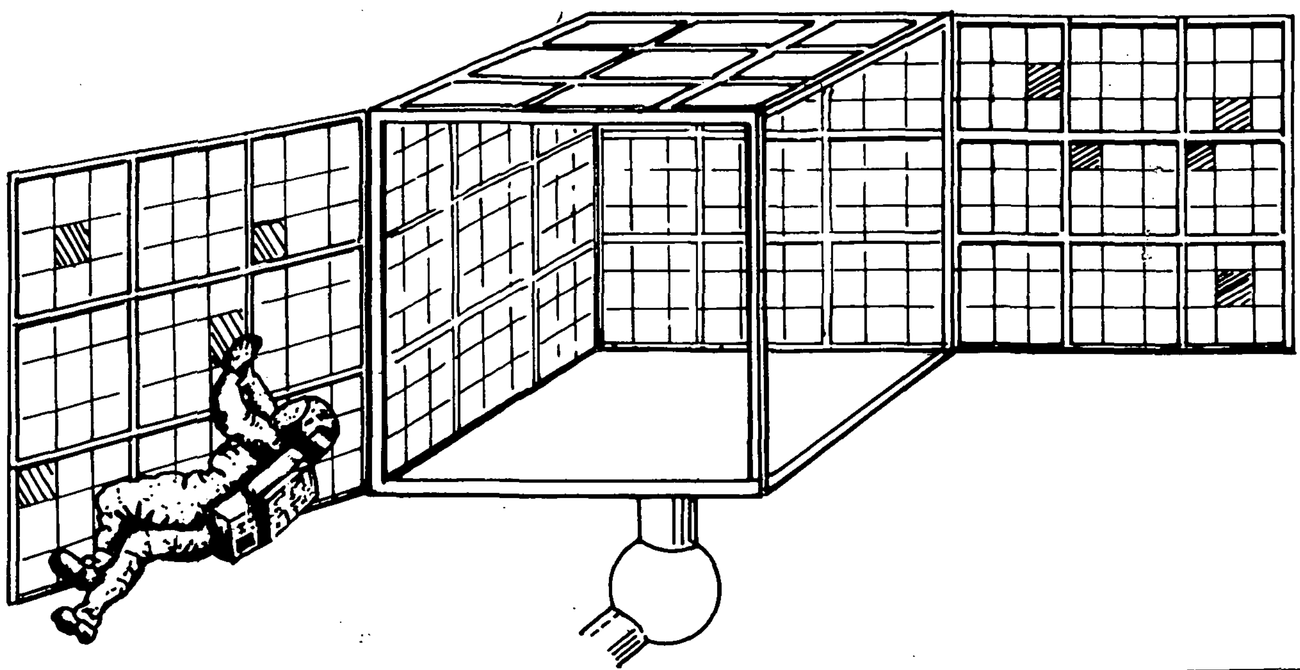
TRAJECTORY DETERMINATIONS AND COLLECTION OF MICROMETEOROIDS ON THE SPACE STATION

—Report of the Workshop on Micrometeorite Capture Experiments—



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TRAJECTORY DETERMINATIONS AND COLLECTION OF MICROMETEOROIDS ON THE SPACE STATION

Edited by
Friedrich Hörz

Report of the Workshop on Micrometeorite Capture Experiments

A Lunar and Planetary Institute Workshop

December 16–18, 1985

Lunar and Planetary Institute 3303 NASA Road 1 Houston, Texas 77058-4399

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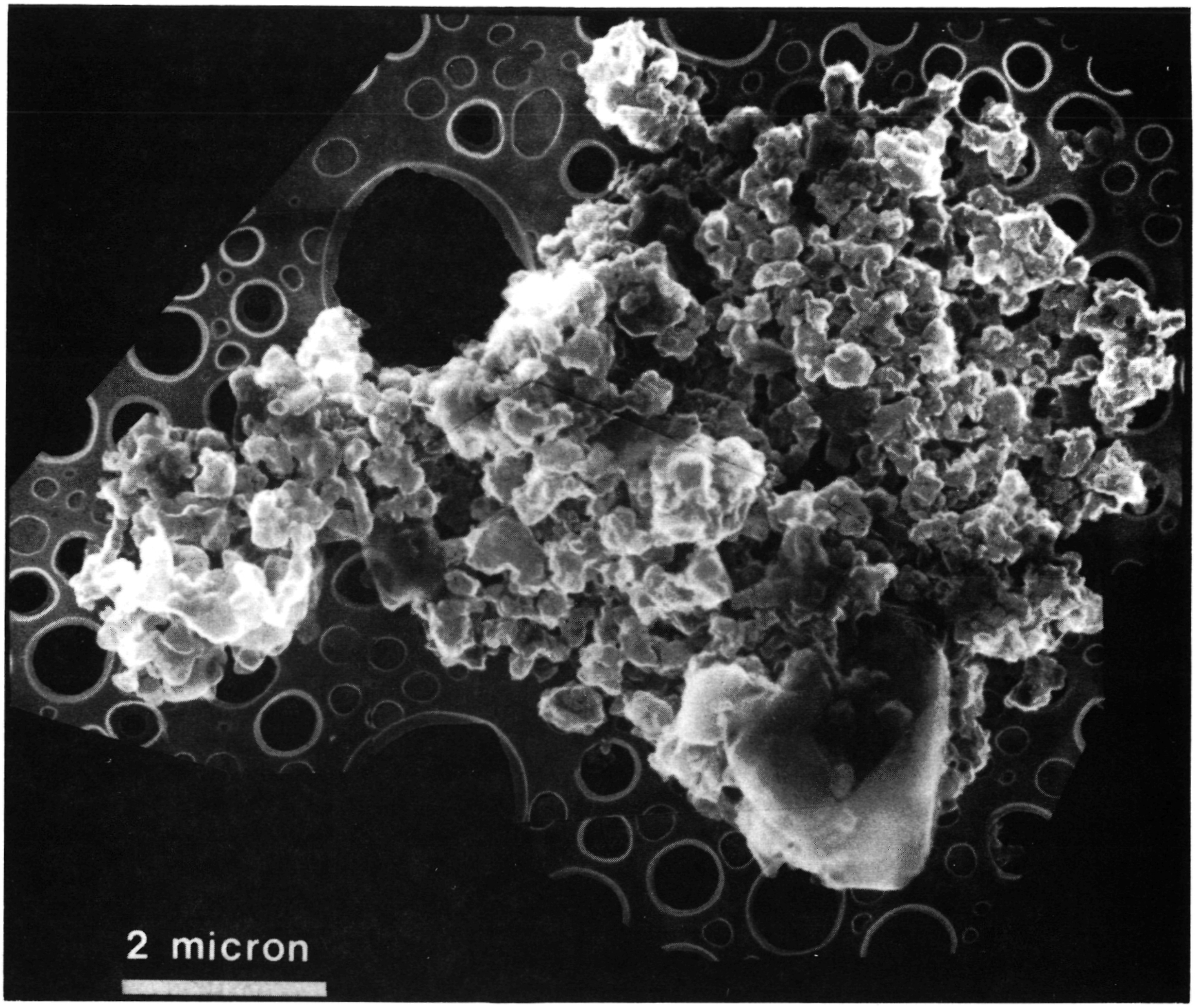

Frontispiece: *Cosmic dust particle recovered via high altitude aircraft in the stratosphere. Specifically this particle represents "chondritic porous aggregates," a common particle type in these collections. Note its complex texture and that it is made up of a wide variety of individual grains, some of which may be crystalline, others amorphous. A diversity of crystalline solids may be present, ranging from olivine to hydrated clay minerals; the amorphous materials include "silicate" glasses and carbonaceous materials (courtesy of F. J. M. Rietmeijer).*

Cover: *Conceptual configuration of the Cosmic Dust Facility, i.e., a cubus approximately 3 m on the side. Each cube face is partitioned into instrument tray compartments approximately 1m × 1m and individual instruments may be subdivided into still smaller detector units. Detector units having registered impact will be periodically retrieved and returned by STS for analysis in the terrestrial laboratory. The cube faces are hinged for easy access from the rear for removal of the capture devices without undue disturbance of the trajectory sensors which are front-facing. Opposing cube faces may be combined into a single experiment, allowing for deceleration paths a few meters long. The sketch depicts a typical EVA scene (courtesy of J. A. M. McDonnell).*

Preface

This report documents the proceedings of a workshop held at the Lunar and Planetary Institute, Houston, Texas, on December 16–18, 1985. The workshop addressed the opportunities for cosmic dust investigations on board the proposed Space Station. Such studies require inherently large surface areas and relatively long exposure periods. The Space Station seems to provide a suitable platform for a dedicated cosmic dust facility.

The goals of the workshop were to define the scientific objectives and the resulting performance requirements of a potential Space Station facility and to identify the major elements of a coherent development program that would generate the desired capabilities within the next decade. Participants in the workshop represented the areas of planetary sciences, exobiology, and orbital debris investigations; these communities are expected to be the major facility users.

This workshop greatly benefitted from and expanded upon a previous workshop that was held at Washington University, St. Louis, Missouri, December 5–7, 1983. However, attendance at this prior workshop was essentially limited to planetary sciences and more specifically to those interested in cosmic dust investigations afforded by the Long Duration Exposure Facility (LDEF). The St. Louis workshop concentrated on improved instrumentation on board the LDEF platform. The community response resulted in eight informal and short proposals for flight participation. Many of the instrument concepts developed in the present report were formulated initially at the St. Louis workshop, a detailed report of which may be obtained from the host and convener, R. M. Walker.

The present workshop was convened by R. J. Williams and F. Hörz of the NASA Johnson Space Center. They gratefully acknowledge generous support by the Lunar and Planetary Institute and its Director, K. Burke. Workshop coordinators Pamela Jones and Lebecca Turner, as usual, assisted superbly prior to and during the meeting, despite occasional nicotine abundances near saturation levels in the conference room. Finally, the report was typeset and produced by LPI, under the able direction of Stephanie Tindell and Pamela Thompson. Most of the writing represents a community effort involving a large number of contributors, coordinated by F. Hörz.

Executive Summary

Small particles known as "cosmic dust" exist at 1 AU and may be collected in near-Earth orbit. Observational and theoretical evidence indicates that they are derived predominantly from comets and asteroids, but interstellar grains should also be present. Comets and asteroids are expected to preserve evidence of physical and chemical processes in the early solar system; this information will provide critical boundary conditions for the formation of planets and the evolution of life. Interstellar particles may offer similar information about prestellar nebulae or other evolutionary stages of other solar systems, and may provide critical tests of current astrophysical theories, including those related to nucleosynthesis.

If the capability were emplaced to capture individual particles in near-Earth orbit and to measure simultaneously their trajectories with sufficient precision, their astrophysical sources may be reconstructed. Significant information on a number of primitive parent bodies may be obtained. Direct sampling of these sources via dedicated sample return missions will be limited—at best—to a comparatively small number of bodies.

The cumulative particle flux from all sources is fairly well established and known to be extremely small. As a consequence cosmic dust studies in near-Earth orbit require inherently large surface areas combined with long exposure times; under these constraints, the Space Station emerges as a highly suitable platform. A workshop was held, therefore, at the Lunar and Planetary Institute, on December 16–18, 1985 whose primary objective was to identify major elements of a coherent development program that would lead to a cosmic dust collection facility on the Space Station. The objectives of such a facility would be (1) to capture individual cosmic dust particles in some form suitable for detailed analysis in state-of-the-art terrestrial laboratories and (2) to measure the orbital parameters with sufficient precision to allow reconstruction of their source areas (e.g., comets versus asteroids); in specific cases unique association with discrete primitive bodies seems possible.

The workshop was attended by 40 people representing planetary and exobiological sciences, the orbital-debris community, NASA Headquarters, and various Space Station planning elements. More than 20 invited and contributed papers were presented and approximately 50% of the time was devoted to discussion in subgroups or plenary sessions.

The following recommendations emerged:

1. It is recommended that a **cosmic dust facility be installed on board the Space Station.** The primary objectives of such an installation should be to capture individual micrometeoroids and manmade debris particles, to measure their orbital elements, and to conduct detailed analysis upon their return to Earth.

2. This facility should be made an **integral part of planning for Space Station science** and a fully operational facility should be part of the Space Station Initial Operational Capabilities (IOC).

3. The use of diverse, specialized instrumentation naturally leads to a **facility-class design** that should accommodate a **variety of instruments** and that should be accessible by a **number of qualified investigators.**

4. The facility should meet the following **specifications:** a surface area of approximately 50 m^2 should be exposed and a number of different viewing directions are needed. The support structure must be compartmentalized into subunits of approximately 100×100 cm, the size expected for individual instrument trays. Each tray should be further subdivided into detector units that may be removed periodically. Each detector unit may possibly be subdivided into still smaller sensor units. Some instruments may require pathlengths (i.e., depth of instrument) of a few meters, others of only a few centimeters. The facility should have self-sufficient electronics for data recording and on-orbit processing. Continuous links to the Space Station will be maintained to provide electrical power and precise positioning data in a geocentric reference frame. Periodic telemetry will be needed for data transmission and instrument interrogation. Crew activities will be necessary to retrieve detector units that have registered impacts. Dedicated, clean containers will be used for all transportation to and from the Space Station by STS.

A cube-shaped structure approximately 3 m on a side could readily accommodate all dimensional (and other) requirements.

5. A **near-term development program** leading to the desired IOC capabilities is necessary and should be supported; it should consist of the following major elements:

(a) **Detector development in the laboratory**. Improvement of present capture devices and trajectory determination methods is needed, especially in terms of their integration into an operational instrument.

(b) **Detector development in Earth orbit**. Near-term flight opportunities will be needed to test and evaluate the performance of individual components and integrated instrument(s).

(c) **Continued Earth-based dust collection, upgrading of analytical capabilities, and theoretical research**. These activities will provide scientific focus and will strongly affect instrument design and performance requirements.

(d) **Continued definition of facility configuration and systems**. Structural, electrical, and electronic design of the facility and its integration with the Space Station will provide the framework for instrument design.

6. Because the Space Station facility and its associated development program will make substantial contributions toward the **characterization of manmade space debris**, technical collaboration and fiscal support from the orbital debris community seems advisable.

7. Advanced collection devices and trajectory determinations should be supported, because cosmic dust investigations on the Space Station should be viewed as a **long-term science activity** that will increase in complexity and sophistication as Space Station capabilities evolve.

8. It is recommended that **international cooperation** be encouraged, including the sharing of costs and intellectual rewards. Much of the expertise in the design, fabrication, and hypervelocity testing of cosmic dust experiments resides abroad and specifically in Europe, where interest in cosmic dust research remains high.

9. **Administrative support** and organization for efficient implementation of this development program is needed. It also requires organization of the facility user communities for continued advocacy and coordination.

In summary, the workshop conveyed scientific excitement and enthusiasm about the prospect of continued acquisition and analysis of extraterrestrial materials. Significant advances in characterizing early solar system processes seem possible if the source area(s) of individual samples could be determined. The level of support received by the near-term development program will affect, in large measure, the realization of this goal.

Workshop Agenda

Monday, December 16
8:30 am

Session 1: Overview and Background

Workshop Objectives
- J. P. Kerwin: Welcome
- R. J. Williams: Purpose of Workshop
- D. DeVincenzi: The Exobiology-Planetary Sciences Connection

Scientific Rationale
- D. E. Brownlee: Cosmic dust: Cometary and asteroidal sources
- R. M. Walker: Cosmic dust: Interstellar sources
- S. Chang: Cosmic dust and exobiology
- D. J. Kessler: Current understanding of the debris environment

Present Collection Efforts: Results, Lessons and Issues
- I. D. R. Mackinnon: Stratospheric dust collections
- J. A. M. McDonnell: Extraterrestrial material recovery experiments
- D. S. McKay: Analysis of Solar Max surfaces

Flight Opportunities
- L. C. Wade: STS flight opportunities
- D. Lilly: The Space Industrialization Platform
- W. Kinard: The LDEF opportunities for cosmic dust studies
- D. R. Thompson: Current Space Station configuration

1:30 pm

Session 2: Instrument Development and Concepts

- J. A. M. McDonnell: Overview of possible instrumentation
- W. Carey: Prospects for an orbital determination and capture cell experiment: A proposed evolutionary sequence
- J. Wortman: Dust experiments utilizing MOS detectors
- J. Wolfe: A nondestructive dust collector concept
- H. Zook: Meteorite velocity measurement needs
- P. Tsou: Intact capture of hypervelocity particles
- F. Hörz: Some considerations regarding target properties

Tuesday, December 17
8:30 am

Session 2 (continued)

- G. J. Corso: The use of tethered satellites
- J. Visentine: Effects of the low-Earth orbital environment
- I. D. R. Mackinnon: Targeted flight opportunities with Large Area Collectors
- F. Radicati: Laser microprobe characterisation of C species in IDPs
- J. D. Bradley: Thin sectioning and electronbeam analysis of extraterrestrial particles
- J. Nuth: Cosmic dust collection on serviceable satellites

10:00 am

Session 3: Programmatic Issues and Views

R. Powell: Planetary sciences and the Space Station
R. J. Williams: Need to update Mission Data Base
Plenary discussion
Organization of discussion groups

1:30 pm

Group Discussions

Group 1: Current capabilities and short-term development needs
Group 2: Space station facility
Group 3: Mission Data Base update

3:00 pm

Plenary Session and Writing Assignments

Wednesday, December 18
8:30 am

Plenary Session

The elements of a development program
Organization of workshop report and writing assignments
Update of Mission Data Base
Administrative support

1:00 pm

Meeting formally adjourned, but writing of executive summary and other assignments continued for many participants, including the updating of the Mission Data Base and other "real time" workshop products that Headquarters needed urgently.

Chapter 1

Scientific Rationale and Justification for Cosmic Dust Studies in Earth Orbit

Interplanetary dust particles (IDP) are samples of primitive materials that have recently been liberated from comets and asteroids; a minor fraction originates from the contemporary interstellar medium. The relative contributions of these diverse astrophysical sources are poorly characterized at present, but a statistically significant particle population will contain samples formed under physical and chemical settings unlike those represented by extraterrestrial materials currently available for analysis. The latter largely reflect processes in the inner solar system, including planet formation, differentiation, and surface evolution.

Laboratory studies on the IDPs that have been recovered from the stratosphere have shown that the particles are complex, heterogeneous assemblages of crystalline and amorphous phases that reflect a wide diversity of formational conditions. The elemental, isotopic, and mineralogic characteristics of some particles are consistent with an origin from the same parent bodies that produced the various meteorite classes. Many of the particles, however, are clearly not derived from the solar system objects that spawned fragments large and strong enough to become conventional meteorites.

The components in many IDPs may have originated as stellar or nebular condensates, interstellar dust, and/or interstellar or nebular molecules; they may also be the products of parent-body processes such as the reworking of surface deposits. The study of interplanetary dust collected in the stratosphere or in space enhances the understanding of comets, asteroids, and the early solar system on one hand, and potentially increases knowledge of the interstellar medium on the other. Therefore, information from general studies of IDPs has high scientific interest for NASA programs in solar system exploration, astronomy, astrophysics, and exobiology; the instrumentation contemplated will also contribute to a better understanding of the nature and evolution of fine-grained orbital debris.

The collection of cosmic dust particles in space provides several unique capabilities in relation to conventional IDPs collected as micrometeorites in the stratosphere. The association of particles with known astrophysical sources requires measurement of the velocity and orbital trajectory elements prior to entry into the Earth's atmosphere. Reconstruction of the source area is possible only via *in situ* measurements on spacecraft. Moreover, collection in Earth orbit will eliminate any atmospheric selection effects. It is possible that there are classes of volatile-rich or very porous, fragile particles that can be collected only in space.

Cosmic dust collection devices in Earth orbit are, however, not without their own limitations. Such limitations relate to potential sample degradation following hypervelocity impact. The particles may fragment, melt, or vaporize. Even extremely degraded particles (i.e., vapors) may be trapped successfully, however, and will yield valuable bulk elemental and isotopic information, including extremely friable or volatile-rich grains previously inaccessible. Hypervelocity simulation studies and examination of space exposed surfaces, such as thermal blankets from the Solar Maximum mission spacecraft (hereafter referred to as Solar Max), indicate the strong possibility of acquiring samples with individual mineral grains still preserved and only moderate levels of degradation, even of hydrated minerals. This will be particularily true for impacts from the anti-apex of the spacecraft's orbital velocity, where impact velocities of extraterrestrial particles can be as low as 3 km/s.

The unique and most important aspect of a cosmic dust collection effort on the Space Station is the ability to measure the orbital elements of individual particles prior to capture. With a moderate collector (e.g., a few tens of m^2 on the Space Station) it should be possible to collect hundreds of particles in the 10^{-15} to 10^{-4} g range and to measure their orbital parameters within a few percent. For some particles it will be possible to identify the exact parent bodies reliably, for others a generic class of sources will be indicated (i.e., comet, asteroid, interstellar, manmade). For the majority of particles, unambiguous identification of a source body will probably not be possible because of parent-daughter orbital divergence caused by a variety of forces. Samples that can be related to a specific source are of great value because they are in a sense "sample return" missions from a variety of primitive objects. Although the samples will be small, and possibly degraded, they will be of enormous importance. A major deficiency with work on meteoritic materials has always been that the samples are orphans with no known means to determine their source of origin. For many samples from the Space Station, this origin will be known in a broad generic sense and, in some instances, at the level of a specific, primitive body.

In addition to studying asteroidal and cometary materials, the unprecedented opportunity exists for the direct measurement of first-order properties of contemporary interstellar materials. Even crude analysis of interstellar grains would provide powerful constraints on the composition, origin, and evolution of interstellar dust. For example, even low-precision isotopic analysis should identify grains produced around stars where the composition of outflowing gas has been strongly affected by nuclear burning within the star.

In addition to providing information on particles with known origins, it is likely that the analyses will also enable the identification of the origin of some of the meteorite and stratospheric particle classes that are already recognized in existing collections. This may provide the information to place at least some of the enormous body of information on meteoritic materials in its true astrophysical context. At a bare minimum this work should allow a comparison between the asteroidal materials that are products of the terrestrial-planet region of the solar nebula and cometary materials that are products of the outer fringes of the planetary/solar system. For example, the collection of even a few mineral fragments formed as cometary particles might show whether comets formed from presolar grains, nebular condensates, or reworked materials. The unique opportunity to collect samples from several comets will provide information on diversity among comets that is important for understanding their origin and evolution. This information could also provide vital input for the planning of missions to short-period comets. For example, the best comet for a pristine sample return mission may be identified or the detailed information obtained from one mission may be extended to other comets with substantially more confidence.

The great interest in and importance of IDPs to exobiology stems from the potential for contributions toward elucidation of the cosmic history of the biogenic elements that make up all life—H, C, N, O, S, and P. Three broad scientific issues are encompassed: (1) the chemical and physical phenomena involved in the path taken by these elements from nucleosynthesis to their incorporation as compounds and minerals in primitive solar system bodies; (2) the use of biogenic elements in components as probes to elucidate aspects of solar system formation; and (3) the properties of these materials that may have influenced processes in the origin and evolution of the solar system.

Current analytical methods and approaches in the investigation of individual dust particles can provide a wealth of information related to the concentration of elements (either in bulk- or phase chemistry), the identification of molecular species, the characterization of isotopes, the determination of physical properties, and the interpretation of morphologic, textural, and other petrographic observations. The anticipated trajectory information can place these results into their proper astrophysical context(s), a new and in some instances unique aspect of extraterrestrial materials research. While aquisition of samples in Earth orbit without some degradation is difficult to envision at present, a significant fraction of the above information may also be extracted from captured residues. While retrieval of unmelted fragments appears promising and highly desirable, valuable first-order geochemical and isotopic information may still be obtained on a particle by particle basis from condensed vapors.

We are thus confident that a dedicated cosmic dust facility on board the Space Station will make substantial contributions toward answering the following questions:

What relationships exist between comets, asteroids, and interstellar grains?

Is there diversity among comets?

Does particle composition correlate with the history of a comet's activity in the inner solar system?

What fraction of interstellar grains came from carbon-rich stars and what fraction from those rich in oxygen?

What fraction of interstellar grains is processed and essentially reformed in the interstellar medium?

Are cometary solids composed of nebular condensates or presolar grains?

What is the organic chemistry of cometary and interstellar grains?

How do the nature, abundance, and distribution of biogenic elements in comets and asteroids impose bounds on aspects of solar system formation?

How complex is the organic chemistry of the interstellar gas phase?

How were solid phases fractionated and distributed among the primitive bodies?

Chapter 2

Definition of the Space Station Facility in the IOC Timeframe

This chapter introduces the functional elements and anticipated requirements of a cosmic dust facility on the Space Station. We will first define the capabilities in terms of scientific objectives. They, in turn, will be the basis for the design rationale, a preliminary facility layout, and the ensuing operational philosophy.

2.1. Capability to Collect Hypervelocity Particles

Cosmic dust particles have a wide range of velocities and masses. Velocities relative to the Space Station may range from a few km/s for natural and manmade impactors to many tens of km/s for interstellar particles, as illustrated in Fig. 1. Principally, all particle masses are of interest, although current analytical capabilities on masses $< 10^{-14}$g are limited. Current best estimates for the flux and mass-frequency distributions of cosmic dust at essentially 1 AU are illustrated in Fig. 2. Accordingly, devices to capture cosmic dust and to determine their trajectories must function properly over a large range of masses, velocities, and associated kinetic energies or momenta. Each candidate device generally has a limited range in dynamic instrument response and it does not seem feasible to conceive of a single capture device or trajectory

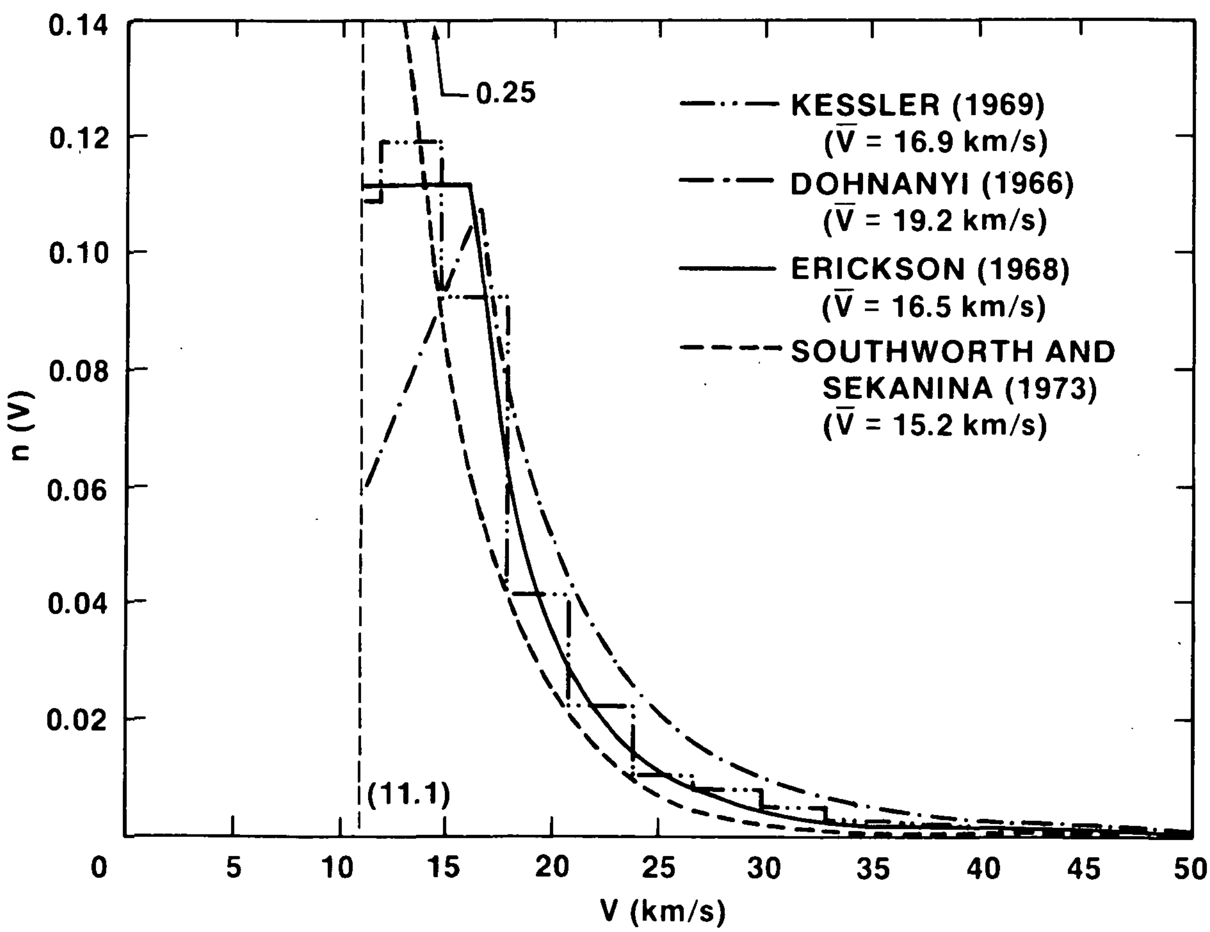

Fig. 1. *The velocity distribution of photographic and radar observations of meteoroids, normalized to Earth, as summarized by Zook (1975). Note that the average velocities estimated by various investigators range from some 15 to 19 km/s, depending on some assumed selection effects. The Space Station velocity vector (7.6 km/s) may of course be added or subtracted vectorially, depending on exact viewing of the sensors.*

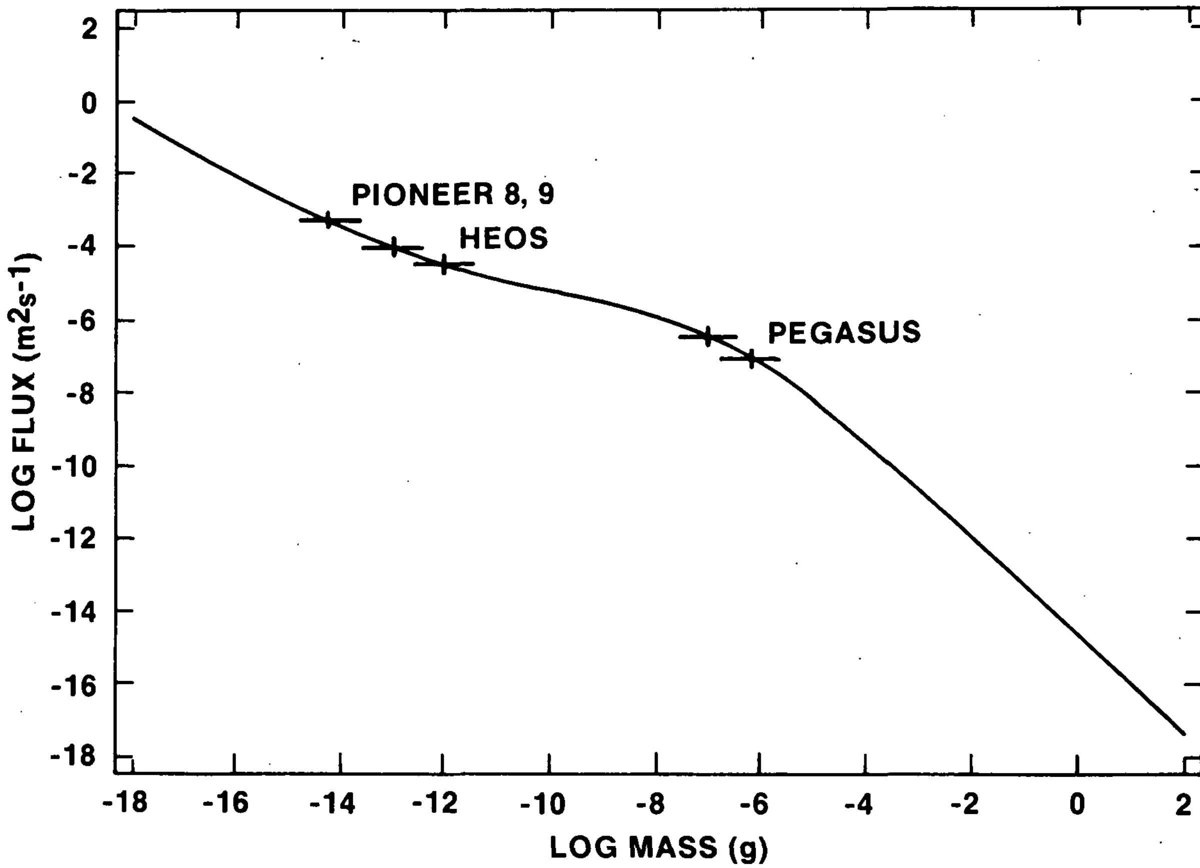

Fig. 2. *The cumulative mass-frequency distribution and associated flux of micrometeoroids according to the summary of Grun et al. (1985).*

detector that operates with optimum efficiency over the entire mass and velocity range(s) represented by natural cosmic dust particles. As a consequence it is suggested that a variety of instrument concepts be incorporated in the Space Station facility.

Currently viable collection techniques rely in one form or another on impact processes for effective particle deceleration, either abruptly by impact on a (infinitely) thick target substrate or more gradually during successive penetrations of ultrathin foils. Other deceleration mechanisms are difficult to conceive as they appear to require impractical deceleration path lengths. The fundamental difficulty in decelerating particles from geocentric velocities is illustrated in Fig. 3: the kinetic energy of most particles exceeds the typical specific heats of melting and even vaporization, commonly by substantial factors if not order(s) of magnitude. Dissipation of this energy without alteration of the particle is indeed difficult. Even gentle deceleration by molecular collisions during atmospheric entry may modify the particles.

Nevertheless, capture of physically intact and unmelted particle fragments appears feasible; experimental demonstrations up to 6 km/s exist (Tsou *et al.*, see abstracts in this volume). Because the velocity vector of the Space Station (7.6 km/s) may be subtracted from the velocity distributions illustrated in Fig. 1 for any collector mounted on the "trailing" edge of the Space Station, some fraction of the dust population may encounter such collectors at velocities < 10 km/s. It is also demonstrated that unmelted particle fragments were returned on space-exposed surfaces (e.g., Blanford *et al.*, 1986; Bradley *et al.*, 1986; Bradley, see abstracts). Fragment capture by means of extremely low-density media may be possible even at velocities as high as 15 km/s (Hörz *et al.*, see abstracts). Thus, capture of particle fragments via impact deceleration seems feasible in Earth orbit, although it may be limited to particles having relatively modest collision velocities.

At impact velocities > 15 km/s, however, and particularly at those characteristic of interstellar particles, complete vaporization of the impactor may not be prevented. Thus, efficient localization of the projectile

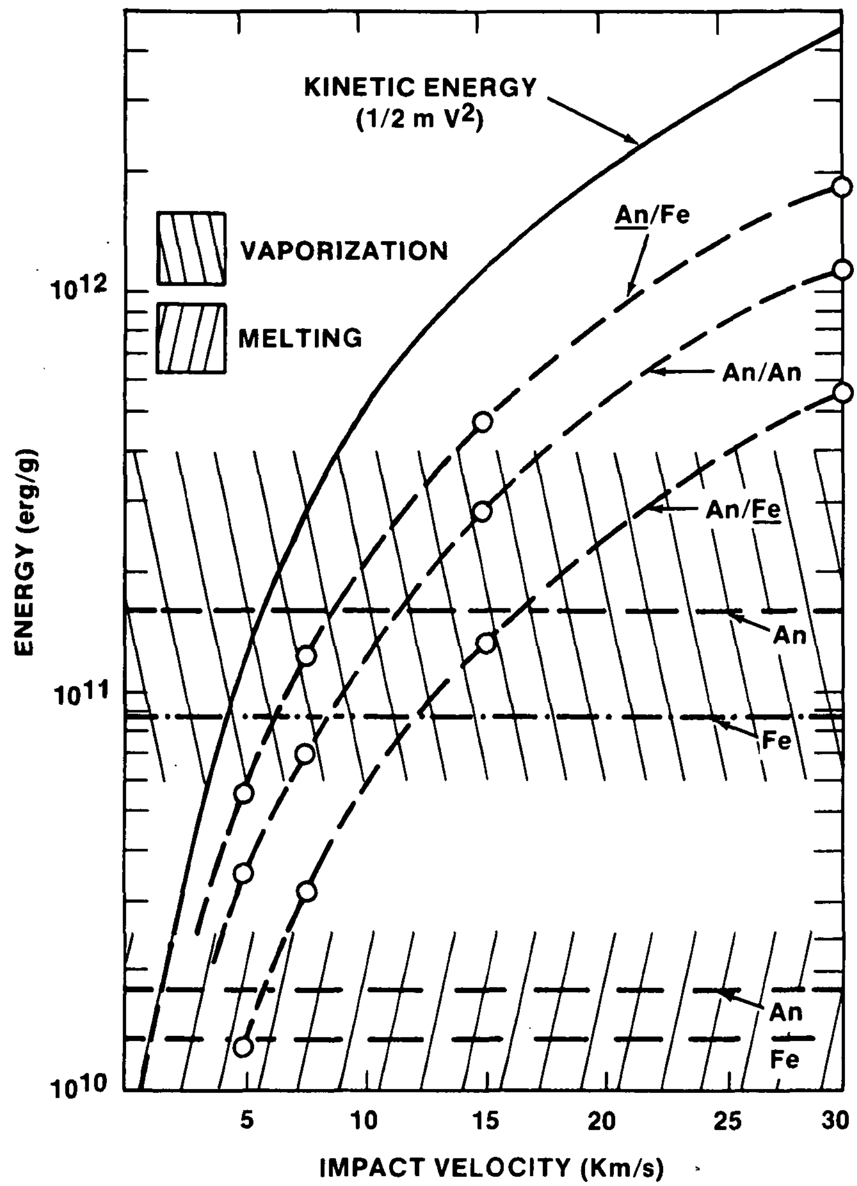

Fig. 3. *Comparison of kinetic energy as a function of impact velocity (solid line) with the specific energies of melting and vaporization for common silicates (hatchured areas) and specifically that of anorthosite and metallic iron. Internal energies from specific cratering calculations by Ahrens and O'Keefe (1977) are indicated by dashed curves; these calculations consider the (kinetic) energy partitioning during impact; only a fraction of the initial energy is converted into thermal energy. The upper curve delineates the internal energy of anorthosite, the lower curve that of iron for an Fe-impactor colliding with an anorthosite target; an anorthosite/anorthosite impact is illustrated by the intermediate curve. Note that the specific energies of melting and vaporization are exceeded for many typical geocentric encounter velocities.*

vapors by means of "capture cells" (Zook and High, 1976) becomes necessary. Prototype capture cells were tested in the laboratory and are currently being exposed on LDEF 1A (Zinner *et al.*, 1982; Lange *et al.*, 1986). The thermal blankets returned from Solar Max may be viewed as some form of capture cell; they successfully trapped projectile melts and vapors (Kessler *et al.*, 1985; McKay *et al.*, see abstracts) as did other foil stacks on board the Shuttle Orbiter (McDonnell *et al.*, 1984). The usefulness of capture cells for the collection of cosmic dust residues has thus been demonstrated.

Impactor residues were also recovered in the form of projectile melts lining the floors and walls of microcraters in relatively thick target plates (e.g., spacecraft windows; Clanton *et al.*, 1980), diverse aluminum plates, and sheets exposed on spacecraft (Brownlee, 1978; McKay *et al.*, see abstracts). Such melt liners were also recovered and analyzed from impact experiments at velocities as high as 8.5 km/s (Hörz *et al.*, 1983 and unpublished data). Clearly, the recovery of impactor melts in microcraters is feasible.

Based on the foregoing, a variety of capture techniques exist. Each technique has advantages and disadvantages, primarily related to impact velocity and the dominating physical state of the impactor. LDEF 1A exposes prototypes of each technique; analysis of these "collectors," therefore, will be important in determining their relative merits. Nevertheless, it appears clear that high-speed particles and their vapors are best trapped with capture cells, while low density target media are needed to preserve particle fragments. The use of two different capture mechanisms—as a minimum—seems required for the Space Station.

The size-frequency distribution of cosmic dust particles, depicted in Fig. 2, requires that the principle capture mechanisms addressed above be dimensionally scaled and optimized for a specific impactor mass range. For example, the wall thickness of foams or the dimensions of capture cells intended to trap 100 μm particles will differ substantially from those designed to capture particles < 5 μm. Thus a variety of dimensionally optimized collectors must be exposed.

In addition, the capture hardware must be constructed from materials that do not adversely affect the anticipated chemical and isotopic analyses. Structurally similar, if not identical, collection devices constructed from different materials may have to be exposed, depending on the chemical element of interest.

It is concluded, therefore, that a variety of collector mechanisms should be incorporated into the Space Station facility. The various collectors must be dimensionally optimized for specific projectile masses and must be constructed from materials compatible with the anticipated cosmochemical objectives. These requirements, very naturally, lead to the involvment and participation of diverse investigator groups.

2.2. Capability of Determining Orbital Elements and Source Regions

Small particulate matter in the inner solar system is continually subjected to a variety of forces (gravity, Poynting-Robertson drag, solar wind, solar radiation pressure, mutual collisions) that tend to modify the initial orbital elements acquired during escape from their parent objects (e.g., Zook, see abstracts). These effects are dependent on particle size and become relatively larger as particle size decreases. That orbital information can be retained is demonstrated by the well-known association of meteor showers with the trajectories of known comets. The orbits of sporadic meteors also fall into different classes, one of which is consistent with a cometary origin. Nevertheless, the fraction of small particles that may be uniquely associated with either a specific object or with a general class of objects (e.g., comets, interstellar grains, etc.) is not well determined. Additional theoretical work on the evolution of orbits is required and should include the growing body of information about the physical properties of interplanetary dust collected in the stratosphere. In the absense of such theoretical work it is not known in detail how much precision in trajectory measurement is required to make unique parent-daughter associations. It is therefore recommended at this stage that *in situ* determinations of orbital elements should be made at the current state of the art. It appears feasible to obtain a precision of several percent, possibly $< 1\%$, in determining vector-velocity components of impacting meteoroids.

A number of velocity measurement concepts exist. They may be classified as "nondestructive" and (potentially) "destructive" in terms of particle degradation during the actual velocity measurement. A number of techniques are flight proven, while others are on board the GIOTTO and VEGA spacecraft.

The only nondestructive technique suggested to date consists of a series of highly transparent, electrostatic wire grids that sense the passage of naturally charged hypervelocity particles; modest laboratory testing exists (Auer, 1975). In a sense this approach is a spinoff of the well-understood detection of impact-triggered plasma, successfully flown on a number of spacecraft (e.g., Pioneers 8 and 9, LEAM, HEOS, and HELIOS 1 and 2; for a summary see McDonnell, 1978). Modern electron multipliers for charge sensing—combined with the plasma detectors—were on board the HELIOS spacecraft (Grun *et al.*, 1980). Thus nondestructive methods exist to measure particle velocities. Such instruments are highly desirable for the Space Station application, because they could possibly be developed into "stand alone" trajectory measurement devices independent of any capture mechanism. This not only seems desirable for the collection of minimally altered particles, but seems to offer operational advantages as well, because only the collector mechanism would have to be harvested/replaced periodically.

Although potentially destructive, other trajectory measurement concepts exist in which the impactor will have to penetrate one or two thin films. This thin film penetration may lead to partial projectile disruption, but the exact degree of projectile alteration remains unknown in many cases; it could be relatively modest compared to the actual capture process, if ultrathin films were used for the pupose of velocity/trajectory measurement (the penetration films can be viewed as part of the capture process and modest sample disruption appears acceptable). Potentially more serious concerns arise from the chemical composition of some specialized film materials, leading to sample contamination. Current velocity/trajectory detector concepts are based on the recording of pyroelectric depolarization and the detection of accoustic energy (see Chapter 4).

Clearly, the anticipated capability of trajectory determination and capture on a particle-by-particle basis will represent a major advance in micrometeorite science. While early versions of some candidate systems have flown successfully in space, their combination and integration into a single instrument has never been attempted. This integration represents the major technical challenge during instrument development for the Space Station. It remains to be determined whether a "stand alone" velocity detector in front of the (independent) capture medium is to be preferred or whether the diverse thin film detectors can be made an integral part of the capture device.

2.3. A Preliminary Facility Layout and Design Rationale

The basic elements for the suggested structural architecture and associated operations derive from the desire to have a dedicated facility on the Space Station that should function as autonomously as possible. The desire for self-sufficient operations extends into the electronic subsystems and the recording and processing of event signals. A relatively autonomous system seems to afford maximum flexibility for the mechanical and electronic design of individual instruments. This is also a particularly important aspect for the continued evolution and upgrading of specific instruments. The autonomous facility, after integration of its major mechanical, electrical, and electronic systems with the primary Space Station, should provide maximum flexibility in accommodating the scientific objectives.

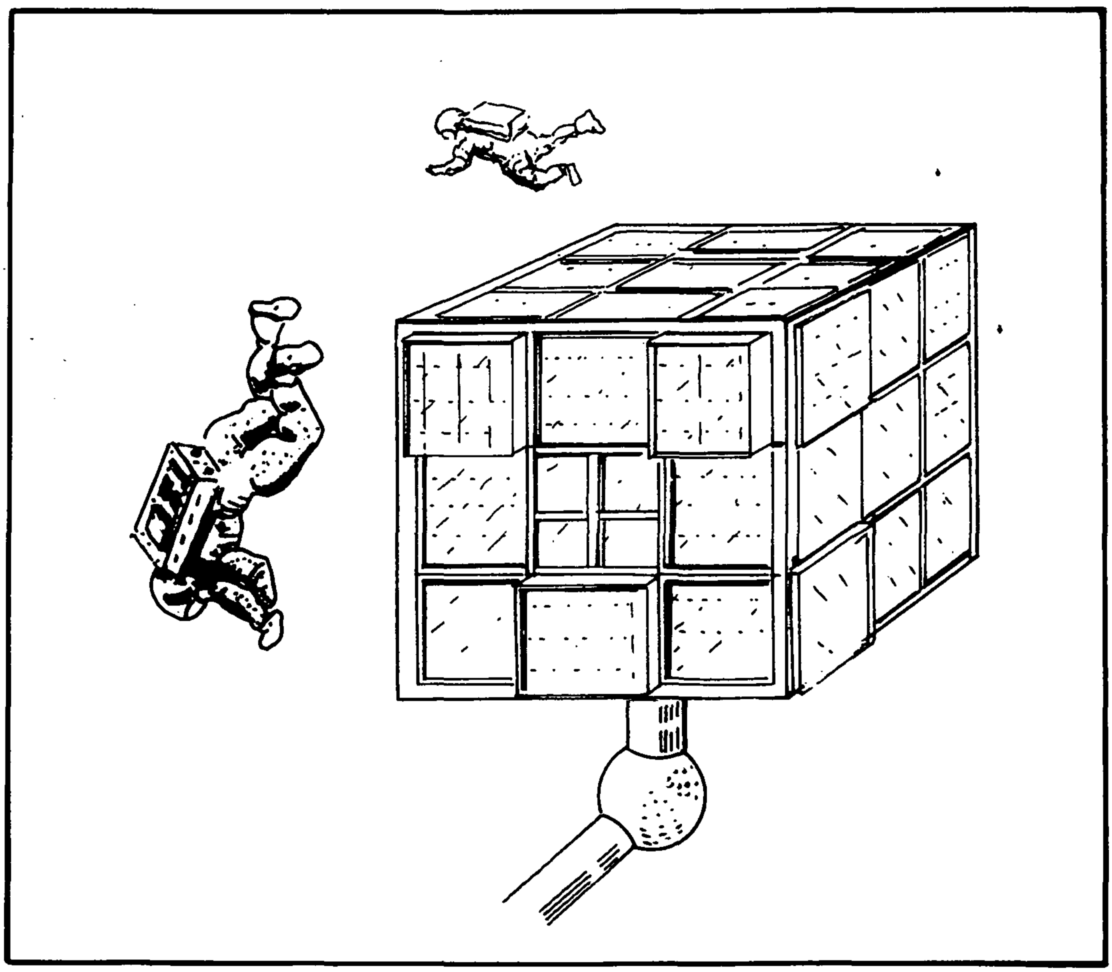

Fig. 4. *Conceptual sketch of the Space Station cosmic dust facility, depicting a cube 3 m on a side, with each cube face subdivided into smaller instrument compartments.*

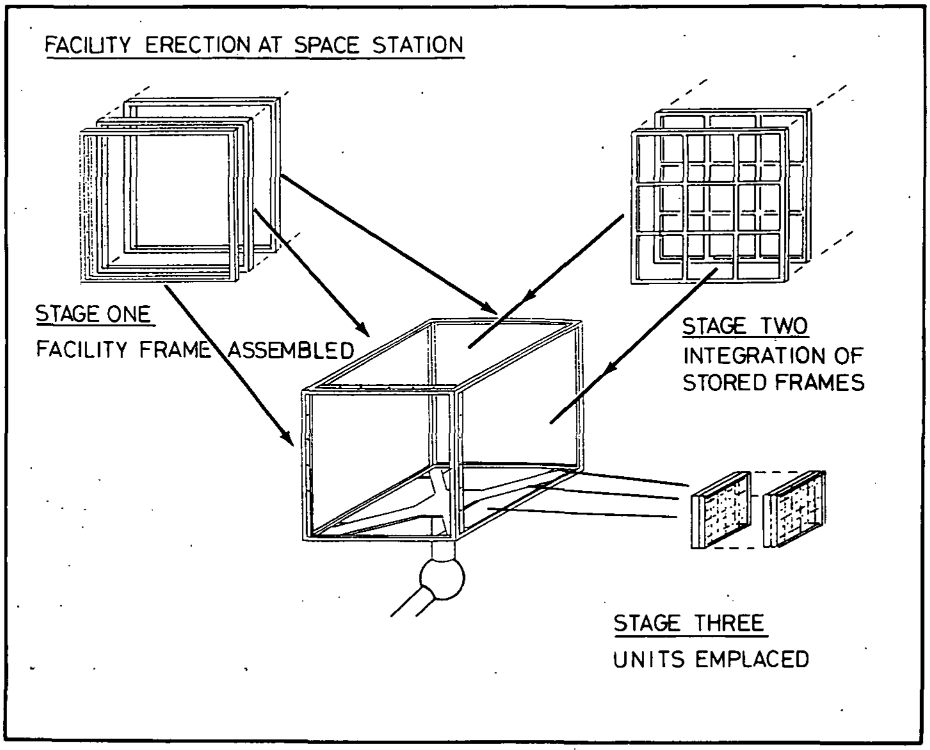

Fig. 5. *Concepts of facility assembly and installation on the Space Station. The basic cube is transported by STS in collapsed fashion and assembled in orbit, including the attachment of instrument trays and detector units, physically the smallest unit to be routinely retrieved and refurbished. The facility may be transported in its entirety during one STS flight, or it may be delivered in parts by a number of flights.*

A cube-shaped structure, approximately 3 m on a side, was identified as a potential configuration (see Fig. 4). It provides the desired surface area (approximately 50 m^2). It is an externally attached payload that views in all major directions; it seems to offer operational advantages, because the sides can be hinged and the instruments can be accessed from the rear for the removal of collectors without disturbing the trajectory detectors (should a stand-alone trajectory detector be incorporated). Furthermore, the 3-m cube provides for substantial deceleration-path-lengths and may readily house the data recording and

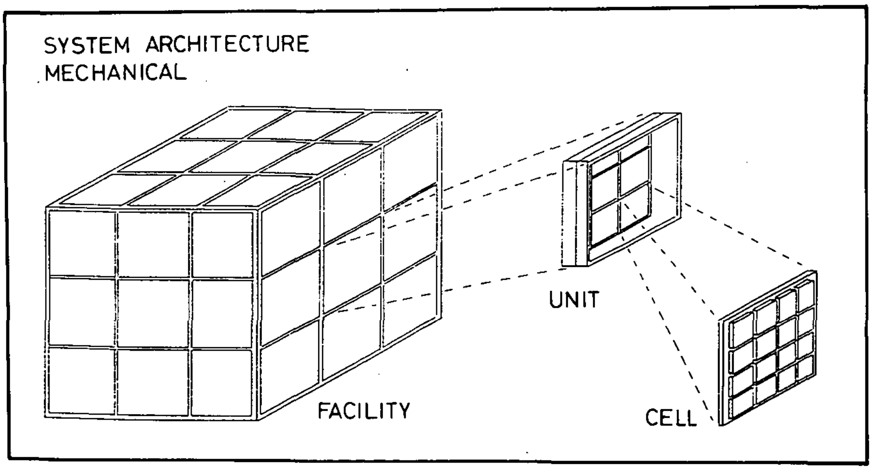

Fig. 6. *Mechanical architecture illustrating again the concept of subdividing the exposed surfaces into a large number of retrievable units and the possibility that the latter may be composed of a large number of individual collectors/ sensors.*

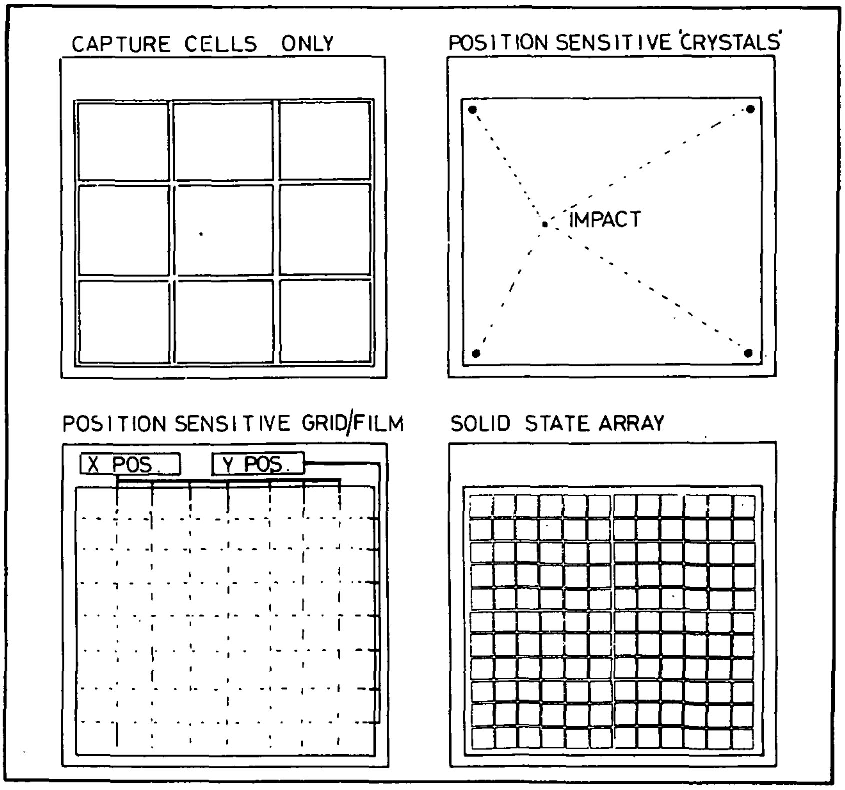

Fig. 7. *Generic examples of capture cell arrangements and potential sensor configurations. The purpose of this figure is to illustrate that collectors and trajectory sensors need not have the same size and that the areas of particle detection by different sensor sets may differ substantially, affecting electronic design.*

processing systems, etc. As further illustrated in Figs. 5 and 6, it is extremely desirable that the 3 × 3 m cube faces be subdivided into subunits of approximately 100 × 100 cm, which is the typical size of an individual instrument tray—a concept similar to that employed by LDEF. These "units," referring to Fig. 6, should be subdivided into detector "cells" of presently unspecified dimensions. Such cells would constitute the smallest physical unit retrieved and replenished with relative ease by the crew; the smaller this cell unit, the better, because only a small fraction of the surface area will contain particles of interest. In detail (Fig. 7), these cells may contain many individual "sensors," capture cell arrays, etc., which must be electronically independent and insulated from each other, as illustrated in Figs. 8 and 9.

A typical instrument may contain the following stack of four subelements as schematically illustrated for a capture cell-concept (Fig. 8):

(1) Front Station Sensing: particle position sensing and time of flight START pulse.

(2) Spacer: providing variable path length determining accuracy of time-of-flight measurement and acceptance angle for particle trajectories.

(3) Second Station: providing position sensing and time-of-flight STOP pulse.

(4) Collector system: possibly up to 3 m long and interior to the facility.

It is desirable to design the instruments such that subelements 1–3 are normally retained on the facility and that they are capable of monitoring a number of impacts. This allows for the removal of the collector system only, currently suggested to occur every 90 days. If subunits 1–3 were indeed retained on the facility, the smallest unit to be designed for removal would be the collector only. This would reduce retrieval and replenishing of (small) cell units to mechanical concerns only and would eliminate restoration of electrical and electronic integrity. A handle on each collector unit and snap action release would offer ready removal and emplacement into an ultraclean container used for hermetic protection until the samples reach the laboratory. Figure 10 sketches a typical EVA scene during removal of captive collectors.

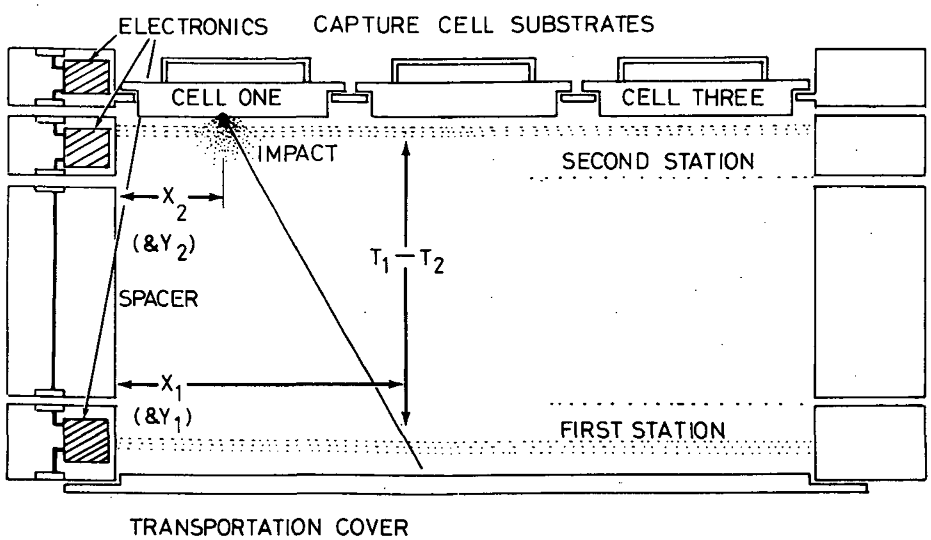

Fig. 8. *Schematic example of a capture cell equipped with (unspecified) trajectory sensors installed at two different planes. Projectile enters from below, passes the two stations and gets trapped in the capture cell.*

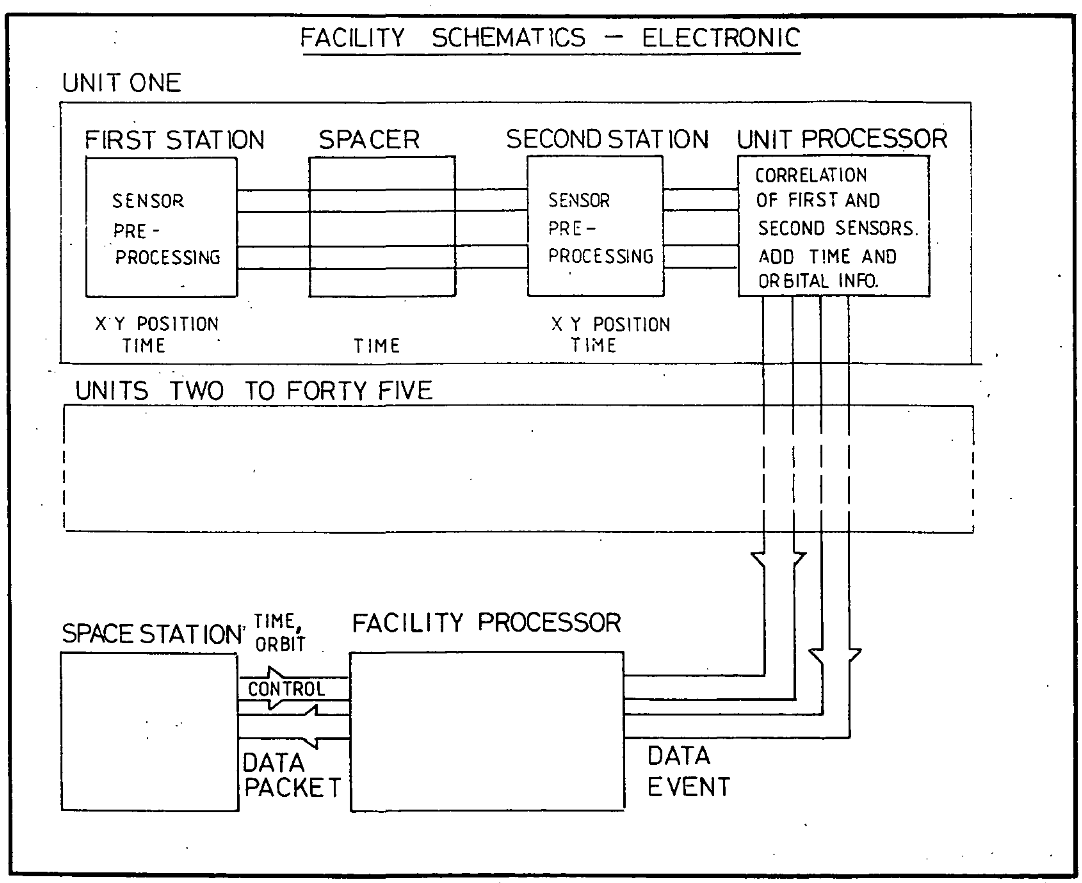

Fig. 9. *Schematic outline of major electronics systems and links, illustrating an autonomous processor and its interaction with an instrument and the Space Station.*

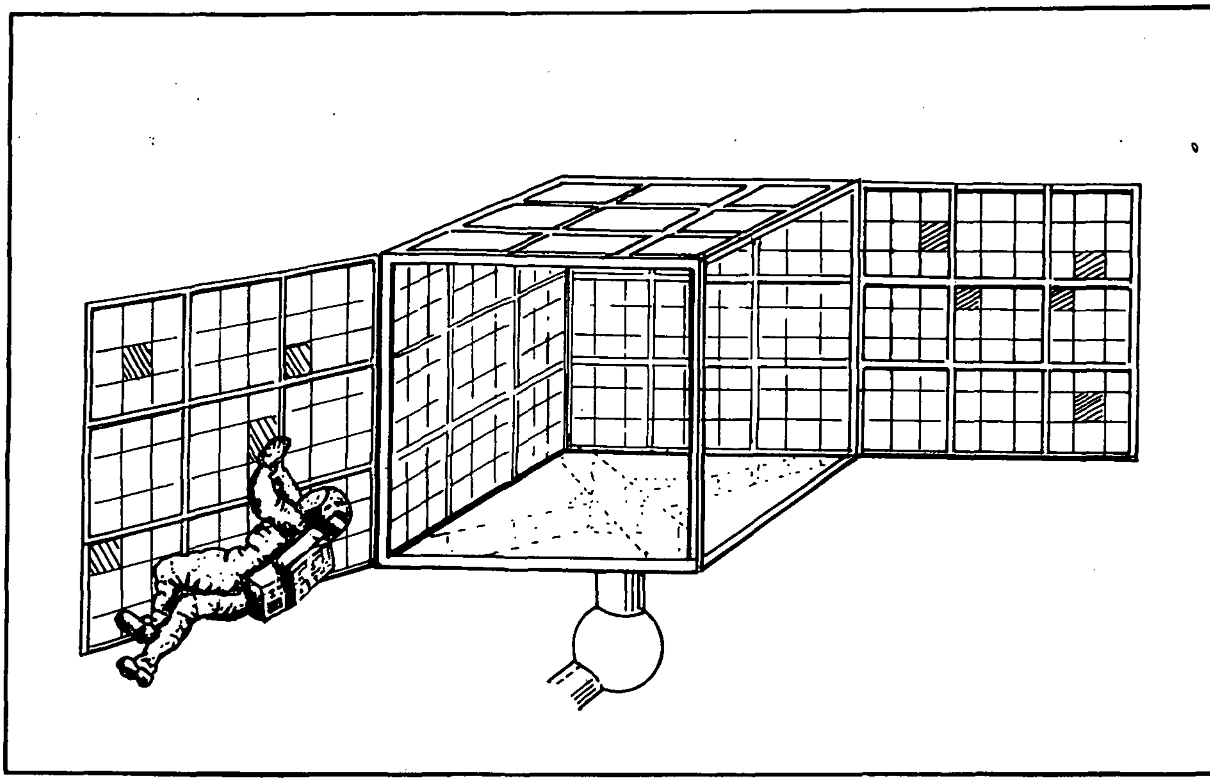

Fig. 10. *Typical EVA scene during the recovery of captive collectors. The faces of the cube are hinged for easy access from the rear without undue disturbance of the velocity/trajectory sensors. It is possible to combine two cube faces into a single measurement, e.g., precision velocity determination with free path-lengths measured in meters, or it is possible to install "collectors" with similar deceleration distances.*

The following approach for the design of the electrical system is envisioned (see Fig. 9): The measured parameters must be preprocessed close to the measurement elements or sensors and hence each unit subelement incorporates a power supply and digital buses for both programming of measurement control and data flow through the unit-processor. Each subelement communicates to the unit processor and it is here that inputs from front and rear stations are correlated, verified, and combined. At this stage, precise position data from the Space Station bus are accessed and incorporated into a packet "event" containing all information necessary for subsequent orbital analysis, including locus prediction of the impact site on the collector. The following information will be continuously available to the unit processor: (a) orbital positioning elements (6) of Space Station, (b) Space Station pointing vectors (3), (c) Time (UT), and (d) solar aspect. If two or more facility locations form a joint experiment (e.g., across the cube interior), the "events" are combined at the facility central electronics unit prior to forming a joint "event" pair. Sensor identity and parity plus instrument status are incorporated to form a larger packet of events for periodic transmission to the ground.

2.4. *Operational Philosophy*

Cosmic dust investigations on the Space Station will be performed in a "facility class" administrative and operational environment: the basic structure will be agency controlled. It must be of sufficiently flexible design to accomodate a variety of instruments simultaneously. Individual instruments will be controlled by individual principal investigators, who will be responsible for instrument design, operation, and subsequent data analysis. Cosmic dust collection on the Space Station must be viewed as a continued, long-term scientific activity and commitment. The facility should function as a major cosmic dust "observatory," similar to the operation of a major astronomical observatory.

The cosmic dust facility on board the Space Station should be open to any qualified researcher and international participation should be encouraged. Specific instrument concepts and collector trays will be selected on their scientific merits. The investigators selected for any particular exposure period will effectively control activities related to science, either preplanned or in real time, in close cooperation with operational personnel.

Chapter 3

Current Capabilities

This chapter outlines current capabilities and thus the starting point(s) of an orderly development program to meet the Space Station goals.

Collection of extraterrestrial particles was not successful until 1976 (Brownlee *et al.*, 1976). Today, particles are routinely collected in the stratosphere and are recovered from deep sea sediments, ice cores, and on space-exposed surfaces. The relatively recent capabilities to "collect" cosmic dust are intimately tied to recent advances in microanalytical instrumentation that provided the ability to positively establish an extraterrestrial origin (Brownlee, 1985; Carey and Walker, see abstracts; Mackinnon, see abstracts). A number of sophisticated dust experiments on board spacecraft performed detailed *in situ* measurements related to the dynamics of the micrometeorite complex (McDonnell, 1978; Grun *et al.*, 1985).

Each of these efforts made substantial contributions to cosmic dust sciences in its own right, but all are limited to determining either potential sources, without detailed compositional information (excepting instrumentation on the recent comet Halley missions), or they are restricted to detailed laboratory analyses without information about their source. Identification of the source area and detailed analytical information on a particle by particle basis have been recognized as the "ultimate" goals since the inception of cosmic dust studies. The opportunity to pursue such an integrated approach in practical terms presented itself only with the advent of STS: large surfaces may be exposed in space and may be retrieved for analysis on Earth.

3.1. Current Cosmic Dust Collection Efforts

Currently, the most active cosmic dust collection effort is that persued via high-altitude aircraft in the stratosphere. Following the pioneering work of Brownlee and co-workers, this effort evolved into a formal activity of NASA JSC's Extraterrestrial Materials Branch and individual particles are now distributed to qualified researchers on a routine basis. Other cosmic dust collection efforts concentrate on deep sea sediments and polar ice caps. It is not readily determined to what degree such particle populations may be biased toward refractory materials surviving atmospheric entry. Nevertheless and significantly, a great diversity in particle morphologies, phase assemblages, detailed textures, IR absorption, porosity, density, and especially elemental composition and isotopic properties characterizes these particles. Such particle diversity is difficult to reconcile with a single source.

Materials returned to Earth after exposure to space have already yielded important information on hypervelocity impacts. The best examples are the surfaces returned during repair of the Solar Max mission (Kessler *et al.*, 1985; Schramm *et al.*, 1986; McKay *et al.*, see abstracts), but other surfaces exist as well (Brownlee, 1978; McDonnell *et al.*, 1984; Alred, see abstracts). Although the Solar Max surfaces were not specifically designed for micrometeorite capture, they yielded analyzable impactor remnants either in the form of vapors, melts, or particle fragments; the latter demonstrate that fragment capture is indeed feasible. A variety of surfaces dedicated to cosmic dust capture are currently being exposed on board the Long Duration Exposure Facility (LDEF 1A, Clark *et al.*, 1984). Capture devices include multiple foil stacks, capture cells, and solid substrates. Independent instruments to measure the flux of cosmic dust are also on board LDEF 1A. It is desirable that these cosmic dust experiments be retrieved for timely analysis. Capture cells currently are also being exposed on board SALYUT (Bibring *et al.*, 1983) and are planned for EURECA (McDonnell, personal communication, 1986).

All capture concepts currently exposed in space and those envisioned for the Space Station IOC rely on the preservation of micrometeoroid residue following hypervelocity impact. As described in Chapter 4, continued improvement of these techniques is necessary, however, and novel approaches can be identified.

3.2. Current Orbital Determination Techniques

As summarized (e.g., McDonnell, 1978; Grun *et al.*, 1985) significant data on the dynamic properties of the micrometeoroid environment exist. Much of this information was obtained from plasma detection devices; having been successfully flown in space for some two decades, these systems are highly evolved. A variety of other detector principles exist, all of which have been tested during experimental impact simulations, if not also as flight instruments. Such techniques include the pyroelectric depolarization of thin films (currently on board the VEGA spacecraft; Perkins *et al.*, 1985; Economou *et al.*, see abstracts), the detection of acoustic energy via piezo sensors (currently part of the GIOTTO instrumentation; Kuczera *et al.*, see abstracts; Weishaupt *et al.*, see abstracts), and the impact-triggered discharge of capacitors (currently on LDEF 1A; Clark *et al.*, 1984; Wortman *et al.*, see abstracts). As outlined in Chapter 4, additional development work is necessary to render these methods of trajectory measurement into viable options for the Space Station instruments.

The rise time of most signals recorded by the above detectors is dependent on impact velocity. Precise velocity values, however, are best obtained by direct measurement between two velocity "stations" of accurately known separation distance, an arrangement that is also necessary to accomplish determination of the angle of incidence for precise trajectory characterization. Because the latter will be recorded initially in an instrument-specific frame of reference, the exact impact site on the collector medium may be determined also, thus enabling efficient particle recovery. Additionally, the amplitude of most detector signals is related to particle mass, directly or indirectly (e.g., sensitive to kinetic energy or momentum). Such an independent mass measurement is highly desirable for the Space Station, because reconstruction of the initial projectile mass may be difficult, if not impossible, on the basis of the recoverable and identifiable projectile remnants.

In summary, the techniques required to perform trajectory measurements, to determine the masses, and to collect fragments, melts, or vapors of hypervelocity impactors are already highly evolved. What is not clear at this time is how these concepts and methods are optimally combined into the desired Space Station capabilities. Integration of trajectory detectors and particle collection devices will constitute the major thrust of Space Station instrument development as detailed in the chapters to follow.

3.3. Current Analytical Capabilities

The measurement of chemical, isotopic, and physical properties on samples generally $< 10^{-8}$g in mass represents a continuing challenge and opportunity to sharpen microanalytical capabilities in the terrestrial laboratory. Stimulated by the study of individual cosmic dust particles collected in the stratosphere, there have been significant advances in analytical capabilities during the last decade. Analytical techniques that are currently feasible can be grouped into the measurement of bulk and phase chemistry, the determination of isotope ratios, and the characterization of physical properties and particle texture. Such measurements combine into a sufficiently broad database to commence meaningful petrogenetic and astrophysical interpretation(s).

An essential technique is scanning electron microscopy (SEM) coupled with bulk elemental data usually obtained with an attached energy-dispersive spectrometer (EDS). SEM studies are indispensable for obtaining textural information and for the identification of major phases and prevalent phase assemblages. SEM techniques also constitute the most useful means of selecting individual particles for other, specialized measurements. Such measurements include mass spectrometry (Secondary and Laser Ion, e.g., Zinner *et al.*, 1982, 1983; McKeegan *et al.*, 1985; Radicati *et al.*, see abstracts). For the ion microprobe (SIMS), calibration experiments have shown that it is possible to make abundance measurements of major elements to ±50% and isotopic measurements of selected elements at concentration levels of several per mil on particles as small as 10 μm in diameter (Zinner *et al.*, 1983; Jessberger *et al.*, 1985). High Resolution Transmission and Analytical Electron Microscopy (HRTEM, AEM; Fraundorf, 1981; Bradley *et al.*, 1983; Christofferson and Busek, 1983; Mackinnon and Rietmeijer, 1984) combined with novel thin-section preparation techniques (Bradley, see abstracts) are currently capable of detecting major element abundances from regions < 10 nm in size. Structural information may be obtained from individual minerals with < 0.35 nm resolution. Other techniques, such as noble gas mass spectrometry, Fourier Transform Infra-Red (FTIR), UV-Visible, and Raman Spectroscopy have also been successfully applied to individual particles (Fraundorf *et al.*, 1981; Rajan *et al.*, 1977; Hudson *et al.*, 1981; Sanford and Walker, 1985).

In summary, impressive progress in analytical capabilities has been accomplished and a wealth of scientific information is currently being extracted from individual cosmic dust particles. Continued sharpening of existing methods and addition of new techniques is considered an integral part of the current Space Station efforts, as detailed in subsequent chapters.

3.4. *Current Simulations of Hypervelocity Impacts*

The design of future micrometeorite detection and collection devices will be guided and tested in large part by the simulation of small-scale hypervelocity impacts in the laboratory. Current launch capabilities, as illustrated in Fig. 11, do not allow high-fidelity simulations of natural micrometeorite velocities at pertinent masses. Limitations in current accelerator technology specifically exclude the simulation of relatively friable, "fluffy" analogs of micrometeorites (such low-strength particles do not survive the forces during acceleration in present hypervelocity launchers). Some improvement in hypervelocity-impact simulations is clearly desirable as detailed in Chapter 4. Nevertheless, even optimistic projections concede that 1:1 simulation of low-density/low-strength impactors at 15 to 20 km/s will remain exceedingly difficult. The current inability to adequately simulate the *in situ* properties of cosmic dust particles in the hypervelocity impact laboratory constitutes a major reason why testing of prototype instruments and/or components via near-term flight opportunities is so strongly advocated throughout this report.

Chapter 4

Proposed Development Program Prior to IOC

4.1. Overview

The transition from where we are now to the realization of a Space Station facility accommodating an initial set of cosmic dust experiments requires an integrated, coherent program with the following major elements:

1. The dust orbital-determination and capture facility should be made an integral part of planning for Space Station science.
2. A laboratory development program to improve on present hypervelocity-particle-collection methods and the measurement of orbital parameters should be initiated.
3. Flight opportunities to test basic instrument concepts should be provided well in advance of the IOC timeframe. This should be done on an opportunistic basis to minimize the costs normally associated with dedicated flight programs; the LDEF program seems to afford the most suitable near-term opportunities.
4. Laboratory studies of cosmic particles collected from the stratosphere, from sediments, and from space should be continued and intensified.
5. Fundamental theoretical research should be performed to better understand the orbital evolution of different types of particles from a variety of sources.
6. Continued upgrading of microanalytical methods and introduction of new analytical techniques is highly desirable to extract a wide variety of cosmochemical and astrophysical information from individual particles.
7. Experimental and theoretical work on impact phenomena at high velocities and small scales should be undertaken to guide instrument design.
8. International cooperation should be encouraged to maximize the range of experimental and scientific expertise, and to share both the costs and intellectual rewards of the Space Station cosmic dust facility.

Cosmic dust particles currently collected from a variety of environments—stratosphere, deep-sea sediments, polar ice-caps, and near-Earth orbit—provide basic information on the nature of cosmic dust and will influence the design and analysis of the Space Station instrument(s). For instance, the discovery of extreme deuterium enrichments in some stratospheric particles not only demonstrates the primitive nature of these objects, but sets boundary conditions on the choice of materials incorporated in a specific Space Station instrument. Another example relates to the characterization of possible organic compounds: instruments collecting specimens of interest to the exobiologist will also be limited in the choice of structural materials.

Theoretical studies of orbit development of different particles released from specific parents need to be pursued, as they determine the performance requirements of the trajectory sensors, an obviously critical aspect in instrument design and analysis. Such studies might also influence future laboratory studies of interplanetary particles, after quantifying the role of such measurable quantities as bulk density and albedo.

Basic concepts applicable to both the orbital determination and the collection aspects have already been demonstrated. Specific instruments for simultaneous trajectory measurement and collection, however, do not currently exist, even in prototype form. The choices for specific materials, structural designs, and electronic systems need to be considered. Prototype instruments need to be built and tested in a hypervelocity impact laboratory; theoretical impact work is intended to aid in the evaluation of instrument performance at conditions not readily simulated. However, there is no substitute for the testing of prototype instruments in space and suitable platforms will be emplaced by STS prior to the Space Station IOC, including LDEF (Kinard, keynote presentation at workshop, 1985), the space industrialization facility (Lilly, keynote presentation at workshop, 1985) and the Shuttle Orbiter itself (Wade, see abstracts); EURECA, an ESA spacecraft, also appears to be suitable.

Improvement of microanalytical capabilities and the introduction of new methods is necessary to extract the maximum scientific benefit from the Space Station collections. This improvement should also include better accelerator performance(s) for more realistic simulation of natural hypervelocity impacts.

Considerable expertise in laboratory ground-support, instrument design, fabrication, flight testing, flight operations, and subsequent analysis resides outside the United States, particularly in Europe. For example, experimental groups at Canterbury (England), Heidelberg and Munchen (Germany), and Paris (France) have developed and successfully flown a variety of dust experiments during the past 15 years, almost to the exclusion of U.S. contributions toward instrument development and design. Accelerators at Munchen, Freiburg, Heidelberg, and Canterbury have played a substantial role in the design and testing of current capture devices exposed on LDEF 1A. This international expertise should be exploited in a cooperative fashion to establish the best possible development and flight programs. The costs and intellectual rewards should also be shared.

In the following, the major development tasks are presented in the form of work statements. The approach is synergistic in the sense that improvement in one area may allow progress in another; the individual program elements should not be viewed as independent efforts, but rather as essential parts of a coherent, integrated program leading to the desired Space Station capabilities within the IOC timeframe.

4.2. Near-term Detector Development: Ground-based Studies

Existing instrument concepts are descibed below. No attempt is made to evaluate the relative merits of diverse concepts, as such comparison was deemed premature by the workshop participants. Improvement of specific concepts, however, was discussed frequently at the St. Louis and Houston workshops, with most suggestions originating from the initial proponents themselves. The descriptions are organized around existing capture concepts and leading suggestions for trajectory/velocity measurements.

4.2.1. Capture by low-density/high-porosity targets. The successful recovery of unmelted projectile fragments at impact velocities as high as 6 km/s was reported by Tsou *et al.* (see abstracts). The targets consisted of low density styrofoams and some projectiles were carbonaceous chondrite powders, pressed into pellets and bonded via epoxy. Projectile remnants were recovered along the penetration path, which was approximately 100 times longer than the projectile diameter. Bradley *et al.* (1986) and Blanford *et al.* (1986) furthermore reported the presence of unmelted impactor fragments in the thermal blankets (= multiple foil stacks) returned from the Solar Max spacecraft.

Low-density targets imply low acoustic impedance and thus relatively modest shock stress and associated heating upon impact. Foamed media with densities as small 0.01 g/cm^3 are commercially available and the equations of state are even known for some of them (Marsh, 1980). As a consequence it appears feasible to keep silicate impactors travelling at 15 km/s from experiencing shock stresses in excess of 20 GPa, preventing them from melting (Hörz *et al.*, see abstracts). This condition, however, may be met only if the thickness of pore walls or foils is kept substantially smaller than the projectile's diameter.

Based on our current knowledge it appears feasible to collect unmelted target fragments at velocities up to perhaps 8 km/s. At still higher speeds, however, recovery of impactor fragments—if preserved at all—will reach limits of practicality; the penetration paths may become excessively long and recovery of these remnants may become difficult and time-consuming to the extreme. The ideal foam collector would be constructed from a medium that is readily dissolved. A regularly spaced stack of ultrathin foils operates principally like a highly porous foam and may offer advantages in locating projectile residues.

4.2.2. Capture via the capture cell method. A regularly spaced volume is capped by a thin front film, to be penetrated by the projectile, and impact will occur on some suitable target medium on the cell's rear surface. Fragments, melts, and vapors will be trapped in this enclosed volume and are concentrated either around the penetration hole or in and around the resulting microcrater. Capture cells employing metal-coated mylar foils as entrance films and ultrapure germanium targets at the rear surface are currently being exposed on LDEF 1A (Zinner *et al.*, 1982; Lange *et al.*, 1986). Because of developments since this LDEF design was frozen, it is possible to specify improvements in similar instruments, even in the absence of LDEF 1A return.

Questions that need to be addressed by additional impact simulations relate to conditions during which complete vaporization of the impactor occurs. The geometrical dispersion of the impactor vapors (rather than target species) must be understood in detail to optimize the dimensions of a capture cell. For example, the separation distance betwen front film and rear target surface must be such that maximum spatial concentration of the vapor condensates will occur on the underside of the penetration foil. Although the choice of materials in the presently exposed capture cells was arrived at from a variety of considerations, other materials, particularly for the entrance foil, must be fabricated and tested.

While treated in the section above as belonging to the porous, low-density capture media, multiple foil stacks are another variant of "capture" cells. If the lateral dimensions of the foils are substantially larger than the stacking distance, impactor materials will be plated out on these surfaces and little to nothing is lost laterally.

All three capture mechanisms considered so far—foams, foil-stacks, capture-cells—require that the impactor penetrate a thin membrane. Hardly any ballistic penetration studies (e.g., Kinslow, 1970; Swift *et al.*, 1982) have considered the fate of the impactor per se, but were fundamentally interested in the degree of damage to the thin-walled target. It is therefore felt that experimentation with specific foils that are candidates for the Space Station instruments should be conducted and that particular emphasis be placed on the behavior of the impactor.

4.2.3. Capture via solid substrates. A variety of space-exposed materials exist that contain microcraters, ranging from lunar rock surfaces to spacecraft windows, aluminum structures, and other spent spacecraft hardware. A fair number of such microcraters contain analyzable impactor residues in the form of glass liners draping the impact pit (e.g., Brownlee, 1978; Clanton *et al.*, 1980). Thick sheets of high purity gold are currently being exposed on LDEF 1A (Hörz *et al.*, 1983) as well as large surfaces of commercial-grade aluminium (Humes *et al.*, in Clark *et al.*, 1984).

While the utility of "infinite halfspace" targets is fundamentally demonstrated, their usefulness compared to the capture methods described above must be evaluated on materials exposed to space. A wide variety of materials should be available for this purpose following retrieval of LDEF 1A. Little additional laboratory simulations are envisioned for projectile capture via solid substrates.

4.2.4. Deceleration and capture by liquid and gaseous media. The successful recovery of extraterrestrial particles in the Earth's stratosphere illustrates that deceleration by molecular collisions and subsequent "capture" may also be considered for the Space Station. Deceleration by pressurized gases to velocities that would allow nondestructive capture by an ensuing, low-velocity impact may be considered. Also, capture by liquids may be possible. While not perceived as primary capture media, the use of gases and possibly liquids may be promising for the purposes of partial deceleration.

4.2.5. Deceleration by electrostatic means. A natural impactor may be charged during passage through a high density electron beam and may then traverse a series of opposing electrostatic grids for effective deceleration. Given sufficient charge and path length for electrostatic deceleration to occur, the particle may be captured intact. This concept was proposed by Wolfe *et al.* (see abstracts) and may be considered as a candidate instrument for the post-IOC growth phase of the Space Station (see Chapter 6).

4.2.6. Trajectory measurement via electrostatic grids. Charge sensing wires or plates are commonly used to measure the impact velocities of micrometeorites. The traditional application, however, is that of monitoring the time evolution of an impact-triggered plasma cloud (e.g., Berg *et al.*, 1973; Grun *et al.*, 1980). This application is not envisioned for the Space Station, because the desire is to keep the projectile from being vaporized and ionized. Auer (1975) pointed out that it should be possible to measure the change(s) in electrical potential of a series of wire grids when a charged particle traverses these grids; although exact charges of natural impactors are poorly known, all particles are expected to be charged to some degree. This principle, partly demonstrated in the impact laboratory, should be developed further and its applicability to the Space Station should be strongly considered. Its obvious advantage in its ideal form is that trajectory information may be obtained in a totally nondestructive fashion. It appears to be the only "stand-alone" system suggested for trajectory measurement and could be combined with almost any choice of capture medium and mechanism. The grids, however, could also be part of a specific capture cell design as suggested by Carey and Walker (see abstracts).

4.2.7. Trajectory measurement via polarized foils. A specialized foil material exists (polyvinylidene fluoride, PVDF) that receives a specific degree of polarization during manufacture. If attached to conducting electrodes, physical damage (i.e., removal of dipoles upon impact penetration) results in a measurable electrical signal. The dependence of signal amplitude on projectile mass and velocity has been demonstrated in the laboratory (Perkins *et al.*, 1985). Concepts exist regarding the geometric and electronic packaging of two successive foils for improved, direct velocity measurement and locus determination from two penetration events. PVDF foils may or may not be part of a capture cell or foil stack, depending how "destructive" extremely thin PVDF foils—currently untested—turn out to be. Also, contamination of projectile remnants by PVDF imposes limitations on some types of chemical and isotopic analyses—a limitation that equally applies, however, to many other thin-film materials.

4.2.8. Trajectory analysis via acoustic sensors. Recent progress in the performance of (ceramic) piezo-sensors renders the detection of seismic energy emanating from a small-scale impact rather reliable. Traditionally, acoustic detectors are mounted to a rigid substrate where they measure particle arrival time and momentum; they are thus predominantly used to measure particle fluxes. Developmental work, however, is underway to monitor the penetration of thin films in front of a more rigid substrate (Kuczera *et al.*, 1985; see abstracts). An array of typically four piezo-sensors is attached to both the front film and the substrate. Transit times between the two "stations" are recorded accurately; triangulation techniques are employed to locate the penetration and impact site(s), using arrival times of the wave at each piezo-sensor. Similar to PDVF foils, front-film penetration is potentially destructive; however, the choice of film material (i.e., composition) appears flexible. The second piezo-sensor array may either be attached to a second thin film, requiring two penetrations (as does the PDVF detector) or it may be mounted directly onto the capture medium; unfortunately, highly porous, foamed targets attenuate seismic energy with extreme efficiency.

4.2.9. Flux measurement. The use of a number of specialized instruments is advocated throughout this report. This position stems primarily from the need for specialized collection techniques, rather then for diverse trajectory sensors. However, it is conceivable that trajectory determination will be tailored to collection objectives (e.g., thin film penetrations are permitted for the collection of "large" particles, but not for "small" sizes, or a specific thin film may not be used in association with a specific chemical objective, etc). It appears prudent, therefore, to include instruments dedicated exclusively to the continued monitoring of the particle flux. These flux measurement devices should be particularily sensitive at small impactor masses (e.g., $< 10^{-12}$ g), because such masses are not readily trapped, much less analyzed, and yet they constitute an important facet of the dynamic evolution of the micrometeorite environment (e.g., Grun *et al.*, 1985).

The classical application of plasma detectors may be considered for this purpose as might the discharge of capacitors, currently on board LDEF 1A (Wortman *et al.*, see abstracts). Metal-Oxide-Silicon (MOS) capacitors are highly advanced components of modern semiconductor technology and are particularily useful for very small masses.

4.3. Detector Development: Flight Opportunities in Low-Earth Orbit

Testing of basic instrument components and the performance of increasingly more integrated prototype instruments for the Space Station requires space flight opportunities in the near future. Such tests represent an integral part of the Space Station development program.

The major rationale for performing such *in situ* tests relates in large measure to the limited degree with which cosmic dust impacts may be simulated in the laboratory, as detailed in Chapter 4.4.3. Areas of concern relate to the ease of fragmentation of friable aggregates, to the length of penetration paths at very high velocities, to the dispersion of impactor fragments, melts, and vapors, and to the (unsimulated) conditions where cratering and penetration mechanics are dominated by total vaporization of the impactor. Similarily, *in situ* measurements and theory will determine, in iterative fashion, the precision with which the trajectories must be measured to yield unique parent-daughter relationships.

Additionally, near-term flight experience would be valuable in the development of suitable protocols for sample analysis, including proper manufacture and handling of the capture devices, sample extraction from the collector, the definition of an acceptable degree of sample degradation to address a specific scientific problem, the evaluation of the most applicable analytical techniques, including their sequencing, and the development of new analytical methods.

Another *in situ* test relates to the natural charge carried by cosmic dust particles. A prime candidate for trajectory measurement—the electrostatic wire grids—relies on the assumption that all particles will possess a charge, typically estimated to be on the order of 1–10 V in free space. Unfortunately, such estimates may not apply to particles arriving at near-Earth orbit where collisions with electrons and ions in the exosphere will probably determine a particle's potential. It is also likely that particles with differing compositions will charge differently and an inevitable bias in the detection-collection process may be introduced.

Lastly, *in situ* testing is also necessary to be prepared for the "unexpected." For example, the degree of "bias" towards refractory species in the stratospheric dust collection is unknown in detail. Do different particle types exist at orbital altitudes? What might the nature of an interstellar dust grain be? Answers to such questions may greatly influence the design of specialized Space Station instruments.

In summary, there is unanimous agreement and wholehearted support by the entire cosmic dust community that *in situ* tests of instrument components, prototypes, and ultimately integrated devices are essential. In the following, the most prominent flight opportunities are identified.

Inherently large structures such as LDEF are ideal platforms, especially when electrical power and modest telemetry are provided (as is currently planned). The proposed Space Industry Facility is similarly well-suited. Even short exposures on STS flights can play a role in instrument development.

Within STS planning, two LDEF opportunities appeared to be the most promising prior to the tragic Challenger accident. These opportunities continue as top priorities for near-term cosmic dust investigations and Space Station instrument development. The need to return LDEF 1A continues; it has been initially manifested for retrieval in September, 1986. It was scheduled to be refitted with plastic nuclear track detectors for cosmic-ray abundance measurements and relaunch as LDEF 1B was planned approximately 6 months after return of LDEF 1A. Photo detectors supplied by DOD may be flown on LDEF 1B as part of the Strategic Defense Initiative, necessitating the welcome addition of power and telemetry to LDEF. The second LDEF opportunity is presented by LDEF 2, a new LDEF structure, currently in fabrication and predominantly intended to assist in the area of space industrialization. Private industry will be the major user of LDEF 2, which was scheduled for launch in late 1987. While launch schedules will change due to the Challenger accident, the LDEF opportunities remain of highest priority. When LDEF 1B and LDEF 2 fly, they should contain cosmic dust experiments. These missions would be used primarily to separately and independently test advanced concepts of particle collection and pilot-type instruments for trajectory measurements.

Prior to the Challenger explosion it appeared that approximately 10 m^2 of surface area could be made available on LDEF 1B, and possibly on LDEF 2. The LDEF 2 opportunity was originally preferred, because exposure was scheduled for only 1 year versus 2.5 years for LDEF 1B. Additionally, feedback from instruments flown on LDEF 1A did not seem possible within the 6 months allowed between retrieval and relaunch of LDEF 1. These plans and priorities—as discussed during the workshop—may change when the active flight program of STS is resumed. Nevertheless, the need for near-term flight opportunities in the development of Space Station instruments remains and the LDEF 1 and 2 platforms should be utilized; this includes timely retrieval of LDEF 1A.

Mid-term flight opportunities in the 1988–1990 timeframe will become essential to test the early versions of integrated trajectory determination/collection devices that may be viewed as reasonable prototypes for the instruments forming the heart of the Space Station cosmic dust facility. Different prototypes based on different design philosophies should be exposed to select the optimum design(s). Such instruments should be approximately 1 m^2 in area and should collect data for at least 6 months and preferably a year.

Several possibilities for such mid-term flight opportunities are currently in the planning stages. First, LDEF is conceived as a continuing program and the current plan is to have one LDEF in orbit at any one time with flights lasting one year. If such a one-up-one-down LDEF program is in effect during 1988–1990 timeframe, it would undoubtedly represent the best platform to develop the integrated cosmic dust collector. Other possibilities exist if the LDEF program does not develop as planned. For example, NASA is currently exploring a cooperative long-duration reflight of the European spacecraft EURECA in collaboration with ESA. Perhaps dust experiments could also be included in the proposed Space Industrialization Facility. In the course of developing the Strategic Defense Initiative it is possible that DOD may also emplace large revisitable structures in low Earth orbit that may be accessed by NASA to expose dust instruments.

The Shuttle Orbiter itself and individual STS short-duration (< 10 days) flights may play a useful role in instrument development. Individual shuttle flights could be used to test basic collection and trajectory-determination concepts and to evaluate—at later stages—the performance of integrated detectors/collectors. Some prototype capture mechanism, different from those exposed on LDEF 1A, is awaiting flight testing as part of the "Get Away Special" (GAS) opportunities (Brownlee, personal communication, 1986).

4.4. Detector Development: Supporting Program Elements

In the following, a variety of additional program elements are described that should be integral parts of an overall Space Station cosmic dust program.

4.4.1. Earth-based cosmic dust collection. Earth-based collection of cosmic dust should continue, and preferably be increased. It will generate the scientific base-line from which design concepts for the Space Station facility may be developed and fine-tuned. Detailed capabilities on board the Space Station must be such that they address current and relevant scientific questions. Many such questions originate from Earth-based dust collections.

Virtually all detailed information on a particle-by-particle basis stems from Earth-based collections. The ranges in physical, chemical, and isotopic properties revealed by these particle populations will largely define the performance requirements of the Space Station instruments and will therefore influence instrument design in significant ways. For example, an important issue for the Space Station collections relates to the degree of acceptable sample alteration during capture. Samples collected in the atmosphere are currently the least degraded specimens and serve therefore as reference for the Space Station collection.

Manmade space debris is also routinely encountered in the Earth-based collections. Again, a comprehensive database for comparison with space-based particle collections could be generated and continually expanded (Zolensky and MacKinnon, 1985).

Current collection capabilities in the stratosphere are somewhat limited by the relatively small size of the collector surfaces. Implementation of the "Large Area Collector" (LAC)—a completely designed system—should proceed rapidly. This larger collector would provide for the retrieval of many more particles per flight and is particularly designed to yield a large number of relatively large particles. Atmospheric settling times of dust particles can be estimated, and it may be feasible to collect particles associated with specific cometary showers using LACs (Mackinnon, see abstracts). Therefore, in favorable cases, source-specific collection may be possible in the stratosphere and a source-specific data base may result for comparison with the Space Station samples.

4.4.2. Upgrading of analytical capabilities. As emphasized in Chapter 3, the variety of analytical methods and facilities currently utilized in cosmic dust research is impressive and generally represents state-of-the-art capabilities. The inherently small masses to be analyzed pose challenges to sharpen and improve current techniques and to develop new ones. For example, diverse forms of mass-spectrometry used in absolute age-dating or in the characterization of organic molecules cannot be used at present to characterize individual cosmic dust particles. Because of ongoing commitments to the stratospheric dust collection, major ingredients for additional improvements in analytical capabilities exist: highly specialized facilities, highly evolved skills, and strong motivation to extract "new" measurements and science from

TABLE 1. *Diagnostic analyses for origins of IDP components.*

Analyses	Stellar Condensates	Interstellar Dust	Interstellar or Nebular Molecules	Nebular Condensates	Parent Body Products
Composition					
Elemental	+	+		+	+
Isotopic	+	+	+	+	+
Molecular			+		+
Mineralic	+	+		+	+
Physical structure	+	+		+	+
Petrography	+	+		+	+

individual particles. Cosmic dust studies represent a frontier area of research where advances in analytical techniques are continually being introduced, and where a certain amount of program support should be devoted to the upgrading of existing techniques and to the introduction of new ones.

We do not advocate a major investment in equipment, but rather the enhancement of existing capabilities through continued upgrading where feasible. An example is the recent development in fabricating thin sections < 500 Å thick from samples a few microns in size (Bradley, see abstracts). A number of dust investigators may desire to have this capability in their laboratories to enhance their existing capabilities. In other cases it appears possible to improve existing methods to a level of sensitivity and precision that meaningful dust analyses may be accomplished. Such efforts could indeed require the occasional, large single investment in new instrumentation. One of many examples in this category is the measurement

TABLE 2. *Analytic information produced.*

	Composition				Physical	Physical
	Elemental	*Isotopic*	*Molecular*	*Mineralic*	*Structure*	*Texture*
Microscopy						
Optical/SEM	+	-	-	+	-	+
TEM/AEM	+	-	-	+	+	+
Spectroscopy						
Scan. Auger/ESCA	+		+			
Infrared			+	+	+	
UV-visible			+	+	+	
Raman			+	+	+	
Mass Spectroscopy						
Static	+	+				
Secondary ion	+	+	+			+
Laser ion	+	O				
Gas Chromat.	+	O	O			
Chromatography						
Gas	O		O			
High press. liq.	O		O			
X-ray Diffraction				+	+	O
Acoustic sensing						O

of the molecular state of carbon compounds, successfully applied to relatively large sample masses extracted from carbonaceous chondrites (Wood and Chang, 1985; Hayatsu and Anders, 1981), but currently not sufficiently sensitive to analyse individual, small dust grains.

A summary of the diagnostic value of analytical techniques for specific extraterrestrial dust sources is shown in Table 1. Incomplete matrix elements in this table indicate specific instances for which (a) the generic analytical technique has not been proven or (b) a cosmochemical model is not yet available. Table 2 provides a complementary list of techniques and instruments currently used in cosmic dust analysis. Matrix elements containing a circled character indicate techniques for which further development seems to be particularily desirable.

4.4.3. Improved hypervelocity-impact simulations. Improvements in hypervelocity-impact simulations are highly desirable. Referring to Figs. 1 and 2, an important particle size range (5 to 100 μm) may not be simulated well at all and simulation of typical geocentric velocities is limited to particles < 5 μm in size, yet accelerator technologies appear to be highly evolved.

Current accelerator performances are illustrated in Fig. 11. Light-gas guns may fire routinely at 7–8 km/s and velocities approaching 10 km/s are within reach. Projectiles < 500 μm in diameter are difficult to accelerate with this method, but modest investment in suitable sabot design should make the use of approximately 100 μm projectiles fairly routine. The electrostatic dust accelerators are inherently limited to very small impactors, generally < 5 μm in diameter, at velocities in excess of 10 km/s. The use of metallic particles (i.e., electrical conductors) is mostly preferred, but acceleration of silicates (i.e., insulators) is possible only after time-consuming sample preparation; the use of silicate projectiles should be made into a routine capability of electrostatic dust accelerators. Only one plasma drag accelerator dedicated to cosmic dust studies exists presently; it is located at the TU Munchen, Germany. It is a unique and

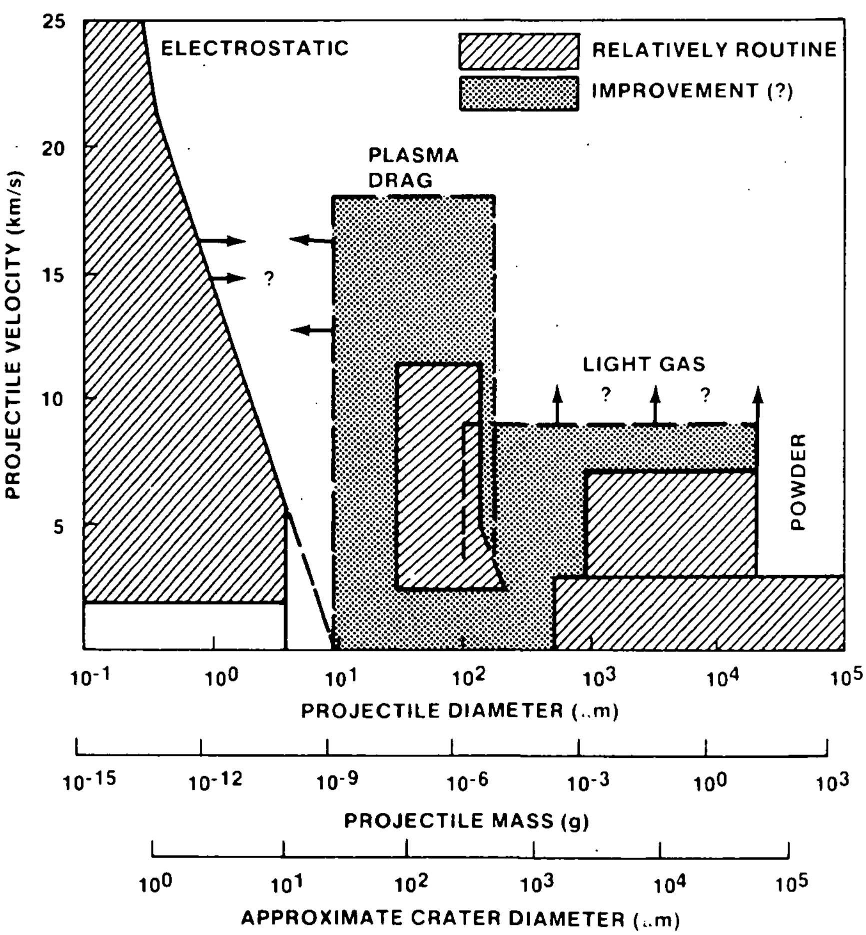

Fig. 11. *Comparison of various accelerators and their current performances. Also included are projections for possible performance upgrading, seemingly without major technological innovations; some of these improvements are actively being pursued at present.*

in many aspects a superb facility, but uncertainties in determining the precise impactor mass exist, because the nominal projectile either ablates (hot plasma) or fragments (high-g forces upon acceleration); developments are underway, however, to eliminate these uncertainties (Kuczera *et al.*, 1985).

Unless formal or informal collaborations are established (or continued), access to suitable accelerators by U.S. investigators will be difficult, as most expertise and facilities reside in Europe. The collaborative spirit and the long-standing commitments to cosmic dust research by the experimental groups in Canterbury, Heidelberg, Munchen, and Freiburg make it advisable not to duplicate the European experimental capabilities—at great cost—in the U.S. Instead, international cooperation is desirable and essential.

4.4.4. Theoretical research. Present-day orbits have evolved. When a dust grain is ejected from a comet, for example, it immediately proceeds on an altered orbit. Radiation pressure will decrease the effect of gravity and increase orbital period and, over time, Poynting-Robertson drag will shrink the orbit size. Gravitational perturbations will then modify, at different rates, the separate orbits of the parent comet and the dust grain. These perturbations, added to the Poynting-Robertson drag, will produce increasing divergence between parent and daughter orbital parameters. Dust grains will seldom, if ever, be detected traveling in orbits identical to their parent objects. As some of the perturbational forces depend upon particle size, orbit evolution will be dependent on particle mass as well as on time. These orbital evolution processes need to be understood in better detail so that association of a collected micrometeorite with a particular type of source is possible. A program of theoretical studies of the problem of divergence of orbits should be supported. These studies are not only scientifically meritous on their own, but they will define the precision with which the present-day orbits must be measured in order to establish parent-daughter relationships. Evolution of the orbits of parent comets under nongravitational forces may also be included in this program.

Detailed cratering and penetration studies at high velocities and at small dimensional scales applicable to the Space Station cosmic dust collection objectives are not available at present. Also, most work focuses on the target, rather than the impactor. More prominent treatment of the fate of the impactor is needed for the Space Station application, such as the fragmentation of a model impactor encountering various types and thicknesses of thin-walled foams or foils or the thermal history of an impactor penetrating multiple membranes in rapid succession. Early support of such studies is recommended to provide laboratory research and near-term flight-instrument development with timely guidance.

4.5. Facility Systems Study

To ensure that the early Space Station opportunities can be utilized, a phased development of the cosmic dust facility compatible with the station must be performed in parallel with the development of the actual detector system(s). A preliminary plan for the suggested systems study is presented in Fig. 12. As indicated, the development of the detectors will be a continuing activity involving ground-based studies and flight exposures. A current Phase A concept may be defined as a dust facility accommodating existing dust instruments and possessing an infrastructure commensurate with the requirements advocated in this report. The Phase B systems study should commence after specific trajectory measurement systems and capture media were successfully tested in orbit. This Phase B study will lead to final facility definition, including realistic projections for additional instrument improvement and capabilities within existing IOC schedules. The Phase B study will basically establish a firm definition for the facility configuration, operational aspects, and size, power, and data requirements. It will also define the single approach to meet each requirement for consideration and implementation in the ensuing design and fabrication phases. Also, the Phase B study will generate firm resource requirements. The final design for the facility will be developed in Phase C. The Phase D efforts will involve manufacture and testing of the facility and its launch, installation, and operational shakedown on the Space Station.

The current Space Station schedule indicates that launches for the IOC build-up will be scheduled for the 1994–1996 time period. This means that the dust facility should be flight-ready in early 1993. Final design, manufacture, and flight-readiness tests will require approximately 3 years and the contracting activity for Phases C/D will last about 1 year. These leadtimes—in turn—control the schedules for the Phase A (1986–1988) and Phase B (1988–1990) studies.

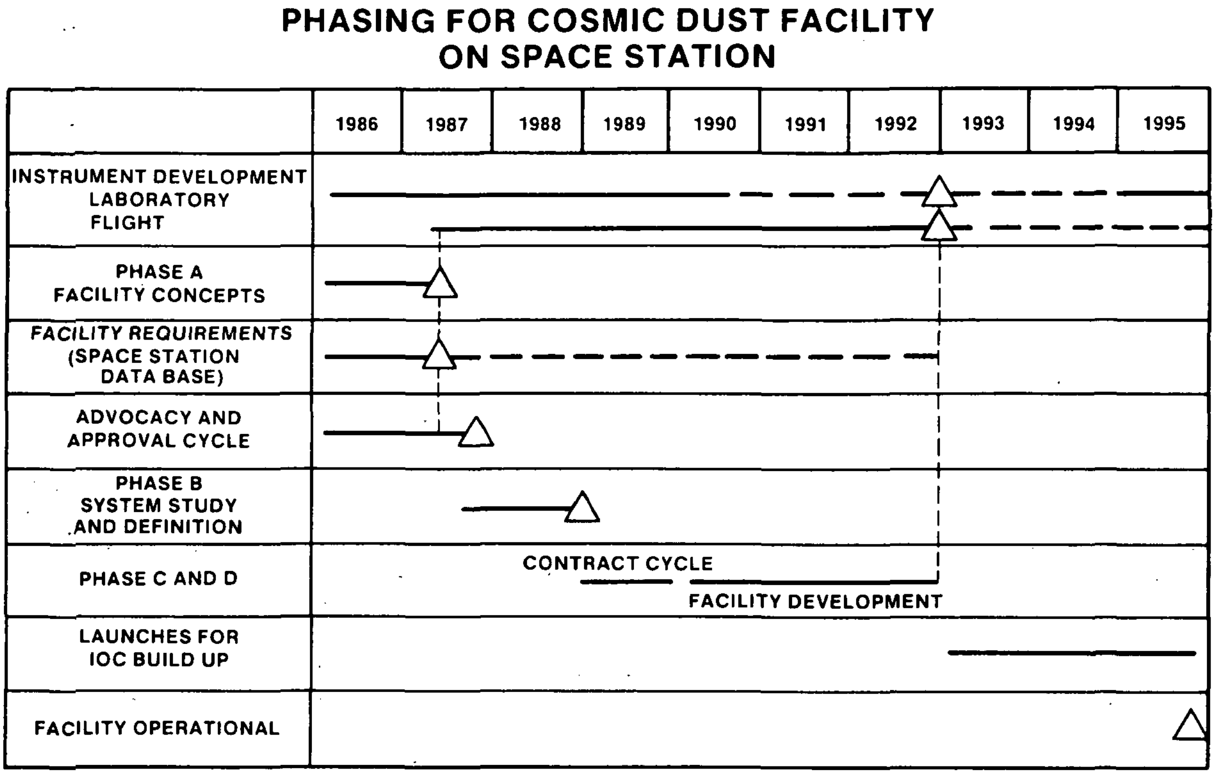

Fig. 12. *Phasing of the cosmic dust facility according to current schedules.*

The present baseline concepts to initiate the Phase A study are described in this report, predominantly in Chapter 2. The facility will be mounted on the Space Station keel structure such that five sides of the cube are exposed with minimum geometric shielding by other Space Station structures. A location is desirable that is minimally contaminated by Space Station effluents and those generated during docking and departure of the STS Orbiters.

Structural considerations: The advantages of various structural concepts including the base-line single cube envisioned in Phase A and multiple, planar arrays mounted in different locations on the Space Station will be evaluated. The cost, weight, Space-Station-interface complexity, crew accessibility, flexibility in instrument design and improvement, etc., will be considered in the final selection of the optimum structural concept.

Data systems considerations: Alternative concepts for data systems will be investigated ranging from plans to make each instrument self-sufficient in terms of data processing and storage, on the one hand, to utilizing central Space Station systems for these purposes on the other. Integration and operational costs will be big factors in the selection of the facility data processing and storage concepts. Trades between costs and capabilities will be significant in selecting and defining the final system during the Phase B activities.

Power system consideration: The power requirements to support the cosmic dust facility should be modest; however, the relationships between the design power level, cost, allowable operating times, allowable experiments, and the data obtainable must be investigated. The need for auxiliary power systems such as storage batteries on the facility to ensure continuous power must also be considered.

Space station crew involvement: The Space Station crew will be involved in the operation of the cosmic dust facility and details will be defined during the Phase B study. The optimum procedures to refurbish impacted units with new detector elements must be established. Trade studies between complexity of EVA operations and operations by automated remote manipulating devices may be made and the level of preliminary analysis that could be accomplished on the Space Station will be explored.

Contamination: The Phase A study will evaluate the Space Station environment in terms of gaseous and solid contaminants and will identify the optimum location of the dust facility. Depending on the level of contamination and the specific species present it may become necessary to deactivate dust detection during specific peak activities (e.g., docking of STS Orbiters) by means of a retractable, protective shield.

Growth potential: The growth potential will be a strong consideration in all Phase B studies. The ultimate desire is to have a facility in space that can capture material with no damage to the sample while simultaneously recording the exact trajectory on a particle-by-particle basis.

4.6 Summary of Development Program

The program elements described above (Sections 4.1–4.5) provide for a logical, orderly development program of a cosmic dust facility on board the Space Station. Such a facility should be part of IOC. All program elements are essential to meet the anticipated objectives: trajectory measurements and capture of individual dust particles with minimum sample degradation.

Considering the present state of the art, some sample degradation, albeit poorly specified, appears unavoidable during the IOC time period, because most capture mechanisms envisioned are based on particle decleration by impact processes. The capture of unmelted particle fragments seems feasible, but it must be emphasized that very significant information may still be extracted from even severely altered samples as documented by the analysis of melts and vapors on space-exposed surfaces. Current capabilities already can yield significant data. The technology and methods for improved sample collection and orbit determinations exist and the anticipated, improved instruments do not hinge on major technological innovations.

Detailed particle analysis combined with the prospects of reconstructing the particle source is the new scientific insight that can only be obtained from space. This new capability is unique and fills long standing gaps in the field of meteoritics and our abilities to understand better the evolution of primitive matter in the solar system; interstellar particles (i.e., products from other solar systems) will not be obtained by other means in the foreseeable future. The merits and quality of the IOC Space Station investigations will strongly depend on the level of support received during the next 5–10 years by each and every program element identified above. It is therefore important to view, judge, and support the suggested development approach as an entity. The combination of particle-capture and orbit-determination can be realized within the next decade (i.e., within the schedule for the Space Station "Initial Orbital Capabilities") including the early man-tended phases.

Chapter 5

Cosmic Dust Facility Program in the IOC Timeframe

We expect that the development of an initial set of micrometeorite instruments will essentially be terminated toward the end of the Phase C study, at which time the design and performance of the facility will also be frozen in. Fabrication of facility and instruments commences in Phase D, which also includes launch, emplacement, and operational testing of the facility installed on the Space Station. It is assumed—following the objectives of the development program—that capture of vaporized, molten, and intact fragments is possible and that trajectory data are obtained on a particle-by-particle basis within the IOC timeframe.

The development aims at early operation within the IOC timeframe. The current design goals are entirely consistent with the "man-tended," early phase of IOC, which envisions the periodic visit by STS for the purpose of Space Station buildup and maintenance of emplaced systems. Permanent habitation is not a requirement for an operational dust facility, because it functions autonomously. It only requires the occasional interaction with STS crews for the purpose of collector retrieval and replacement, currently suggested to occur every 90 days, but by no means tied to a rigorous schedule.

Operational aspects: Efficient operation of the Space Station cosmic dust facility will require teamwork between the scientific users and operational personnel. While some activities may be preplanned, some decisions will have to be made in real time. For example, procedures on retrieval of captive collectors will be predetermined, but the determination of which specific collectors will actually be retrieved can only be made in real time. During the early IOC phases, the impacted collectors will be placed into ultraclean containers, which will also house the replacement collectors; these containers will be closed and sealed during the EVA. The containers will remain sealed until they are opened by the investigators in suitably clean environments following their return to Earth by STS. Programmatic support and organization is necessary for such an observatory type operation involving scientists and operational personnel on the ground, as well as flight crews. Periodic telemetry is vital to this operation.

Detailed aspects of this operation will be investigated as part of the Phase C study. Operational procedures will be finalized during the early Phase D efforts. Some procedures will evolve in real time.

Instrument development: Improvement of instruments must be viewed as a continuing activity. New technologies must be incorporated as they become available, such as superior sensor elements, novel electronic designs, improved data processing and management, etc. Predictably, specialized instruments will be conceived and developed as scientific insight increases and as the initial characterization of the particle populations changes toward specific, problem-oriented cosmic dust investigations. For example, specific elements, molecules, or isotopes may become of overriding interest to warrant specialized collector materials or collection techniques; or a specific particle-size or velocity-regime, perhaps indicative of a specific source, may require specific dimensional instrument changes, etc. Capture of interstellar grains may warrant dedicated, specialized instruments.

The requirement for a vigorous scientific analysis program is self-evident, including the advancement of microanalytical techniques.

Chapter 6

Long-term Evolution of Cosmic Dust Collection on the Space Station

Cosmic dust collection is expected to be a long term activity on the Space Station, not only because of continually improving instrumentation, but also because the long-term behavior and variability of the micrometeorite environment is of fundamental scientific interest. For example, the time evolution of particles shed from a specific comet is of interest as indicated in Chapter 1. Improvement of capture techniques by impact processes may well extend into the growth phase of the Space Station; novel capture methods may be possible. The level of instrument sophistication will parallel the evolution of the intrinsic Space Station capabilities; the latter may sufficiently advance to make preliminary analyses of captured particles feasible on board the spacecraft.

Improvement of capture methods by impact processes during the growth phase of the Space Station may relate to temperature control of part of the facility to allow capture by media of frozen volatiles. This will also be an era where introduction of deceleration techniques totally unrelated to impact processes may be considered if they yield less-altered impactor residues or ideally totally "pristine" samples. One of the latter concepts was introduced by Wolfe et al. (see abstracts): a particle is allowed to be charged by passing through an electron beam; it will then be decelerated while traversing through a series of grids kept at high, opposing voltages. Preliminary calculations show that it seems possible to decelerate (small; < 10 μm) particles from 20 km/s to effectively 0 km/s over distances of < 20 m. In principle, this technique reverses the electrostatic accelerator. Feasibility studies on novel approaches for hypervelocity particle collection should not be limited, however, to the post IOC timeframe; such studies may well be part of the current Phase A activities.

Some investigators advocate that preliminary analysis be performed on the Space Station. Such investigations would require special sample handling capabilities in a "class 1000" clean-room environment. An electron microscope would be needed; miniaturization and adaptability of such instruments for manned and unmanned missions is currently being supported by NASA. Cosmic dust investigators actively participate in this development. The purpose of a preliminary examination on the Space Station would be to characterize the entire particle population and to identify specimens for more specialized studies upon delivery to Earth. Such selection and handpicking may be desirable after the Space Station program has matured and evolved into a series of specific, problem-oriented investigations.

An intermediate step toward the preliminary on-board analysis relates to the inspection and partial processing of retrieved collector units in a shirt sleeve environment. It is very likely that the collector unit removed by the crew contains a number of individual capture elements (i.e., physical or electronic entities, if not both). The subelements containing particle residues are identified by the trajectory measurement; many elements may still be pristine. Manipulation of the "unit" to remove the captive cell could possibly be performed inside the Space Station. Fewer collector elements (less mass, less volume) would have to be transported by STS to and from the Space Station and fewer elements would have to be refurbished. Such on-board processing may become important if the trajectory sensors were physically an integral part of the collectors: disassembly, reassembly, and functional check-out of refurbished sensors could be performed in space.

Chapter 7

Investigations of Manmade Space Debris

The characterization of manmade particulates, such as rocket exhaust products or collisional and explosive spacecraft fragmentation products, is developing into an area of increasing concern regarding collisional hazards to manned and unmanned structures in Earth orbit. The issue is an international one, as effective countermeasures to prevent the buildup of an ultimately intolerable debris population mandate establishment of and adherence to international agreements and policy. Current technical efforts concentrate foremost on the characterization of the present-day debris populations, on extrapolation and prognosis of its future development, and on generating awareness and appreciation of the problem.

The anticipated dust facility is capable of substantial contributions toward the characterization of fine-grained, manmade debris, a capability not greatly emphasized in the preceding chapters, but clearly recognized by most investigators. The anticipated Space Station facility will collect particles and determine their trajectories, regardless of their origins. Only after a specific level of analysis is accomplished will it be possible to differentiate the natural particles from manmade materials. Information on manmade particulates will be generated routinely even during the most basic, preliminary scientific investigation (e.g., McKay *et al.*, see abstracts). All techniques applicable to the study of extraterrestrial particles also apply to the characterization of manmade materials; however, not all techniques are needed for the debris analysis. The debris populations are known to be highly diverse also, ranging from metals to nonmetals and including organic sources. Manmade impactors can be differentiated from natural particles, minimally in the form of detailed trajectory analyses and at a substantially increased level of confidence after compositional

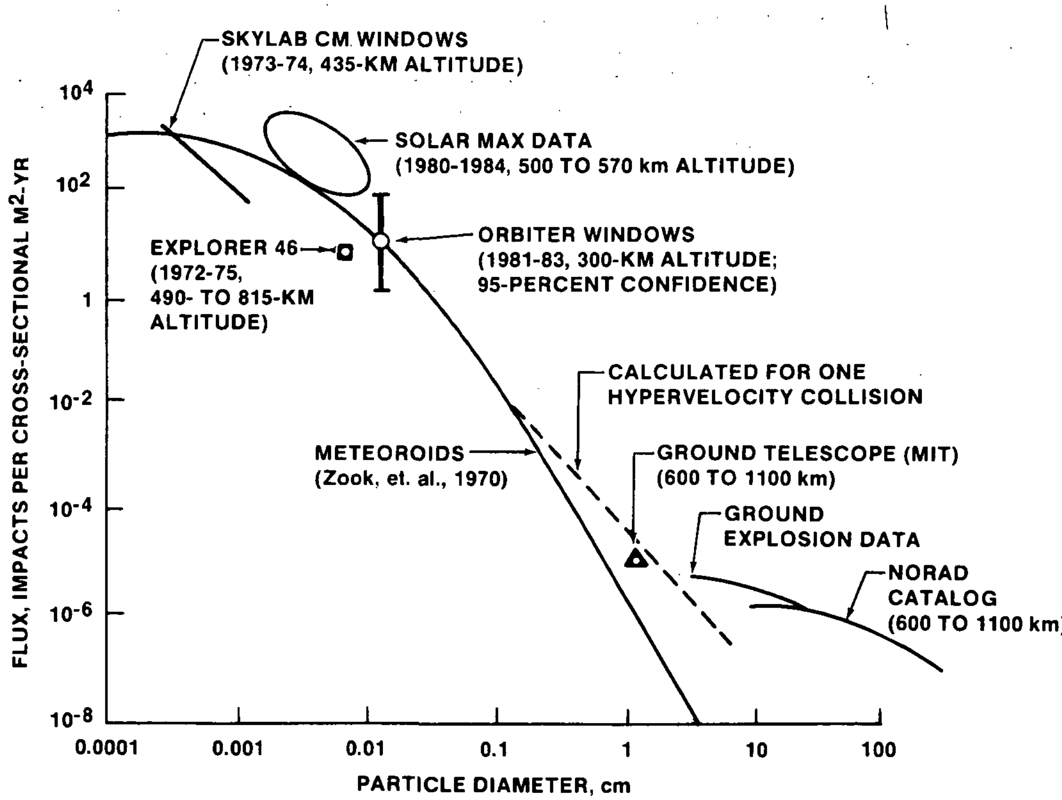

Fig. 13. *The flux of natural objects (meteoroids, solid line) compared with that of manmade debris according to Kessler (see abstracts). A large variety of observations indicates that the flux of manmade objects is in excess of the natural meteoroid environment, especially at large masses, but (where measurable) also at very small masses (e.g., SOLAR MAX). Few observations exist for the millimeter size range, but extrapolations from collisional and explosive fragmentation events indicate that they must be very common also.*

information is obtained. Current analyses of Solar Max surfaces serve as a prime example for the level of analytical effort and detail required to differentiate natural from manmade particles (e.g., Kessler *et al.*, 1985; Schramm *et al.*, 1986; Bradley *et al.*, 1986; McKay *et al.*, see abstracts). By definition and design, the Space Station dust facility will contribute to an improved understanding of the manmade particle environment and its potential hazards.

Estimates of the present-day debris population were presented at the workshop by Kessler (see abstracts) and are illustrated in Fig. 13. Accordingly, the flux of manmade impactors already exceeds that of the natural environment at specific sizes and masses, possibly at all sizes, because information on some intermediate sizes (Fig. 13) is difficult to obtain. The kinetic energies associated with the mass-frequency distribution of Fig. 13 indicate that particles having diameters between 0.1 and 10 mm define in large measure the collisional hazard to spacecraft. On one hand, structural shielding against particles < 100 μm appears possible and on the other hand, particles > 1 cm appear to be sufficiently infrequent (at present) to result in acceptable collision probabilities during the expected operational lifetimes of most spacecraft.

A substantial size (mass) range of manmade particles will be within the performance range of most Space Station cosmic dust detectors. In particular, "small" particles will be collected frequently according to Fig. 13. While most of them do not constitute a direct hazard to catastrophic spacecraft failure, they will contain valuable dynamic information for improved models of debris generation, fragment dispersion, and orbital lifetimes at relatively low altitudes. The Space Station facility is particularly well-suited to study short-term and long-term variations of the debris environment, and to monitor the behavior of specific particle or fragment sources (e.g., solid rocket firings or collisional events).

Clearly, the facility is capable of making substantial contributions to debris investigations and will generate such information as a matter of course. It is thus advisable to seek cooperative arrangements in the areas of instrument development, sample analysis, and facility definition and operations; associated fiscal support should be forthcoming from organizations interested in the characterization of orbital debris. Such arrangements, however, should not jeopardize open access to the facility by any qualified investigator, including international participants, nor can the arrangements adversely affect the generation and dissemination of scientific information at any time.

Chapter 8

Administrative Requirements and Organization

The program advocated in this report is realizable within the timeframe dictated by the development of Space Station itself; however, the level of success depends on proper administrative support and timely funding.

The cosmic dust facility will serve a variety of interests and communities, such as planetary sciences, exobiology, and those concerned with space debris. It clearly crosses traditional scientific disciplines and especially current administrative organizations at NASA Headquarters. All user groups and associated administrative organizations must stay involved in the development and decision making, as well as in the cost sharing.

From a user-community(ies) point of view it is highly desirable to establish a single point of contact for this cosmic dust facility at NASA Headquarters. Such a single point contact assures that everyone is informed in a timely manner, has a comprehensive overview of all activities ranging from systems studies to laboratory investigations, and understands the scientific objectives and accomplishments for effective advocacy. This person would also be responsible for budgetary matters. Effective communication with the user community is essential and opportunities for international collaboration must be generated. This person should also establish the links to the various Space Station planning elements. Because much of the scientific thrust relates to an improved understanding of early solar system processes, it is suggested that this single point contact be appointed within Code EL, Planetary Sciences and that she/he chair a possible working group composed of all other Headquarters interests. We do not advocate that this must be a full time or even new position, as existing discipline scientists could function perfectly well in this role.

Some urgent administrative support and decisions are needed now:

1. The installation of a cosmic dust facility on the Space Station should be made part of the planning for Space Station science, preferably as an independent, autonomous structure and project.
2. The near-term flight opportunities by LDEF 1B and LDEF 2 must be utilized for instrument development. Appropriate administrative steps are necessary to assure flight participation.
3. Fiscal support for ground-based instrument development as well as the design and fabrication of improved LDEF instrumentation is needed. Strong community support, backed by eight informal proposals, was generated during the St. Louis workshop in late 1983; this support was reiterated at the recent LPI workshop. The proposals following the St. Louis workshop may serve as a starting point for budgetary planning.
4. Timely return of LDEF 1A remains high in priority and every effort should be made for speedy retrieval.

Because the cosmic dust investigations on the Space Station are performed via a facility class installation, the prospective users have to get organized themselves. Individuals were identified at the workshop to organise the user communities. A steering committee will be formed shortly and will include representatives from planetary sciences, exobiology, and space debris interests. Its chairman will assure effective communication with Headquarters, inform the dust investigators about important developments, and will provide advocacy and representation wherever needed. The major purpose of the committee is to assure technically and scientifically sound and timely progress of the program within the resources allocated, to provide advocacy for the facility and to assist—where needed—the various Headquarters elements in the implementation of this program.

Both Headquarters and the user community have an ongoing responsibility to collaborate closely and to establish good communications. This responsibility also includes interaction with the Space Station program such as the "Space Station Users Working Group" or the "Task Force on Scientific Use of the Space Station."

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ABSTRACTS

AN IN-SITU MEASUREMENT OF PARTICULATES FROM SOLID ROCKET MOTORS FIRED IN SPACE

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ABSTRACT

INTRODUCTION

The ability of the Space Transportation System to routinely deploy orbital payloads has been remarkably and repeatably demonstrated since the fifth Shuttle mission. Among these deployed payloads have been communications satellites designed to operate in geosynchronous orbit (GEO). The Space Transportation System currently uses solid rocket motors (SRM's) to boost these satellites from the Shuttle's orbit to GEO. However, powdered metals or metallic compounds are added to the fuel of the SRM in order to dampen the motor's burn rate instabilities. These metals, or metallic compounds, are ejected from the SRM in the form of aluminum oxide particles that range in size from 0.1 to 20 microns in diameter. The particles are ejected from the SRM nozzle at speeds from 1.0 to 4.0 km/s and account for approximately 35% of the mass of the SRM plume. Since the second stage burn of a GEO transfer has an out-of-plane component and since some particles leave the SRM at angles as large as 40 degrees from the center line of the nozzle, the majority of the particles are inserted in orbits that do not immediately decay into the Earth's atmosphere. Recent studies have shown that as high as 5% of the particles remain in orbit for over one year. Furthermore, this man-made particulate flux is distributed evenly from low Earth to geosynchronous altitudes. Also, the flux from a single SRM burn can exceed the natural meteroid flux for similar diameter particles. Hence, a permanent manned presence in space will not only have to protect cosmic dust and micrometeroids but also from the aluminum oxide flux from SRM's.

Current models exist that predict the damage caused by the impact of these particles as well as their lifetime in useable space. In both models, two necessary inputs are the size of the aluminum oxide particles and the flux of these particles. An experiment was designed for the Remote Manipulator System of the Space Shuttle Orbiter that could be used to measure in-situ the flux and material effects of a SRM firing in space. The objectives of this paper are to present the results of this experiment, compare these results with ground-based SRM firings, estimate the lifetime and locations of the ejecta, and, finally, compare the experimental results with the predictions of the current plume trajectory/plume damage model.

UPPER STAGE PLUME MODEL, DAMAGE MODEL VERIFICATION EXPERIMENT

The aforementioned experiment was the Upper Stage Plume Model, Damage Model Verification, also called the Plume Witness Plate. The experiment was designed to update the safe separation distance required between an upper stage and the Space Shuttle Orbiter before the SRM ignition. The experiment has been flown on two Space Shuttle missions, STS-41B in February 1984 and STS-41D in August 1984. The experiment is also scheduled to fly on STS-61B in November 1985. The latter flight will expose the experiment to a different

SRM than the previous two. The technique used in the experiment was the exposure of materials representative of the Orbiter structure to the particulates in the SRM plume. To accomplish this goal, the experimental samples were chemically bonded to three sample trays mounted on the Remote Manipulator System (RMS) of the Orbiter. Five different types of samples were used to provide a broad range of substances :

1) Fused Quartz Glass (Representative of Orbiter Windows).
2) Germanium Micrometeroid Capture Cells.
3) Orbiter HRTS Tiles from the Thermal Protection System.
4) Kapton Foil.
5) Metallic Disks of Aluminum, Copper, Titanium, Graphite Epoxy, and Gold.

During the normal operations for deploying an upper stage, the Orbiter is oriented in a protect attitude that exposes the underside of the vehicle toward the SRM prior to its ignition. The RMS is positioned at that time so that the samples are perpendicular to the line-of-sight between the Orbiter and the SRM. The samples are exposed to the full duration of the SRM burn. After return, the samples are analyzed via optical and scanning electron microscopy to determine the flux of the particulates through the total number of impacts, the diameter of the particles from the size of the impact craters, the velocity of the particulates from the crater depths, and the chemical composition of the residue in the impact craters.

CONCLUSIONS

The analyses of the Plume Witness Plate data show excellent agreement with ground-based SRM firings in terms of particle size distribution and mass distribution. The Particle Impact Damage Integrator computer model used to calculate potential damage of Orbiter surfaces by SRM exhaust plumes agrees favorable with the results in terms of particle size and velocity distributions though it may be conservative by as much as 20%. The results of the Plume Witness Plate experiment provide a sound physical basis from which detailed studies of the particulate environment and lifetimes can be pursued for the benefit of future space activities.

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THIN-SECTIONING AND MICROANALYSIS OF INDIVIDUAL EXTRATERRESTRIAL PARTICLES

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A longstanding constraint on the study of micrometeorites has centered on difficulties in preparing them for analysis. This is due largely to their small dimensions and consequent practical limitations on sample manipulation. Chondritic micrometeorites provide a good example; although much has been learned about their chemistry and mineralogy almost nothing was known about such basic properties as texture and petrographic associations. The only way to assess such properties is to examine microstructure indigenous to the particles. Unfortunately, almost all micrometeorites, out of necessity, have been crushed and dispersed onto appropriate substrates prior to analysis, and most information about texture and petrography was lost. Recently, thin-sections of individual extraterrestrial particles have been prepared using an ultramicrotome equipped with a diamond knife. This procedure has been applied to stratospheric micrometeorites and Solar Max impact debris. In both cases the sections have enabled observation of a variety of internal particle features, including textures, porosity, and petrographic associations.

Sectioning Procedure

Because of the small dimensions of a typical micrometeorite careful sample preparation and good quality light optics (stereobinocular) on the ultramicrotome are important. In addition, illumination of the specimen during sectioning may be facilitated using supplementary high-intensity lighting. Initially, a selected particle (usually 5-20 μm diameter) is mounted in a low viscosity epoxy (e.g. Embed-812), which upon curing forms a bullet-shaped mount 7-mm x 18-mm. The particle is embedded towards the tapered extremity of the mount, and in order to highlight its exact position several carbon fibers are arranged symmetrically about the particle. Then using glass knives the mount is trimmed until a "mesa" ($\sim$ 200 μm square) is fashioned around the embedded particle. At this point the particle should be located close to the center of the 200 μm square and be at least within a few microns of the surface on which sectioning is to take place. Then using a diamond knife, sections are cut from the working face, floated away from the diamond edge, and transferred onto TEM grids for analysis.

Whilst sections are being produced it is essential to position the illumination so that the floating sections exhibit maximum reflectivity to incident light. This is important for two reasons: firstly, incident light is reflected both off the surfaces of the flotation liquid (usually H_2O) and the upper surface of the floating sections. These light waves, moving out of phase, produce interference colors related to the thickness of the sections. It is therefore possible to monitor specimen thickness during sectioning. Secondly, it is important to observe the point at which the diamond knife intercepts the embedded particle. This is determined by examining each section as it is cut. When viewed through a stereobinocular, sections containing meteoritic material will be marked by the presence of a small black speck (the sectioned particle) surrounded by dark lines (the sectioned carbon fibers). These sections are then concentrated (using a single human eyelash mounted on a stick), and retrieved from the flotation liquid. (Details of ultramicrotomy technique are provided by Reid (1)).

Results

Chondritic micrometeorites - The most striking result of the thin-sectioning procedure is that it simplifies classification of this group of stratospheric particles. Until now classification has been based either on particle appearance or the presence of characteristic infrared transmission absorption bands. Observations of morphology and surface microstructures enable particle descriptions like CP (chondritic porous), CF (chondritic filled), CS (chondritic smooth) (2). The major drawback with this type of scheme is that not all micrometeorites fall clearly into a given category. Using infrared spectroscopy Sanford and Walker (3) find that most chondritic micrometeorites fall into one of two categories; those whose mineralogy is dominated by anhydrous silicates and those dominated by hydrated (layer lattice) silicates. Examination of thin-sections confirms the infrared results. There appears to be only two classes of chondritic micrometeorite, those that are hydrous and those that are not. Moreover, these classes of particles can be easily distinguished from one another in thin-section on the basis of texture alone. One is a highly porous aggregate of anhydrous mineral grains and carbonaceous material, while the other is a low porosity assemblage of hydrated silicates.

Solar Max Particles

Two particles were hand-picked from Solar Max impact substrates. These particles were chosen because their morphologies and chemical compositions suggested that they might be relatively unaltered particles. (Both particles exhibit chondritic elemental signatures, although their sulfur abundances seem to be depleted). However, thin-sections reveal that, despite outward appearances, both particles are structurally perturbed and chemically segregated. Additional Solar Max particles are being sectioned in order to determine whether any material has survived impact without melting.

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INTERPLANETARY DUST: THE INTERSTELLAR CONNECTION.

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Although not proven, there is the widespread belief that comets consist, at least in part, of interstellar material that was originally present in the solar nebula. Furthermore, there are strong arguments in favor of the view that much of the interplanetary dust complex is derived from comets. The main arguments supporting this view are based on mass balance,(1) analysis of the orbital parameters of meteors,(2) and the long known association between meteor showers and specific comets.

Laboratory measurements on interplanetary dust particles (IDPs) collected in the stratosphere have confirmed the view that many of the dust particles are "primitive" in the sense that they show striking enrichments of D/H relative to average solar system materials.(3) It has also been demonstrated that the mid-infrared absorption spectra of one infrared red class of particles show strong similarities to IR sources such as the , "protostar" W-33A.(3)

However, the laboratory studies of IDPs have shown that they represent a diverse set of objects. Three infrared classes have been identified and labeled olivine, pyroxene, and layer-lattice silicates because of the similarities in their spectra to terrestrial mineral standards. TEM observations confirm these assignments to first order. However, the TEM observations also show that particles in a given IR class can have significantly different structures when viewed at high spatial resolution. Five out of eight particles show D/H enrichments but three do not. Although we are in the midst of unraveling all this, we have the impression that different sources will be required to explain the diversity of particle types. As an illustration, we find that the IR spectrum of Comet Kohoutek cannot contain a large contribution from particles of the olivine class although this class accounts for ~one-third of all IDPs so far studied.(4)

The measurement of the orbital parameters of specific dust particles is essential to answering the question of sources. The observation of the IRAS dust bands reopens the question of the role of asteroids in supplying a significant fraction of the dust and part of the diversity we observe may be due to the fact that some of the dust is asteroidal and some cometary.

But we also consider it likely that comets themselves are quite diverse. In fact, it is known from meteor studies that the physical properties of dust in different showers (and hence different comets) varies considerably.(5) One of the major goals of the dust orbital determination and isotopic analysis program will be to find out if different particles whose orbits are consistent with a cometary origin show a great diversity of properties. This ability to sample *many* comets addresses an issue that a sample return mission to a <u>given</u> comet can never resolve.

Some fraction of interplanetary dust must consist of an interstellar component intercepted by the solar system in its motion through the local interstellar medium. Although calculations indicate that interstellar particles $\geq 10\ \mu m$ would penetrate into the inner solar system,(6) there is no evidence for the existence of an appreciable flux of such particles. Precision orbital measurements of larger (≥ 1 gm) optical meteors show that $\leq 1\%$ of these have hyberbolic orbits. The same is true of smaller radio meteors ($\geq 10^{-6}$ gm). However, it has recently been shown(7) that dust derived from nearby stars will have 75% of their orbits with eccentricities ≤ 1.1 and might be difficult to distinguish from interplanetary dust based on orbital measurements alone.

Since measurements of the orbital parameters of particles in the 10μm size range have never been made, it is impossible to rule out the possibility that an appreciable fraction of such particles are interstellar. However, calculations based on estimates of the gas/dust ratio and the gas density of the local interstellar medium suggest that at most 1% of the dust flux in the 1 to 100 μm region could be interstellar.(8)

If an interstellar component exists, the small fluxes expected indicate that a very large detector will be required to identify them. It is partly for this reason that we believe that the space station collector should be planned to have an initial design size of 10 meters on a side. With such a size an interstellar component of $< 5 \times 10^{-4}$ could be found in a year's operation. The intellectual rewards of such a discovery would be great, but the probability of success is uncertain.

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PROSPECTS FOR AN ORBITAL DETERMINATION AND CAPTURE CELL EXPERIMENT. William C. Carey and Robert M. Walker, McDonnell Center for the Space Sciences, Physics Department, Washington University, St. Louis, MO 63130 USA.

A dust experiment which combines measurements of the elemental and isotopic composition of individual particles with orbital information would contribute fundamental, new scientific information on the sources contributing to the micrometeoroid population. The general boundary conditions for such a system are: a) it must be capable of measuring velocities in the range of 10 km/sec to 100 km/sec with several percent accuracy, b) it must collect particles in such a way that the debris atoms are locally concentrated so that precise isotopic measurements are possible, c) it should collect particles over a wide range of sizes starting with a lower limit of 10 μm, d) it should incorporate materials that will not compromise the isotopic measurements and e) it should be large enough to obtain statistically meaningful results within a reasonable exposure time.

Using calibration experiments we have previously shown that it is possible to make abundance measurements of major elements to $\pm$50% and isotopic measurements of selected elements at the level of several per mil for impacting particles as small as 10 μm in size.(1-3) The fundamental approach of the capture cell is to collect the material of interest within a small area and analyze this region using a sensitive SIMS method of surface analysis. An entrance foil and a target plate are placed in close proximity and atoms from the impact are collected on the underside of the entrance foil, and on the top surface of the target plate.

One approach to the problem of measuring the velocity of a particle has been described by S. Auer (4). Results from two devices, both of which rely on the fact that a charged particle passing next to a conducting wire will induce an electrical signal in the wire, were described. Combinations of grids of wires separated by 10 cm were used to determine the x, y, t coordinates of a particle at two different crossing planes separated by ~10 cm (Fig. 1A). Such an array can be made > 90% transparent and if the system works, decouples the velocity measuring device from the subsequent capture cell configuration. One advantage of such a system is that the capture cells can be removed for return to the laboratory, leaving the electronic systems intact.

However, the system relies on the assumption that individual dust particles will possess a charge when they arrive at the detector. Typical estimates for the potential of an interplanetary dust particle in free space are ~1 to 10V,(6) which would be sufficient to make this scheme viable. Unfortunately such calculations are probably irrelevant for particles arriving at near earth orbit where collisions with electrons and ions in the exosphere will probably determine the potential.(5) It is likely that particles with differing compositions will charge differentially and thus an inevitable bias is introduced into the detection - collection process. The array of unshielded wires may also lead to severe electrical noise problems in the space station environment.

The system has the distinct advantage of separating the velocity determination and capture cell portions of the sensor, making it possible to preserve the principle of using the capture cell to produce large local concentrations of impact atoms.

Another approach is to use a thin metal foil at the top of a closed velocity determination - capture cell instrument (Fig. 1B). The arrival of the particle could be measured by collection of a plasma pulse on a system of grids immediately below the top foil. A second foil grid collector separated some 10 cm away would be used to time the passage. In this system the second detection foil would double as the collector.

The major disadvantage of such a system is that the top foil tends to disrupt the particle, producing fragments which would result in multiple perforations of the secord foil thus losing directional information and dispersing material over such a wide area that istopic analysis is no longer possible. This is particularly true of very fragile, friable particles that are known to exist in the interplanetary dust and which may be of high scientific interest. If such a system is used, it is clear that the entrance foils mus. be made as thin as possible.

Interplanetary dust particles show large differences in their hydrogen isotopic composition and there is also a suggestion of carbon isotopic effects. Advances in technology may also permit measurements of the oxygen isotopic composition in the future. It is thus essential to avoid thin film materials such as plastics that would introduce unwanted isotopic contamination.

The capture cell design also needs additional testing and study. Most particles will be small and the impact debris from them needs to be well localized to be measurable. At the same time, larger particles are inherently more interesting because they are less sensitive to nongravitational perturbations of their orbits. This suggests that the capture cell should be constructed of a series of collector-target foils of increasing thickness and separation rather than the single foil, plus thick target plate assembly as used in our LDEF I experiment.[1]

Although the open wire detector system would be ideal in principle, there is no guarantee that it will work in practice, and we believe that several velocity determination and capture cell concepts should be tried. Thus additional flight opportunities are required before an optimum instrument can be designed for the space station. Because of the low flux of interplanetary dust, experiment modules at least 1 m^2 in size must be flown for periods of $\sim$1 year for statistically significant results to be obtained. Sufficient electrical power must also be provided. One evolutionary approach, consistent with the time available for design and construction would be to fly advanced capture cells on LDEF II and complete velocity measurement and capture modules on a following LDEF (or other) flight opportunity.

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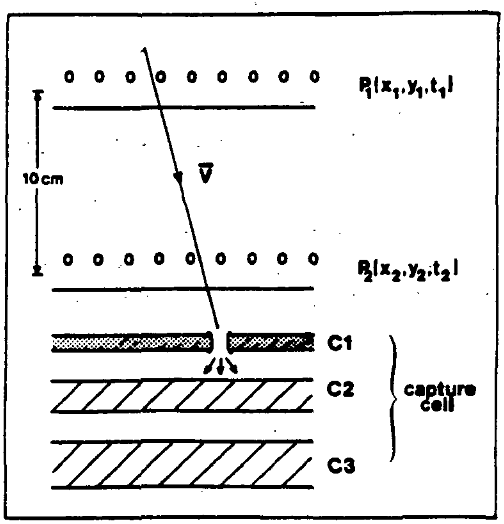

Figure 1a: A schematic (not drawn to scale) showing an 'open' Auer-type sensor configuration. The incident particle velocity vector $\vec{v}$ is determined from *particle charge* measurments P_1 and P_2. C1, C2 and C3 are the primary, secondary and tertiary collecting surfaces of the capture cell respectively. Note that the capture cell portion of the sensor is separate from the measurement of $\vec{v}$.

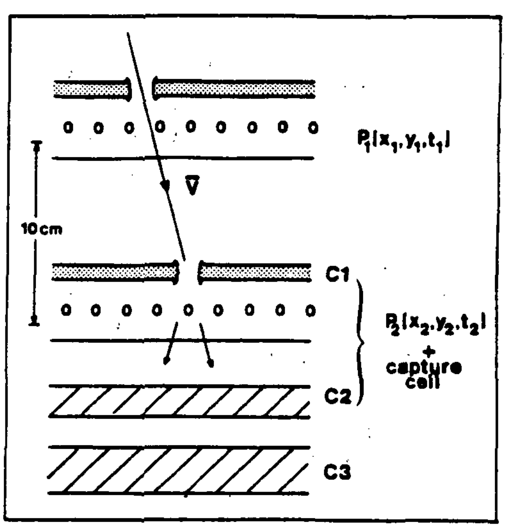

Figure 1b: A schematic of a closed sensor configuration, in which $\vec{v}$ is determined from *impact plasma* measurements P_1 and P_2. In this case, the capture cell portion of the sensor is involved in the measurement of $\vec{v}$.

THE USE OF TETHERED SATELLITES FOR THE COLLECTION OF COSMIC DUST AND THE SAMPLING OF MAN MADE ORBITAL DEBRIS FAR FROM THE SPACE STATION

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All attempts to collect samples of the smallest micron and sub micron sized cosmic dust particles in space with collectors on board the space shuttle, the Long Duration Exposure Facility (LDEF), and the Space Station are subject to two main difficulties:

1) Contamination by orbital debris associated with the shuttle, the space station or other satellites (rocket exhaust, paint flecks, outgassing, etc.)

2) Hypervelocity impact speed of tens of km/sec. resulting in the destruction of the smallest particles with only small amounts of chemically fractionated impact debris remaining.

The use of a tethered subsatellite employed downward into the earth's upper atmosphere to an altitude of about 110 km. above the earth would eliminate the orbital contamination problem while at the same time affording a measure of atmospheric braking to reduce the velocities of many particles to where they may be captured intact or nearly so with properly designed collectors (1,2).

The same technique could also be used to monitor the flux of all types of man made orbital debris out to a distance of more than a hundred kilometers in any direction from the space station (3). It this way the build up of any debris belt orbiting earth could be determined.

The actual collecting elements used for both purposes could be of several different materials and designs so as to optimize the collection of different types of particles with different densities. Stacks of foils, films, plastics, and foams, as well as simple capture cells would be mounted in clusters around the outside of a tethered satellite and protected by iris covers until the tether had been fully deployed. Before retrieval the covers would be closed and the collectors returned to earth for study. If the orientation history of the satellite were known the direction of the incoming material could be infered. A chief advantage in deploying such tethered collectors from the Space Station instead of from the shuttle is the ability to maintain deployment of the tether for days instead of hours resulting in much greater yields of intact particles and impact debris.

THE USE OF TETHERED SATELLITES

G.J. Corso

The first test of the tethered satellite facility being developed by the Marshall Space Flight Center for the acquisition of upper atmospheric data will employ a tether which is 30 km. long. Eventually tethers which are 100 or more km. long will be deployed. It should be noted that cosmic dust collectors could be easily added to the outside of any satellites designed for upper atmospheric studies. Such collectors, with little or no power requirements, would add little to the cost of a planned mission but would yield important information on the composition and flux of micron and submicron cosmic dust particles.

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N86-30590

A NEW INSTRUMENT TO MEASURE CHARGED AND NEUTRAL COMETARY DUST PARTICLES AT LOW AND HIGH IMPACT VELOCITIES*

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Recently, we have developed a new class of dust particle detector, the PVDF dust detector (1), designed for space missions such as the Halley Comet missions where the particle impact velocity is very high (2). In this paper, we demonstrate that this same PVDF detector (operating in a different mode) also has the capability of detecting dust particles having low velocity (~ 100 m/s). This low velocity detection capability is extremely important in terms of planned missions requiring measurement of low velocity dust particles such as comet rendezvous missions (3).

During the course of experimentally demonstrating that PVDF detectors will detect low velocity dust, we were able to develop an additional detecting element (charge induction cylinder) which, when combined with a PVDF detector, yields a system which will measure the charge (magnitude and sign) carried by a cometary particle as well as the particle velocity and mass for impact velocities in the range ~ 100-500 m/s. Thus, this system should make it possible to analyze in detail the characteristics of charged (and neutral) cometary dust at low velocity.

Since the cylinder-PVDF detector system has a relatively small geometry factor, we have included an array of PVDF detectors having a total sensing area of ~ 0.1 m^2 for measurements in regions of space where the dust flux is expected to be low. The characteristics of the detectors in this array have been chosen to provide optimum mass sensitivity for both low-velocity cometary dust as well as high-velocity (~ 15 km/s) asteroid associated and interplanetary dust. The PVDF detectors in the array are of the type we have used in the dust counter experiments from the University of Chicago, called DUCMA, which are presently aboard each of the two USSR VEGA spacecrafts which will encounter Halley's comet in March, 1986. The characteristics of these detectors and our DUCMA instruments have been described in detail (1,2).

The array portion of our DUST COUNTER experiment is shown in fig. 1 and will measure the flux and differential and integral mass distributions of cometary particles having mass $> \sim 8\times10^{-11}$g, and of asteroidal (or interplanetary) dust having mass $> \sim 8\times10^{-14}$g. Figure 2 shows the response of detector B to a high-velocity dust particle. Figure 3 shows the portion of our DUST COUNTER which will measure the magnitude and sign of the charge carried by cometary dust particles as well as their velocity and mass and fig. 4 shows an example of experimental results obtained. From the response of the charge induction cylinder, the sign and magnitude of the charge and particle velocity are determined. The particle mass is determined from the output signal from detector C.

Figure 5 shows the lowest mass thresholds of our DUST COUNTER experiment in relation to expected cometary (4) and interplanetary (5) dust spectra. The Dust Counter mass thresholds shown in fig. 5 have been determined from detector calibrations carried out at the Heidelberg (FRG) dust accelerator facility (1-12 km/s) as well as from calibrations using a dust accelerator developed earlier at the University of Chicago (6) to which we have added our charge induction cylinder to measure the charge and velocity of the accelerated dust (200 m/s, 400 m/s). The DUST COUNTER described here has the unique advantage of providing a combination of measurements for studying the physics of the comas of comets at both low and high impact velocities (4,7).

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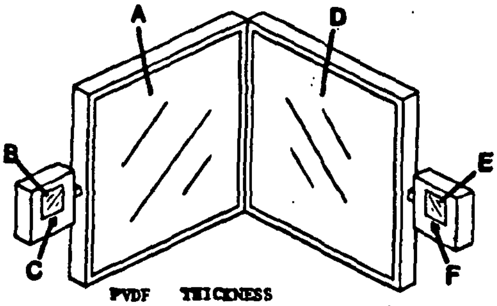
A NEW INSTRUMENT TO MEASURE CHARGED AND NEUTRAL COMETARY DUST

Economou, T., Simpson, J.A., Tuzzolino, A.J.



PVDF DETECTOR	THICKNESS (µm)	AREA (cm²)
A	25	500
B	6	10
C	6	1
D	25	500
E	6	10
F	6	1

Fig. 1 Schematic of DUST COUNTER sensor system. A-F are PVDF dust detectors.

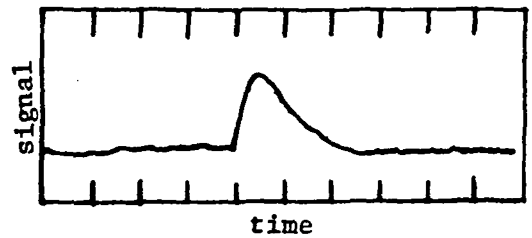


Fig. 2 Signal from detector B of sensor system resulting from dust particle of mass 7.2×10^{-13}g and velocity 9.3 km/s. Signal amplitude is equivalent to 5.1×10^{5} electron charges. Horizontal scale = 20 µs/div.

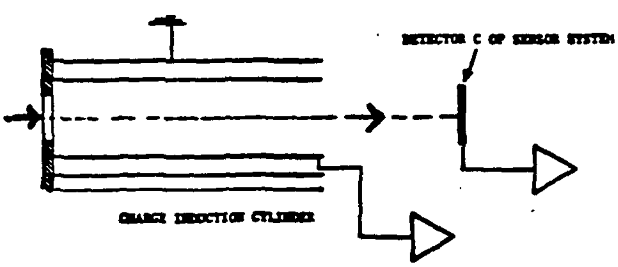


Fig. 3 Portion of DUST COUNTER for measurements of cometary dust particle charge, velocity, and mass.

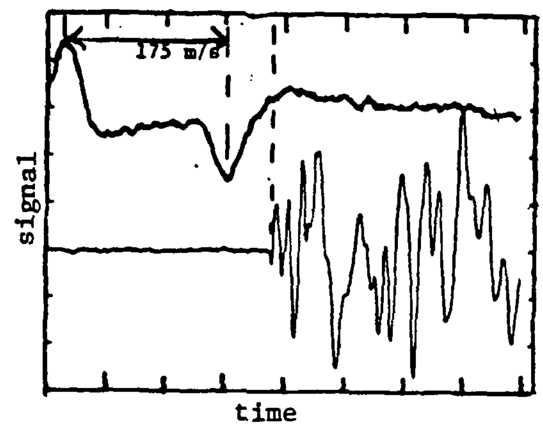


Fig. 4 Signals from cylinder (upper trace) and detector C of sensor system (lower trace) resulting from *a charged dust particle having velocity 175 m/s.* Horizontal scale = 125 µs/div.

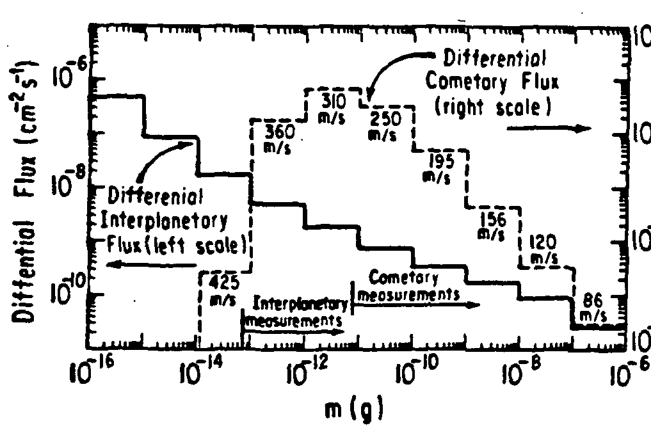


Fig. 5 Expected differential flux of cometary and interplanetary dust. The lowest mass thresholds of the DUST COUNTER are indicated.

LASER MICROPROBE STUDY OF COSMIC DUST (IDPs) AND POTENTIAL SOURCE MATERIALS; E. K. Gibson, Jr., SN4/NASA JSC, Houston, TX 77058 and M. S. Sommer, II, LEMSCO, NASA JSC.

The study of cosmic dust or interplanetary dust particles (IDP) can provide vital information about primitive materials derived primarily from comets and asteroids along with a small unknown fraction from the nearby interstellar medium. The study of these particles can enhance our understanding of comets along with the decoding of the history of the early solar system. The study of the cosmic dust or IDP particles can assist in the elucidation of the cosmic history of the organogenic elements (i.e., H, C, N, O, S, etc.) which are vital to life processes. Studies to date on these particles have shown that they are complex, heterogeneous assemblages of both amorphous and crystalline components. In order to understand the nature of these particles, any analytical measurements must be able to distinguish between the possible sources of these particles. We have undertaken a study using the laser microprobe interfaced to a quadrupole mass spectrometer for the analysis of the volatile components present in cosmic dust particles, terrestrial contaminants present in the upper atmosphere along with the primitive carbonaceous chondrites (CI, CM and CV). From the study of the volatiles released from the carbonaceous materials by the laser microprobe, it is hoped that one could distinguish between components and sources in the IDP particles analyzed.

An Nd-glass, Q-switched laser microprobe has been interfaced to a quadrupole mass spectrometer. Samples of cosmic dust or analogs are placed in a chamber with a quartz window. The chamber is evacuated to at least 10^{-8} torr during bake-out at 110 ^{o}C. Samples are "zapped" by the laser and the released volatiles are measured with the mass spectrometer. The sample chamber can be moved to allow distinct different areas to be analyzed within the sample to be studied. For a meteorite fragment of 1-2 mm size, regions of different lithologies can be studied in situ for their volatile contents. The laser beam which interacts with the samples can be varied in size from 10 to 50 microns. For most cosmic dust grains the beam diameter is similar in size to the particles and the volatiles released are a composite of those present within the total particle.

Our studies have concentrated on CI, CM, and CV meteorite compositions along with cosmic dust particles. Single "chunks" of the Orgueil CI meteorite maximum size 1 mm) along with freshly broken surfaces of the Murchison CM and Allende CV carbonaceous chondrites were studied. Studies of a chondritic type cosmic dust particle (W7027B8) and an aluminum oxide particle (W7027C7) have shown that significant differences in volatile inventories can be measured. This type of analysis provides a new technique for the study and characterization of these important IDP materials.

Volatiles released from CI and CV carbonaceous materials are shown for the dark matrix of the Orgueil (CI) (Fig. 1) and the gray matrix of the Allende (CV) (Fig. 2) meteorites. As expected, the CI sample released a factor of six more volatiles than the CV material. The volatiles released from the Orgueil included H_2O, CH_4, CO + N_2, hydrocarbons, O_2, H_2S, Ar, CO_2, SO_2, COS, and CS_2. The greatest abundances were seen for the H_2O, CO_2, followed by CO + N_2 (mass 28), and O_2. Volatiles released from Allende included CH_4, H_2O, CO + N_2, and CO_2 along with minor amounts of hydrocarbons and argon. As expected the CI matrix contained considerable more volatiles than the CV matrix (ion current abundances 32,767 vs. 5000).

Cosmic dust particle W7027B8 (identified as a Type C particle) was analyzed with the laser microprobe-mass spectrometer (Fig. 3). The major gas phase released was CO_2 with minor amounts of H_2O, CO + N_2, and CH_4, and trace amounts of O_2 and CS_2. The volatiles released were similar to those previously seen from the analysis of carbonaceous chondrite matrix materials. Semi-quantitative measurements of the water and carbon abundances in the particle have shown the minimum water and carbon abundances are around 1% H_2O and 1% CO_2. These abundances are similar to those observed for CM or CV carbonaceous chondrites. Analysis of particle W7027C7 (identified as a TCA or Al particle) showed that the particle was indeed depleted in volatiles. The only species present from the analysis was CO + N_2 (mass 28) and CH_4 along with trace amounts of H_2O and Ar (Fig. 4). It appears that most of the mass 28 may be related to residual silicon oil from the collecting surface. Studies are currently underway to determine if the observed volatiles might be from the silicon oil of the collecting plate. The total ion current from the TCA particle was 30% less than the chondritic particle. From the studies carried out to date using the laser microprobe-mass spectrometer analysis technique, it appears that the method can be used to provide useful information about the nature of cosmic dust particles and further analysis are planned.

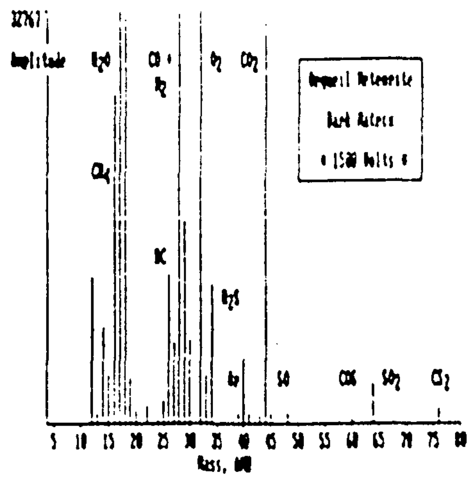


Fig.1 Volatiles released from Orgueil

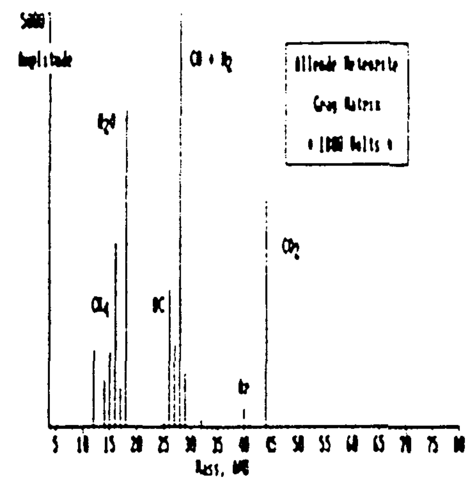


Fig.2 Volatiles released from Allende

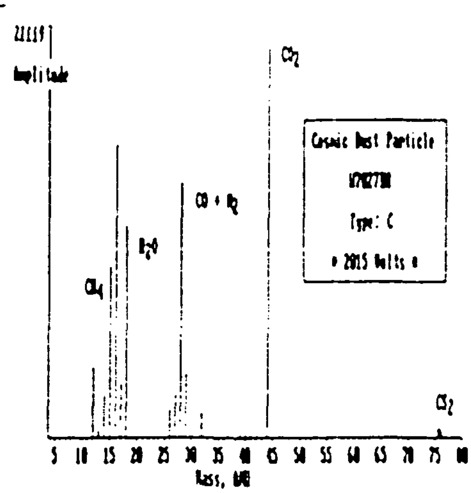


Fig.3 Volatiles released from W7027B8

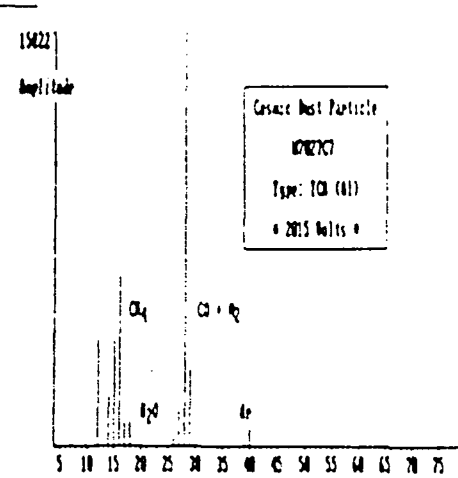


Fig.4 Volatiles released from W7027C7

N86-30592

HYPERVELOCITY PARTICLE CAPTURE: SOME CONSIDERATIONS REGARDING SUITABLE TARGET MEDIA

Friedrich Horz, Mark J. Cintala, NASA Johnson Space Center, and Thomas H. See, Lockheed EMSCO, all Houston, TX 77058

INTRODUCTION:

Hypervelocity particles colliding with passive capture media will be traversed by shock waves; depending on the stress amplitude, the particle may remain solid or it may melt or vaporize. Any capture mechanism considered for cosmic dust collection in low Earth-orbit must be designed such that sample alteration and hence loss of scientific information is minimized. Capture of pristine particles is fundamentally difficult, because the specific heat of melting and even vaporization is exceeded upon impact at typical, geocentric encounter velocities (e.g., Ahrens and O'Keefe, 1977).

The phase relations of a number of representative geologic solids subjected to shock stresses typical of hypervelocity impacts are illustrated in Figure 1, calculated by Cintala (1984); similar results were reported by others (e.g., Ahrens and O'Keefe, 1972, Orphal et al, 1980). The calculations are in part based on measured equation of state (EOS) data and on their extrapolation to high pressure states based on (model dependent) thermodynamic assumptions. In contrast, Figure 2 illustrates some typical experimental results: basalt targets were traversed by shock stresses of well known amplitude and the recovered specimen were analyzed by petrographic means (Schaal et al, 1979; such recovery experiments are limited to < 100 GPa stresses and thus to solid/liquid phase transitions). While some discrepancies exist between calculated and observed melting behaviors, the differences are subtle for the purposes of the present discussion. Typical, dense rocks and silicates melt at > 40-50 GPa. The introduction of porosity causes multiple shock reverberations at the free surfaces and lowers the equilibrium stress for shock induced melting (e.g., Kieffer, 1971, Cole and Ahrens, 1974, and Cintala, 1984). Although incipent melting is observed in porous media at pressures as low as 8 GPa, these melts are extremely localized and essentially confined to grain boundary melting. Most porous targets, however, are noticeably compacted and thus texturally altered even at 5 GPa; pore-space is decreased and component minerals may be mechanically disaggregated, exhibiting distinct mosaicism under the petrographic microscope.

We conclude that shock stresses in excess of 50 GPA should be avoided during hypervelocity particle capture on board Space Station and that stresses < 20 GPa, even at 15 km/s collision velocities, should constitute desirable instrument design goals. In the following we will identify some principal characteristics of the capture medium that may satisfy these requirements.

CAPTURE MEDIUM: MATERIAL PROPERTIES

The stress amplitude generated upon impact is controlled by the EOS of both target and impactor. Pertinent data for many materials were determined experimentally (see, for example, the compilation by Marsh, 1980) and include geological solids as well as prospective media for Space Station collectors. Hugoniot curves for some representative materials are illustrated in Figure 3; the particle velocity (u_p) and peak stress (P) plane was selected because, for a one dimensional case

$$V_i = u_{pt} \text{ (Target)} + u_{pp} \text{ (Projectile)} \qquad \text{(eq. 1)}$$

Note that the peak stresses (Fig. 3) at any given u_p may vary significantly, depending on a material's compressibility, which in turn depends partially on initial specific volume and thus density. Notice also the dramatic differences between metals and rocks (Figure 3A) versus low density, porous media (Fig. 3B). In accordance with eq. 1, the so called "impedance match" method (Duvall, 1962) may be used to calculate u_p and hence P for any target/impactor combination and impact velocity. Using graphical extrapolations of the measured EOS, we have solved eq. 1 for three representative projectile materials (dunite, sintered quartz-glass, and highly porous tuff), which impact potential capture "targets" at velocities as high as 15 km/s. Note that capture media of ultra-low densities result in peak stresses < 20 GPa, even at typical heliocentric particle velocities. Low-density materials are therefore the preferred, if not required, media for the capture of hypervelocity particles.

CAPTURE MEDIUM: MEMBRANE THICKNESS

In general, only highly porous media have suitably low bulk densities. The impactor will sense them as "low density" materials only, if their typical pore dimensions are substantially smaller than the impactor dimensions, (D); especially the pore septa or fibers, i.e., the "solids" in a porous substance must have thicknesses << D. This thickness (L) controls the shock pulse duration (t), because t = 2L/U, where U is the shock wave velocity. According to Ahrens and O'Keefe (1977) the attenuation of a shock wave strongly depends on the quantity L (or t) and may be scaled dimensionally. If L << D, part of the impactor may not be shocked to high pressure states. Fragmentation, however, may not readily be avoided, because much of the impactor may still be engulfed by isobars in excess of the particle's tensile strength (<0.2 GPa for dense, crystalline rocks; Cohn and Ahrens, 1979). Upon impact with a porous target, a series of compressive and tensile waves will result in the impactor, all of small (t) and thus of small spatial extent relative to D; compressive and tensile waves may overtake and cancel each other, as multiple free surfaces will set up multiple rarefactions (e.g., Gehring, 1970 or Swift et al, 1982). The one dimensional analysis of Ahrens and O'Keefe (1977) suggests L / D approximately 1/20 or smaller.

CONCLUDING REMARKS:

Survival of unmelted impactor fragments at relatively high collision velocities was demonstrated in the laboratory (Tsou et al, 1986) and on Solar Max thermal blankets (McKay et al, 1986, Blanford et al, 1986). It thus appears possible to collect relatively unaltered hypervelocity particles in Earth orbit. Additional impact experiments are necessary to evaluate materials of ultra-low densities that satisfy the above considerations. Ultimately a stack of very thin foils, rather than some foam material, may also be considered and may be tailored (= L) for capture of specific impactor masses. Operationally, recovery of projectile fragments from such materials becomes a concern, because penetration paths may be tens of projectile diameters in length. Target media that may be dissolved quantitatively without adverse effects on the contemplated microanalyses appear desireable for expedient recovery of particle fragments.

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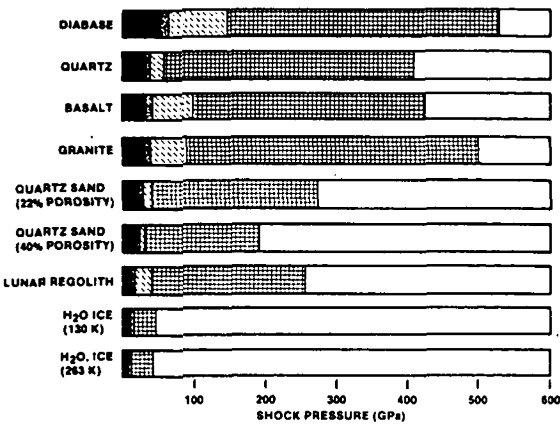

FIG.1

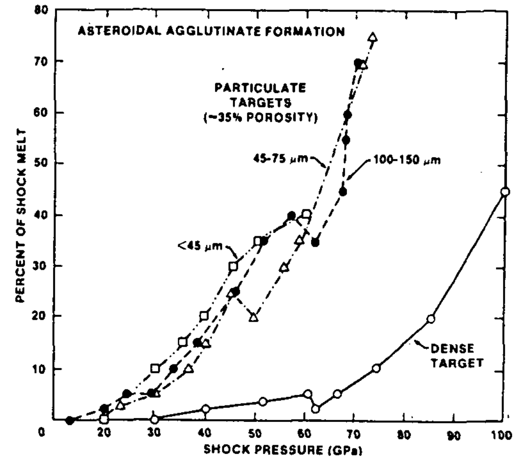

FIG.2

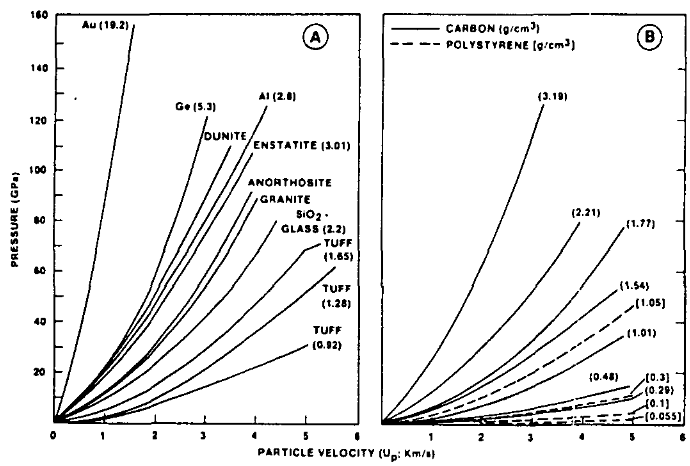

FIG.3

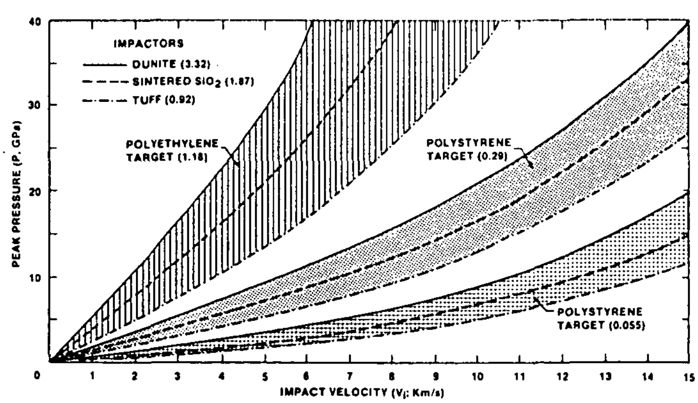

FIG.4

FIGURE CAPTIONS:

Fig. 1: Phase relations of representative geologic targets (or impactors) subjected to shock stresses typical of those encountered during collisions at cosmic velocities (after Cintala, 1986).

Fig. 2: Experimentally determined melting behavior of dense and porous basalt. (Schaal et al, 1980).

Fig. 3: Typical Hugoniot curves for a variety of materials of generic significance for Space Station cosmic dust instruments.

Fig. 4: Peak-pressures as a function of impact velocity encountered by a variety of projectiles colliding with targets of 3 different bulk densities.

ORBITAL DEBRIS MEASUREMENTS: D.J. Kessler, NASA, Johnson Space Center, Houston, Texas 77058

An any one time, there are about 200 kgm of meteoroid mass moving through altitudes below 2000 km at an average speed of about 20 km/sec. Most of the mass is found in particles of about 0.1 mm diameter [1]. The meteoroid environment has been a design consideration for spacecraft. The Apollo and Skylab spacecraft were built to withstand catastrophic impacts on critical systems from meteoroids having sizes up to 3 mm. in diameter. Larger sizes were so few in number as to be of no practical significance for the duration of the mission. Some small spacecraft systems required additional shielding against meteoroids as small as 0.3 mm. diameter in order to maintain an acceptable reliability. The trend in the design of future spacecraft (as for example, the Space Station) is towards larger structures, lighter construction, and longer stay times in orbit. These factors increase the range of concern from about 0.1 to 10 mm. in diameter.

However, it is no longer sufficient to consider only the natural meteoroid environment in spacecraft design. Since the time of the Apollo and Skylab programs, launch activity has continued and increased. As a result, the population of orbital debris has also increased substantially. The total mass of debris in orbit is now approximately 2,000,000 kgm at altitudes below 2000 km. Relative to one another, this mass is moving at an average speed of 10 km/sec; or only half the relative speed of meteoroids. The most significant difference between the orbital debris population and the meteoroid population is that most of the debris mass is found in objects several meters in diameter, rather than 0.1 mm diameter as for meteoroids [2]. This large reservoir of mass may be thought of as a potential source for particles in the 0.1 to 10 mm. range. That is, if only one ten-thousandth of this mass were in this size range, the amount of debris would exceed the natural meteoroid environment. The potential sources for particles in this size range are many: (1) Explosions - more than 80 spacecraft are known to have exploded in low Earth orbit. The fragment size distribution is a sensitive function of the intensity of the explosion [3,4]. (2) Hypervelocity collision in space - One or two of the known satellite breakups may have been from hypervelocity collisions. The fragment size distribution of such a collision is known to include a large number of particles in the 0.1 to 10 mm size range. (3) Deterioration of spacecraft surfaces - oxygen erosion, UV radiation and thermal stress are known to cause certain types of surfaces to deterioate, producing small particles. (4) Solid rocket motor firings - A third of the exhaust products of a solid rocket motor is aluminum oxide particles in the size range 0.0001 to 0.01 mm. (5) Unknown sources - Other sources are likely to exist. Particulates are commonly observed originating from the Shuttle, and other objects in space.

What is currently known about the orbital debris flux is from a combination of ground based and in space measurements. These measurements have revealed an increasing population with decreasing size. Beginning with the largest sizes, a summary of these measurements follows.

<u>NORAD Catalogue</u>. The North American Aerospace Defense Command (NORAD) is responsible for tracking and maintaining a catalogue of "all man-made objects" in space. The catalogue as of September 30, 1985, contained 5712 objects in space [5], most in low Earth orbit, and nearly half resulting from satellite breakups. The ability to catalogue small objects is limited by the power and wave length of individual radar sites, as well as the limitations

on data transmission within the network of radar sites. Consequently, objects smaller than about 20 cm are not usually catalogued.

PARCS Radar. The Perimeter Acquisition and Attack Characterization System (PARCS) at Concrete, N.D. is NORAD's most powerful radar. It can typically detect objects as small as about 8 cm in low Earth orbit. Past [6] and continuing tests with this radar have shown an uncatalogued population which is between 7% and 18% greater than the catalogued population.

Ground Based Optical Telescopes. Lincoln Laboratory was contracted to use their Experimental Test Site (ETS) to search for centimeter sized debris in low Earth orbit. The ETS consists of two, 31 inch telescopes located in White Sands, New Mexico. The telescopes tracked identical overhead star fields for about an hour when the region of space between 500 km to 1000 km was sunlit. The star-like images were detected using low-light level TV cameras and recorded on video tape. Centimeter size objects were seen as 16th magnitude objects moving at about a degree per second through the field of view. Two telescopes were required to obtain the altitude of the object, using parallax. This permitted discrimination between orbiting debris and meteors which are only found below 120 km. Part of the observing program was coordinated with NORAD. The search detected eight times as many orbiting objects as were predicted using the catalogued population [7], indicating that a total population of approximately 45,000 objects larger than about 1 cm are in low Earth orbit. Additional tests of this type are planned to determine probable sources, and to improve statistical uncertainties.

Explorer 46 Meteoroid Bumper Experiment. Explorer 46 was launched into Earth orbit in August, 1972. One of the experiments, the Meteoroid Bumper Experiment, consisted of 3 orthogonal surfaces with areas totaling 19.2 sq. met. These areas were sensitive to penetrations by particles larger than 0.075 mm at 7 km/sec. The distribution of impacts on these orthogonal surfaces illustrated that the surfaces experienced a highly directional flux, one direction measuring a factor of 10 greater flux than another. Assuming the experiment performed as expected, the only explanation is that the satellite became gravity gradient stablized and mostly measured an Earth orbiting population [8].

Spacecraft Windows. Since the beginning of manned space activities, returned windows have been examined for meteoroid impacts [1]. Beginning with the Apollo/Skylab windows, the windows were examined in the Scanning Electron Microscope (SEM), and some chemistry of the impacting particles was determined. About half of the Apollo/Skylab hypervelocity pits were aluminum lined, and concluded to likely be man-made in origin [9]. However, since Shuttle windows are reused, they cannot be as easily examined.

Three days after the launch of STS-7, the crew reported a pit, about 4 mm in diameter, on the external surface of one of the windows. This damage exceeded safety requirements for launch and the window was replaced. Consequently, this window was examined to the same detail as were previous Apollo windows for meteoroid impacts. Energy Dispersive X-ray Analysis (EDS) was again used to determine the composition of partially fused material found in the bottom of the pit. Titanium oxide and small amounts of aluminum, carbon, and potassium were found added to the pit glass. Crater morphology places the impacting particle diameter at 0.2 mm, and a velocity between 3 km/sec and 6 km/sec. From this data, it is concluded that the particle was man-made and likely an orbiting paint fleck [10]. This is the first conclusive case where orbital debris can be shown to have caused the operational loss to a space vehicle subsystem.

Solar-Max Surfaces. Approximately 1.5 sq. met. of thermal insulation surface, and 1.0 sq. met. of aluminum louvers were returned from the Solar-Max satellite after 50 months of exposure to space at more than 500 km altitude. The thermal insulation consisted of 17 layers of aluminized Kapton, each separated by a dacron net. This type of surface has capture properties similar to the capture cell experiment on LDEF and offers an excellent opportunity to obtain chemistry of impacting particles. About 160 impacts which had penetrated the outer layer were found in 0.5 sq. met. These penetrations deposited ejecta on the following layers. Over a thousand craters were found which did not penetrate the 1st layer -- more than expected from meteoroid impacts alone. EDS analyses shows clear evidence that most of the smaller craters were produced by particles with sufficient velocity to produce melting. EDS analysis also shows that a large number of these pits contain titanium, zinc, potassium, silicon and chlorine. Except for chlorine, this chemistry corresponds to the chemistry of thermal paints currently used by NASA for space applications. Meteoroid impacts have also been identified. While analysis is far from complete, the preliminary results are finding twice as many orbital debris impacts as meteoroids, suggesting that billions of 0.1 mm debris particles are in Earth orbit [10, 11, 12].

Nearly all of the orbital debris measurements to date show an orbital debris flux which exceeds the meteoroid flux. These measurements are summarized and compared with the meteoroid flux in Chapter 7 of this volume.

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ACOUSTIC PENETRATION AND IMPACT DETECTOR FOR MICROMETEOROID AND SPACE DEBRIS APPLICATION

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ABSTRACT

In the past the study of interplanetary dust particles (and probably also small-sized space debris) has mainly been restricted to the measurement of a few parameters like flux, momentum and velocity. Information about the chemical and isotopic composition could be obtained from some Brownlee particles which were collected in the upper atmosphere. An important step has been done with a new experiment on LDEF (Long Duration Exposure Facility) which is still in orbit (launch: April 6, 1984).
LDEF provides the first opportunity to collect micrometeoroid material in space which, afterwards, will be subject to isotopic analysis in the laboratory

The LDEF capture cell experiment for chemical and isotopic measurements of micrometeoroids by secondary ion mass spectrometry will for the first time enable a differentiation between real cosmic dust and man-made space debris, preferably small-sized particles of solid rocket engine exhaust. Information concerning debris flux and size distribution is now of rapidly increasing interest due to the high production rates in current space activities.

The simulation experiments which were performed for the development of the capture cell design and the calibration of the involved analysis instrumentation revealed the necessity to have more information about the impact parameters, such as the impact location on a capture cell, velocity and projectile mass. As a result of these measurement efforts an active detector has been developed with which all required impact parameters can be obtained, and, in addition, the flight path direction of a projectile can be calculated.
The measurement principle is illustrated in Fig. 1. A thin penetration foil is mounted at a distance d above the target plate. This foil is stretched and glued to a support frame. Four piezo microphones, one at each corner, will detect the acoustic bending waves which have been originated by a projectile penetrating the foil. This front foil should be very thin in order not to destroy the particles during penetration, even at high velocities. A metallic coating of one or both sides of the foil, due to electrical shielding reasons or some chemical analysis premises, is still acceptable.

The target plate will be a solid metal plate (with a thickness up to a few millimeters) with another four microphones attached to the rear side. The edges of the target plate are embedded in silicone rubber in order to get sufficient acoustic insulation from the mounting structure. The damping behaviour of the plate can be significantly improved if the rear side is covered with a thick layer of silicone rubber, too. Thus, the signal decay times will decrease and the frequency of detectable events will increase.

An impacting particle originates a circular bending wave propagating towards the positions of the microphones at the front foil and - if penetration occurs - at the target plate, too. Thus, the arrival times of the acoustic waves according to the different propagation lengths are given.

The evaluation of the impact locations at the foil and at the target plate can easily be performed if always the differences of wave propagation times for two opposite microphones are taken into consideration. These curves for constant time differences are hyperbolae. This overdesigned measurement set-up (three microphones would be sufficient for a definite destination) allows a simple and redundant evaluation procedure for the impact location and the event time.

This procedure is schematically shown in Fig. 2. The propagation speeds of the acoustic waves in the front foil and in the target plate can be measured experimentally. With these values and the dimensions of the detector only hyperbola geometry has to be used in order to get the impact location and the event time ($P_1 - P_3$ and $P_2 - P_4$ are the focal distances of the hyperbolae). This detector principale has extensively been tested in the Munich Plasma Accelerator Facility. For the LDEF impact simulation tests the microphones have been attached to the rear-side of the original Capture Cells in order to detect the impact location. In despite of the multi-layer construction (aluminium plate, silicone glue, germanium plate) a sufficient signal-to-noise ratio could be obtained. This has mainly been achieved by an optimization of the microphone set-up.

As an example, the time-of-flight record of three impacts at only an aluminium target is shown in Fig. 4. The time differences ΔT_{13} and ΔT_{24} can be calculated and - by use of a corresponding diagram as depicted in Fig. 2 - the impact locations can easily be evaluated within an accuracy of < 1 mm. This accuracy is defined by the sample rate of the recording instrument. A similar sequence of signals will be measured for the front foil if a two-stage detector is used.

The Two-Stage Acoustic Penetration and Impact Detector is a simple device for measuring the impact event time, the projectile velocity, the flight path direction and the momentum. The results of the laboratory tests have shown that this detector can be used in a wide range of projectile size and velocity. According to measurement purposes the size of the detection area, the distance between the front foil and the target plate and the number of microphones as well as the evaluation procedure can easily be adjusted. The target plate area can also be replaced by another foil detector, if two penetration stages are preferred.

This active detector is well suitable for a variety of applications in meteoroid and space debris exploration. It can also be supplied with capture cell properties for chemical analysis of inside-deposits.
Therefore, this measurement principale has been taken into consideration as a possible flight experiment for instance for a later LDEF flight or future space station activities.

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H.Kuczera, H.Iglseder, U.Weishaupt, E. Igenbergs "Two Stage Acoustic Pentration and Impact Detector for Meteoroid and Space Debris Application", Adv.Space Res. Vol.5, No. 2, pp.91-94, 1985

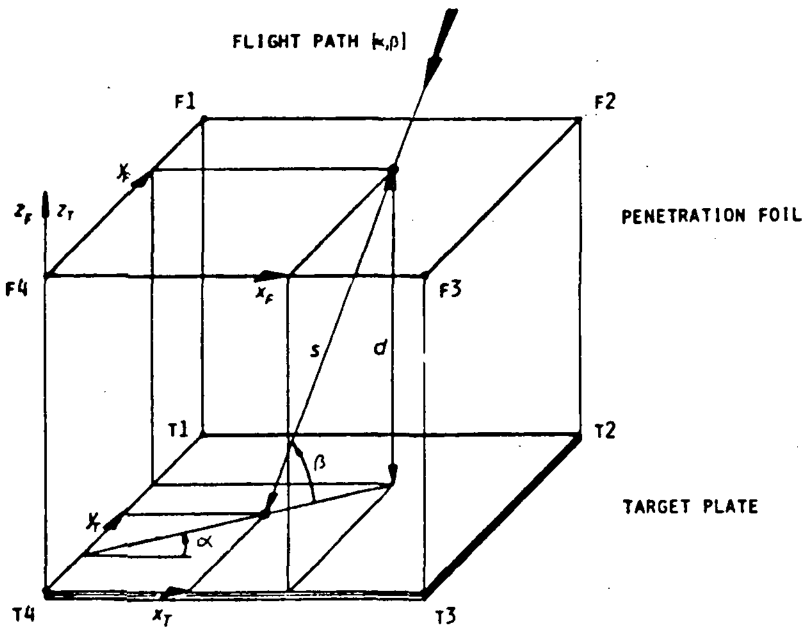

Fig. 1
Detector Principle

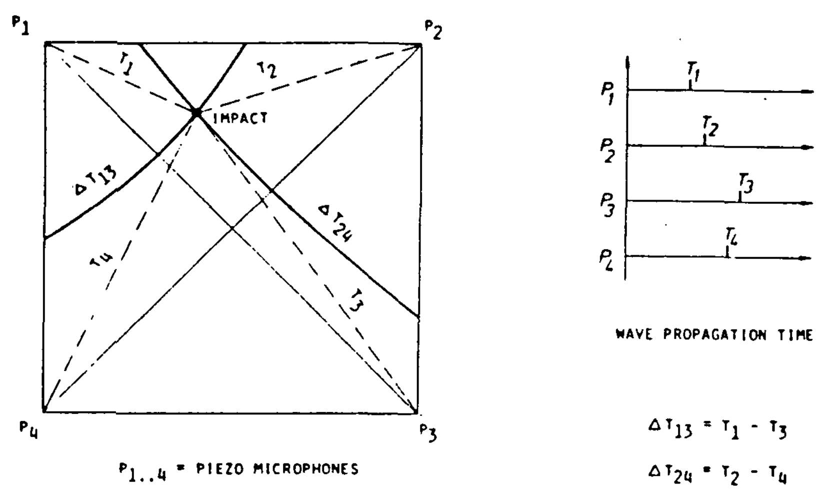

Fig. 2
Evaluation of the Impact Location

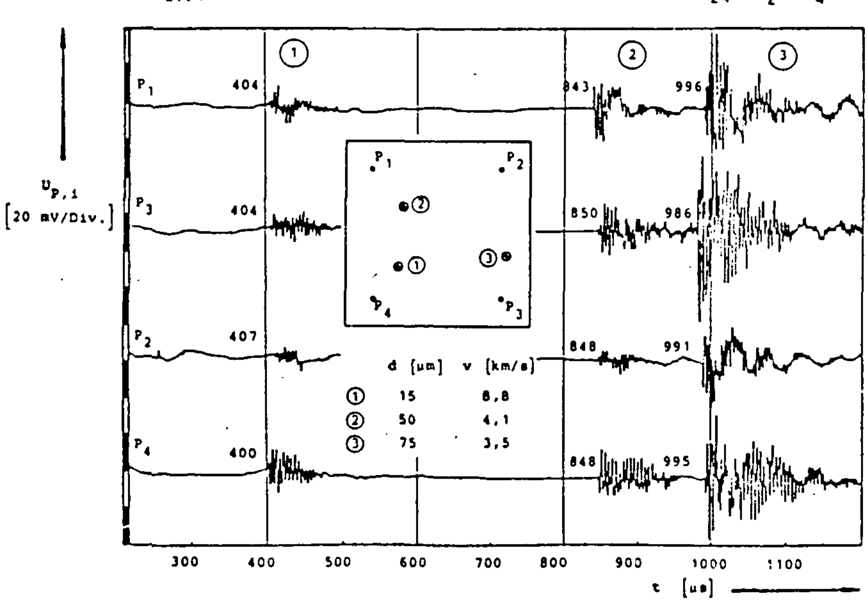

Fig. 3
Time-of-Flight Record for a Target Plate with three Impacts (t=0: Trigger of the Plasma Gun)

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ABSTRACT

It is evident from space flights during the last 3 years that the low Earth orbital (LEO) environment interacts with spacecraft surfaces in significant ways. One manifestation of these interactions is recession of, in particular, organic-polymer-based surfaces presumably due to oxidation by atomic oxygen, the major component of the LEO environment. Three experiments have been conducted on Space Shuttle flights 5, 8 and 41-G to measure reaction rates and the effects of various parameters on reaction rates. Surface recession on these flights indicates reaction efficiencies approximately 3×10^{-24} cm^3/atoms for unfilled organic polymers. Of the metals, silver and osmium are very reactive.

Effects on spacecraft or experiment surfaces can be evaluated using the derived reaction efficiencies and a definition of the total exposure to atomic oxygen. This exposure is obtained using an ambient density model, solar activity data and spacecraft parameters of altitude, attitude and operational date. Oxygen flux on a given surface is obtained from the ambient density and spacecraft velocity and can then be integrated to provide the total exposure or fluence. Such information can be generated using simple computational programs and can be converted to various formats. Overall, the extent of damage is strongly dependent on the type of surface and total exposure time. A nomograph will be presented which can be used to assess effects for specific conditions.

N86-30596

STRATOSPHERIC DUST COLLECTIONS: VALUABLE RESOURCES FOR SPACE AND ATMOSPHERIC SCIENTISTS; Ian D. R. Mackinnon, Department of Geology, University of New Mexico, Albuquerque, NM 87131.

Collections of solid particles from the Earths' stratosphere have been a significant part of atmospheric research programs since 1965 [1], but it has only been in the past decade that space-related disciplines have provided the impetus for a continued interest in these collections. Early research on specific particle types collected from the stratosphere established that interplanetary dust particles (IDP's) can be collected efficiently and in reasonable abundance using flat-plate collectors [2-4]. The tenacity of Brownlee and co-workers in this subfield of cosmochemistry has led to the establishment of a successful IDP collection and analysis program (using flat-plate collectors on high-flying aircraft) based on samples available for distribution from Johnson Space Center [5]. Other stratospheric collections are made, but the program at JSC offers a unique opportunity to study well-documented, individual particles (or groups of particles) from a wide variety of sources [6]. The nature of the collection and curation process, as well as the timeliness of some sampling periods [7], ensures that all data obtained from stratospheric particles is a valuable resource for scientists from a wide range of disciplines. A few examples of the uses of these stratospheric dust collections are outlined below.

A number of attempts have been made at a taxonomy for stratospheric particles [6,8], including those of extraterrestrial origin [9]. The most recent classification scheme for all stratospheric particles [10] appears to provide a simple and reliable method for their documentation. A useful classification scheme is an essential element of any broadly-based data set as it allows communication between different disciplines (e.g. orbital debris vs. atmospheric dynamics). In addition, new materials entering the stratosphere may be readily identified. Thus, as additional fine-grained (<100μm) material from orbiting spacecraft (satellites, shuttles or a space station) enter the Earths' atmosphere, a frame of reference is available from current stratospheric particle collections and classification. This frame of reference will become quite important for cosmochemists interested in the collection of "exotic" IDP's such as high-temperature condensates [e.g., 11].

An understanding of global parameters at a particular point in time in the stratosphere can also be obtained from a study of complete collection surfaces. For example, an accurate assessment of particle concentration over a wide range of sizes was experimentally determined for the stratospheric cloud formed one month after the eruption of El Chichon [7]. Additional studies on the El Chichon cloud over a six-month period showed that volcanic ash settles out of the stratosphere at a rate determined primarily by particle shape and density [12]. Another study during a volcanically quiescent period [13], has shown that total particle number density during the Summer of 1981 was $\sim 2.7 \times 10^{-1}$ cm^{-3}, for particles >1μm diameter. However, >95% of these particles were <5μm diameter. With the above classification scheme, an estimate of micrometeorite number density at ~20km altitude can also be made. The estimate for Summer, 1981 is 5×10^{-2} cm^{-3} for particles >1μm diameter. This micrometeorite number density is comparable to predicted concentrations of orbital debris of similar size range for the latter part of this decade [14]. However, under current ambient conditions, number density and particle collision calculations indicate that the probability of IDP contamination by solid anthropogenic particles in the stratosphere is negligible [13]. Continuation of these types of studies, for shorter collection periods at regular intervals, can provide important experimental data on the contributions of orbital debris, rocket firings and transient events (e.g. volcanic eruptions, nuclear explosions) on the total stratospheric particle budget.

Sophisticated analyses of individual particles collected from the stratosphere have already provided a wealth of data on IDP's [15-17]. A more recent study on known terrestrial particles (e.g. Al_2O_3 spheres from solid rocket exhausts) has shown that large (10μm diameter) spheres reside in the stratosphere for a time long enough to react with ambient sulfate aerosols [18]. This observation provides atmospheric scientists an experimental boundary condition for sulfate aerosol reactivities with specific substrates. Further work of this type may allow estimates of in situ aerosol reactivity over a range of particle types, or, conversely, estimates of particle residence time at specific altitudes.

The collection and curation of all stratospheric particles through the JSC Curatorial Facility has provided new insight into the nature of natural and man-made particles which occur at ∿20km altitude as well as the fine-grained extraterrestrial materials intensively studied by scientists in the NASA Planetary Materials Program. With time and imagination, this valuable resource can provide a significant increase in our understanding of the lower stratosphere and an excellent platform from which to train and develop younger scientists interested in the synergy of the Earth/Low-Earth-Orbit environment.

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TARGETED FLIGHT OPPORTUNITIES WITH LARGE AREA COLLECTORS; Ian D. R. Mackinnon, Department of Geology, University of New Mexico, Albuquerque NM 87131.

The collection of stratospheric dust utilising flat plates attached to aircraft wing-pylons currently requires approximately 40 hours of accumulated exposure time [1]. These long exposure times are attained on a relatively ad hoc basis, through the summation of short 4-8 hour flights which are often subject to the demands of other higher priority experiments on the same aircraft. Thus, total collection periods for stratospheric particles at ~20km altitude may range from 3 to 6 months. For example, collection of particles on Flag No. W7029 began on September 21st, 1981 and was completed on November 30th, 1981 [1]. During this collection period, the longest continuous flight time was for ~8 hours on October 15th while several flight times < 2 hours were also recorded [2]. A major factor in the stratospheric collection process is the relative density of particles at the collection altitude. With current collector plate geometry, one potential extraterrestrial particle of about 10µm diameter is collected approximately every hour. However, a new design for the collector plate, termed the "Large Area Collector" (LAC), allows a factor of 10 improvement in collection efficiency over current conventional geometry [3]. The implementation of LAC design on future stratospheric collection flights will provide many opportunities for additional data on both terrestrial and extraterrestrial phenomena.

With a factor of 10 improvement in collection efficiency, LAC's may provide a suitable number of potential extraterrestrial particles in one short flight of between 4 and 8 hours duration. Alternatively, total collection periods of ~40 hours enhances the probability that rare particles (e.g. ~100µm diameter CP aggregates) can be retrieved from the stratosphere. This latter approach is of great value for the cosmochemist who may wish to perform sophisticated analyses on greater than picograms of interplanetary dust. The former approach, involving short duration flights, may also provide invaluable data on the source of many extraterrestrial particles. The time dependance of particle entry to the collection altitude is an important parameter which may be correlated with specific global events (e.g. meteoroid streams) provided the collection time is known to an accuracy of < 2 hours.

Many meteoroid streams occur with predictable regularity, although the relative intensity of a particular event is not always easily determined in advance [4]. Nevertheless, the orbital parameters of many common meteoroid streams are precisely determined and can be readily correlated with the known orbital elements of periodic comets [4]. The components of these meteoroid streams reach a termination height (i.e. the altitude at which the entry velocity vector is zero) between ~55 and 95 km altitude. Thus, after the termination height is reached, particles derived from a meteoroid stream contain a velocity component which is only dependant upon the settling rate of particles through the mesosphere. This region of the Earth's upper atmosphere is relatively quiescent, and, at least at the upper altitudes of the mesosphere, particle transport via transverse winds may not be significant. Experimental data on the settling rate of irregularly shaped particles [5] provides a simple procedure for estimating the settling time for various particle types to fall from an observed termination height to the collection altitude. This settling rate calculation accounts for the viscosity of the medium, particle shape, size and particle density - factors which greatly influence fall time through an atmosphere [5].

Sample calculations for typical particles encountered in the Cosmic Dust Collection [7] indicate that a CP aggregate (with σ = 0.1 $gm.cm^{-3}$ and effective diameter, d_a, 50µm) can fall from a termination height of 55km to a collection height of 18km in > 80 days. However, if the collection altitude is increased to ~35km, the settling time decreases to ~45 days. A sphere with the same density should fall the 20km column height in ~20 days. These settling time estimates are based upon a simplified, linear extrapolation of Wilson-Huang and Stokes' formulations at higher altitudes [2]. More explicit calculations would provide precisely-defined upper and lower bounds on the lead time available for the collection of stratospheric particles for various combinations of parameters (e.g. sphere vs aggregate; σ ~0.1 $gm.cm^{-3}$ vs 2.5 $gm.cm^{-3}$ etc.). These calculations can be optimised to suit the turn-around time for mission-readiness, the propensity of particles to accumulate in the lower stratosphere and other environmental factors (e.g. shuttle launches, volcanic eruptions). Thus, dust collection missions using an LAC geometry may be targeted towards specific collection altitudes, latitudes and collection times. These space-time points may be defined by the probability that a high flux of incoming extraterrestrial material (e.g. meteoroid streams) will be present. Within a given meteoroid event, it may be possible to obtain separate, short period collections which sample more rapidly settling ablation spheres as well as later settling porous, fluffy and irregularly-shaped particles.

Source-specific data on the micrometeorite flux (commonly misconceived as constant through time) via retrieved samples would provide a significant increase in our understanding of solar system small-body chemistry and mineralogy (e.g. that of comets and asteroids) as well as upper atmosphere dynamics. This type of program is also well-suited to the monitoring of short-term events which may influence the solid particulate environment in the stratosphere. For example, particle debris swarms from the rapid orbital decay of space or near-Earth orbit structures can be assessed. In addition, short-duration collection flights may also provide more timely and precise (experimental) assessments of mans' increased activities in the near-Earth orbital environment [e.g. 6].

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THE SOLAR MAXIMUM SATELLITE CAPTURE CELL: IMPACT FEATURES AND ORBITAL DEBRIS AND MICROMETEORITIC PROJECTILE MATERIALS.

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The Solar Maximum satellite (Solar Max) was launched on February 14, 1980 into a near circular orbit at 570km altitude. After its orbit had decayed to 500km, the satellite was retrieved by the STS 41-C crew on April 12. 1984. Some Solar Max surfaces were brought back to Earth after 4 years and 55 days of exposure to the near-Earth space environment. The returned surfaces include ca. 1.5m^2 of thermal insulation materials (multiple-layered blankets) and 1.0m^2 of aluminum thermal control louvers (two 140µm-thick Al-foils separated by about 3mm). These surfaces have been completely scanned by optical microscopy for impact features, i.e. craters and penetration holes. In this survey only impact features with diameters larger than ~40µm were mapped. Smaller impact features on the thermal insulation blankets may have been partially obliterated because atomic oxygen has eroded ~20µm of the exposed Solar Max Kapton surfaces [1].

Impact features up to ~500µm were observed on the thermal insulation blankets. The thickness of the first (Kapton) layer of the thermal blankets is different for various parts of Solar Max, e.g. the first layer on the Attitude Control System (including blankets #6 and #9) is initially 50µm thick while this layer on the Main Electronics Box (MEB) is initially 75µm thick. The observation that impact features >70µm in diameter on blankets #6 and #9, and impact features >80µm in the MEB blanket, are usually penetration holes rather than craters is probably related to the difference in thickness of this layer [1, 2]. In the following we will concentrate on our observations of the MEB thermal blanket which, to date. is the most intensely studied surface recovered from Solar Max.

The MEB thermal blanket consists of an initially 75µm thick, Al-coated (backside) Kapton layer followed by 15 doubly-aluminised Mylar layers (6µm thick) and finally an Al-coated (frontside) 25µm thick Kapton layer, each separated by a ~100µm thick Dacron mesh. We recognised two basic types of impact features in the first layer: craters ranging up to ~140µm in diameter and penetration holes 80-500µm in size.

One or more of three different types of halos on the front side of the first layer can be recognised surrounding each impact feature, viz. a bright halo, an irregular spall halo with a jagged outer margin in which a thin surface layer of material has been removed and a dark smokey halo [2]. The dark smokey halo is a rather diffuse phenomenon that sometimes extends a considerable distance away from an impact feature. Generally confined within this halo, a spall zone may surround an impact feature. We tentatively suggest that an impact feature surrounded by a spall zone represents a lower velocity impact compared to an impact feature of similar size but without a spall halo. A narrow, bright halo often directly surrounds an impact feature. The bright halo is confined well within the spall halo. The origin of the bright halo is uncertain but we suggest that this halo represents a shock metamorphosed region of the Kapton layer, viz. a region of structural or chemical changes. One or more halo types are typically present around holes but they may be absent around craters.

The rims around craters are generally smooth, raised and may be overturned although in some cases the rims are subdued or lacking. The holes are typically surrounded by raised, usually overturned, nearly circular rims on both the "entrance" side and rear (exit) side [2]. The almost identical rims on both front and rear sides of the first layer are evidence for hypervelocity impact [3]. Partially detached rims could be consistent with hypervelocity impact [3].

A generally circular spray pattern of roughened second layer material with elongated pits, holes and entrapped particles is found beneath most of the first layer holes [4]. The pits and holes may be arranged in a concentric symmetric pattern in some cases but show no apparent symmetry in others. The diameter of the spray pattern is typically larger than the diameter of the hole on the first layer by ratios of 2.5-20.0 : 1 [2]. In a few impact features the projectile penetrated the second layer. Penetrations of subsequent layers are rare. Penetration holes in the second, or subsequent, layers are typically irregular and have no raised rims.

Small-sized (1-50µm) particles are present in craters, on the front and backsides of the first layer around a penetration hole, and within spray patterns on the second layer beneath a penetration hole [5]. However, in these locations the amount of particles can be highly variable. These particles may represent the remains of impacted micro-meteorites and orbital debris or derive from molten target (Solar Max) material [4].

Particles on Solar Max surfaces were studied using a JSM-35CF scanning electron microscope equipped with a PGT System IV energy dispersive spectrometer for _in situ_ micro-analysis. Selected particles were removed from impact features for detailed mineralogical analysis using a JEOL 100CX analytical electron microscope [4-6]. Because of the extreme sensitivity of the technique, contamination is a serious concern in electron microscope studies of small-sized particles [7]. This issue is of particular concern in analysis of Solar Max particles. However, the satellite was not designed to be returned for laboratory studies and appropriate stringent pre-flight cleanliness procedures were not invoked.

Contamination may have occurred during handling of the satellite prior to launch, during STS rendez vous, or in the laboratory after return to Earth. Contaminants include materials of anthropogenic and natural (terrestrial) origin. For example, analysis of discolorations and wipe-marks on Solar Max surfaces show the presence of silicone oil [8, 9] while abundant silica-rich particles commonly associated with the wipe-marks may represent recrystallised silicone oil [8, 10]. In addition, Ca,P-particles were proved to be calcium-phophate used in the manufacture of this particular type Mylar [5]. Albeit rather unusual. ice particles from the shuttle waste management system impacted on Solar Max surfaces during STS rendez vous [1]. In addition, paint particles also contaminated Solar Max surfaces forming both low- and high-velocity impact features as well as a nevenly distributed spray on the front side of the first layer [5].

It should be remembered that Solar Max was not intended to act as a capture device. One important source of orbital debris is solid rocket effluent related to rockets fired in space [1, 11]. A typical sample of solid rocket effluent consists of spheres of Al_2O_3 [12]. However, the presence of aluminum on Solar Max (louvers and thermal blanket coatings) virtually eliminates the satellite as a detection device for externally derived Al-rich orbital debris even though Al-rich particles are commonly present near Solar Max features [4, 8].

After a detailed study of surfaces exposed in space, as well as surfaces shielded from the space environment, we developed the following criteria to separate contaminant particles from potential projectile materials.

Potential projectile materials are defined as particles associated with an impact feature. That is, they are (1) found within one crater or penetration hole diameter of the impact feature in the first layer, on both front and back sides, and occasionally on other penetrated layers and (2) within the spray pattern on the second or subsequent layers [5].

The particles associated with impact features generally show droplet (spherical or globular), irregular or fragmental (angular) morphologies [5, 6], although porous, fluffy particles have been reported [8].

The chemistry of associated particles is variable; however, two distinctive and major categories are prominent: meteoritic particles and paint particles. The former. associated with 12 out of 39 impact features, are concentrated on the front side of the second layer. Paint particles are associated with 25 out of 39 impact features and are concentrated on the front side of the first layer. Both particle types co-occur associated with six impact features [5].

Meteoritic particles include Mg-silicate (Mg,Si) particles and Mg-Fe silicate particles (MSF) [cf. ref. 4]. Some MSF particles are angular-shaped, unshocked olivine single crystals (Fo76-78) that survived capture without melting, although rounded olivine grains within the same impact feature appear to be slightly modified during impact [4, 6]. The composition and texture of olivine from Solar Max are comparable to those in primitive meteorites. The presence of Ca and/or Ni [1] and sulfur [8] in other MSF particles suggests a chondritic affinity [4. 8]. Some of these particles associated with penetration holes in the first layer have a fluffy morphology similar to chondritic micrometeorites collected from the stratosphere [8]. The chondritic micrometeorite particles in Solar Max impact features display varying degrees of fractionation as indicated by varying amounts of sulfur and the presence of metallic (Fe-Ni-Cr) mounds [8]. However, layer silicates in a chondritic micrometeorite particle associated with a crater are witness that shoch induced metamorphism is not always severe [8].

A second type of micrometeoritic particle are iron sulfides (Fe,S) and approximately stoichiometric Fe,Ni-sulfides (FSN) [4, 5, 8].

Paint particles associated with Solar Max impact features typically contain at least two of the elements Ti, Zn and Si as major elements. These elements are typically present in thermal-control spacecraft paint (MS74) which is a physical mixture of pigments (Ti- and Zn-oxides) in a potassium silicate binder and contains varying amounts of Ti, Zn, Si, K, Al [5]. A fraction of the paint particles also contain chlorine [1]. The source of chlorine in these particles is not yet understood. Small-sized (ca 2-3μm) paint particles associated a penetration hole and a crater on one of the louvers are mostly of the Zn,Si-type [13].

A third category of particles associated with impact features is formed by particles containing Al, Si, S, Fe, Ni, Cr, K and Cl in various combinations, Na-Cl, Ba-S. Bi-(Cl) and Ag-S. Particles from this category are the only type of particles associated with 8 out of 39 Solar Max impact features. Although the origin of this category remains largely enigmatic some particles probably derive from spacecraft paints and coatings [5].

CONCLUSIONS. The physical properties of impact features observed in the Solar Max MEB blanket generally suggest an origin by hypervelocity impact. We are confident that impact features containing only meteoritic particles are the result of impacting micrometeorites. The chemistry of micrometeorite material suggests that a wide variety of projectile materials have survived impact with retention of varying degrees of pristinity. Impact features that contain only paint particles are on average smaller than impact features caused by micrometeorite impacts. In case both types of materials co-occur, we believe that the impact feature, generally a penetration hole, was caused by a micrometeorite projectile. The typically smaller paint particles were able to penetrate though the hole in the first layer and deposit in the spray pattern on the second layer. We suggest that paint particles have arrived with a wide range of velocities relative to the Solar Max satellite. Orbiting paint particles are an important fraction of materials in the near-Earth environment.

In general. the data from the Solar Max studies are a good calibration for the design of capture cells to be flown in space (LDEF) and on board Space Station. The data also suggest that development of multiple layer capture cells in which the projectile may retain a large degree of pristinity is a feasible goal.

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N86-30599

Dust Collection on Serviceable Satellites

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One rationale for the Space Shuttle program which was dramatically realized during the repair of the Solar Maximum Mission (SMM) is the efficiency of in orbit satellite servicing. An unexpected benefit of this repair mission was the return of parts of the Solar Max satellite which had been exposed for four years to the space environment. Studies conducted on these "spare parts" have yielded valuable data on the micrometeorite flux and composition at shuttle altitudes during this time period. The scientific results from studies of the cosmic dust component of the observed particle impacts are not yet complete but it is clear from the preliminary data available that such studies will be a valuable adjunct to the studies of cosmic dust particles collected in the atmosphere.

The success of the initial studies of particles collected during repairs of the SMM spacecraft on a surface not specifically designed as a particle collector nor retrieved in a manner intended to minimize or eliminate local contamination raises the possibility that even more interesting results might be obtained if serviceable satellites were initially designed with these objectives in mind. All designs for modern satellites utilize some form of thermal blanket material in order to minimize thermal stresses inside the spacecraft. This is true of commercial and defense department payloads as well as of those built by NASA. Many satellites now incorporate a catch ring designed to enable them to be retrieved by the Space Shuttle's robot arm and either serviced in the cargo bay or returned to the ground. Many of NASA's advanced orbiting observatories such as the Hubble Space Telescope and SIRTF have been designed so that the on-board instrumentation can be changed on a regular basis. I propose that all future satellites be designed with standardized removeable sections of thermal blanket material which could be replaced during on-orbit servicing and returned to earth for detailed study.

At the very least, these panels could simply be easily removeable sections of the standard thermal blanket material which could be "peeled" on the ground to search the layers for dust particles and impact "tracks" through the various layers. Some calibration efforts using existing electrostatic dust accelerators could yield data on the expected penetration depth in the standard blanket material vs. impact angle and initial particle velocity. Since the impact angle is measurable if the entry hole can be traced through several sheets, it may be possible to detect hypervelocity impacts which could be due to extrasolar system grains. If the thermal blanket material does not contaminate the specimen, then it may be possible to chemically and isotopically characterize the more interesting finds.

Although it may be possible to design an efficient thermal blanket which is also optimized for particle collection (e.g., very thin layers of low-z, non-contaminating materials) the best design will be one which is relatively inexpensive (so that it is reasonable to ask <u>all</u> shuttle customers to place one or more of these on their spacecraft) and which has minimal effect on the thermal characteristics of the blankets. If <u>all</u> serviceable satellites were outfitted with such panels then it should be possible to collect a great deal of information on the flux and characteristics of both man-made and natural micrometeors as a function of orbital orientation and altitude for a very modest investment in flight equipment. The major expense will be the upkeep of the ground based analytical facilities.

Laser Microprobe Characterization of C Species in Interplanetary Dust Particles (IDP)

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This communication presents preliminary results of a study whose aim is the characterization of C species in microvolumes of materials by means of the Laser Ionization Mass Spectrometry (LIMS).

LIMS, described in detail by Simons [1], employs a pulsed UV laser to produce nearly instantaneous ($\sim 2\times10^{-8}$ s) vaporization and ionization of materials, followed by acceleration and time-of-flight analysis of the ions produced. LIMS provides a survey technique, with nearly simultaneous acquisition of mass spectra covering the entire elemental range.

The main limitation of the LIMS technique at present is its limited ability to perform quantitative analysis, due in part to insufficient knowledge of the mechanism of laser-solid interaction. However, considerable effort is now being directed at making LIMS a more quantitative technique. Very interesting results bearing on the two issues of quantitative microanalysis [2] and identification of complex molecular species [3] have already been published.

In this study, we have analyzed a variety of different C samples, both natural and man made, to establish the ability of LIMS to differentiate among the various C phases. The results of preliminary analyses performed on meteoritical and IDP samples are also presented.

The C standards selected for the LIMS characterization range from essentially amorphous soot to diamond, which exhibits the highest degree of ordering.

The figures on page 3 show positive and negative ion spectra obtained from:

1. Soot,
2. Turbostratic carbon, (Lumpkin [4]),
3. Plasma reaction C,
4. A natural diamond from Arkansas,
5. Calcite.

The unknown specimens analyzed include:

6. Chondritic Porous Aggregates (CPA) from U2 collections,
7. Murchison matrix samples.

Positive ion spectra acquired from amorphous C (soot) (Fig.1), under our standard instrumental conditions, are characterized by a C cluster distribution skewed towards low masses, such as C (and CH), C_3 and C_5. The intensity of the higher mass clusters falls off rapidly. Negative ion spectra (Fig. 2) exhibit essentially the same pattern, except that the even number C clusters are favored over the odd-numbered ones, C_2 being the most intense peak.

Turbostratic C spectra are available only in the negative ion mode. These spectra (Fig. 3) exhibit a different pattern of C clusters, essentially centered around C_6.

Plasma-reaction C (Fig. 4) is characterized by peak distributions similar to those of turbostratic C, but with very significant C_xH_y peaks present in the even numbered clusters.

Diamond (Figs. 5 and 6) shows spectra with a dominance of C_1 in positive ion mode and C_2 in the negative ion mode.

Calcite (Fig. 7), presents the most extreme case, with C_1(mass 12) being essentially the only C species identified in positive ion spectra.

The spectra acquired from U2 particles (Figs. 8 and 9) reveal substantial diversity in the constituent C species. One spectrum exhibits essentially a pure C pattern, centered at C_4, plus intense CN and CNO peaks and weaker Cl signals. Another spectrum reveals the presence of C species (C_2 to perhaps C_7), phosphates (PO_2 and PO_3 anions), Cl and F, and possibly Cl-bearing organic species.

The spectra acquired in the Murchison matrix (Fig. 10) reveal C cluster patterns up to C_{10}, with the most intense signal being that of C_4. In addition, intense peaks interpreted as SiO_2 and SiO_3 are detected, as well as PO_2 and PO_3 signals. Cl is also detected.

The LIMS technique thus shows the ability to acquire simultaneous elemental and molecular information on microvolumes of materials of interest to cosmochemists with essentially no sample preparation required. Limitations and possible improvements will also be discussed.

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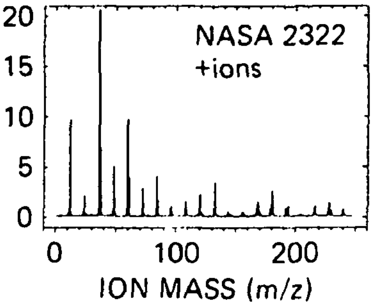

FIGURE 1

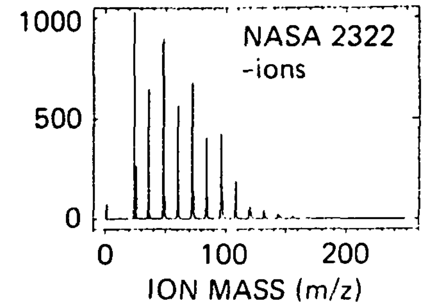

FIGURE 2

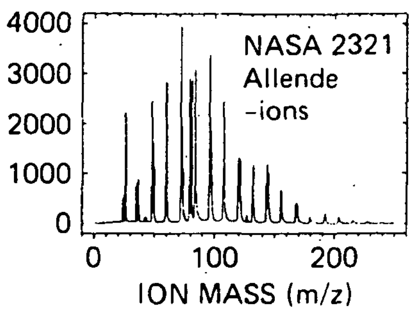

FIGURE 3

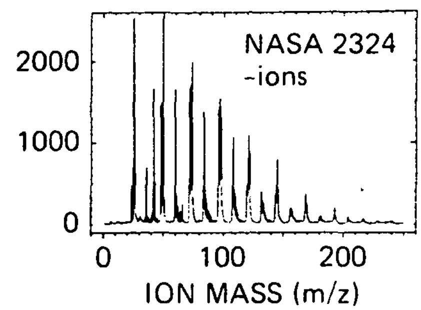

FIGURE 4

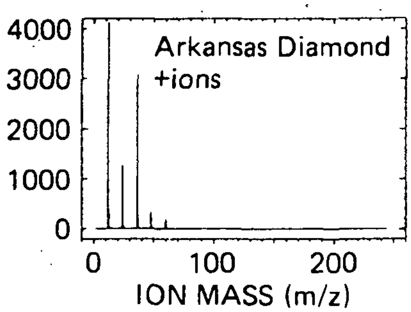

FIGURE 5

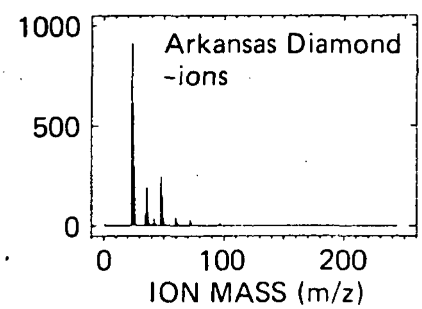

FIGURE 6

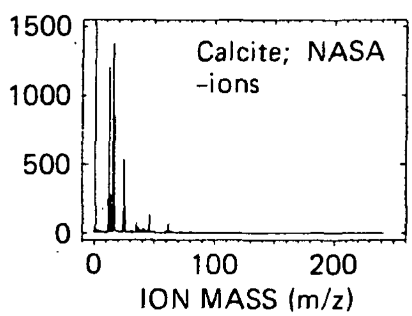

FIGURE 7

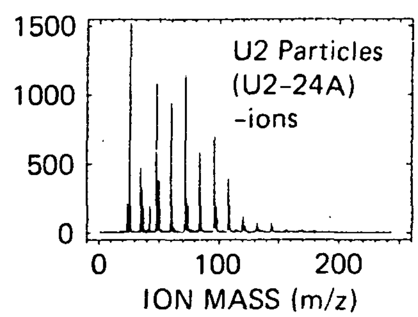

FIGURE 8

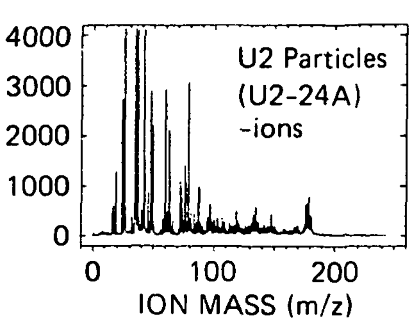

FIGURE 9

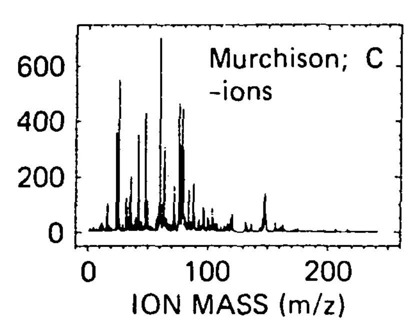

FIGURE 10

N86-30601

THE IMPORTANCE OF CAPTURING UNMODIFIED CHONDRITIC POROUS MICROMETEORITES ON THE SPACE STATION.

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The survival of interplanetary dust particles (IDP's) during deceleration by the Earth's atmosphere is determined by their entry parameters, velocity, size and mass [1]. These IDP's reach their terminal velocity at about 55-95 km altitude before they gradually settle to 18-21 km altitude where they are collected by high flying aircraft [2]. Chondritic porous IDP's (also called Chondritic Porous (CP) aggregates) show properties consistent with an extraterrestrial origin [3, 4] [TABLE 1]. It is conceivable that CP aggregates may be collected above the Earth's atmosphere using capture devices on a Space Station or satellite. In order to preserve 'pristine' CP aggregates, i.e. aggregates with minimal perturbation or degradation of its particulate matter, it is necessary to transfer the kinetic energy on impact so that a minimum amount of energy is dissipated into the impacting particle [this report]. It is likely that low-temperature minerals (e.g. layer silicates), volatile phases (e.g. sulfides), structural defects (e.g. nuclear tracks) and hydrocarbons in CP aggregates are sensitive to the efficiency of kinetic energy dissipation. Before we can evaluate information contained in particulate matter on capture devices, we need a complete understanding of the mineralogy of CP aggregates.

Chondritic porous aggregates may be cometary debris representing unaltered remnants from the early history of the solar system [1, 5, 6]. In addition, some CP aggregates may derive from the asteroid belt since dust from this belt may be in Earth-crossing orbits [7]. The physical, chemical and mineralogical properties of CP aggregates and carbonaceous chondrites suggest the existence of a continuum between these two types of primitive extraterrestrial materials [4, 8]. In this scenario CP aggregates are pristine solar system materials that have not been subjected to metamorphosis in a parent body as opposed to the primitive meteorites.

Chondritic porous aggregates have a varied and complex mineralogy of Mg-rich olivine, Ca-poor and Ca-rich pyroxenes, layer silicates, sulfides (low-Ni pentlandite and pyrrhotite), metallic FeNi, metal-oxides (magnetite, Ti- and Al-oxides), FeNi-carbides and minor amounts of phosphides and sulfates [4, 9-15]. These minerals are embedded in carbonaceous material including hydrocarbons and poorly graphitised carbon [16, 17]. The mineralogy of CP aggregates typically forms a heterogeneous mixture of high- and low-temperature minerals; some are predicted by solar nebula condensation models, but others may have formed at low temperatures prior to or after accretion of the dust into a (proto-) planetary body [12, 18, 19].

It is possible that the original heterogeneous mixture of minerals in CP aggregates could form because of turbulent conditions in a cooling solar nebula [20]. Indeed the proximity of reduced and oxydised phases (low-Ni Fe-metal, magnetite and low-Ni Fe-sulfides) suggests chemical disequilibrium. Alternatively, the proximity of these phases may indicate unique equilibrium conditions in a cooling solar nebula [13]. Physical properties of individual minerals in CP aggregates may be related to specific processes. For example, enstatite whiskers and platelets and platey magnetite grains suggest that these minerals formed by condensation from the solar nebula gas [21, 22].

Filamentary carbon indicates that heterogeneous catalysis occurred after accretion [23]. Solar flare tracks in olivine [24] show that CP aggregates resided in small bodies during solar system sojourn.

The size and shape of grains in CP aggregates also contain information of processes that occurred in early history of the solar system. Grain sizes in CP aggregates range between 1nm to <~10um [5] but larger grains may be present in some CP aggregates [1, 13]. Most solar nebula condensation models assume that crystalline solids form directly from the vapor phase. However, it is possible that these condensates are really amorphous solids. The issue has considerable impact on processes that take place in the final stages of solar nebula condensation, e.g. formation of hydrated silicates [25]. The mineralogy of carbonaceous chondrites is inconclusive on this point but CP aggregates may still contain information about the nature of solar nebula condensates. Thus, Mg-rich glass [26] and a chemically complex, proto-crystalline phase [13] in two CP aggregates suggest that amorphous condensates were indeed present in the early solar system.

The grains in the proto-crystalline phase display a range of size and shape: grains <~30nm in size tend to be (sub-) rounded while larger grains tend to form sub- to euhedral, thin (<1.5nm), often slightly elongated, hexagonal and octagonal plates [13]. These observations are comparable with changes of grain size and shape observed during experimental annealing of amorphous to proto-crystalline Mg-SiO smokes [27]. Thus, structural evidence in CP aggregates shows that annealing of amorphous solar nebula condensates may have been a necessary part of early solar system evolution [13].

I have only considered the mineralogy and certain physical properties of minerals in CP aggregates which contain information about conditions in the solar nebula and early solar system. This information is obliterated in primitive meteorites due to metamorphic processes after accretion of the dust into planetary bodies. In addition, during deceleration of CP aggregates in the Earth's atmosphere these particles reach flash-heating temperatures of ca 300-400°C [12, 15]. Although this thermal event apparently does not destroy CP aggregates, it affects some of the aggergate mineralogy [15]. This selection effect will be eliminated by capturing CP micrometeorites above the atmosphere and reduces the collection of unmodified ('pristine') particles to a technical challenge. We need 'pristine' micrometeorite samples in order learn about solar nebula condensates, low-temperature reactions towards the end of the condensation history (e.g. formation of layer silicates and hydrocarbons [16]) and in the very early stages of protoplanet formation. Thus, a high degree of 'pristinity' for particles collected on impact devices is desirable.
Presently. a technique for capturing intact, 'pristine', particles is not available but it is encouraging that unshocked and unfractionated Mg-rich olivine single crystals have been retrieved from the Solar Max satellite [28].

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TABLE 1: EVIDENCE FOR AN EXTRATERRESTRIAL ORIGIN OF CP AGGREGATES

BULK COMPOSITIONS OF CP AGGREGATES RESEMBLE "SOLAR" ABUNDANCES FOR CONDENSIBLE ELEMENTS [1].

IR FEATURES OF SOME CP AGGREGATES RESEMBLE IR SPECTRAL SIGNATURE OF INTERPLANETARY DUST.

^{4}HE CONTENTS OF SOME CP AGGREGATES INDICATE "SATURATION" BY SOLAR WIND [29].

XE CONTENTS OF SOME CP AGGREGATES RESEMBLE THOSE OF CARBONACEOUS CHONDRITE ACID RESIDUES [30].

D/H RATIOS OF CP AGGREGATES RESEMBLE THOSE OF CARBONACEOUS AND UNEQUILIBRATED CHONDRITES; HIGHE RATIOS IN SOME CP AGGREGATES SUGGEST THEY MAY BE EVEN MORE PRIMITIVE THAN THESE METEORITES [31, 32]

NUCLEAR TRACKS IN CP AGGREGATES ARE EVIDENCE FOR EXPOSURE IN SPACE [26].

SPACE STATION

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The Space Station is being defined as a multi-purpose facility with emphasis in the following areas:

- o Scientific and Technology Research Laboratory
- o Permanent Observatory
- o Spacecraft Servicing Facility
- o Construction and Assembly Facility
- o Manufacturing Facility
- o Transportation Node
- o Staging Base for Future Space Endeavors

The Station complex, in its initial operating capability configuration, includes a continuously habitable manned element, a polar orbiting unmanned platform, and a second unmanned platform co-orbiting with the manned element. All elements are dependent on the Space Transportation System (STS) for initial placement on-orbit and for subsequent logistical services. The manned element will be designed for long duration operations with systems maintainable on-orbit and operationally autonomous from ground control. A major feature of the Station will be its adaptability to evolutionary technology upgrades. And, the Space Station, as a system, is to be designed for maximum ease of use by its Users.

The Station is being designed to requirements principally defined by currently identified potential users, both domestic and international. Future endeavors are less well-defined but are being considered in a secondary manner. It is probable that primary consideration of these potential large-scale future endeavors would place design driver requirements on the Station and, because of resource limitations, might erode expected accommodations for other Users. Indeed, the development of a Space Station with the currently defined multi-purpose character and growth accommodations as a service facility within the prescribed budget is a major challenge.

A reference Station configuration was devleoped by NASA as part of the Request for Proposal preparation activity. This currently serves as the Program baseline pending results from the 21-month contractor definition activity initiated in April 1985. Selection and development of implementation technologies are part of this activity and will address specific topics such as:

- o Environmental Control Life Support System -- Closed vs. Open Loop Operation?
- o Automation/Robotics Applications
- o Transparency to Technology Upgrades
- o Artificial Intelligence/Expert Systems Applications
- o Orbital Maneuvering Vehicle/Orbital Transfer Vehicle
- o Growth Accommodations - Extension vs. Replication
- o Power Generation -- Photo-voltaic, Solar Dynamic, Nuclear
- o Servicing Accommodations
- o Module Design -- Size, Radiation Shielding, Configuration, etc.
- o Construction and Assembly Accommodations
- o Long Duration Systems serviceability and onboard maintenance

Currently, NASA is trying to fully understand Space Station requirements. The definition studies underway will converge and select a configuration which, necessarily, will be severely constrained by budget.

INTACT CAPTURE OF HYPERVELOCITY PARTICLES

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INTRODUCTION Knowledge of the phase, structure, and crystallography of cosmic particles, as well as their elemental and isotopic compositions, would be very valuable information toward understanding the nature of our solar system. This information can be obtained from the intact capture of large mineral grains of cosmic particles from hypervelocity impacts. Hypervelocity experiments of intact capture in underdense media have indicated realistic potential in this endeavor [1]. The recovery of the thermal blankets and louvers from the Solar Max spacecraft [2] have independently verified this potential in the unintended capture of cosmic materials from hypervelocity impacts. Passive Underdense media will permit relatively simple and inexpensive missions to capture cosmic particles intact, either by going to a planetary body [3] or by waiting for the particles to come to the Shuttle or the Space Station.

Experiments to explore the potential of using various underdense media for an intact comet sample capture up to 6.7 km/s were performed at NASA Ames Research Center Vertical Gun Range. Explorative hypervelocity experiments up to 7.9 km/s were also made at the Ernst Mach Institute. These experiments have proven that capturing intact particles at hypervelocity impacts is definitely possible. Further research is being conducted to achieve higher capture ratios at even higher hypervelocities for even smaller projectiles.

EXPERIMENTS A wide range of polymer underdense foam media, with both open and closed cell structures, was used as capturing targets. The foam densities varied from 9 to 528 mg/cc; both uniform media density and combinations of densities were used. Several fibrous target materials with a density range from 36 to 430 mg/cc were also utilized, as were multiple layers of thin organic films. Most of the capturing experiments were performed under vacuum; for selected experiments, gas with several different molecular weights was also back filled.

The projectiles used were mostly polished aluminum spheres of 1.5 to 3.2 mm diameter and accelerated with a two-stage light-gas gun from 1 to 7.9 km/s. In order to assess the effect on more realistic, fragile, and comet-like particles, projectiles of Pyrex glass, Wellman meteorite, Epoxy-bonded Allende meteorite powder, and Epoxy-bonded olivine/FeS/glass microspheres were used. For speeds higher than the capability of the Ames facility, limited explorative experiments were also made at the University of Munich on a plasma drag gun with about 100 micron sized glass spheres at about 8 to 12 km/s.

RESULTS The experiments seemed to show that polymer underdense media were superior to other types of underdense media for capturing particles intact at about 6 km/s. Fibrous materials tend to break up the projectiles. The typical track left in the underdense medium is characteristically carrot-shaped as shown in Figure 1. The track has two distinct sections: the burn section, B, and the shear section, S. The burn track is marked distinctly with black residues from pyrolysis or melt, and the diameter is very much larger than the projectile diameter. The width of the shear track, on the other hand, is nearly the same as the projectile diameter and is devoid of any burnt residues. The entry hole size, a, is on the order of one to three times the projectile diameter. For a given foam density the maximum track diameter, b, seems to be proportional to the projectile speed; and for a given speed, the maximum track diameter seems to increase with foam density, while the stopping distance shortens with increased foam density. Higher hypervelocity experiments using a plasma drag gun indicated an expected scale down of the stopping distance because of a decrease of kinetic energy due to considerable smaller projectile mass.

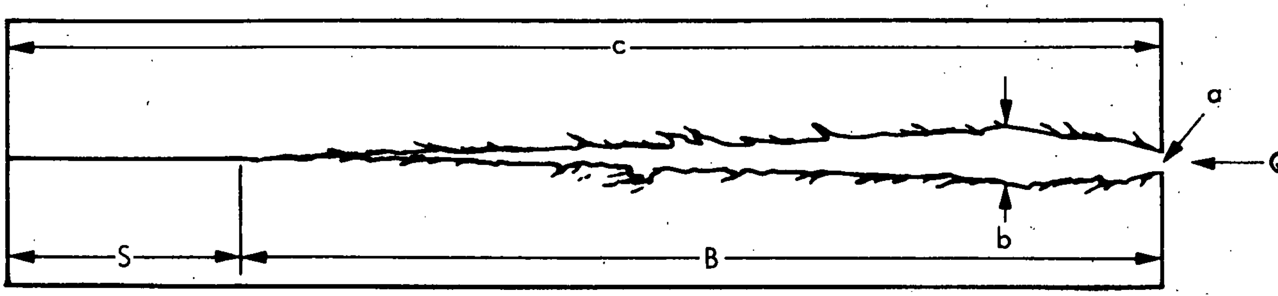

Figure 1. Underdense Intact Capture Track

The projectiles' captured-mass to original-mass ratio for aluminum projectiles becomes to less than one for projectile speeds greater than about 2 km/s for a 16 mg/cc expanded polystyrene foam. The capture ratio decreases with increased speed. Up to 83% of the projectiles original mass has been captured at 6.3 km/s for 3.2 mm size projectiles. About 60% has been captured at 7.9 km/s for 1.5 mm size projectiles.

For more cometary-like projectiles, disks of Wellman meteorite, epoxy-bonded Allende meteorite powder, and olivine/FeS/glass microspheres were accelerated. Figures 2, 3, and 4 show the captured Wellman, epoxyed Allende, and olivine mixture at 3.5 km/s, 2.3, and 3.9 km/s, respectively. Note that the circular perimeter of the Wellman projectile is still intact in Figure 2. The capture ratio of epoxyed Allende was 72% and the cross-section in Figure 3. shows that the loss of the projectile is due to shear rather than melt. Large chunk intact capture of olivine mixture has been achieved at 3.9 km/s to date as shown in Figure 4 and 5, respectively the before impact and after impact SEM image. Intact projectile grain capture has been achieved up to 6.7 km/s.

FINDINGS These intact capture experiments provide very positive and encouraging results for the intact capture of cosmic dust of speeds around 5 km/s. As increased understanding of intact capture in underdense media is gained, an optimum underdense medium should be designed to achieve the desired capture ratio at a specific hypervelocity and for a specific particle type. The ability to capture conglomerated fragile cosmic particles and the development of methods to detect small particles in the underdense media is one of the objectives to be achieved in the near term development.

Based upon the entry hole size and capture track characteristics found in the underdense medium, the projectile speed, projectile impact direction, and momentum can be estimated from calibrated data. The capture of micrometeorite in underdense medium achieves both the intact capture of the particle as well as retaining the pertinent record of the particle flight data: elemental and isotopic composition, mineralogy, velocity, and mass.

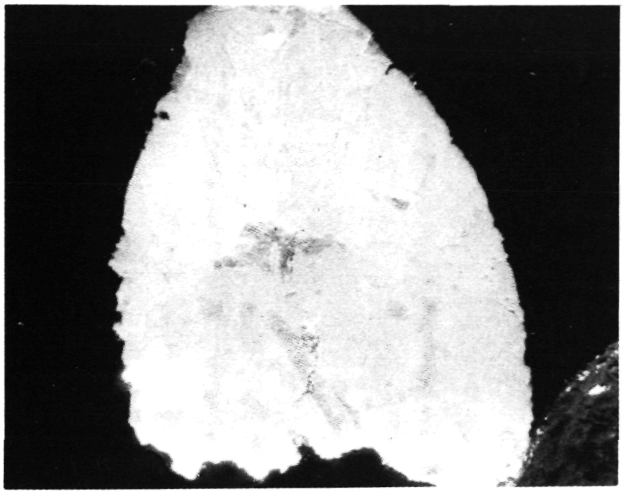

Fig. 2 Captured Wellman

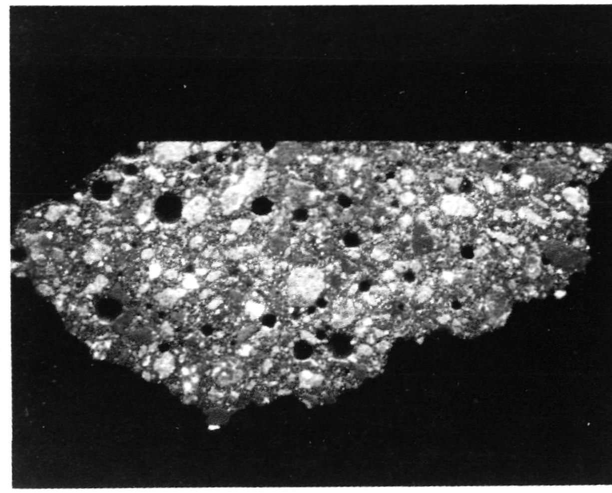

Fig. 3 Captured Epoxyed Allende

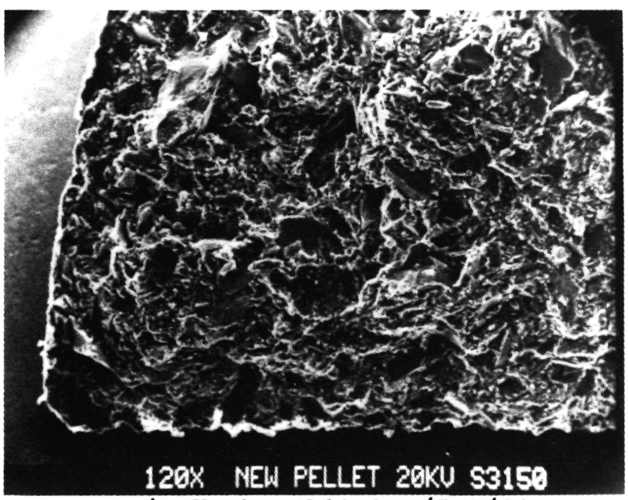

Fig. 4 Unshot Olivine/FeS/Glass

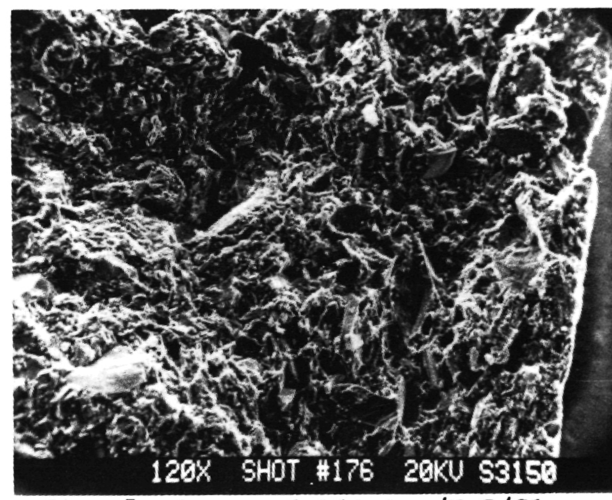

Fig. 5 Captured Olivine/FeS/Glass

The next-phase goal in the intact capture experiments will be to capture a substantive portion of simulated cometary particle intact at 6 then at 9 km/s with minimum modification of the phase, structural, and crystallographic information of the particle.

ACKNOWLEDGEMENTS Without the cooperative support of the NASA Ames Vertical Gun Range, Ernst Mach Institute, and University of Munich, this research would not have been possible. This work was carried out, in part, by the Jet Propulsion Laboratory, California Institute of Technology, under NASA contract.

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Cosmic Dust Detection with Large Surface Piezoceramics

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ABSTRACT

I. Introduction

Piezoelectric transducers mounted on targets made out of metal plates or plastic foils have been used in many former space missions to detect impacting dustparticles and to determine some of their parameters (e.g. momentum). The proposed detector is based on a large disc made out only of piezoceramic material.

II. Basic Principle

Dustparticles impacting on the detector will cause electrical charge pulses due to the piezoelectric nature of the targetmaterial (Fig. 1). These charge pulses are measured on the electrodes of the disc and transformed with a charge sensitive amplifier (CSA) to voltage pulses. Counting the number of pulses leads to the dustflux impacting on the detector. Additionally the amplitude and the risetime of the pulse slopes are determinated to evaluate the momentum and the size of the dustparticles. Due to the high charge production rate per force unit of piezoceramics and a momentum transfer without loss the sensivity of this acoustic sensor is very high.
To derive size and momentum from the rising slope of an acoustic signal is a new method and will be described shortly in the following paragraph.

III. Theory

The dimensions of the target are assumed much larger than the particle ones. When a small mass is impacting on a target with high velocities (Fig. 2a) compressional shockwaves are travelling from the contacting area both into the target and the particle (Fig. 2b). The shock waves travelling through the particle are reflected inversely at the free end of the rear of the particle and travel back again through the particle. On the other hand the shock waves inside the target are travelling unchanged deeper into the target increasing the internal pressure; this represents the partly transfer of momentum from the particle to the target (Fig. 2c). Due to the interferences of the shock waves the particle and the contacting zone of the target are heated up very strongly and material is vaporized. Nevertheless its deceleration the particle has still a velocity along the former flight direction. Although the particle and the contacting area begin to explode into a debris cloud the shock waves in the particle will be reflected again into the exploding particle and will travel through and back again. So the piezoceramic target is pressed continuously under the impacted area and the pressure waves are travelling from the contacting zone deeper into the target. Due to the piezoelectric effect a piezoelectrical material which is polarized in the direction of impact will respond to the impact with a monotonic increasing charge displacement which can be measured at the electrodes (Fig. 2b-f, right part). When the momentum transfer from the particle to the target is finished the internal forces and therefore the generated charge begin to decrease (Fig. 2c-f), because the velocity vector of the loading debris cloud is versed by 180°. If the first front of shock waves has not reached yet a free end of the target the amplitude of the charge signal at this time is the sum of all "shock packages" which are transferred from the particle to the target; it is correlated to the force which is caused by the now totally transferred momentum of the particle prior to the impact. This condition can be fulfilled with the target design so that the travelling time of the compressional shock waves in the target in and cross the travel direction is longer than the momentum transfer times for the considered particle sizes. Because the momentum transfer time is a function of travelling time of shock waves through the particle, the risetime of the slope of the charge signal depends on the size of the particle.

IV. Sensivity

The resolution of particle size depends on the available time resolution of the rising slope, the time delay due to the electrical capacities, and the momentum transfer time. At the present the available clock frequency is 1 GHz, the time delay can be held < 10 ns, and the momentum transfer times take ≅ 5 times the time of shock waves travelling through and back the particle. To achieve a considerable accuracy the momentum transfer time should be at least as long as the time delay. Therefore only the size of particles with diameters ≧ 5 µm can be determinated directly from the risetime of the charge signals slope. For the counting mode of the detector these restrictions are less important. Therefore the sensivity for counting is much higher than in the size determination mode; it is only limited by the maximum frequency of the electronics: It is possible to count high-velocity-particles with diameters down to 0.5 µm.

The accuracy of determining the particle size varies with the diameter: For particles of diameters ≅ 5 µm the error accounts to ca. 50 %, for diameters of 10 µm the error is ca. 35 % and so on.

The momentum of the particle can be calculated from the amplitude and the time of the rising slope. At this evaluation the errors of the two components are partly compensated. So the momentum-error accounts only to e.g. 30 % for particles with diameters of 5 µm or 20 % for particles of 10 µm.

V. Options

In Fig. 3 a possible option is depicted where the generated charges of the piezoceramic are not measured by a CSA but directly transformed in a voltage by a resistor. This option has the advantage that no power source is necessary at the experiment, because the detector works as a voltage source. The sensivity in the counting mode is reduced to particles above 4 µm in diameter.

Another option is shown in Fig. 4: A thin plastic foil is stretched in a distance before the detector plate. The foil is electrically conductive at the circumference so that impact generated plasma charges of the foil can be measured as the start puls of a time-of-flight-measurement. The stop puls is derived from the detector signal. So the velocity of the particle can be calculated. The advantages of such a two-stage-detector are both a highly improved accuracy respectively the particle mass and the possibility of determination of the density or the shape or the impact angle of the particles.

VI. Conclusions

The proposed detector principle of exposing a large surface piezoceramic to cosmic dust to determine the dustflux, the momentum and the size of the impacting particles is a newly developed method. Two possible options are discussed to improve the accuracy and the modes of the present experiment. Further studies will be made to improve the determinable sizes to submicron ranges and to combine the basic detector with extensions for multiple applications.

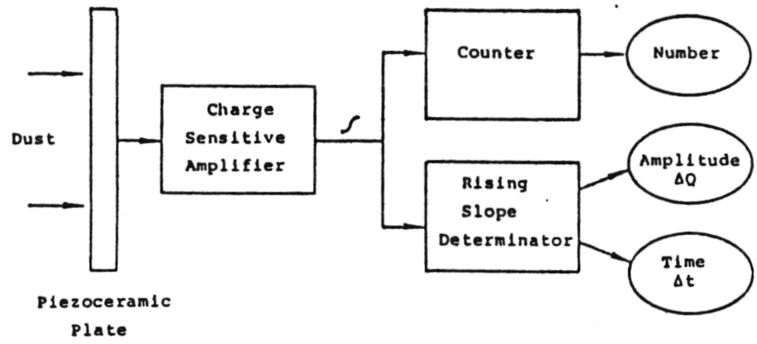


Fig.1
Detector Principle

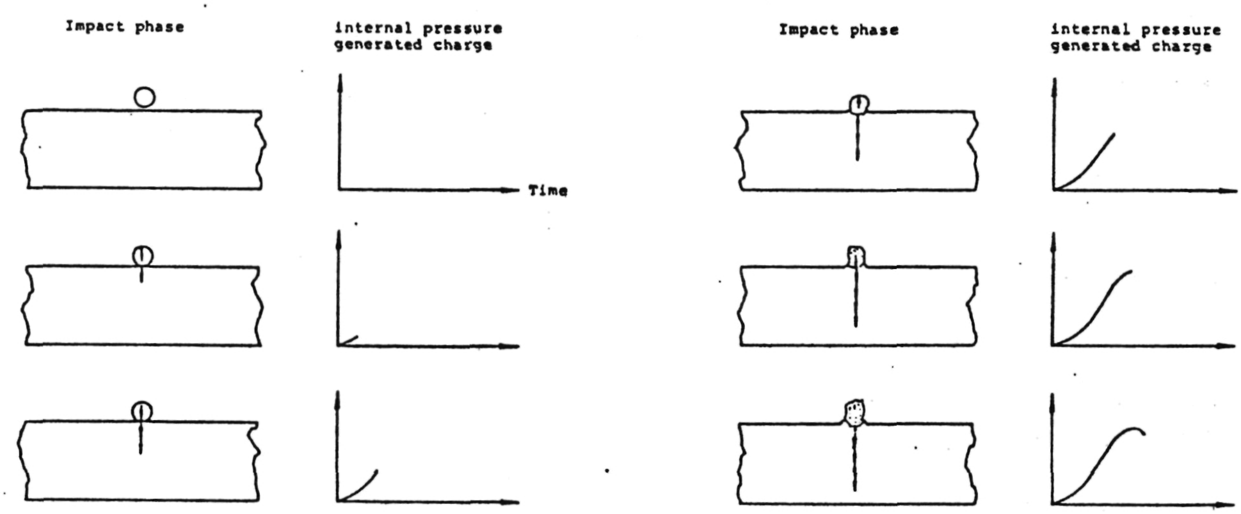


Fig.2
Impact on a Piezotarget

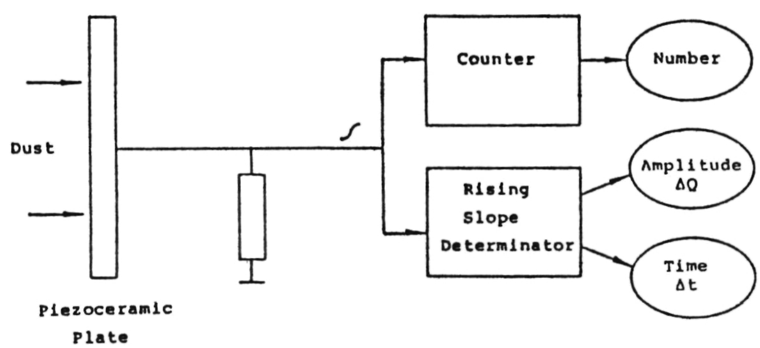


Fig.3
Option 1:Voltage Source

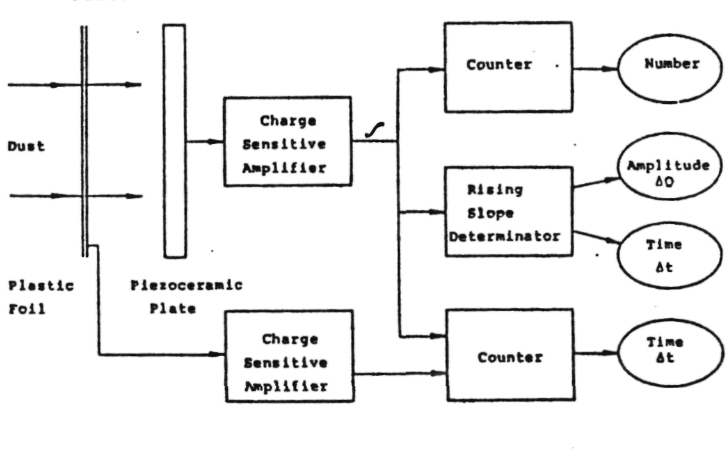


Fig.4
Option 2:Two-Stage-
Detector

A MICROMETEOROID DECELERATION AND CAPTURE EXPERIMENT: CONCEPTUAL EXPERIMENT DESIGN DESCRIPTION; J. H. Wolfe and R. W. Ballard, San Jose State University; G. C. Carle and T. E. Bunch, NASA Ames Research Center.

To determine the prevalence of biogenic and prebiotic compounds in the solar system, it will be necessary to examine material from many classes of objects. Elemental, isotopic and molecular measurements of returned samples of comets, asteroids, and micrometeoroids, including those of possible extra-solar origin, would provide information on a particularly important class, namely the primitive objects. Extraterrestrial micron-sized particles in the vicinity of Earth are one source of such materials that might otherwise be inaccessible. The Space Station seems ideally suited as a platform to provide the required space, power, long lifetime, and logistical support for the collection of these particles.

The key issue regarding the collection of extraterrestrial particles in a pristine form concerns their capture in a nondestructive manner which cannot be accomplished after atmospheric entry or hypervelocity impact in space. The collection experiment must be designed to minimize thermal and mechanical alteration(s). It is well known from many studies of extraterrestrial particles, collected by NASA's U-2 high-altitude flights, that cometary particles are quite friable and contain a high proportion of volatile constituents. Little is known about interstellar dust that may be entering the solar system, but it is likely that these particles may be simularly delicate and, in addition to possible organic components, they may be mantled by ices. Among the many constraints that must be considered in designing a collection experiment in line with our goal, the most critical issue is the problem of dealing with the hypervelocities (about 20 km/sec) of the incident particle. Preliminary calculations show that an electrostatic microparticle collector in principle, should be able to sufficiently decelerate micron-sized (or smaller) particles traveling at speeds of about 20 km/sec, relative to the collector, to less than 2 km/sec.

The preliminary conceptual design for a Cosmic Dust Collector is illustrated in the attached figure and is described below:

1. For the case of Low Earth Orbit (LEO), dust particles enter the collector through the collimator at a few volts negative potential due to charging in the ionosphere, at a velocity of 1-50 km/sec. The collimator is required in order to provide the particles with a rather well-defined path through the measurement and collection system. In the interplanetary medium the incoming dust particles would have similar velocities, but would be charged to a few volts positive due to photo effect.

2. The particles then pass through an electron stream and are charged to about 1 KV negative (regardless of incoming polarity). A magnetic field of about 1 gauss is applied perpendicular to the electron stream in order to greatly increase the electron path length and thereby reduce the current (power) requirements for the electron gun.

3. The 1 KV negatively charged particle then passes through three sensing grids coupled to charge sensitive preamps (CSP). The comparison of the two pulses provided by S_1 and S_2 are utilized by the microprocessor to determine the charge, q, on the particle (pulse amplitude) and its velocity, v (by time of flight). The third sensing grid, S_3, is kept at about 20 KV negative so that the dust particle will now be decelerated in passing from S_2 (zero potential) to S_3. S_3 is capacitively coupled to its CSP and the pulse from S_3 is utilized by the microprocessor to determine the particle's energy,

E, and therefore its mass, m (again by time of flight) by comparison with the pulses from S_1 and S_2.

4. After traversing all three sensing grids, all critical information on the dust particle (q, v, and E) has been determined so that the microprocessor can now precisely program the high-voltage switching network for the proper timing in the grounding of the successive deceleration grids.

5. As determined by the microprocessor, each successive deceleration grid, D_1, D_2, D_3, etc., is grounded just after the dust particle passes, thus reducing the particle's energy by the amount q*100 KV at each stage.

6. The microprocessor also determines at which stage the particle will fall below a certain critical energy ($E \leq q*100KV$) where all remaining grids remain unswitched so that the particle will drift to the collector.

7. The collector is kept at about 100V positive and is covered with gold foil to eliminate contamination and is removable for subsequent return to earth for detailed analysis. The whole collector area is bathed with low-energy electrons so the particles, after they come to rest on the collector, will electrostatically "stick" to the collector foil.

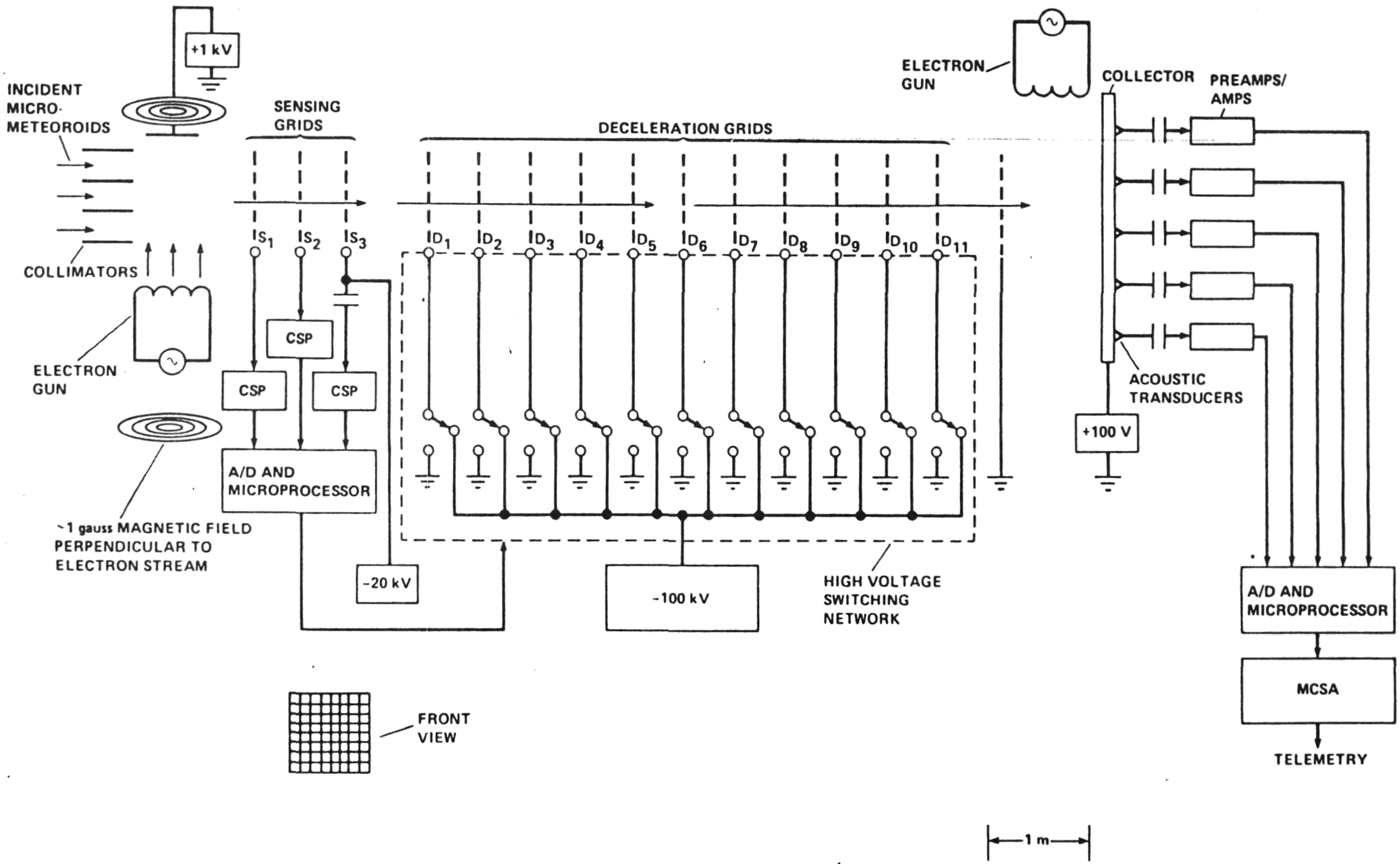
8. Affixed to the back of the collector plate is an array of acoustic detectors. These detectors provide information to the Space Station telemetry system to varify that an event has taken place. When a "hit" occurs, the signals from each acoustic detector are analyzed by the microprocessor to: (a) determine exact location of the hit (for data analysis), and (b) pass the largest amplitude signal on to the multichannel spectrum analyzer (MCSA) for spectral analysis. Spectral analysis provides: (a) distinction between actual micrometeoroid and a "false" signal (due to thermal creaks for example), and (b) information on particle momentum and possibly even information on composition.

9. These acoustic detectors can also be attached to the instrument housing (about 90 m^2 or more) in order to determine the total micrometeoroid flux in the vicinity of the Space Station. Signals from these sensors would utilize the Cosmic Dust Collector microprocessor and MCSA with a priority interrupt when a particle is detected by the Dust Collector sensing grids.

Rough estimates of flight hardware requirements on the Space Station are as follows:

Size: 4 m x 4 m x 20 m
Volume: about 320 m^3
Area: about 340 m^2
Weight: about 1200 kg
Power: 10's of KW continuous, but can be duty cycled
Telemetry: < 1 Kb/sec
Location: attached to outside
Field of View: about 20° x 20°
Orientation: not critical (but prefer not to view sun)
Crew Time: 16 to 32 hours to assemble; 1 hour/month for servicing

COSMIC DUST COLLECTOR



N86-30606

CAPACITOR-TYPE MICROMETEROID DETECTORS

J. J. Wortman*, D. P. Griffis**, S. R. Bryan***
W. Kinard**** and P.C. Kassel Jr.****

The Metal Oxide Semiconductor (MOS) Capacitor Micrometeroid Detector consists of a thin dielectric capacitor fabricated on a silicon wafer. In operation, the device is charged to a voltage level sufficiently near breakdown that micrometeoroid impacts will cause dielectric deformation or heating and subsequent arc-over at the point of impact. Each detector is capable of recording multiple impacts because of the self-healing characteristics of the device. Support instrumentation requirements consist of a voltage source and pulse counters that monitor the pulse of recharging current following every impact. The devices are suitable for micrometeoroid detectors on satellites because of their wide temperature tolerance, low power requirements, simple instrument interface and low system complexity.

Figure 1 illustrates the cross-section of the MOS capacitor micrometeoroid detector. The detector is fabricated from a 50 to 100 mm silicon wafer. The silicon is boron-doped (p-type) to form a low resistivity substrate which becomes one plate of the capacitor. Both sides of the silicon are coated with a layer of insulating silicon dioxide (SiO_2) by a thermal oxidation process. The thickness of this oxide layer determines the energy range of particles detected by the device. Devices with thinner oxides are sensitive to lower energy particles. Common oxide thicknesses used for detectors are 4000 Å and 10,000 Å.

An aluminum coating is placed on both sides of the detector. The outer surface becomes the second electrode to the capacitor. The lower aluminum surface is used to provide electrical contact to the substrate through a hole etched in the silicon dioxide surface.

In operation, the detector is placed in the circuit shown in Figure 2. A fixed voltage is supplied to the capacitor through a one-megohm resistor. The magnitude of the voltage is selected to produce a field which is approximately 10^6 volts/cm. The impact of a particle on the upper aluminum surface will result in a partial discharge of the MOS capacitance through the dielectric in the vicinity of the impact. The high density current flow in the upper 1000 A aluminum layer will cause the alumnium in the area of the impact to vaporize and thus effectively isolate the impacted area of the dielectric from the circuit. The capacitor will then recharge through the one-megohm resistor with a time constant of a few tenths of a second. This recharge current flows through the one-megohm resistor, producing a voltage spike which may be detected by the associated instrumentation. The size of the resistor is a parameter selected based on the desired output signal level and duration and the maximum short circuit current which can be tolerated in the case of a massive dielectric breakdown which cannot be cleared by alumnium vaporization from the stored charge.

An investigation has been conducted in which 0.5 to 5 µm diameter carbonized iron spheres traveling at velocities of 4-10 Km/sec were impacted on to detectors with either a dielectric thickness of 0.4 µm or 1.0 µm. Figure 3 is a plot of projectile diameter as a function of projectile velocity normal to the detector surface. The data shown in Figure 3 was for a dielectric of 0.4 µm and the impact angle was varied from 0 to 75 degrees. The open symbols are registered impacts while the dark symbols represent no signal or discharge. As shown the detector is very sensitive.

The craters of several of these discharges was studied with a Cameca IMS-3f ion microscope [1]. The Cameca is a direct imaging instrument capable of acquiring elemental images with lateral spatial resolution of approximately 0.5 µm. The standard ion microprobe slate has been replaced with a dual microchannel slate and a digital imaging system has been added [2,3]. High mass resolution ($M/\Delta M$, 10% valley definition) greater than 2960 was employed. High mass resolution spectrum acquired from stainless steel was used as a calibration source.

A series of ion images from the area surrounding one of the impact craters is presented in Figure 4. The images are displayed in grey scale from low ion intensity (black) to high ion intensity (white). The circular Al images delineates the 60 µm diameter image field used. The 20 µm diameter dark circular area in the center of the Al image indicates the absence of Al resulting from the Fe particle impact. Images of ^{56}Fe, ^{28}Si and $^{28}Si_2$ were also acquired from the same area and were found to be present within and surrounding the impact hole. As shown the ^{56}Fe distribution shows localized regions of high intensity and does not entirely fill the crater. Digital overlaying of the Fe and Al images indicated that some of the Fe is actually outside the impact crater as expected.

This study clearly demonstrates that the ion microprobe tuned to sufficiently high resolution can detect Fe remaining on the detector after the impact. Furthermore, it is also possible to resolve Fe ion images free of mass interferences from Si, for example, giving its spatial distribution after impact. Specifically this technique has shown that signficant amounts of impacting particles remain in the crater and near it which can be analyzed for isotopic content. Further testing and calibration could lead to quantitive analysis. This study has shown that the capacitor type micrometeroid detector is capable of not only time and flux measurements but can also be used for isotopic analysis.

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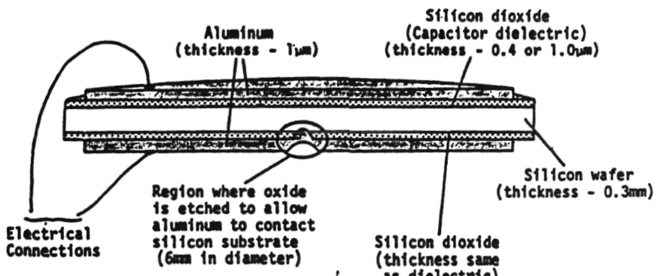

Figure 1. MOS Capacitor Micrometeoroid Detector Cross Section View.

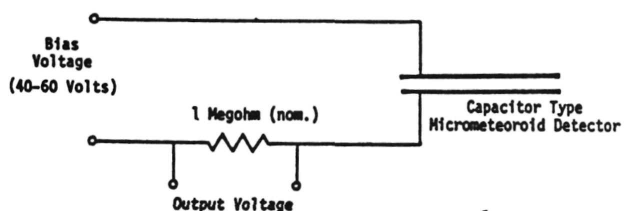

Figure 2. Electrical Connection of Micrometeoroid

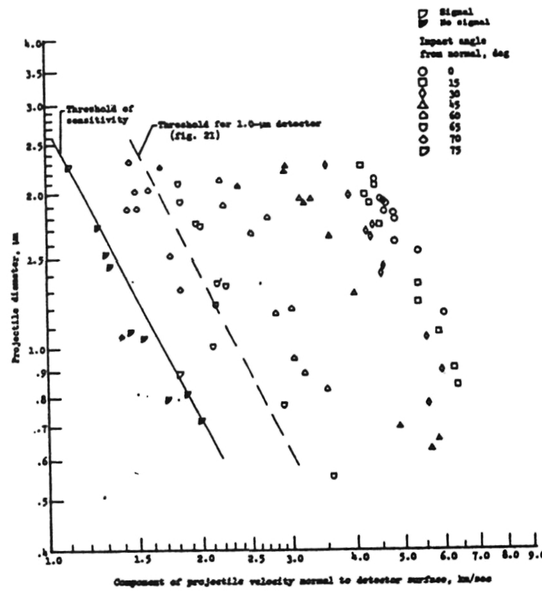

Figure 3 - Response of a 0.4-μm detector relative to projectile diameter and component of velocity normal to detector surface.

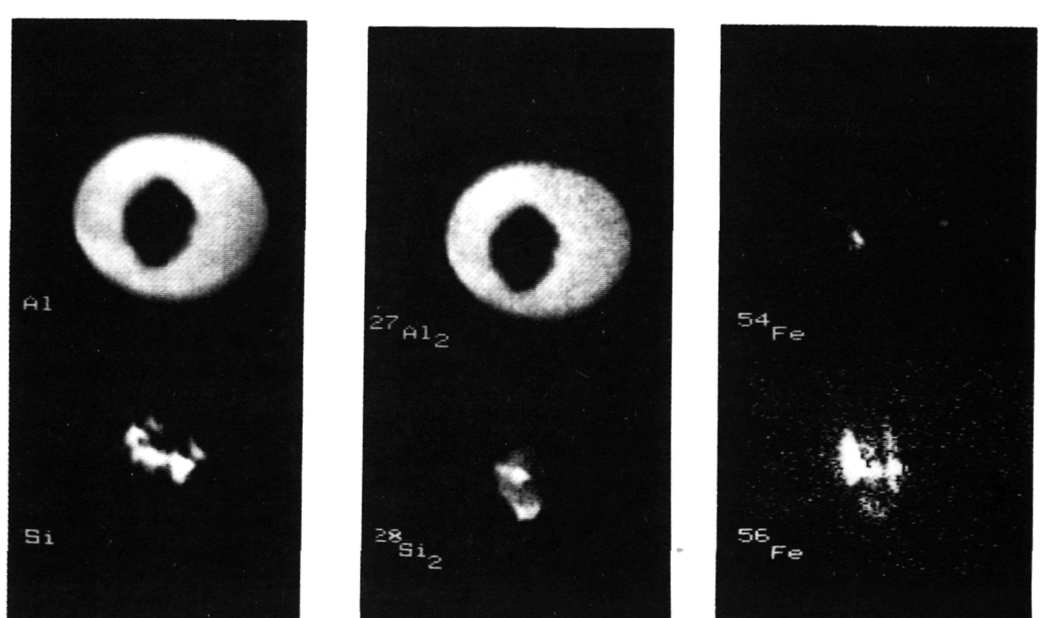

Figure 4. Secondary ion images from a 60 μm diameter area surrounding an Fe particle impact cracter.

N86-30607

PRECISION REQUIREMENTS ON COSMIC DUST TRAJECTORY MEASUREMENTS

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It has been known for some time that the orbital parameters of certain major meteor streams rather closely match those of presently observed comets (Lovell, 1954; Whipple, 1954). There is therefore a clear parent-daughter orbital relationship between meteoroids in certain streams and the comets that they derived from. For meteoroids in the photographic meteor range, it has been estimated that from 1% (Kresák, 1980) to 10% (Cour-Palais et al., 1969) of the meteoroid mass is concentrated into the major streams. However, for the smaller, more numerous meteoroids observed as radar meteors, streams are less intense but there are more of them; Southworth and Sekanina identified 256 streams in their synoptic year search. Sekanina (1973) has established for the radar meteors that, in addition to comets, some of the parent bodies appear to be asteroids. As noted by Grün et al. (1985), meteoroid lifetimes, due to collisional destruction or Poynting-Robertson (P-R) drag losses, range from 10^5 yr downward to less than 10^3 yr; these meteoroids therefore need to be continuously be replenished by source bodies to maintain the meteoritic complex in some sort of temporal equilibrium.

It will also be very important to obtain their precise trajectories when meteoroids are collected with a capture apparatus in Earth orbit, as is made apparent with the following logic: a chemical, istopic, or other analysis of any particular meteoroid constitutes a similarly detailed analysis of a small part of the parent comet or asteroid that is orbitally associated with it. One can, consequently, do rather detailed cometary or asteroid science utilizing only an Earth-orbiting cosmic dust capturing facility. And it will be possible to know what parent body we are analyzing. There is also the possibility that interstellar grains will be collected and analyzed.

When a dust grain is ejected from a comet or an asteroid, it immediately proceeds on an altered orbit. There are two reasons for this. First, due to the drag of the outward flowing gas, grains are emitted from comets with a variety of velocity directions relative to the parent comet; similary, impacts of meteoroids onto asteroids cause grains to be ejected with a variety of velocities relative to the parent asteroid. Second, for small grains, radiation pressure is a significant factor relative to the gravitational pull of the sun, which causes a weaker inverse square force or "effective gravity" field to be felt by the grain; this causes the heliocentric orbital period and semi-major axis of a small grain to increase relative to large grains with identical heliocentric velocities. After ejection, gravitational perturbations and Poynting-Robertson (P-R) drag will modify, at different rates, the separate orbits of the parent comet or asteroid and the daughter dust grains. These perturbations and drag will generally produce increasing divergence, in time, between parent and daughter orbital parameters. Dust grains will seldom, if ever, be detected traveling in orbits identical to their parent bodies. As some of the perturbational forces depend upon particle size, the divergence of orbital parameters will depend upon particle size, as well as on the time since parent-daughter separation. In order to associate collected meteoroids with specific source bodies (such as a particular comet), these orbital evolution processes need to be understood in detail.

Southworth and Hawkins (1963) developed a semi-empirical "D" criterion to determine whether or not a meteor belonged to a stream. The D criterion is given by

$$(D(m,n))^2 = (e_m-e_n)^2 + (q_m-q_n)^2 + (2\sin((i_m-i_n)/2))^2$$
$$+ \sin(i_m)\sin(i_n)(2\sin((\Omega_m-\Omega_n)/2))^2$$
$$+ ((e_m-e_n)\sin((\Omega_m+\omega_m-\Omega_n-\omega_n)/2))^2 , \quad (1)$$

where m represents the mean orbital parameters (eccentricity e, perihelion distance q, inclination i, longitude of ascending node Ω, and argument of perihelion ω) of the assumed stream and n represents the corresponding orbital parameters of a meteoroid whose membership in the stream is to be tested (q is in AU). If D is less than some value chosen from experience (e.g. D = 0.2), then the meteoroid is said to belong to the stream. Over some range of the parameters, according to Southworth and Hawkins, D is approximately equal to 3/2 times the velocity increment (in units of the Earth's orbital velocity) needed to derive one set of orbital parameters from the other.

Such a criterion is probably justifiable if members of a stream are related to one another by impulsive gravitational scattering. It is almost certainly not a universally valid criterion, however. This is especially true for small meteoroids that have largely evolved under P-R drag (which primarily changes e in Eq. 1). It should be a future theoretical effort to study the prior orbital evolution of meteoroids that intersect the Earth's orbit as a function of meteoroid size. The purpose of the study would be to derive new "D" criterion that would correctly relate daughters to parents via well understood orbital evolutionary paths. One could then more confidently establish true parent-daughter relationships.

Next it is asked what kind of precision is required in measuring the trajactory of an impacting meteoroid, in order to determine which parent object it derived from. The answer to this question will partly depend upon how well the orbital evolution of each meteoroid is understood, as noted in the previous paragraph. But it also depends upon how widely separated are the orbital parameters of the objects that are to be tested as potential source, or parent, bodies. Consider, for example, two meteoroids that have very similar orbital parameters except that the aphelion of one is at 5 AU (normally a cometary object) and the aphelion of the other is at 4 AU (potentially an asteroid). Depending on the inclination and perihelion distances assumed, one derives geocentric velocities that differ from one another by from 1% to 6% for the two cases. Therefore to be sure we can cleanly separate objects derived from these two great families of parent objects, precisions as high as 1% in measuring the trajectory are needed. Fuzziness introduced due to uncertainties of orbital evolution paths will make the required precision even higher. For reference, precision photographic meteor trajectories are obtained with accuracies of 0.1% to 0.4% (Jacchia and Whipple, 1961). One also would also like to separate different populations of Earth-orbiting spacecraft debris from each other (e.g. see Kessler, 1985 for a discussion of orbital debris issues) in order to determine sources for the debris; lunar ejecta should also be differentiated from man-made Earth-orbiting debris generated in geosynchronous transfer orbits.

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In short, the greater the precision, the greater the liklihood that many unique parent-daughter associations can be made. It is not now known how much precision will be required to make certain potentially interesting associations in the future, so near-maximum state of the art measurements should be sought. It appears both feasible and desireable to obtain a precision better than 1% in determining vector velocity components of impacting meteoroids.

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