LABORATORY STUDIES OF INTERPLANETARY DUST

R. M. Walker

McDonnell Center for the Space Sciences
and
Department of Physics
Washington University
St. Louis, MO 63130, USA

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I. INTRODUCTION

Interplanetary dust particles collected in three different ways are now available for laboratory study. Impact collectors flown on aircraft sampling the stratosphere have provided the most important source of (more or less) unaltered interplanetary dust material [1]. Larger cosmic particles have been recovered from sediments, both from the sea [2], and, most recently, from temporary glacial lakes in Greenland [3]. Finally, debris samples from impacting interplanetary particles have also been collected in experiments flown in earth orbit and returned to earth [4, 5, and 6b].*

This brief review treats only the analysis of dust particles collected in the stratosphere. These particles are the best available samples of interplanetary dust and have been studied using a variety of analytical techniques. The particles are systematically collected and curated by a group at the Johnson Space Center, Houston. Catalogs of the collections have been published and individual particles are made available to qualified investigators on request [8].

The stratospheric dust particles have been called by a variety of names (including the deserved description as "Brownlee particles") and a word about nomenclature is in order. In what follows, stratospheric particles whose major element compositions are similar to those of chondritic meteorites, are referred to as "interplanetary dust particles or IDPs." Some particles in this chemical class are demonstrably extraterrestrial. To facilitate discussion, certain IDPs have also been given individual names, e.g. Calrissian, Skywalker, etc. Particles in other chemical classes are not treated in this paper. Although some of them may be extraterrestrial, both man-made and natural contaminants are abundant in the non-chondritic chemical classes.

For a more complete view of IDPs and other cosmic dust particles the reader is referred to two reviews [9,10].

The following questions are addressed in this workshop paper:

1. Is it certain that chondritic stratospheric dust particles are extraterrestrial?

2. What are the general physical, chemical, mineralogical, isotopic and infrared properties of IDPs?

3. How do IDPs compare with other extraterrestrial materials, specifically unequilibrated meteorites and comet dust?

4. Do IDPs consist of primitive and/or primordial matter?

5. Is there any relationship between IDPs and interstellar matter?

6. Can the study of IDPs contribute to the understanding of basic astrophysical problems? e.g.: the conditions under which solids form in space?

Some of these questions have clear answers, others not. Nor, are the questions independent of each other.

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*In fact, there is currently a spacecraft that has been in near-earth orbit since April of 1984 (the Long Duration Exposure Facility - LDEF I), which has several dust collection experiments on board. Originally scheduled to return to earth in March of 1985, the recovery has now been delayed. Just in the last few weeks, portions of a thermal blanket returned by astronauts from the Solar Max Repair Mission have been found to contain impacts of likely extraterrestrial origin [6b]. This impact debris material will shortly be made available for general scientific study [7].

II. IS IT CERTAIN THAT CHONDRITIC STRATOSPHERIC DUST PARTICLES ARE EXTRATERRESTRIAL?

Yes. However, many early studies of purported interplanetary dust particles were erroneous, and it is useful to review the evidence bearing on this fundamental point.*

The simplest proof that IDPs are extraterrestrial is the recent observation of large densities of fossil nuclear particle tracks in silicate crystals contained within IDPs [12]. Massive nuclear particles ($Z \geq 20$) are needed to produce tracks in silicates. In the terrestrial environment the only natural source of such nuclear particles is the spontaneous fission of ^{238}U, and even in old terrestrial samples, fission track densities are low in silicates. In contrast, samples of extraterrestrial silicates, such as lunar soil grains, typically show high track densities produced by energetic heavy nuclei from the sun and by galactic cosmic rays [a complete discussion of fossil nuclear tracks is given in Reference 13].

The extraterrestrial origin of IDPs had been firmly established even before the recent track observations. Ion probe measurements demonstrated that some IDPs are highly enriched in deuterium relative to hydrogen compared to terrestrial samples [14a]. Still earlier measurements [15,16] showed that the particles possessed nonterrestrial abundances and compositions of noble gases. The fact that IDPs are chondritic in composition is strong evidence in itself of an extraterrestrial origin.

Although the presence of tracks or a large D/H anomaly can be considered as proof that a particular dust particle has resided in interplanetary space, the absence of these effects does not preclude an extraterrestrial origin. It is thus impossible to be certain that all particles labelled IDPs are micrometeorites; however, this is a plausible working hypothesis.

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*An excellent description of the early confused state-of-affairs is given by Hodge in his recent book [11]. At one point, there was general agreement between a priori estimates of interplanetary dust influx, particle collections performed with high altitude balloons, and data from electronic detectors in space. Unfortunately, these were all in error by a very large factor. Interplanetary dust collection proved a more formidable problem than early investigators realized.

III. WHAT ARE THE PHYSICAL, MINERALOGICAL, ISOTOPIC AND INFRARED PROPERTIES OF IDPs?

IDPs are an extremely diverse set of objects. It is beyond the scope of this paper to describe all the observations that have been made. The general kinds of measurements that are possible will be briefly described and some particular features will be highlighted.

In spite of their small masses ($\sim 10^{-8}$ to 10^{-10} gms) it has proven possible to develop a variety of techniques for studying individual particles. Initial examination in a scanning electron microscope (SEM) equipped with an X-ray detection system (EDX) reveals the morphologies and major element compositions. Particles can then be individually weighed and their densities determined, although this has been done in only a few cases [17]. More typically, a particle is crushed or otherwise dispersed and parts of it are transferred to an electron microscope grid where detailed measurements of structures and mineralogies can be made by transmission electron microscopy (TEM)[18a-q]. The bulk of the crushed particle can be transferred to a KBr crystal for measurement of its infrared transmission spectrum [19]. If the particle is subsequently mounted on a gold substrate isotopic measurements on different parts of a particle are possible using an ion probe [14a-d]. Alternatively, the particle can be totally consumed in a thermal ionization source mass spectrometer to obtain precision isotopic measurements of several selected elements, or an ensemble of particles can be vaporized in a noble gas mass spectrometer to obtain elemental and isotopic information on noble gases [15,16]. Micro-Raman techniques have been used to establish the presence of "disordered graphite" in at least one particle [34] and Auger spectroscopy has been used on two non-chondritic stratospheric dust particles to look for evidence of surface contamination due to interaction with atmospheric aerosols [35].

Most measurements have been reported by groups specializing in one kind of instrumentation or another, and in only a few cases have the same particles been studied by a variety of techniques. Increasingly, however, sequential or parallel measurements of different types are being made on single particles.

Many IDPs consist of extremely porous aggregates with a typical "cluster of grapes" morphology [9]. Indeed, the erroneous belief has arisen that all IDPs consist of low density, fluffy materials. This is not true. Although all IDPs consist of aggregates of material in the sense that they are not fragments of an igneous rock or pieces of a melt droplet, many are quite compact and have densities of ~ 2 gms/cm^3 or higher [17].

Detailed measurements of the mineralogies and structures of about two dozen particles have been reported [18a-q]. Some particles consist of collections of small anhydrous crystalline grains which are imbedded in an amorphous carbonaceous material. The proportion of amorphous material is highly variable from one particle to the next. The minerals olivine and pyroxene are common, as are magnetite and sulfides of different types. The proportions of different mineral phases vary from particle to particle as do the morphologies and compositions of a given mineral type. Microchondrules, flattened where they are in contact with one another, have been observed, as have lath-like whiskers of pyroxene. Still another large class of particles contain phyllosilicates and give evidence of interaction with water.

A first order result of these studies is that different particles have qualitatively different assemblages of minerals. IDP's cannot be lumped together as a single class of objects; they must be studied individually.

Although infrared transmission measurements were undertaken to provide data that could be compared with astronomical observations, they have also provided a relatively quick means of measuring the dominant silicate mineralogy of whole IDPs. Most IDPs fall into one of three

IR spectral classes called "olivine," "pyroxene," or "layer lattice silicate" from the similarity of the 10 μm features with those of terrestrial mineral standards [19]. Complementary detailed TEM measurements on several particles in the different spectral classes confirm the IR designations. However, the detailed structures seen in the TEM are different for particles in the same spectral class, underlining the importance of treating IDPs as individual objects.

IR spectroscopy can also be used to locate particles with unusual mineralogies. For example, Calrissian, a particle in the layer lattice silicate class, has an atypically strong absorption at 6.8 μm and an accompanying weaker absorption at 11.4 μm. These spectral features were interpreted as evidence for carbonates [19] and subsequent TEM measurements have confirmed the presence of numerous grains of Fe and Mg carbonate [18m].

Ion probe isotopic measurements show large, but variable deuterium enrichments in 5 of 8 IDPs measured to date [14]. Maximum enrichments of ~250% are seen. In particles with deuterium enhancements the D/H values are variable on the scale of a few microns. Correlation of the isotopic signatures with other ion signals indicate that the deuterium excess is associated with C but not with OH [14b]. In contrast, carbon isotopic ratios are found to be constant from one part of a particle to the next although differences between particles are found [14c]. Both Mg and Si give constant isotopic ratios consistent with terrestrial values in three particles [14c]. Earlier, higher precision measurements on several IDPs made using a thermal ionization source mass spectrometer indicated the possible presence of Mg isotopic anomalies at the level of up to 0.4% [20].

IV. HOW DO IDPs COMPARE WITH METEORITES AND COMETS?

Similar in some ways, apparently different in others. Consider first the comparison of IDPs with the fine-grained matrix material of unequilibrated meteorites. The question that dominated the original studies of IDPs was whether they were simply smaller versions of the larger, better known carbonaceous meteorites. No fragments resembling the porous, fluffy IDPs have yet been found in meteorites. It quickly became evident that IDPs were a unique form of extraterrestrial material, different from carbonaceous chondrites and deserving of detailed study in their own right. Moreover, there are distinctive differences in the detailed mineralogies seen in both porous and compact IDPs and the mineralogies observed in meteorites. For example, although CM carbonaceous chondrites and one IR class of IDPs have similar IR spectra dominated by phyllosilicates, the detailed structures of the phyllosilicates are different [18h].

Given the initial question, most authors have emphasized the differences between IDPs and meteorites. Yet there are strong similarities e.g.: the deuterium enrichments seen in IDPs, acid residues of carbonaceous meteorites, and matrix materials from some unequilibrated chondrites. It is not clear whether the differences between IDPs and meteorites are fundamental or whether they represent differences in degree, rather than in kind. It must be remembered that meteorites represent a subset of objects that survive atmospheric entry. There may be large objects, consisting of assemblages of material similar to IDPs, that never reach earth because of their fragility.

At this point it would appear prudent to reserve judgement on the relationship between IDPs and meteorites and treat them as related parts of the same larger puzzle.

Whether true or not, there is a widely held belief, based largely on mass balance arguments, that interplanetary dust is composed primarily of comet dust [23]. It is also believed by many that comets consist largely of primordial material. Direct comparison of IDPs with cometary material suffers from the obvious problem that no one has yet mounted a space mission to return a comet sample.

In the absence of a returned comet sample, the only direct comparison between IDPs and comet dust is based on their optical properties [19]. The best astronomical observations in the infrared are those for Comet Kohoutek where the spectral emission properties of the dust have been obtained from deconvolution of the observational data using an assumed black body spectrum [36]. Comparison with the spectral transmission data for IDPs shows that none of the spectral classes of the particles gives a good match to the comet result. However, a composite spectrum consisting of equal contributions from the pyroxene and layer-lattice silicate classes gives a reasonable match. The olivine spectral class gives the worst fit and it appears unlikely that many particles in this class (some of which are known to be extraterrestrial) are present in Comet Kohoutek.

The present results therefore suggest either that the olivine component of interplanetary dust is not derived from comets or that Comet Kohoutek is not representative of all comets. The olivine class of particles may also be over represented in the limited population of particles (a total of 26) so far measured. These possibilities are obviously not mutually exclusive.

Spectral matching is not a very satisfactory way to approach the question of the relationship between IDPs and comets since even a perfect spectral match would not guarantee that IDPs came from comets. The main thing in its favor is that it is currently the only way to attack the problem.

Apart from obtaining additional, sorely needed spectral data on both comet dust and IDPs, there are several experimental approaches to solving the IDP-comet comparison problem. It has

long been known that most meteor showers have orbits that link them directly with specific comets. Collection and analysis of material from a meteor shower would be a major accomplishment, and a joint Franco-Soviet space experiment which will attempt to collect impact debris from particles associated with the comet Giacobini-Zinner is currently in progress [24].

As discussed more fully elsewhere [25], another important approach would be to construct a space instrument that would measure the <u>orbital parameters</u> of individual particles whose impact debris atoms would be analyzed upon return to the laboratory. Interstellar grains traversing the solar system conceivably could also be located and measured with such an instrument.

Comet rendezvous missions performing sophisticated in situ measurements on dust grains would also help settle the question. And, of course, a sample return mission to a comet would be invaluable.

Scientific interest in IDPs would likely be enhanced if comet samples proved to contain particles of a similar nature. At best, space missions can sample only a few comets in the foreseeable future. If IDPs do indeed come predominantly from comets they are samples of many different objects; further, their heterogeneity shows that they contain a record of a variety of processes.

V. DO IDPs CONSIST OF PRIMITIVE AND/OR PRIMORDIAL MATTER?

Yes and maybe. No generally accepted criteria exist to classify material as either primitive or primordial. For the purposes of this paper, primitive matter is defined as material which has isotopic struc·ures different from those in "average solar system material" and of a nature that cannot be explained by known processes such as spallation reactions by cosmic rays during exposure in interplanetary space. The implication is that primitive materials can be used to obtain information about conditions in the early solar system.

Primordial matter can be defined as (more or less) unaltered material that existed in the (presumed) gas-dust cloud that existed the prior to the present solar system i.e.: interstellar dust. Certain authors have interpreted isotopic data as indicating the presence of such material in meteorites [21]. However, the evidence is circumstantial; no one to date has isolated specific meteoritic grains that have been definitively identified as unaltered interstellar material.

One of the most intriguing of the many isotopic anomalies that have been discovered in meteorites in recent years in the case of Ne-E. This component of Ne consists almost exclusively of ^{22}Ne [22]. A plausible explanation of Ne-E is that live ^{22}Na was incorporated into solid grains where it subsequently decayed into ^{22}Ne. Preservation of the isotopic signature would require that the solid carrier phases were never heated to the point where they totally degassed. Thus they might still be present in recognizable form. However, it remains to be proven that this is the case.

Primordial matter may well exist in both meteorites and IDPs. However, it may be more difficult to identify such material in IDPs simply because of their small sizes. More detailed studies using improved analytical techniques and working with larger IDPs (a program to collect larger stratospheric dust particles is currently in progress) will help address this question. Other aspects of the relationship of IDPs to interstellar matter are treated in the next section.

VI. IS THERE ANY RELATIONSHIP BETWEEN IDPs AND INTERSTELLAR MATTER?

Maybe, maybe not. The most plausible place to look for such links is in dense gas-dust clouds containing strong infrared sources that have been interpreted as protostars. A comparison of the IR absorption features of the protostar W33A with the spectrum of a typical IDP of the layer lattice silicate class shows certain common features. Present in both spectra are features at $3\mu m$, $6.8\ \mu m$ and $10\ \mu m$. The dominant $3\mu m$ feature in W33A has been attributed to water ice, a constituent that cannot be present in IDPs where the weaker $3\mu m$ feature is attributable to water incorporated in a layered silicate structure. The $10\ \mu m$ feature seen in both spectra is likely due to silicates.

In the IDPs the $6.8\ \mu m$ feature is certainly primarily due to carbonate minerals, although a smaller contribution from other phases cannot be ruled out at this time. It is an open question whether carbonates are also responsible for the ubiquitous $6.8\ \mu m$ feature seen in W33A, and other protostellar objects. Such a possibility was originally suggested based on a comparison of the IR spectrum of the meteorite Murchison with protostellar spectra [26]. However, the absence of an expected accompanying carbonate feature at $> 25\ \mu m$ [27] was also noted. In principle, the presence of carbonate minerals in protostellar sources can be settled by additional astronomical measurements.

Another possible connection between IDPs and interstellar cloud material is provided by the deuterium results. Radio observations show that simple molecules such as HCN can be greatly enriched in deuterium in cold interstellar clouds [28a,b]. If interstellar grains are partly composed of complex organic molecules built up from simple molecules by processes such as photolysis [29], it is plausible that the complex molecules would reflect the deuterium enrichments present in the simple precursor molecules. The large deuterium enrichments seen in IDPs (and in certain extracts from unequilibrated meteorites) could be due to such deuterated interstellar material [30].

Although it is useful to consider points of contact between IDPs and interstellar material, it is equally important to consider what has not been observed. The depletions of certain elements (e.g.: Al and Ca) in the interstellar gas phase have led to the view that interstellar grains in clouds should consist in part of refractory cores [31]. No such refractory cores have yet been reported in IDPs, although fassaite, a common constituent of calcium aluminum rich refractory inclusions in meteorites has been recently found in one IDP [18k].

That grains with the properties expected for interstellar material have not yet been reported in IDPs, does not necessarily mean that such material is not present. Perhaps the problem is one of concentration and scale. Most of the astronomical observations relate to particles of $\sim 0.1\mu m$ or less. While grains of this size are routinely measured in electron diffraction studies of IDPs, detailed TEM measurements tend to be made on the largest sub-grains, on those which have euhedral external morphologies, and those which, by definition, give the strongest electron diffraction signals. Many sub-grains of the kind inferred from astronomical measurements could be present as constituents of modest crystallinity without having been singled out in the experimental studies done to date.

VII. CAN THE STUDY OF IDPs CONTRIBUTE TO THE UNDERSTANDING OF BASIC ASTROPHYSICAL PROBLEMS?

Probably - especially on the question of the formation of solids in space. Wherever and whenever the various components of IDPs were formed, several lines of evidence indicate that vapor-solid processes were important. Crystal morphologies unlike those found in terrestrial, lunar, or meteoritic rocks are a common feature in IDPs. Specifically, in fluffy, anhydrous particles the mineral pyroxene is observed to occur in the form of whiskers (rods and ribbons) and very thin platelets. The presence of axial screw dislocations and absence of extensive twinning have been used to argue that the crystals were formed by direct vapor phase condensation [18e]. It is interesting that the results of laboratory experiments on crystal growth served to predict the presence of the observed morphologies prior to their observation in nature [32].

Mineralogical and morphological features found in other anhydrous porous aggregates have been interpreted as evidence for the formation of carbon compounds by heterogeneous catalytic reduction of carbon-rich gases [18f, 18g]. Carbonaceous mantles filaments and fine-grained matrix material are found intermixed with Fe-Ni grains and Fe-Ni carbides of several types, notably hexagonal ϵ-carbide. Similar phases are characteristic by-products of the laboratory decomposition of CO by fine metal particles. Such catalytic processes are widely used industrially with an important subset being the Fischer-Tropsch reactions. Based largely on the observed distribution of molecular weights of extracted hydrocarbons, such processes had been previously proposed as a mechanism for the formation of organic compounds in meteorites [33].

Although these results are intriguing, the lack of detailed knowledge of the kinetics of catalytic reactions in plausible astrophysical environments currently limits the constraints that can be put on the physical conditions under which the observed structures were formed.

Although olivine and pyroxene platelets have been more commonly observed in anhydrous particles, they also occur in IDPs of the hydrated silicate type. In one case, a phyllosilicate crystal is observed in intimate association with a pyroxene crystal suggesting that phyllosilicates are produced by aqueous alteration of pyroxenes [18-k]. Whether this was a liquid or vapor reaction is not clear. It has also been suggested that the carbonates observed in layer-lattice silicate IDPs may have been formed by catalytic reaction with silicates and magnetite in a cooling gas [18-m].

The ensemble of these mineralogical studies, coupled with the fact that many of the particles possess anomalous deuterium abundances, suggest that IPDs contain a record of processes going on early in the history of the solar system, or possibly, before.

VIII. CONCLUDING REMARKS

IDPs are a unique form of primitive extraterrestrial material. Their systematic study is less than a decade old. In spite of the formidable experimental problems in working with particles that are too small to be seen with the naked eye, it has proven possible to obtain considerable information concerning their properties and possible origins. Like any new field, there are many unanswered questions. Continued work by a growing number of investigators, using ever more sophisticated analytic techniques, can be expected to give continued progress and almost certainly to produce some surprises.

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