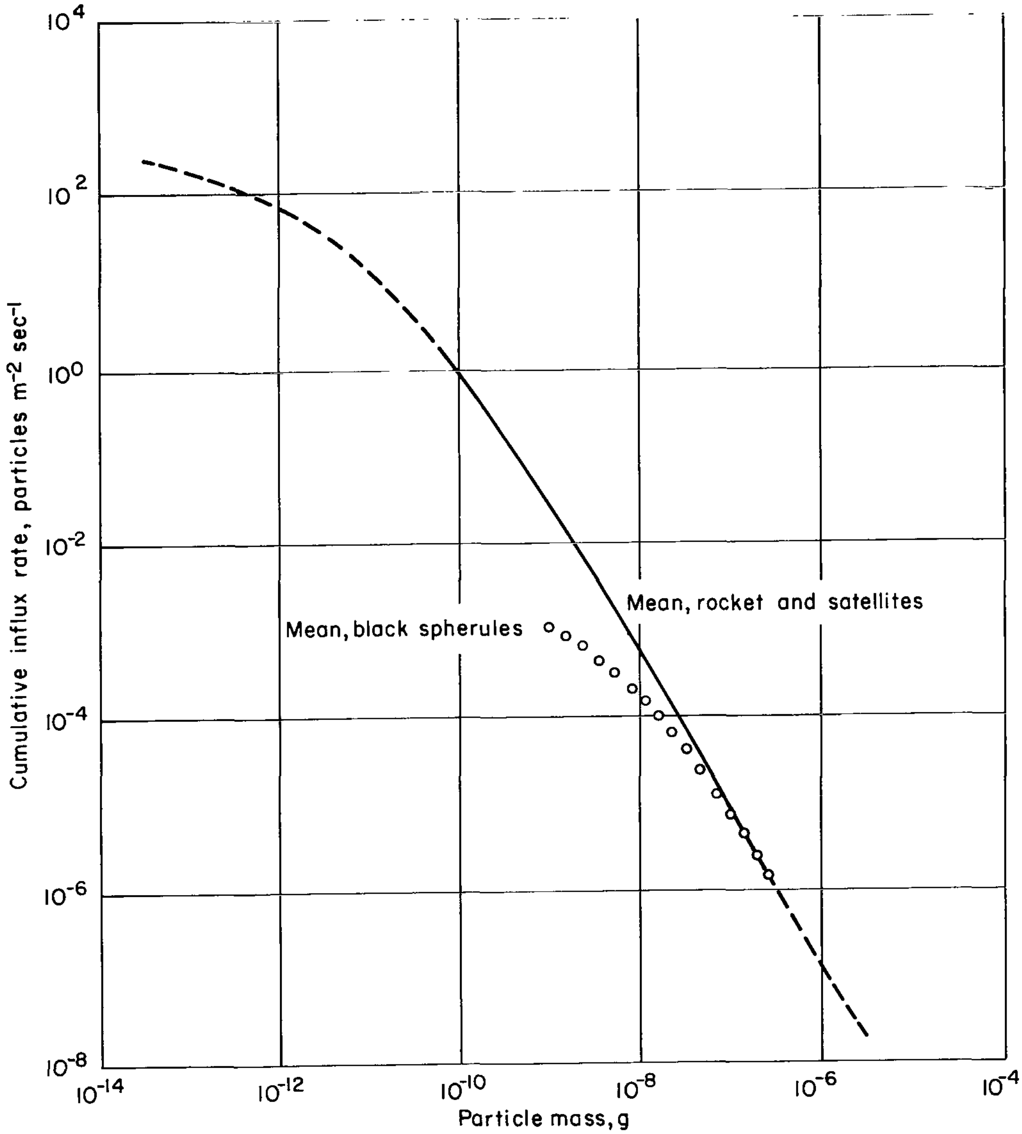

Figure 12.- Average cumulative distribution of interplanetary dust near the Earth as determined by rockets and satellites (after Alexander et al., 1962).

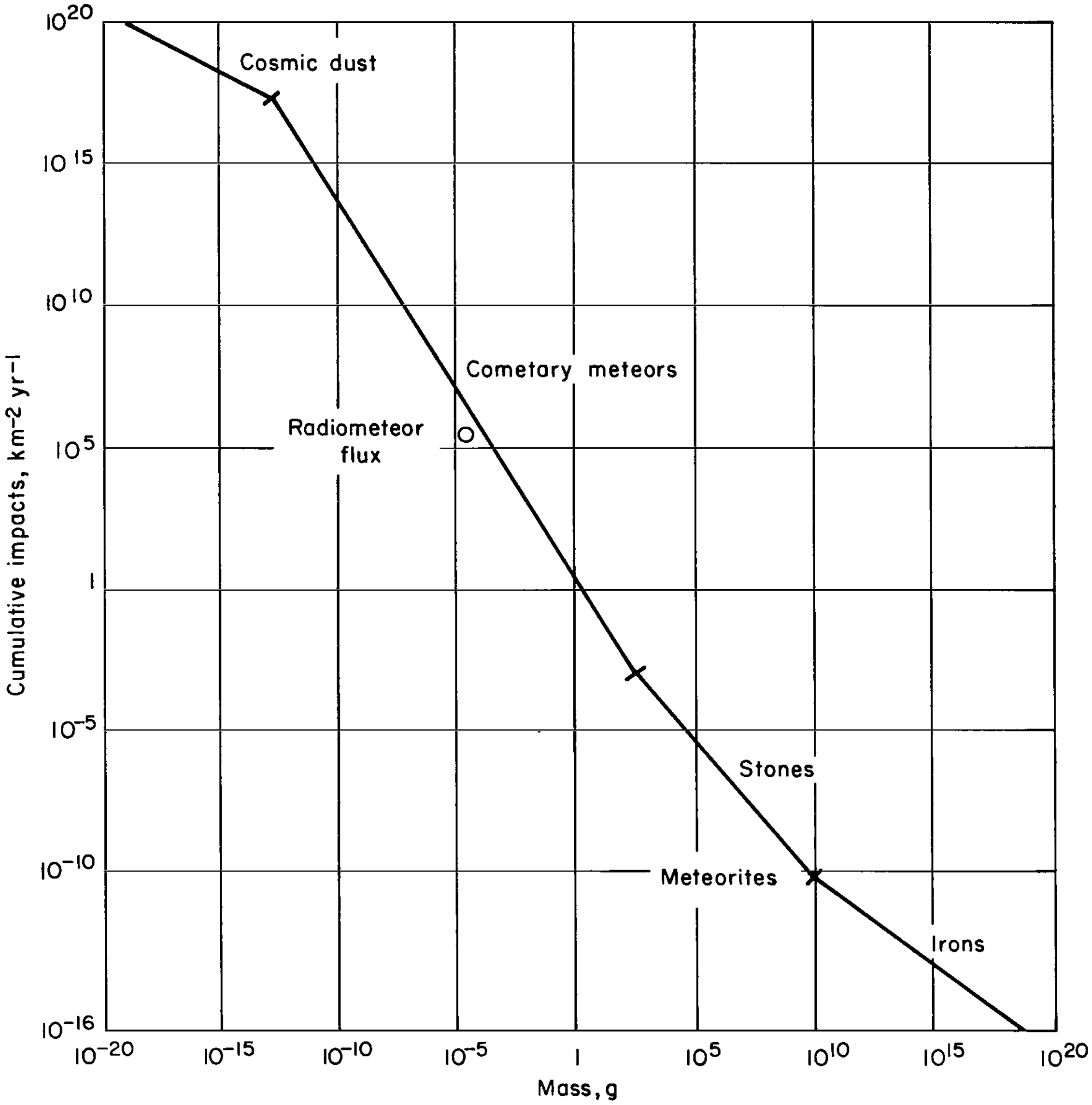

Figure 13.- Flux of extraterrestrial objects (after Hawkins, 1964).

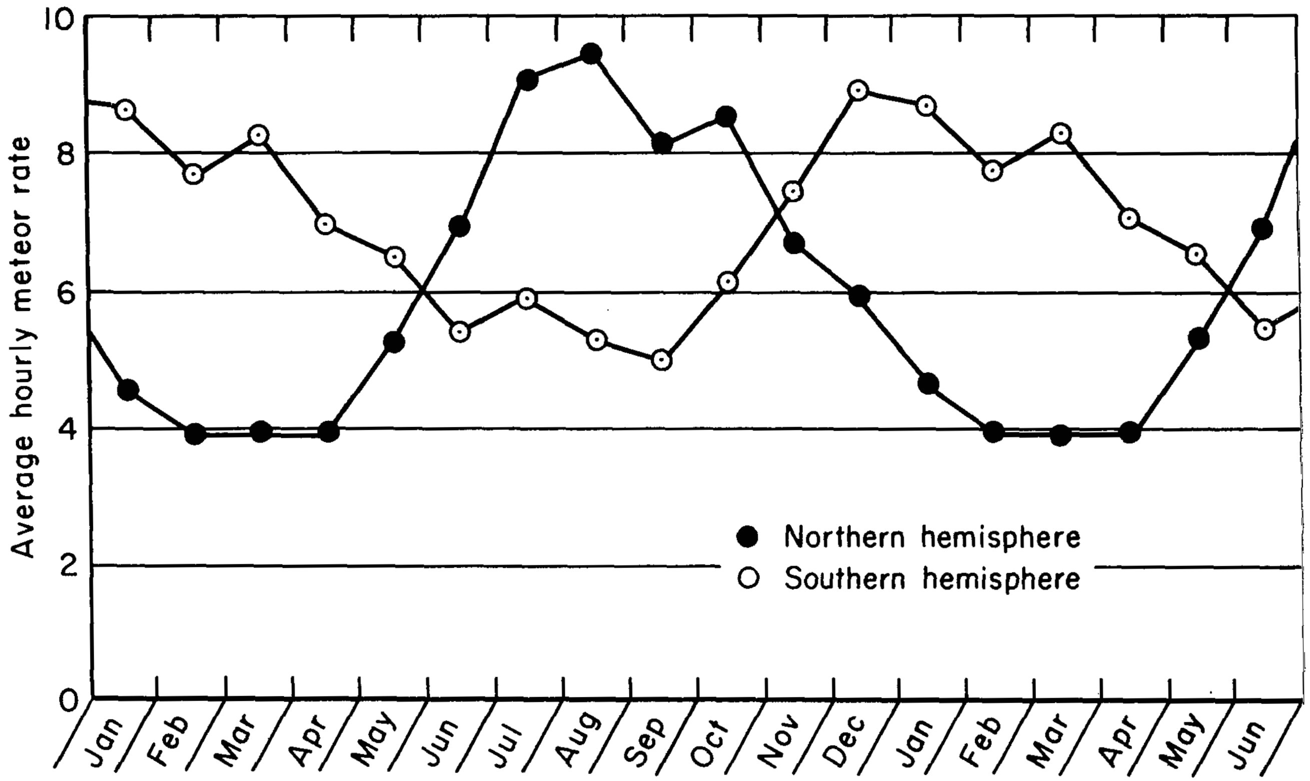

Figure 14.- Comparison of seasonal variation of meteor rates in both hemispheres (after Keay, 1963).

NASA-Langley, 1965 A-1031

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