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Microgravity Particle Research on the Space Station

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FOREWORD

A number of participants at the Space Station Microgravity Gas–Grain Simulation Facility Experiments Workshop (held in Sunnyvale, California, August 31 to September 1, 1987) requested that the proceedings of the previous workshop (held at Ames Research Center in August 1985) be made more widely available. Thus, in order to provide a wider audience with this document, relevant to the history of the Gas–Grain Simulation Facility (GGSF), these proceedings are published here as a NASA Conference Publication. More current information about the GGSF can be found in "Space Station Gas–Grain Simulation Facility:Application to Exobiology," by Chris McKay,*et al.*, Adv. Space Res., 6, 195 (1986) and in "Life Sciences Space Station Planning Document:A Reference Payload for the Exobiology Research Facilities," (NASA Technical Memorandum 89606, November 1986). The Solar System Exploration Branch of the Life Sciences Division at Ames Research Center plans to release the proceedings of the 1987 Sunnyvale workshop as a NASA Conference Publication in late 1987.

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Executive Overview

This document is the report of the Microgravity Particle Research Facility Workshop held at NASA Ames Research Center on August 22–24, 1985. The contents of the report outline the multi-disciplinary science rationale for a dedicated, adaptable facility on board the Space Station to conduct studies involving small suspended particles.

Given the constraints involved in development of flight experiments for the Space Station, it is desirable that experimental facilities developed *(a)* address scientific problems of fundamental importance, and *(b)* be useful to as broad a range of scientific disciplines as possible without detracting from their ability to meet specific important research goals. A wide range of fundamental scientific experiments can be conducted on the Space Station that involve microgravity studies of small particles. The range of particle experiments that require the Space Station covers many disciplines and involves a variety of methods and measurement techniques. However, these experiments share the common requirement of study of particles in an extremely low-gravity environment since, in general, they require that particles be suspended for periods substantially longer than are practical at 1 g. Because of this commonality, it is reasonable to suppose that a particle suspension chamber with adaptable configurations and measurement capabilities might provide a generic research facility. At the same time care must be taken to avoid development of a concept that is so adaptable that it is unable to meet many specific requirements of high priority experiments.

The goal of the workshop was to bring together experts in a number of disciplines (including astrophysics, atmospheric science, planetary science, exobiology, and particle physics and chemistry) to define the science questions that could be addressed by a Space Station Microgravity Particle Research Facility, and to identify the broader scientific context in which these questions are meaningful. Having compiled a list of relevant experiments, individuals from each discipline placed constraints on the design and operational modes of the facility, and a preliminary picture of the multi-disciplinary facility was developed.

The results of the workshop indicate that the concept of a generic particle facility is viable, and a broad brush design has emerged. A Space Station Microgravity Particle Research Facility would require on the order of several cubic meters of space (about two racks) in a Space Station research module. The chamber would require a fairly sophisticated environmental control system capable of controlling internal gas composition, pressure and temperature. Access to the external space environment is not a strong design constraint except as a source of high vacuum. The key to the multi-disciplinary success of the chamber is its adaptability. In at least two important ways the chamber must be adaptable: particle production and handling equipment within the chamber, and optical ports and measuring equipment. Required g levels are $\sim 10^{-5}$ g for most experiments. Considerable care will have to be taken during the early stages of development of such a facility to identify the high priority scientific experiments that can make effective use of a general-purpose facility, and to differentiate them from those that will require more specialized equipment.

Based on the scientific requirements of the many relevant disciplines, this report outlines the desired capabilities of a microgravity particle facility and support hardware. It is the recommendation of this report that the concept of a facility for study of particle processes in microgravity on the Space Station receive further study. Two steps are necessary:

1. An engineering design study should be conducted in order to more fully define the nature of such a facility, and to realistically estimate its power, mass, volume, and maintenance requirements. This is necessary to support Space Station planning efforts. The study should be conducted on the basis of the scientific objectives and capabilities outlined in this report, tempered with the realization that not all of the suggested experiments can realistically be accommodated in a single facility.

2. An attempt should be made to prioritize the scientific objectives outlined in this report, as an aid to conducting the engineering study. Priority should be based on both the extent to which the possible investigation addresses fundamentally important scientific issues, and the technical ease with which the investigation can be conducted.

These two steps should be conducted concurrently, with the goal of developing a detailed plan for a facility that provides the optimum combination of high quality science and practical feasibility.

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Chapter 1

Introduction

The Space Station will provide a unique capability to do experiments in the space environment. Because of the very low gravitational acceleration (microgravity) in the Space Station, many experiments that are impractical or impossible on Earth become feasible in the space environment. These experiments are those in which gravity either interferes directly with the phenomenon under study (*e.g.*, gravitational convection masking diffusional processes) or in which gravity precludes the establishment of the proper experimental conditions (*e.g.*, by accelerating test objects to unacceptable velocities). With the Space Station definition studies already underway it is timely to begin seriously considering the science objectives for Space Station research and the implications for the design of research modules.

Many processes of astro-geophysical interest that involve interactions between small grains or particles are not amenable to experimentation in a 1 g environment. Examples of particles involved in processes that would be difficult to model on Earth include interstellar grains, protoplanetary particles, atmospheric aerosols, combustion products, abiotic organic polymers, *etc.* Condensation, evaporation, coagulation, and charge accumulation are a few of the processes that influence these particles. In many astro-geophysical systems of importance, small particles and particle processes determine the overall behavior of the system. These include atmospheric clouds, interstellar clouds, planetary rings, Titan's organic aerosol, martian dust storms, lightning *etc.*

Although there is a wide range of disciplines in which problems involving small particles occur, the fundamental constraints on particle handling are similar. These constraints involve long times periods during which the particles must be suspended, and low relative velocities for the particles. This commonality of requirements might form the basis for a generic facility aboard the Space Station for particle research in microgravity. Based on this suggestion, a workshop was organized at Ames Research Center in order to bring together a group of people with interests and expertise in a variety of particle research fields.

The workshop was held at NASA Ames on 22–24 August 1985. The goal of the workshop was to define the capabilities and requirements of a useful microgravity facility for the Space Station. The approach of the workshop was to consider each discipline and prepare for that discipline a list of the specific science questions that *could* be addressed by a Space Station microgravity facility and *could not* be answered without the microgravity facility. Only those experiments for which the Space Station was a key enabling technology were considered.

Each chapter in this report considers a specific scientific discipline. In general, each chapter was compiled by a working group that considered all aspects of a microgravity facility within the context of that discipline. Within each chapter recommendations are made with respect to the design and operation of the facility. These recommendations refer only to the context of that chapter's discussion.The overall conclusions are summarized at the end of the report.

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Chapter 2

Astrophysics and the Solar Nebula

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2.1 Introduction

Small grains play an important role in many of the processes that occurred in the primitive solar nebula and that are now taking place in other astrophysical environments. Refractory particles are known to condense in the expanding shells around stars undergoing mass loss. Such materials could accrete volatile, icy mantles while in the outer regions of the circumstellar shell in which they form, or in the general interstellar medium. Collisions between these particles could result in coagulation into larger, irregular grains, in the loss of accreted, volatile mantles, or in the breakup of previously aggregated particles. Similar processes very probably occurred in the primitive solar nebula, although other mechanisms such as the evaporation or melting of grains due to viscous heating, shocks, or lightning discharges may also have been important. The coalescence of small particles into larger bodies such as asteroids, comets, meteor parent bodies, and planets must have occurred in the early solar nebula while the particles were embedded in a turbulent gaseous medium. Very little is known about coagulation processes in such systems.

The optical properties of the grains present in a circumstellar shell or in the primitive solar nebula need to be determined if the infrared opacity of the gas/grain system is to be calculated. The infrared opacity caused by the presence of small grains plays a dominant role in models of the evolution of the primitive solar nebula or the temperature structure in dusty circumstellar envelopes. In addition, reliable measurements of the scattering properties of many types of refractory core/volatile mantle grains are needed in order to interpret observations of astronomical sources such as reflection nebulae, the diffuse interstellar background, and the zodiacal light. Similarly, measurement of the extinction and polarisation properties of such compound grains are necessary in order to model observations in giant molecular clouds, HII regions and the general interstellar medium.

Section 2.2 contains a list of types of experiments that could be carried out over a period of years using a particle research facility aboard the Space Station. Specific explanations for some of these experiments will be given in the next section; many of those not discussed are simply more elaborate extensions of these simpler, initial experiments.

We feel certain that many more experiments than those listed in Section 2.2 will be suggested prior to the flight of the Space Station in the mid 1990's. We also feel that it is important that proposed flight experiments be complemented wherever possible by a strong ground based laboratory program. Such an effort should be started as soon as possible in order to have the "ground truth" data in hand with which flight experiment data can be calibrated and interpreted.

We have identified two general areas — optical techniques and sample collection/analysis — that are of central importance to many of the studies listed in Section 2.2. These are discussed in Section 2.3

2.2 Suggested Experiments for Space Station

1. Nucleation of refractory vapors at low pressure/high temperature.
2. Coagulation of refractory grains;
   (a) coagulation in a quiescent gas-grain system
   (b) coagulation in a turbulent gas-grain system
3. Optical Properties of refractory grains;
   (a) measurement of single particle emission efficiency
   (b) measurement of the optical properties of aggregate (fractal?) grains
   (c) measurement of the effect of absorbed gas on the optical properties of grains
4. Mantle growth on refractory cores;
   (a) measurement of the initial growth rate of volatiles on various cores
   (b) determination of the effect of UV radiation on the initial mantle growth rate
   (c) determination of the long term effect of UV radiation on the stability of mantles
5. Coagulation of core-mantle grains;
   (a) coagulation in both quiescent and turbulent gas-grain systems
   (b) determination of the effect of mantle thickness on "sticking coefficient"
   (c) can coagulation of UV processed grains cause mantle explosions?
   (d) can mantle explosions disrupt grain aggregates?
   (e) determination of the structure of the resultant particles
6. Optical Properties of core-mantle grains;
   (a) determination of the properties of single core/mantle grains
   (b) determination of properties of aggregates as a function of their previous history
7. Lightning strokes in the primitive solar nebula;
   (a) collection of debris from electrical discharge in simple gas-grain mixture
   (b) collection of debris from discharge in core-mantle grain-gas mixture
8. Study the separation of dust from a grain-gas mixture that interacts with a meter sized "planetessimal"; does accretion occur?

2.2.1 Microgravity Nucleation Experiments

Little information is currently available on the vapor-solid phase transition of refractory metals and metal oxides. What little experimental data do exist, however, are not in agreement with currently accepted models of the nucleation process for more volatile materials. The major obstacle to performing such experiments in the laboratory is the susceptibility of these systems to convection. Consequently, it has so far proved impossible to controllably nucleate carbon, aluminum oxide or silicone carbide smokes which should be among the first condensates in stellar outflows. Measurement of the conditions under which such smokes condense and of the morphology and crystal structure of the resulting grains is essential if we are to understand the nature of the materials ejected into the interstellar medium and the nature of the grains which eventually became part of the proto-solar nebula.

Evaporation of refractory materials into a low pressure environment that has a carefully controlled temperature gradient will produce refractory smokes when the "critical supersaturation" of the system has been exceeded. Measurement *via* light scattering or extinction of the point at which nucleation occurs can not only yield nucleation data, but, if optical monitoring is continued, will also yield data on the sticking coefficients of newly condensed submicron refractory particles by determining the time evolution of the particle size distribution. Optical methods should be supplemented by active particle collection (and subsequent analysis) in order to determine the morphology and degree of crystallinity of such newly formed particles.

2.2.2 "Vacusol" Measurements

Interstellar and interplanetary dust particles exist in a very high vacuum environment, and hence a realistic simulation of such particles should include this factor. Small particles (<0.1 μm) have a large surface to volume ratio and it is well known that the surface layer can be influenced by ambient gas. We must therefore control the exposure of candidate grain materials to "reactive" ambient gas in order to completely characterize such particles. This will require suspension of a particulate cloud at total pressures much less than 10^{-6} torr.

A microgravity environment can make the attainment of a stable particle cloud possible even in the absence of gas (note that for these purposes the entire particle facility may need to "float free" for a short period of time in order to achieve "zero" g). One major problem is how to separate the dust from gas used to inject the particles. This may be achieved cryogenically, or by gathering the gas on a reactive surface. Ideally the system will never expose the particles to ambient gas and an alternative method may need to be devised. This could involve mechanical dispersal of the particles, laser heating that both removes residual gas from the particles and also separates them, or yet another method still to be devised. If the spectra of vacuum suspended particles are indeed different from those obtained in the laboratory, then one would also need the ability to bleed small quantities of interesting gases into the chamber to look for the surface signatures of such species.

2.2.3 Coagulation of Interstellar Dust

All of the bodies of the solar system were formed out of the material of the interstellar medium. If we accept the concept of continuity from interstellar gas and dust to the formation of planetary systems we have before our eyes many examples of dust coagulation. However, with the exception of comets and possibly some classes of meteorites, what survives today bears little resemblance to the original coagulated solid particles. If we focus our attention on comets (the most primitive bodies in the solar system) there exists an increasing body of evidence that they must have formed at exceedingly low temperatures (T<25 K). Comets, therefore, preserve an almost perfect sample of interstellar material that coagulated 4.5 billion years ago. A laboratory simulation of such coagulation would provide the basic information needed to infer the processes and materials by which they were made, and therefore the ability to interpret astronomical observations of comets within a more advanced model of their composition and structure.

It is reasonable to expect that precometary grains could spin with very large angular velocities due to non-thermal processes. These particles are likely to be elongated, refractory core/volatile mantle particles which may contain free radicals embedded in the icy mantle and a photoprocessed organic polymeric "skin" over the refractory core. Total thickness for an average particle is a few tenths of a micron and the cloud temperature is on the order of 10 K.

To perform meaningful simulations of the full set of conditions under which cometary grains coagulated requires: *(a)* injection of a cloud of refractory submicron particles (*e.g.*, silicates) into a microgravity chamber, *(b)* cooling the particles to about 15 K (*e.g.*, using liquid He in the wall), *(c)* injection of appropriate gas components into the chamber which will accrete onto the refractory cores, *(d)* vacuum ultraviolet irradiation of the particles to photoprocess the mantles, and *(e)* a high frequency magnetic field (or another mechanism) to spin-up the particles as they coagulate.

It should be obvious that the microgravity environment is essential for this experiment not only because it is the only means by which particles can be suspended for the length of time necessary to perform the coagulation experiment itself, but also because of the length of time necessary to prepare the photoprocessed mantle grains that must also be kept suspended during preparation.

2.2.4 Chondrule Formation via Electrical Discharge

Despite widespread agreement that chrondrules were formed by localized melting of pre-existing lithic particles, the actual heating mechanism is still uncertain. One mechanism that has been proposed is fusion by lightning resulting from charge separation in a turbulent, dust-laden solar nebula. However, it is not clear that thermal coupling between the lightning stroke and the particulate material would have been adequate to melt more than just the surface of each mineral grain.

A possible test of the above hypothesis would, therefore, involve an experiment in which an electric discharge is generated in a cloud of suspended particles approximately simulating the solar nebula at an early stage of accretion. Such a simulation would require a microgravity environment in order to eliminate wall effects from influencing the population of suspended particles.

Experimental parameters whose variation could be investigated would include particle size and composition, ambient gas composition (specifically oxygen fugacity) and ambient temperature. Although some characterization of the experimental products could be carried out in orbit, detailed analysis might best be performed on earth. Such studies would include optical and electron microscopy and chemical analysis by electron microprobe. Features which would be sought in resulting chondrule-like material would include those textures characteristic of meteoritic chondrules and the prevalence of both relict grains in chondrules and compound chondrules, and distinctive features of actual chondritic material.

2.2.5 Solar Nebular Turbulent Coagulation

There are two apparently divergent scenarios for early solar system formation: *(a)* that derived from hydrodynamical calculations that imply a relatively cool nebula (T<1500 K), and *(b)* that derived from meteoritic evidence that suggests that the protoplanetary cloud was initially quite hot (T>1500 K). This divergence of opinion may be resolved by consideration of the effect of turbulence on gas-solid coupling in the nebula. This process was initially invoked to resolve issues of angular momentum transfer and mass inflow in the protoplanetary cloud. However, recent analytical solutions to a turbulent protoplanetary cloud suggest that some physical and chemical parameters calculated for solid materials compare well with meteoritic observations (*e.g.*, CAI rims). Thus turbulence may be an important factor in the formation of small (<mm size) solid bodies in the solar nebula. Two important aspects of turbulence in a protoplanetary cloud are the transportation and the coagulation of solid grains. Although turbulent models can provide well defined equations for these two processes, experimental data obtained under comparable conditions to those in the solar nebula are not readily available.

The two important aspects of turbulence in a protoplanetary cloud (dust transport and coagulation) both depend upon the size of the turbulent eddy considered. Specific effects of model dependent assumptions on cosmochemical parameters such as chondrule size have been studied. The growth of the mean particle radius with time due to turbulent coagulation can be calculated for an idealized dust density in the turbulent collisional environment. However, strong boundary conditions can not yet be placed on these types of calculations. Thus, only order of magnitude estimates on the relative timescale of this process can be made at this time. In addition, the significance of turbulent coagulation in a protoplanetary cloud can not be fully evaluated due to the lack of experimental data such as: *(a)* the sticking coefficient, q, for a particular type of grain, *(b)* the sticking coefficient, q′, for different combinations of grains, *(c)* the variation of q and q′ as a function of temperature and grain size, and *(d)* the absolute timescale for turbulent coagulation at specific eddy velocities and densities (where $V_t < C_s$).

The capabilities offered by a microgravity particle research facility on the Space Station provide an ideal environment for the experimental assessment of the processes involved in models of solar system formation. The Space Station environment is essential for these types of experiments because: *(a)* the influence of gravity induced convection must be removed in order to study the turbulent coagulation of fine grained particles (submicron – mm size); *(b)* timescales for significant observable turbulent coagulation may be longer than a few seconds and could be as long as days; *(c)* experiments on larger, more fragile aggregates (>cm size) and the study of the collisional dynamics of such particles are impossible at normal gravity. Quite sophisticated experiments related to nebular evolution could also be pursued once basic aspects of grain nucleation, condensation and coagulation are understood. These experiments could include the provision of a heat source within a turbulent cloud in order to simulate the chemical effects of mass transport through critical temperature regimes.

2.2.6 Single Particle Measurements

In a microgravity environment it will be possible to suspend single particles and particle aggregates within the field of view of both infrared and optical detector arrays for extended periods of time. Suspension of such particles will allow their optical properties (*e.g.*, albedo and emissivity) to be determined at a number of wavelengths. This could be accomplished by heating the particle using laser radiation of known intensity and wavelength while monitoring the particles infrared emission at various wavelengths. Particle positioning could be accomplished *via* electrostatics in a vacuum or by an acoustic levitator system in a low pressure gas. Such a system would be a direct calibration of the microwave analog scattering experiments discussed in the next section and would allow the determination of the optical properties of "real" interstellar dust particles. This would greatly aid the interpretation of optical and infrared studies of cometary and circumstellar dust particles.

2.3 Required Capabilities of an Orbital Facility

Two types of measurements are common to virtually all experiments proposed for study in this chapter: determination of the optical properties of the particle cloud and the collection and analysis of discrete particle samples. Each of these topics will be treated below.

2.3.1 Optical Measurements

It is critical to the understanding of particle dynamics experiments, including studies of nucleation, growth, and coagulation, to accurately monitor the number density, size, shape and chemical characteristics of particles in the experimental system as function of experimental parameters and time. Optical diagnostic techniques are the major means of obtaining experimental data on particle phenomena in real time. Light can be scattered or absorbed from a particle with or without a change of wavelength. The scattered light can be used to directly image particles greater than approximately the wavelength of scattered light, while below this size range, interferometric or intensity measurements are used.

Several classes of experiment require a system capable of imaging particles in the chamber to as high a spatial resolution as is possible (*e.g.*, approximately 1 μm). If a chamber is supplied by the facility, this capability should be provided. Several approaches are possible. Optical microscopes with large depth of field are available using reflective optics. An alternative technique is microscopic halographic imaging which might be suitable for space station use, but which will require further study.

In specialized cases, fluorescence or other physical processes occur which change the wavelength of the incident radiation and provide data on the physical and chemical state of a gas-particle system. Raman spectroscopy can also yield substantial information on gas-particle systems, but the cross section is orders of magnitude less than the scattering cross section.

The cross sections for light scattering and for absorption, which may also effect the polarization of the incident light, are both functions of the particle properties including size, shape and composition, and are also functions of wavelength. The optical properties of simple shapes, such as spheres or infinitely long needles, can be calculated analytically. However, the optical properties of particles of complex shapes, including coagulated particles or euhedral crystals, cannot be calculated from first principles. Converting the optical data obtained in a particle experiment to yield detailed information on particle shapes, sizes, number densities and chemistry requires a large body of knowledge, both theoretical and experimental, concerning the optical properties of irregular particles. Such knowledge needs to be developed from ground-based experiments and theoretical studies to allow the complex data obtained from particle studies in microgravity to be interpreted to yield the maximum information possible. Detailed optical experiments on well characterized particles of various shapes need to be carried out to establish a base for the interpretation of particle dynamics in microgravity. For very complex shapes, including coagulated grains, microwave scattering from centimeter-sized solid models, which simulate the interaction of visible light with micron sized grains, is the most quantitative scattering method for use in ground-based comparison studies.

In order to provide sufficient data to allow particle dynamics to be monitored, wavelength, angle, and polarization-resolved scattering data are required. Rapid modulation of the light source polarization and intensity coupled with phase sensitive detection will allow high sensitivity detection of scattered light. For multiple wavelength scattering measurements, multiple wavelength lasers or white light sources can be used in conjunction with wavelength resolved detection techniques, including multiple photodetectors or detector arrays. A computing controller must monitor the system's physical and chemical parameters including pressure and temperature and provide automatic or semiautomatic experiment operation. The controller must be capable of performing system calibration and operation as well as data reduction and display in real or near-real time for the local operator, and allow some system diagnosis and experiment summary to ground based experimenters.

Development of this system should begin well before IOC since a considerable amount of experience will probably be necessary in order to work most of the problems out of the system. Similarly, ground based microwave analog experiments are also important and have already been implemented. Support for such programs should be continued at the current level, or expanded.

2.3.2 Sample Collection and Analysis

Most experimenters will at some stage wish to "see" what the particles in the chamber look like. To some extent this information can be provided by optical analysis, but whenever the conversion of optical data to other information (*e.g.*, particle size, shape or composition) occurs, some degree of "ground truth" or system calibration becomes necessary. For this purpose, representative samples must be collected in real time by an active particle collection system (Note: passive systems that rely on particles settling out of the chamber will be extremely inefficient in microgravity). Although there are some instances where a piezoelectric mass detector may yield all of the data required to determine the particle mass distribution, such systems can not yield data on particle shapes, crystallinity, or composition. For this reason some form of microanalytical technique such as SEM or TEM will be required. The need for an analytical electron microscope (AEM) can be accommodated in one of two ways: collected particles can be returned to earth, or analysis can be performed using an AEM aboard the Space Station. Of the two options an AEM system onboard the Space Station makes the most sense since such a system could also be used for life sciences and materials procession experiments as well. We would recommend that such a facility be included as part of the IOC analytical laboratory capability.

The prime concern in all particle analysis considerations is the degree to which samples will be altered by the collection and handling process. For this reason, at least in the initial experiments, any unnecessary sample handling should be eliminated. Once the initial nature of the particles is established, then the effects of transporting the samples to earth for further analysis can be determined. As an example, we feel that it is extremely unlikely that a macroscopic dust aggregate will survive the trip to earth without some degree of internal compression. Similarly, it may be extremely difficult to preserve the structure of core/mantle grain aggregates collected at 10–15 K during transportation to earth. Initial analysis on the Space Station followed by similar analysis on the ground could eliminate this source of uncertainty in the experiments.

Sample manipulation will be greatly facilitated if the sample collector is also the sample holder in an AEM and if the collection system could be coupled in some way to the analytical facility (*e.g.*, by standard ports). The collector itself may need to be quite sophisticated; it may be cryogenically cooled to 10–15 K and/or a particle filter with nanometer sized holes while at the same time it must remain compatible with the AEM facility if sample handling is to be minimized. For this reason, we feel that it is necessary to begin the development of a particle collection system immediately. The system can be tested aboard the KC-135 microgravity aircraft or the Space Shuttle and should incorporate as many of the future requirements — perhaps in separate subsystems — as is possible.

2.3.3 Hardware and Facilities

The following list of requirements for a particle science facility have been identified. Although all are required for the full capability of the system to be realized, the elimination of one or two does not imply that meaningful astrophysics/solar nebula experiments are impossible. It will simply indicate that the full range of experiments cannot be done. The list has been divided into those capabilities that must be provided by the Space Station to the facility and those capabilities which are probably facility specific. Although we think that the facility may be able to provide one or two experimental chambers, we feel that individual experimenters will probably wish to build their own chamber, optimised for their own specific needs, but which will take advantage of certain standard capabilities.

Space Station provides the following to the facility:

1. Access to vacuum reservoir at 10^{-6} torr or less.
2. Access to cryogenic cooling capable of attaining temperatures at least as low as 80 K but preferably down to 10 K and possibly as low as 4 K.
3. Power with which gas in the chamber can be heated locally; peak power required may be 5kW for several hours.
4. Access to chilled cooling water at approximately 5–15°C.
5. A working volume of at least 3 m^3.
6. Access to various analytical facilities such as transmission and/or scanning electron microscopes, a mass spectrometer, and various devices to measure materials strength and surface chemistries.
7. The possibility of remote operation of particle experiments *via* telescience in real time.
8. The possibility of at least 24 hours at 10^{-5} g or less.
9. Low voltage (10V), high current (100A) power for short times (hours).

The facility provides the following to experimenters:

1. One or two "standard" experimental chambers which can be easily removed and replaced by the experimenter's chamber.
2. Active particle collection and mass monitoring systems.
3. A wall cleaner — either ultrasonic, laser, or equivalent.
4. A device that can establish an ultrasonic well to confine a particle cloud as gently as possible.
5. An electrostatic particle positioner capable of dealing with micron sized particles.
6. An optical bench, lenses, lasers at various wavelengths as well as other light sources and a variety of optical and infrared detectors.
7. A strong UV light source for photoprocessing grain mantles.
8. The capability to induce controlled turbulence into the experimental chamber.
9. The provision of video, high speed photography, still photography and microscopic images.
10. An "outer box" that can contain particle contaminants but which can be removed for easy access to the experiment.
11. Provision of a standard gas handling system, including vacuum.
12. Provision of a method to control the temperature of the experimental chamber between approximately 4–400 K.
13. A mechanism to induce a high voltage discharge into the system.
14. A mechanism to spin-up grains; *e.g.*, alternating strong magnetic fields
15. A mechanism to introduce and disperse previously characterized particulates into the system.
16. Access to low voltage, high current (10V, 100A) power supply to heat crucibles.

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Chapter 3

Planetary Science

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3.1 Introduction

Planetary Science is concerned with both the cosmological processes that led to the formation of the solar planets (and planetary systems in general), and the behavior of geological and atmospheric materials within existing evolved planetary bodies. More specifically, the research projects discussed here center around the behavior and interaction of particulate materials that have free paths which are distant from the influence of a solid or liquid surface. The particulates of interest range in size from centimeter balls of ice and dust to submicron comminution products.

The Solar System, in its nebular state, began as particulate material that interacted at low relative velocities to form ever larger aggregates of material, and ultimately, the planetary bodies. These ice and dust particles, in the form of relatively loose, fragile balls, could only have collected together if their interaction involved some "sticking" process that was greater in magnitude than any dynamic forces tending to disrupt or disaggregate clusters of particles.

Within the evolved planetary system, particles of ice and dust form an unconsolidated component of some planetary bodies in the form of ring structures such as those of Jupiter, Saturn, and Uranus. Again, interest lies in understanding the interaction of low energy collisions of such particulates since this process determines the structure and behavior of ring systems. In this case, the particles of interest are more coherent solids than the ice/dust accretions noted above.

The evolution of the planetary ring systems may also be dependent on the interaction of electrostatically-charged micron to sub-micron dust particles that interact electrically with an ambient plasma. An interest in the behavior of such particles also has direct relevance to the understanding of comets that emit dust at large heliocentric distances.

On the terrestrial planets, particulates with the ability for free interaction are also to be found within planetary atmospheres. Such material ranges from grains less than a micron to several tens of microns in size, and owes its presence in suspension to the action of aeolian, volcanic, and impact (meteorite) processes. Electrostatic interaction of these atmospheric particulates may strongly influence the life-span of dust storms, the behavior of volcanic eruption plumes and the potentially global effects (such as species extinction) of impact dust palls.

3.2 Suggested Experiments for Space Station

3.2.1 Low Velocity Collisions Between Fragile Particles

Microgravity offers unique opportunities to simulate phenomena in the early solar nebula. One important area for study is the dynamics of collisions of weak, unconsolidated bodies at low relative velocities. Collisional behavior of grain aggregates may have indirectly controlled large-scale processes in the nebula. There is a class of nebular models that are convectively unstable, maintaining turbulence by a feedback mechanism involving viscous dissipation. Such models involve the redistribution of mass and angular momentum in the nebula disk, thereby establishing the general configuration of the solar system. A key assumption for convective instability is a high opacity of the nebular material; however, the dominant source of opacity is solid grains rather than gas. Thus, the possibility of convection depends on the concentration and size distribution of grains, and the degree to which they may form larger aggregates by coagulation.

The process of coagulation in a turbulent nebula has been modeled numerically. Qualitatively, it is known that turbulence promotes coagulation of small grains; however, relative velocities increase with size, eventually causing destruction of larger aggregates. Various assumptions lead to values of opacity and turbulent velocity that decay monotonically or reach a steady state; there is also the possibility of intermittent turbulence. The outcome is sensitive to the collisional strength assumed for grain aggregates. Their collisional behavior is modeled by analogy with the existing data base from high-speed impacts of strong projectiles, including cratering of loose regolith and shattering of finite, competent targets. The assumed behavior includes net accretion at low impact energy, erosion at intermediate energy and an abrupt transition to shattering at a critical energy density, or "impact strength". While this treatment is more realistic than a simple sticking coefficient, it must be emphasized that there are no relevant experimental data for the appropriate regime.

Nebular models imply collision velocities < 100 cm/s in the sub-cm size range, where the influence of aggregate size on opacity is greatest (eddy velocities are much higher, but the grain motions are correlated). Indirect arguments from cratering in silicate powders at one g suggest that the transition from erosion to shattering for grain aggregates bonded by van der Waals forces would occur in this velocity range. This can be verified only in a gravity-free environment; while it may be possible to construct very weak targets in the presence of gravity, their behavior would be dominated by internal stresses needed to support their shapes. This can be alleviated somewhat by constructing smaller targets, but ideally, they must be much larger than their individual constituent grains.

The type of data acquired using a microgravity impact facility would include: the velocity threshold for the transition from net mass gain to erosion; the sizes of ejecta particles (single grains or aggregates?) in "cratering"; the nature of the transition from cratering to disruptions (sudden or gradual, energy density or other criterion?); and the size distribution of fragments in disruption. Given the uncertainty of the composition and physical state of primordial grains in the solar nebula, precise numerical values for those quantities are not important. Rather, the objective is to determine "generic" collisional behavior of aggregate bodies. Some useful precursor experiments can and should be performed in a terrestrial environment before going to an orbital facility. Impact experiments can be performed with aggregate targets of moderate strength, such that internal stresses due to gravity are much less than the material strength. Also, drop tests of compacted dust-ball projectiles into powdery regolith layers can be compared with similar impacts using competent projectiles. After such a data base is acquired, it will be necessary to proceed to gravity-free collisions. While one characteristic time scale in a collision, the projectile or target size divided by impact velocity, can generally be less than one second, experience has shown that the bulk of ejecta mass generally moves at much less than the impact velocity. Tracking fragments over distances of a few target diameters in order to derive mass versus velocity distributions will require timescales ranging from seconds to tens of seconds. While such timescales may be marginally attainable in an aircraft, one still faces the prospect of fabricating aggregate targets and projectiles and measuring their properties during this interval.

3.2.2 Low Velocity Collisions of Ice Particles

The dynamics of ring structures, such as the rings about Saturn, are strongly dependent on the energy losses in low velocity collisions. For example, in the structureless regions of the rings, the dispersion velocities on top of the Keplerian orbital motion determine the thickness of the rings. The magnitude of the dispersion velocity is determined by an energy balance between collisional losses and energy gained from gravity. Another example is in wave or ripple features of the rings. The damping of such waves again occurs through energy losses in collisions, but in this case the relative particle velocities are larger since now they include the wave motion velocities.

No empirical data have been available until recently for the coefficient of restitution of ice particles at velocities typical of the dispersion velocities in the rings: $<10^{-3}$ to 10 cm/s. Some data have been obtained for zero impact parameter collisions using a compound pendulum apparatus. The effective accelerations of the ball in these experiments are of the order 10^{-6} g for very low amplitudes of oscillation ($\sim$1 mm). The compound pendulum, balanced very close to its center of mass and oscillating at very low amplitudes, provides a means of achieving very low velocity collisions, but the collisions are not free. Further, for the lowest velocities, the collision amplitudes are approaching the size of ice chips on the surface of the ice balls. Such measurements provide an estimate of the coefficient of restitution for direct collisions, but do not address the very important problem of glancing collisions. There is a continuing effort to make such measurements as a function of ball radius, temperature and various surface coatings — frost, ammonia, carbon dioxide, *etc.* These measurements will provide a basis for future measurements in space.

On the Space Station, low velocity collisions of free particles are possible without the constraint of very low amplitudes and without being attached to a rigid pendulum. We would be able to measure the coefficient of restitution over a wide range of very low velocities (10^{-4}–1 cm/s) under very high vacuum conditions (not available on earth). These experiments will, of course, provide a means of checking the results obtained on earth, but more importantly will for the first time measure the energy loss and the transfer of energy to rotation in non-zero impact parameter collisions at very low velocities. These results, for a variety of ice surface structures, will be very important for future modeling of the observed structures in planetary ring systems. Measurements of the sticking forces at extremely low velocities may also be possible, and would be relevant to understanding accretion processes.

The low g environment is ideal for the low velocity collisions in the ice ball experiments. For the higher velocities ($V \sim 0.5$ mm/s), free fall collisions (onto a flat surface) from various heights (1 mm to 100 cm) would be used. Glancing collisions would be obtained by giving the ball a small forward momentum. However, for the low velocity regime, even 10^{-5} g is too large and a simple pendulum, 50 to 100 cm in length, would be used. With an amplitude of 1 mm (and an acceleration of 10^{-5} g), velocities down to 10^{-2} mm/s would be easily obtained, and even smaller values are possible if the remaining gravitational acceleration is closer to 10^{-6} g. Glancing collisions against a flat surface and non-zero impact parameter collisions between ice balls on two adjacent pendulums would be easily set up; a situation not possible on earth.

3.2.3 Plasma-Dust Interaction

The interaction of dust particles (micron to sub-micron size) with plasma (dusty plasma physics) has generated a considerable amount of interest since the Voyager mission to Saturn. Although still in its infancy, a large amount of theoretical work has been done in the past few years to explain such phenomena as the spokes in Saturn's rings, the "braids" in the F-ring of Saturn, the dynamics and morphology of a number of other rings including those of Jupiter, the emission of dust from comets at large heliocentric distances, the striae in cometary dust tails, *etc.* These calculations are generally single particle; however, interactions between the dust particles themselves must also be considered. Theoretical work addressing this problem has begun. For instance, the charge that will accumulate on an isolated dust grain is quite different from that when other grains are nearby. It has also been postulated that a dust disk orbiting a central body, and providing a current through the surrounding plasma, may degenerate into ringlets via the tearing-mode instability. Since different sized particles have different charges and hence different orbital velocities, each ringlet may be conducive to forming larger and larger grains.

A microgravity environment is needed for study of these processes, because in an earth-based setting, dust particles fall out of plasmas. The charging time to reach equilibrium conditions (*e.g.*, the potential on a given grain) depends upon various plasma parameters and dust characteristics (especially size). These charging time scales can range from milliseconds to days, the entire range being important to solar system conditions. The fact that the charged particles may grow in size compounds the situation on earth, thus further justifying the need for microgravity.

3.2.4 Aggregation of Finely-Comminuted Geological Materials

Extremely finely-comminuted geological materials are injected into the atmospheres of planetary bodies by three principal mechanisms.

1. Volcanic eruptions (especially phreatomagmatic)

2. Aeolian entrainment (dust storms)

3. Meteorite impact.

Both the residence time of injected material in an atmosphere and the method by which this material is ultimately precipitated to the ground have important geological, atmospheric/climatological, and biological implications.

Volcanic and meteoritic (and to some extent aeolian) events actually cause the comminution: they are responsible for both the production of dust and its immediate injection into an atmosphere. Extremely fine, "freshly"-disrupted materials tend to be highly charged electrostatically and there are probably few (if any) exceptions to the tendency for this charging to produce aggregation of materials. Both the rate and the mode of aggregation will influence the rate at which an atmosphere is cleansed of suspended dust. At the present time, we have limited knowledge of how this aggregation may occur, the size to which aggregates can grow, the electrical charges involved and the types of materials most prone to charging.

Triboelectric effects occur simultaneously with comminution processes and it might be expected that an increase in charging due to friction will correspond to an increase in charging due to breakage. Material comminuted in wet environments would not be expected to retain significant charging, although little is known about the acquisition of charges upon drying of the material. It is pertinent to note at this point that silt and clay size pyroclastic material that has resided in ground water for many thousands of years is commonly found to be highly charged after drying, although it would be speculative to attribute this charging to the initial volcanic event that generated them.

The present concern is with unconfined aggregation of these charged particles while they are present in the atmospheric medium. Subaerially erupted pyroclastic particles are, of course, injected directly into the atmosphere. So too, are comminution products of meteorite impact. Charged particles from subaqueous or subglacial environments become injected into the atmosphere through aeolian action that may occur around a receding ice sheet or ephemeral stream system. Wind also picks up loose comminution products from weathering mantles that may be electrostatically charged prior to aeolian entrainment.

Laboratory-crushed material probably has some similarities to volcanically or glacially comminuted material. Crushed glassy basalt injected by an air pulse into a settling column produced the following effects: after approximately 30 seconds of suspension of the fine dust fraction, visibility through the column improved rather suddenly and was accompanied by a "rain" of filamental aggregates about the thickness of hair, and with lengths commonly exceeding 2-3 cm. In addition to filaments, aggregates formed extremely thin flakes of irregular outline up to 0.5 cm in diameter. Aggregates on the floor of the column were spheroidal, as were minute globular attachments to some of the filament ends.

In volcanic eruptions that vertically eject large quantities of finely-comminuted material, the gravitational collapse of the ejecta column can produce rapid (and devastating) out-surging of material for distances of several tens of kilometers. The velocity and density of these pyroclastic surges and flows is in part a function of the column collapse rate. It is well known that eruption columns are highly charged electrostatically and the possibility therefore exists that the collapse rate is a function of aggregation of fines into relatively large clumps of material that fall more rapidly than their individual components. It is difficult to determine the role of aggregation in the field, since the aggregates will be destroyed during impact with the ground.

Aggregates of pyroclastic material are commonly observed in ash-fall deposits and, again, aggregation may be a significant factor in determining the rate of atmospheric cleansing and thus the distance over which ash is distributed.

Aeolian dust storms embody the same potential for control of fallout rates and distribution distances by aggregation of atmospherically-suspended particulates. The method by which an atmosphere is cleansed of aeolian dust is of significant interest for both Earth and Mars. Dust storms on Mars are presently a significant geological phenomenon. In the recent past on Earth, dust storms initiated in the periglacial regions of receding ice sheets were responsible for the loess accumulations of North America, Europe and Asia. Loess has also been attributed to aeolian material brought from deserts. Understanding aggregation in this context will not only set limits to dust concentrations, but may also provide insight into the provenance of the material since aeolian and glacial comminution products may respond differently to aggregation.

Aggregation of windblown particulates may also occur close to the ground where dust concentrations are greatest. This particular possibility is relevant to the entrainment, transport and removal of clay fractions from large tracts of agricultural land in the U.S.

It has recently been suggested that meteorite impacts in the geological past have led to the extinction of certain species of animal life. This annihilation is attributed to climatic changes brought about by relatively long-term suspension of the comminution products of impact. Without doubt, the comminution products would be electrostatically charged. It is therefore important to be able to set limits on the concentration and longevity of such dust clouds by experimentation with the aggregation of suddenly-comminuted materials. An understanding of aggregation in this particular case would also have relevance to the potential extinction of the human species by the postulated mechanism of a "nuclear winter".

Generating aggregates in an Earth-based, laboratory-confined dust cloud is relatively straightforward. However, the process is difficult to observe (even with high-speed photography) because as soon as an aggregate develops to a reasonable size, it falls from view to the floor of the apparatus.

Further, this uncontrolled descent tends to destroy the delicate aggregate structure on impact, and at the very least, presents a problem in retrieving single aggregates for study.

Motion of an aggregate relative to the gaseous medium is also undesirable because of its potential influence in determining the shape, size and structure of the aggregate and the interaction of the aggregate with its neighbors. Air currents could not, therefore, be used to artificially maintain suspension of aggregates in the medium since this introduces an additional variable to the system whose effect cannot be isolated from the role of interparticle forces.

A microgravity environment would permit the following:

1. Study of aggregation purely as a function of interparticle (principally electrostatic) attraction.

2. Study of virtually stationary subjects.

3. Sufficient time for useful observations to be made. Implicit in this is the ability to observe upper limits to growth. Larger samples also permit greater ease of observation.

4. Ability to collect suspended aggregates without disruption caused by impact with the ground.

The long time required to conduct a single experiment precludes the use of aircraft to simulate microgravity. The complete test matrix would also require a total time in excess of that available for typical Shuttle flights. Earth-orbital (Space Station) facilities would be most appropriate.

The overall objective of the microgravity experimental program outlined here is to acquire an understanding of the way in which finely comminuted materials aggregate within, and ultimately precipitate from, planetary atmospheres.

The study would provide knowledge of the following:

1. Rate of aggregation.

2. Mode of aggregation (shape, packing density and particle orientation).

3. Size to which aggregates can grow within the confines of a fixed supply of dust.

4. Interaction of one aggregate with another.

5. Type and size of material most prone to aggregation.

6. Dependency of aggregation on initial dust-cloud density.

7. The role of the comminution process in aggregation (e.g., crushing versus explosive generation of dust).

With knowledge of the above, attempts can be made to address questions such as the following:

1. To what extent does aggregation play a role in "closing-down" both martian and terrestrial dust storms?

2. Does aggregation cause the sudden and catastrophic collapse of volcanic eruption plumes (which ultimately gives rise to pyroclastic surges spreading great distances from the eruption site)?

3. Could meteorite impact or other explosions on a terrestrial body give rise to global shielding of solar input (with biological implications for Earth) or would aggregation tend to cleanse the atmosphere when critical dust densities were exceeded?

4. To what extent does the rate and nature of aggregation control the global distribution of loessic deposits on planetary bodies such as Mars and Earth?

The experiments envisaged above would benefit from comparative tests conducted at 1 g. Both orbital and "ground" test matrices would include different types of material, different methods of initial comminution, different size ranges for the particles and variable experimental times. Tests would also be conducted for a range of atmospheric pressures varying between vacuum and 1 bar which is appropriate for the range of conditions encountered on Mars, Earth, and other terrestrial bodies (including satellites of the outer planets).

Sample aggregates would be examined with optical and scanning electron microscopes (SEM) to determine aggregate shape, size, packing, and particle orientation. Backscatter and X-ray capabilities of the SEM would be used to ascertain any selective mineralogical accretion or particle orientation.

3.3 Required Capabilities of an Orbital Facility

1. Volume: to accomodate an environmental chamber and supporting equipment. Two standard electrical rack volumes are considered adequate. One rack would be entirely devoted to the environmental chamber, its enclosing glove box, and attached thermal and optical probes *etc.* The second rack would contain power supplies, gas reservoirs, vacuum pumps, controls, indicators and gauges, sample storage, microscopes, *etc.*

2. Environmental Integration: The 2-rack facility has many power requirements that will generate heat. This must either be dissipated by the system itself, or accommodated by the environmental controls of the module. The facility also handles fine dust and (possibly) toxic gases, and must therefore be capable of confining potential environmental contamination without loss of technical flexibility.

3. Process Control: The facility must be capable of providing sustained microgravity of the order of 10^{-5} g with minimal perturbations. Samples under investigation must be suspended in a chamber of sufficient size to essentially eliminate the attractive or repulsive forces (*e.g.*, electrostatic) of the confining walls. The experimental process should be capable of generating temperatures between 600 K (for decontamination baking of the walls) and 80 K (for simulating the Space environment). The facility should support pressures ranging from vacuum to a few atm, and the capability to control the gas composition.

4. Production: Some materials such as fragile dust/ice balls will require *in situ* production with all the appropriate instrumentation (molds, manipulators, etc.)

5. Handling: The system must be capable of positioning, launching, manipulating and tracking fragile ice/dust composites and other materials with extreme precision. It must also be capable of injecting and controlling dust clouds in the environmental chamber.

6. Monitoring/Inspection: Samples in the environmental chamber must be monitored during an experiment which requires continuous illumination; cameras, lenses, and viewing ports capable of imaging fine dust and cm-size objects; and instrumentation provided with continuous output for temperature, pressure, gas content, sample position, sample concentration, gravitational (and other) acceleration, electrical fields, *etc.* Samples must also be removed from the chamber and examined with various instruments such as microscopes after experimentation, and this maneuver must also take account of the potential for environmental contamination.

7. Cleaning: The capability must exist for cleaning the experimental chamber, decontamination, and disposal of used gases and particulate samples.

8. Hardware Requirements:

(a) Basic Facility: The core of the envisaged facility is an environmental chamber into which both gases and particulates can be injected. Chamber volume should be approximately 1 m^3. Because of the potential for contamination of the environment in the space module either by gases or particles, the process chamber should be enclosed in a glove box. Experimentation and later scientific input will undoubtedly lead to a desire to make changes or additions to the basic unit: it is therefore imperative that the system be designed with maximum flexibility and the following requirements should be viewed as minimum requirements.

Chamber characteristics:

i. Volume approximately 1 m^3
ii. Enclosable by glove box
iii. 5m extension tube for use as a launching route
iv. Viewing ports (7) 1 vertical, 6 in horisontal plane at 0°, 45°, 90°, 180°, 225° and 270°
v. Access ports. One should be at least 30 cm in diameter. Required for introduction of samples, cleaning of chamber, insertion of equipment.
vi. Heated walls that serve as a temperature control for the environment and as a means of baking-out contaminants from the walls if hard vacuum is required.
vii. Cooling lines for cryogenic system attached (Temperatures down to 80 K)
viii. Vacuum access lines either to pump or space
ix. Gas supply lines and venting lines for certain gases
x. Wall-enclosed electrostatic field generators
xi. Illumination
xii. Thermocoupled probes
xiii. Many electrical pass-throughs
xiv. Dust feed line from sample hoppers

(b) Support Systems

i. Cryogenic cooling system
ii. Vacuum generation – either pump inside module or valving to outside
iii. Compressed gas bottles/regulators
iv. Sample containers and storage system
v. Cameras – fast frame and video high-speed motion camera high-resolution lenses
vi. "Housekeeping" equipment – disposal containers for dust, vacuum pump extension hose with filtration system for cleaning chamber, cylinders for used gases with pump to recompress the gases, antistatic cleaners, *etc.*

(c) Process Controls and Instrumentation

i. Gas supply controls and pressure indicators for both gas reservoirs and chamber
ii. Vacuum pumping controls and vacuum gauge
iii. Heating power controls and temperature indicators
iv. Cooling controls and temperature indicators
v. Gravitimeters measuring accelerations in several planes

(d) Experiment-Specific Equipment

i. Microscopes – optical essential, scanning-electron optional
ii. Nephelometer
iii. Optical dust-concentration measuring device
iv. Electrometers
v. Mechanical projectile launchers
vi. Sample preparation molds for ice balls
vii. Uniaxial bearing strength testing equipment

viii. **Dust injectors and dispersers**
ix. **Strobe light**
x. **Pendulums**
xi. **Motorized translation stages**
xii. **Mechanical manipulators**
xiii. **Recording devices**
xiv. **Power supplies**
xv. **Microcomputer**
xvi. **Electrical actuators**

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Chapter 4

Atmospheric Science

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4.1 Introduction

The atmospheric science subgroup considered a number of possible experiments which might be carried out under low gravity conditions. These experiments were considered in the light of two basic questions: (1) Why carry out these particular experiments? and (2) Why carry them out in space? The reason for asking the first question was the feeling that any proposed experiment should answer an important open question in atmospheric science and should be expected to yield significant results. In some cases, however, a proposed experiment may not answer pending questions, but will open up new areas of research not available to investigators in an earth gravity environment (an example of this is the study of liquid-liquid separation phenomena). The second question highlights the fact that we should only consider experiments which cannot be carried out under normal earth gravity. The members of the group were quite aware of the high costs and extraordinary difficulties associated with experiments in space. An underlying theme of the discussion was, "If it can be done on Earth, it should be done on Earth."

A number of experiments were described and discussed by the participants and are listed below. The experiments included in this report are not intended to be a comprehensive or final list of the important atmospheric particle experiments to be carried out in the Space Station. By the time a low gravity facility is available, other experiments unenvisaged by us may well have priority. Nevertheless, these experiments are representative of the types that atmospheric scientists will wish to perform, and it is reasonable to assume that the constraints on the experimental set-ups will not be considerably different from those discussed here. Consequently, the facilities required for these experiments will almost certainly be appropriate for future atmospheric experiments involving particles.

Of particular interest to atmospheric scientists is the formation of clouds, fogs, and aerosols. A low gravity facility is of particular value to cloud physicists because clouds and cloud particles can be studied without the effects of convection and particle settling. Individual particles and populations of particles can be studied for long periods of time. An especially important project is the analysis of very large drops. These cannot be generated in the presence of gravity due to spontaneous break-up. Clouds cannot be duplicated in the low gravity environment because their development depends on gravity and convection, however, one can isolate certain processes that are not controlled by gravity and study these processes over long periods of time. Similarly, processes occurring in atmospheric aerosols such as coagulation, growth, and chemical reactions, can be studied without strong gravitational influences and this will shed light on the basic physical processes which are taking place.

These experiments cannot be carried out on Earth because they require that no convection take place. Furthermore, these experiments require low gravity to produce long suspension times. The experiments will shed light on important areas of concern, including cloud growth, scavenging of atmospheric aerosols and an understanding of planetary cloud optical properties.

4.2 Suggested Experiments for Space Station

4.2.1 Growth of Liquid Water Drop Populations

Theory predicts that the size distribution of a population of liquid water droplets will become narrow due to continued condensation. Various processes, such as radiative cooling/heating, *etc.*, may affect the actual development of the size distribution. On Earth, the experimental determination of the time development of a droplet population is affected by sedimentation in which the larger droplets are continually being removed to a different region of space, not only changing the size distribution at a point (by removal of large particles) but also changing the size distribution by the coalescence of smaller particles with the sedimenting larger particles. Furthermore, the condensation process is accompanied by the liberation of latent heat. In a gravitational environment this generates convection which will also affect the droplet size distribution. The growth of a population of cloud droplets is of particular interest in understanding the formation of rain in warm clouds.

4.2.2 Coalescence (not collision)

Most experiments in 1 g measure collection which is the product of collision and coalescence efficiencies. However, most experiments cannot separate collision from coalescence. When only coalescence is measured in 1 g, the drops are normally suspended from a support which inhibits some of the natural deformations and oscillations. In addition, only relatively small drops (<2 mm radius) can be used in these experiments which makes it difficult to observe the deformations. A micro-gravity environment is a very suitable place in which to study the coalescence of any size drop. Using very large drops, it will be possible to study the drop deformation prior to contact and the mechanism by which first contact is made. By using different size drops, one may be able to extrapolate down to smaller drops such as those found in clouds.

4.2.3 Drop Breakup

The breakup of drops due to collision can be studied with large drops. This will permit a better evaluation of the hydrodynamic effect occurring during the merger and subsequent separation of the drops than is presently known. The size distribution of the breakup fragments can be studied as well. Such an experiment could be very important for the understanding of the development of rain drop spectra between cloud base and ground.

4.2.4 Breakup of Freezing Drops

It has been suggested that ice multiplication (or ice enhancement as it is sometimes called) results from the fragments of ice which are ejected from freezing drops. A microgravity environment is ideal for studying this phenomenon as the number of fragments ejected from the drops can be analyzed. The effect of the supersaturation around the freezing drop on the interstitial aerosols can be studied as a function of time.

4.2.5 Ice Nucleation for Large Aerosols or Bacteria

Large aerosols are difficult to suspend in cloud chambers. In microgravity it would be possible to determine whether large particles (even large ice nucleating bacteria) act as condensation-freezing or as deposition nuclei when exposed to a water saturated environment.

4.2.6 Scavenging of Gases (e.g., SO_2 oxidation)

By floating large drops for long periods of time, SO_2 absorption can be studied. Similar experiments with smaller drops (smaller than 50 μm) could very well duplicate the occurrence in 1 g, since the fall speed of small drops is small. Even though some convection mixing occurs, the diffusion of the reactants to the drops is sufficient to keep up with the relatively slow oxidation rate.

4.2.7 Phoretic Forces: Thermophoresis Versus Diffusiophoresis

In an environment where a temperature gradient is present, aerosol particles will experience thermophoretic forces due to the difference in the momentum transferred by gas molecules impacting them from both the warm and cold sides. Therefore, aerosols will move down the temperature gradient, toward the colder region. A diffusiophoretic force is the one given to an aerosol particle due to concentration gradients in the gaseous mixture. During condensation, the diffusiophoretic forces will cause aerosol particles to move towards the condensing surface. On the other hand, the release of latent heat will raise the surface temperature driving the aerosol away from it due to the thermophoretic forces. Some experiments show that thermophoretic forces dominate. Therefore, when ice and water co-exist and ice grows at the expense of the drops, it is expected that interstitial aerosols will move to the evaporating drops. However, some experiments report a dust free region around evaporating drops, suggesting that diffusiophoresis dominates. Similarly, when ice crystals, suspended from a fine fiber, are allowed to flow, aerosol particles are collected on their surfaces. The lack of agreement among experimenters may be a direct result of the heat conducted away through the fiber supporting the drop or the ice crystal. The conduction of heat away from the surface reduce the temperature gradient and hence reduce the thermophoretic force, making the diffusiophoretic force dominant.

An experiment in microgravity conditions could resolve this question by having ice crystals, water drops and aerosol particles all floating in a water saturation environment. The concentration gradients and velocities of the aerosol particles could be measured with the aid of a Doppler laser or by other means. It is important to note that these phoretic forces are useful in the scavenging of the particles that are too large to be affected by diffusion and are too small to be captured by gravitational impaction.

4.2.8 Rayleigh Bursting of Drops

This process is thought to be the trigger to lightning. Here drops are charged to the limit at which they burst. This limit is achieved when the electrical stresses just equal the surface tension forces. There is some evidence to suggest that drops larger than 7 mm diameter will disrupt when their surface tension energy is exceeded by their electrical energy. This will also happen to very small droplets. For drops in the size range from 50 μm to 7 mm, corona discharge precedes breakup. In 1 g large drops cannot be studied since they cannot be produced, while small ones disrupt too easily. With microgravity we have the opportunity to study large drops and their disruption.

4.2.9 Charge Separation Due to Collisions of Rimed and Unrimed Ice

In this experiment a large ice crystal, previously grown by rime, would be introduced into a cold chamber and floated. Small diffusionally grown ice crystals would be forced to impact the floating one. Once rebounded, all crystals could be captured in a Faraday cage for analysis of the charge that has been separated. The microgravity condition makes it possible to float nonspherical crystals and analyze them after impact with other crystals. Since this kind of charging is thought to be the main mechanism of charge separation in thunderclouds it is important to test it with different crystal sizes and under different temperatures.

4.2.10 Coalescence

Coalescence is the process by which particles with differing velocities impact one other and unite to form a larger particle. This process is essential to the formation of rainfall and lightning as well as to the removal of particles in dense clouds such as those from larger fires or volcanic eruptions. Unfortunately, these interactions are so complex that no theory exists which is adequate even for spheres of all sizes. Indeed, various theories strongly disagree with one other and with data. The experimental data base is also strongly restricted.

When particles of moderate size approach one other, their coalescence may be inhibited by hydrodynamic interactions. For example, a small particle may simply follow the flow field around a larger one and never make physical contact so that coalescence fails to occur.

Unfortunately, experiments to study coalescence are very difficult on earth. The difficulty is partly due to the inability to easily observe particles falling in the earth's gravity field because they move across the sampling chamber so rapidly. Suspending the particles in the gravity field is unsatisfactory too, because it leads to changes in the flow fields. The experimental difficulty is also partly due to the fact that turbulent coalescence cannot be easily separated from gravitational coalescence because one cannot eliminate the gravitational interaction. Also, one cannot examine a large range of collision velocities because on earth, the velocities are fixed by gravity. All of these problems might be eliminated by performing studies in a microgravity environment.

We envision studying turbulent coalescence, coalescence due to differential velocities, and Brownian coalescence and the interactions between each each of these processes as functions of particle velocity, density, and particle shape. The major advantages of doing this in space is that the particle differential velocity can be controlled, and the particles can be easily contained while the experiment is being conducted.

4.2.11 Charged Drop Dynamics

In charged drop dynamics we are interested in vibrational and rotational dynamics and the stability characteristics of the drop. Furthermore, we wish to explore Rayleigh bursting, corona discharge and other such phenomena at all levels of charges on the drop.

The electrohydrodynamical problems have been computer simulated primarily by Scriven, Brown and coworkers. The results of these studies are waiting for experimental verification.

In order to carry out charged drop dynamics experiments it is necessary to position a large drop at a desirable position, and its charge levels and surface tension should be accurately measured or monitored. Any levitation force in 1 g (either electrostatic or acoustic) creates large perturbations to the system which in turn creates great theoretical difficulties in interpreting the results.

Knowing the fundamental dynamic characteristics of a charged liquid drop will lead to a clear understanding of electrohydrodynamical problems in cloud physics, shell technology (core centering effect, *etc.*), aerosol physics and the scavenging of aerosol.

4.2.12 Growth of Particles in Other Planetary Atmospheres

In addition to usefulness of a microgravity environment for studying the properties of stratospheric (H_2SO_4) and tropospheric (water) clouds on the Earth, an even wider range of questions can be addressed with such a facility regarding the clouds that occur on other planets. Recent space missions have revealed the presence of bright zones, and darker belts of troposheric clouds on Jupiter and Saturn. Stratospheric aerosols have also been observed on these planets and on Titan. Equilibrium chemical models suggest that the uppermost layer of tropospheric clouds on Jupiter and Saturn consist of NH_3 ice crystals, but this suggestion remains to be confirmed by spectroscopic observations. Even if ammonia is a major constituent of these clouds, it cannot be the only constituent as pure ammonia ice clouds would be white at visible wavelengths in contrast to the color observed on these planets. Similarly, several constituents have been suggested for the photochemically produced stratospheric aerosols on these planets including polyacetylenes, N_2H_4, and P_2H_4, but a definitive identification remains to be made. For these planets even the basic composition of the cloud and aerosol particles are still uncertain. A host of other questions concerning the vertical and horizontal distribution, shapes, crystal types, production and transport remain to be answered.

A considerable amount of indirect information that bears on these questions has been collected in measurements of the photometry and polarimetry of the sunlight reflected from the Pioneer and Voyager missions, and more such data are anticipated from the Galileo orbiter and probe. Scattering calculations have been used to convert the observations of multiply-scattered light to constraints on the single-scattered phase function and polarizing properties of these cloud particles. However, because the cloud particles exist as solid crystals rather than as spherical liquid droplets at the low temperatures on the outer planets, Mie scattering calculations cannot be used to convert their single-scattering optical properties to constraints on their size distributions and refractive index. Rather, a systematic program of scattering measurements of candidate cloud particles is needed for comparison with the existing observations.

Some preliminary measurements of the crystal habits of ammonia ice as functions of temperature and pressure are just now beginning to be made. These measurements must:

1. Map the crystal habits formed by ammonia and other candidate materials as functions of temperature and degree of saturation.

2. Simultaneously measure the optical scattering properties of these particles (intensity and degree of polarization) as functions of scattering angle (preferably at more than one wavelength).

3. Provide a high-resolution record (photographs) of the crystal shape and size distribution whose optical properties have been measured.

4. Extend over a range of temperature appropriate for Jupiter and Saturn (down to 80 K).

The program of measurements currently under way has produced some important results for some range of conditions, but also suffers from fundamental limitations. A real cloud of large particles (including a range of particle sizes and orientations) is difficult or impossible to measure because the particles fall out before they grow to large sizes. Measurements in a low-g environment would eliminate this fundamental difficulty.

Further, because the production rates for producing photochemical smog particles tend to be lower than setting rates, this material can accumulate in the bottom of the chamber instead of producing a cloud of aerosols whose scattering properties can be measured. Existing studies have been limited to calculations for spherical shapes using the properties of samples from the bulk material scraped from the bottom of the reaction chamber. Production in a low-g environment would permit scattering measurements to be made of aerosol particles as aerosols before they settle on the chamber walls.

4.2.13 Freezing and Liquid-Liquid Evaporation

Unless efforts are made to ensure equilibrium, phase changes (*e.g.*, condensation, boiling, crystallization) involve the nucleation of the new phase. All nucleation processes have a random component. Thus, if one cools a particular drop it will subcool to slightly different extents each time. However, a large population of drops will have the same freezing temperature distribution each time one subcools it. For this reason one tries to devise experimental approaches that study large populations. Unfortunately, this is not always possible.

One example of a phase transition that is difficult to study on Earth is the effect of charge on the separation of a liquid mixture into two separate liquids as cooling occurs (*i.e.*, liquid-liquid nucleation). The two liquids always have very different densities. As a result, as soon as the phase separation occurs, the liquids separate. One needs to then mechanically re-mix the system since diffusion velocities in liquids are very small. This method imposes enormous additional difficulties. In addition, it is not possible to study the growth and aggregation of the charged particles. Microgravity will greatly reduce the difficulties since the rate of fall of the dense component will be much smaller. One can thus detect the nucleation by light scattering, then reheat the liquid and allow diffusive mixing to take place.

4.3 Required Capabilities of an Orbital Facility

To carry out these experiments which are important to the study of atmospheric science will probably require more than one experimental chamber or an adaptable chamber. For example, for light scattering (*i.e.*, optical properties) of aerosols, it is most convenient to have a chamber with many windows, or even better, a continuous window running all the way around the circumference of the chamber. On the other hand, to maintain a saturated environment within the chamber, the window area should be reduced as much as possible.

The chamber need not be too large. Although wall effects may be an important constraint, particle stabilization can probably be effected by electric or acoustic techniques. Consequently, a chamber of the order of 250 cm^2 by $\sim$50 cm in depth would probably be sufficiently large for most experiments.

Provisions should be made for optical sensor and photographic equipment to be integrated with the experimental chamber. In addition, the chamber should allow for a controlled humidity and temperature (from about 80 K to 300 K). There should also be the possibility of carrying out high temperature experiments. For heterogeneous chemistry experiments, appropriate chemical apparatus will be required. The mechanical removal and insertion of particles should be possible, and the chamber should be easily connected to an aerosol generator.

Requirements of these types of studies on a microgravity particle measuring facility would include:

1. Provision to cool a chamber to temperatures as low as 80 K and maintain it at specified low temperature gradients.
2. The presence of a double cylindrical window in the chamber to permit scattering measurements over a range of scattering angles (10° to 165°).
3. Provision to record the size and shape of crystals in the chamber to as small a size as possible (1 m).
4. Light sources at several wavelengths (at least red and blue) to illuminate the crystals, a system to control the polarization state of the incident beam and a set of detectors spaced at angles to make the scattering measurements.
5. A gas handling system for admitting controlled amounts and mixtures of gas.
6. Windows and UV lamps for producing photochemical aerosols.

Probably such a low-temperature chamber would be distinct from a high temperature facility which could be used to study condensation of refractory materials. It is also possible that three distinct types of chambers are desirable to allow for three different types of experiments:

1. High temperature refractory condensation ($T > 1000$ K).
2. Water liquid and ice cloud physics studies ($-50°C < T < 20°C$) possibly without any scattering measurements.
3. Optical scattering measurements ($80 \text{ K} < T < 290 \text{ K}$).

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Chapter 5

Exobiology and Life Science

C.P. McKay

5.1 Introduction

Exobiology is the study of life in the universe. It is concerned with the origin and distribution of the biogenic elements (C, H, N, O, P, S) and the relationship between the physical and chemical evolution of the solar system and the appearance of life. It is clearly an interdisciplinary field and there is much overlap with the disciplines represented in other chapters of this report. However, exobiology brings a different perspective to the astro-geophysical phenomenon discussed herein. Often this perspective involves the study of a trace constituent (*e.g.* the organic component of meteorites) or minor chemical processes (*e.g.* the abiotic production of organics by lightning).

Many of the current research problems in exobiology concern the behavior of small grains and particles. The processes that govern the interaction of these grains occur in environments that cannot be adequately simulated on earth because of the presence of gravity. Nonetheless, laboratory simulations are desirable since they provide a powerful tool in studying the behavior of cosmic systems for which there are no terrestrial analogs. The Space Station provides a long-term microgravity environment in which to do experiments that would otherwise be impossible. Several exobiology experiments are described in this chapter that rely on the Space Station. This list is not meant to be definitive, only suggestive, of the type of research that can benefit from microgravity.

5.2 Exobiology Microgravity Particle Experiments

5.2.1 Biogenic Elements in the Interstellar Medium

Exobiology begins with the formation of the biogenic elements in the stars *via* nucleosynthesis. As the star evolves, these elements condense in the cool extended stellar atmosphere or are ejected into the interstellar medium. The mineral phase and physical characteristics of the condensation products of these elements (of particular interest is C) are poorly understood. Laboratory simulations in 1 g to characterize the condensation of carbon in the interstellar medium or stellar atmospheres would be impractical due to wall effects. In a microgravity facility, the problem is greatly simplified and meaningful experiments can be done. A stream of the vapor that is of interest would be injected into the chamber and the temperature cycled gradually, possibly over a periods of many days or longer. Small condensation particles that form would be held in the center of the chamber by gentle acoustic or optical levitation techniques. At 10^{-5} g the forces required would be negligible. The particles can be studied optically with scattered laser light and samples can be removed for detailed analysis (*e.g.* SEM, pyrolysis).

In the strange environment of interstellar clouds complex organic molecules have been detected (C_9 and above). The reactions that form these complex molecules presumably involve surface reactions on the interstellar grains. The presence of organic molecules in interstellar space may have implications for the origin of life on Earth. Studies of the chemical reactions that form the organics observed in interstellar clouds would also require long particle suspension times. Grains of material could be placed in the chamber under controlled temperature (~25 K) and high vacuum conditions, then irradiated with UV light. Microgravity suspension is required since surface reactions play an important role in the experiment.

5.2.2 Organic Material in the Solar Nebula

During the collapse of the solar nebula and the formation of the solar system the fate of the interstellar organic matter is uncertain. As discussed in Chapter 2, there are a number of experiments that could be done on the Space Station that would provide information on the thermodynamical and hydrodynamical state of particles and grains in the solar nebula. The implication of these processes for the survival of organic material in relevant to exobiology. Understanding these processes is necessary in order to trace the history of organic matter on the terrestrial planets and the importance of abiological sources of organic matter in the primitive solar system. Was there significant abiologically produced organic matter throughout the solar system as remnants of the primordial solar nebula or was the abiological production of organic matter restricted to the primitive earth?

The experiments would involve the production of "interstellar" grains that include organic material for use in nebular simulations. Gas chromatographic techniques and isotopic analysis of samples removed at periodic intervals could trace the evolution of the organic material.

5.2.3 Volatiles in Comets and Icy Planetesimals

It is believed that comets provide probably the best examples of undifferentiated solar system material. Current theory suggests that comets were formed well beyond the orbit of Saturn and have spend most of the last 4.5 billion years since the formation of the solar system in the Oort cloud, many hundreds of A.U. away from the sun. Spectral observations of comets suggest that they are composed of ~50% volatile material, including water and carbon dioxide. Hence they may have played an important role in distributing the biogenic elements among the forming planets of the early solar system. While pristine comets may represent undifferentiated primordial solar system material, once a comet enters the inner solar system its volatiles begin to sublime. The outflowing gas can readily escape the comets slight gravitational field and carries at least some of the dust component along. The spectacular gas and dust tails of comets as they approach within about two A.U. of the sun are direct evidence of this evolution. To determine the contribution of comets to the volatile inventories of the terrestrial planets it is necessary to have a detailed understanding of the physical processes on a comets surface during its passage in the inner solar system.

Migration of Volatiles — As a comet approaches perihelion its surface temperature rises and ices on and near the surface begin to sublime. These gases escape to space and form the comet's brilliant coma. However, if a mantle is present, inhibiting the flow of gas through the surface, it is possible that some volatile material migrates to deeper (and colder) regions of the comet. Modeling studies have demonstrated that mantle thickness is a function of solar insolation (which sets surface temperature). Far away from the sun the mantle can be quite well developed while very close to perihelion the mantle may be blown off by the large vapor pressure of water. Molecules that sublimate at temperatures below the point at which the mantle is removed may preferentially concentrate in the comet core by this "cold-cracking" processes. This is particularly relevant for organic molecules with low vapor pressure.

Isotopic variations — The diffusion and bulk flow of gases through the porous cometary nucleus and through the mantle may result in elemental and isotopic variations that could provide clues to the history of organic material within a comet. Such isotopic and elemental fractionation could have implications for understanding the distribution of the biogenic elements in the solar system.

Applicability of Earth-Orbiting Facilities — The surface gravity on a cometary surface is extremely low ($\sim 10^{-4}$g). This undoubtedly has a profound influence on the processes described above and makes accurate simulation impractical on Earth. Structures of cometary material would be distorted, and possibly collapse under their own weight at 1 g. In a Space Station facility it would be possible to produce a small icy ball of dust and ice with trace organic materials mixed in. By exposing the ice ball to a heat source, sublimation and mantle formation could be simulated. The migration of the volatile organic material and the isotopic fractionations that occur as a result could provide a basis for modeling comet behavior.

5.2.4 Pre-biotic Atmospheric Chemistry

Since the classic work of Miller and Urey it has been recognized that abiological processes would have produced organic material in the atmosphere of the primitive earth. Recently the discovery of CH_4 and nine heavier hydrocarbons in the atmosphere of Titan has reinforced the notion that important prebiological processes are occurring in planetary atmospheres. One very interesting product from these experiments is the bark brownish solid organic material termed ***tholin***. It is probable that the upper atmosphere of Titan has an optically thick layer of these organic haze particles. Unfortunately it is not possible to simulate the production of the haze particles in the laboratory due to the fact that small particles collide and stick to the walls of the production chamber. In a microgravity experiment tholin production could be accomplished by focusing a pulsed laser beam into the target gas mixture. (This has been shown to be a good simulation of lightning in planetary atmospheres.) In a manner similar to that described above for studying C condensation, the formation of tholin aerosols could be investigated.

5.2.5 Analysis of Cosmic Dust Particles

One of the key goals of exobiology is to understand the origin and distribution of the biogenic elements. Direct sampling of particles that represent primitive solar system material (*e.g.* dust from comets) and collection of interstellar dust particles would therefore be of strong interest.

An experiment has been proposed that would collect dust particles (typical size 1 μm in radius) while in orbit at the Space Station. The collector would non-destructively decelerate the particles and simultaneously determine their mass, velocity and direction. This complete description of the particle trajectory would allow determination of the origin of the particles (*i.e.* cometary, interstellar, *etc.*). The collector would be attached to the outside space station and would require a minimal amount of maintenance.

One use of a Space Station microgravity particle facility would be for on-site analysis of these particles.

5.3 Other Life Science Experiments

5.3.1 Microbial Exposure

Understanding the potential for survival of terrestrial microorganisms provides fundamental information about the microorganisms under study and in addition can be used in two areas of interest to exobiology: *(a)* determination of quarantine requirements, and *(b)* scientific evaluation of the hypothesis that life was carried to earth from elsewhere in the cosmos (*i.e.* panspermia).

The objectives of the series of experiments suggested here are to expose a variety of terrestrial microorganisms to the space environment (including radiation, vacuum, microgravity and temperature extremes) and determine the effect on their survival and growth.

Some research along these lines has been carried out in Spacelab and in the Long Duration Exposure Facility and could be continued under more controlled conditions in a Space Station facility

5.4 Required Capabilities of an Orbiting Facility

The experiments discussed above could each be accommodated with a total volume of $\sim$3 m^3. The particle handling equipment and environmental control required is not excessive and would most likely be similar to that used by other experimenters.

Many of the experiments involve observing the formation of aerosols condensing from a gaseous material. To monitor this processes effectively would require sensitive particle counting and measuring instrumentation. In addition some of the exobiology measurement requirements are unique in that exobiology experiments would require gas chromatographs and other analytical instruments for determination of organic compounds.

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Chapter 6

Physics and Chemistry

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6.1 Introduction

Four sets of experiments are described that use either the reduced gravity or the large pumping speeds and vast reduced pressure domains available on or outside the station. The scientific rationale for each of the four sets is contained in the individual descriptions that follow below. In addition, we propose an analysis facility with surface analysis instrumentation that in our view would be crucial onboard the Space Station. Although our suggestions by way of experiments are quite specific, we recognize that with a ten year lead-time many details will necessarily change in the interim and our specificity is to be regarded only as an attempt to give our proposals substance, realizing that what we are proposing are classes of experiments.

We also realise that there is considerable overlap with the science and most certainly with the technology required by other disciplines. For example, experiments regarding the formation and stability of planetary rings clearly overlaps with the two projects involving assemblies of inelastic frictional particles of this section. Likewise, the light-scattering technology needed in some of the experiments proposed in the astrophysics chapter will be essential in ours.

6.2 Suggested Experiments for Space Station

6.2.1 Rheology of Assemblies of Inelastic, Frictional Particles

The rheologic properties of granular solids is important in a wide variety of scientific as well as engineering fields including such diverse problems as: the energy loss mechanisms acting in planetary rings, the slumping behavior of impact craters, landslides, the frictional resistance across (sand-filled) faults, the flow of solids in industrial, mining or agricultural applications and even proposed designs for inertially confined fusion power reactors. Yet, this behavior is poorly understood. Microstructural theories are advancing; however, inelastic, frictional contacts and multiple particle effects make progress difficult. Experimental measurements of shearing flows invariably have undesired density gradients due to gravity or centrifugal forces. Equal density liquids have been used (*e.g.*, with wax spheres in attempts to eliminate gravity induced gradients, but these have added the complication of a second phase (and its viscous damping effects). No existing experimental techniques for measuring shear and normal stresses in shearing flows can be used at solids packings as low as would exist, say, in planetary rings. Relatively low solids densities (on the order of 3% by volume solids) have been observed in the upper layers of rapid chute flows, but these have been insufficiently characterized to be useful for checking new theories or computer simulation calculations. At the high and moderate solids packings that can be achieved in earth bound shear test cells (above ~40% by volume solids) computer simulation calculations, indicate that the stress components are only moderately sensitive to such binary collision parameters as the coefficient of restitution and the coefficient of friction acting between particles. While at low solids packings the magnitude of the stress under steady shearing conditions is extremely sensitive to these collision parameters with all stress components decreasing as the energy loss in individual collisions increases.

A very low g environment such as on the Space Station offers a unique opportunity to obtain shear data without gravity induced gradients and to extend such data at least an order of magnitude lower in solids packings than can be achieved in earth bound experiments. Stresses in shearing flows at solids packings in the range from 1% to 10% solids by volume are dominated by the momentum carried by particles themselves and are very sensitive to the magnitude of the energy loss per collision. At low shear rates, nearly elastic collisions dominate and we expect a nearly Maxwellian distribution of particle velocities. At higher shear rates, higher energy losses are expected to produce a highly anisotropic distribution of deviatoric particle velocities with deviatoric velocities perpendicular to the shearing direction much lower than deviatoric velocities in a direction parallel to the shear. Experimental confirmation of these expectations is lacking.

We propose a rectilinear shear flow test to be performed in a very low g environment. One long wall in a thin rectangular box containing simple spherical grains would consist of a moving belt (probably roughened by having half-particles glued to its surface). A "floating" stress sensing area would be located in the opposite, stationary wall suspended on strain gauged elastic members. Both transverse and normal direction forces on this stress sensing element would be measured. In addition, motion pictures, through transparent side walls, would provide data on the velocity and density profiles in the sheared sample. With only one moving wall on the test cell, a particle recirculation loop would need to be provided. If desired, a second test cell could be included on the return side of the belt simultaneously measuring stresses at a different solids packing or shear rate.

(With a test cell of this design, it may be possible to achieve results sufficiently close to steady state during the several seconds of near zero-g acceleration on the NASA KC-135 aircraft. If so, this would obviate the need to do such experiments on the Space Station.)

6.2.2 Grain Dynamics in Zero Gravity

The dynamics of granular materials has proved difficult to model, primarily because of the complications arising from inelastic losses, friction, packing and the effect of many grains being in contact simultaneously. One interesting limit for which it has recently been possible to construct a theory is that where the grain-grain interactions are dominated by binary collisions. The kinetic model of granular systems is similar to the kinetic theory of gases, except that collision energy losses are always present in the former and must be treated explicitly. Few granular materials on earth are describable by this limiting model, since gravity tends to collapse the grains into a high-density state where Coulombic friction effects are dominant.

The planned Space Station offers an unusual opportunity to test the kinetic grain model and to explore its predictions. Without gravity, we will be able to investigate the regime of low interparticle velocities, where an elastic description of the collision is still valid. This will allow for direct interpretation by dynamical computer simulations and comparison to the kinetic theory.

One effect predicted by the kinetic theory is the tendency for inelastic grains to cluster together away from a source of energy. For instance, if one wall of a box partially filled with grains in the absence of gravity is vibrated, the density of grains close to this wall will become small, while near the opposite (cold) wall the grain density approaches its maximum value. Correspondingly, kinetic grain models predict that grain "thermal" velocities become very small at a characteristic distance from the hot wall. Computer simulations of this situation also predict that the particle velocities should fall and that they should cluster away from the hot wall.

A basic experiment to be performed on the Space Station could examine the dynamics of spherical grains inside a clear box. Data would be obtained primarily from a film of the experiment and analyzed using techniques presently under development. Results would be compared with the predictions of the kinetic theory and computer simulations. In addition, the effect of grain rotations would be studied.

Planetary rings can be theoretically modeled using the kinetic theory of granular dynamics. We would like to use this experimental apparatus to investigate some of the parameters needed for such a model. In particular, we could study the clustering effect for realistic materials, as well as the details of individual two-body collisions.

6.2.3 Properties of Tenuous Fractal Aggregates

The process of aggregation of small particles to form layer clusters is an important example of a random, kinetic growth process. Very often, the structure of the clusters formed has a highly disordered and tenuous appearance, that, until recently, has defied quantitative characterization. However, application of modern concepts in statistical physics has enabled the development of a quantitative description of both the structure and the physical properties of such objects. The key element in this description is the recognition that the objects possess what is called dilation symmetry, that is, their structure is invariant in a statistical sense, to a change in length scale. Such objects are called fractals, because the scale invariance implies that the mass of the clusters is related to their size by a power law, $M \sim R^D$, where the fractal dimension, D, is less than the dimension of space (3) and is typically not an integer.

There are two fundamentally important scientific issues concerning these aggregates that should be investigated. The first is their actual growth process. The power-law, or fractal, scaling of their mass with characteristic size has been demonstrated over roughly two decades in some systems on earth. At larger sizes, sedimentation precludes continued random aggregation. It is of fundamental interest and importance in the theories of kinetic growth to know how far the fractal scaling extends, and to determine the exact type of symmetry possessed by very large aggregates. These questions can probably only be answered in a low g environment because any attempt to make a neutrally buoyant suspension of particles will lead to great difficulty in controlling the aggregation process itself.

The second fundamentally important scientific question that must be investigated concerns the physical properties of these fractal objects. The fractal scaling of their mass with size implies that their density scales as R^{D-3}, and thus decreases as they grow. Therefore, these clusters are examples of a class of materials that becomes more tenuous and less stable as they grow larger. Such materials are predicted to have unique behavior in that their physical properties will scale with their size in a fashion that is completely different than that of most forms of matter. Thus an understanding and measurement of their mechanical, optical, thermal and electrical properties should lead to completely new behavior. Again, our ability to perform such measurements on earth is limited in two ways. First, sedimentation can prevent the formation of samples large enough for macroscopic measurements. Secondly, a more fundamental constraint is imposed by gravity in that it limits the ultimate size of the objects that can be formed. If scale invariance is maintained to large enough sizes, the clusters will literally collapse under their own weight. Thus a low-g environment will allow us to obtain material in a regime that has never before been achieved, much less studied. This new class of materials is bound to have some fundamentally interesting and potentially important properties.

The experiments envisaged are relatively simple and can probably be integrated with many others. A source of small particles is required — they can either be produced in space or brought up from earth. Kinetic growth is initiated and the structure and kinetics of this growth monitored. This can be conveniently done with laser light scattering techniques, although electron or optical microscopy would also be useful. When formed, the clusters would be collected and their physical properties measured. This would probably involve some simple measurements of electrical conductivity, mechanical strength and rheological behavior. The major problem would be in the extreme fragile nature of the structures, which would require fairly delicate measurements.

The knowledge gained from this work will be directly relevant to the many questions being asked about the formation and aggregation of particulate matter of astrophysical importance, such as cosmic dust. It also represents the study of a new class of materials with many potentially important properties, that cannot be formed in the gravitational environment found on earth.

6.2.4 Orientation of Weakly Ferroelectric Dust Grains

Low-Z elements, in particular carbon, play an important role as contaminants in structurally dense oxide and silicate matrices. Carbon becomes structurally incorporated when any oxide/silicate crystal grows in an environment that contains a finite partial pressure of CO/CO_2: the gaseous components form solid solutions with the refractory minerals. The solubility is small, because carbon is a structurally incompatible impurity in any dense oxide/silicate matrix. The solubility depends, however, on the grain size and imperfection: small grains which are not well crystallized (because, for instance, they condensed out a chemically complex vapor at relatively low temperatures) contain more carbon than large single crystals. Yet even traces of carbon have a pronounced effect upon certain physical and chemical properties of the mineral grains as will be briefly outlined here.

When carbon becomes structurally incorporated, it forms anion complexes, in particular CO_2^{2-} and CO^-. One of the outstanding features of these complexes is that they are dipolar: they are electric dipoles as well as elastic dipoles. When sufficient defects of this nature are present in a given oxide/silicate grain per unit volume, they undergo ordering. The main consequence of this is that it leads to the formation of ferroelectric domains, even if the structure of the oxide or silicate is intrinsically centrosymmetric and thus unable to exhibit physical properties which require a polar axis.

The ferroelectric response of olivine has been demonstrated recently as part of an on-going research effort to understand the role of carbon and other low-Z element impurities in structurally dense minerals. From these results we deduce that small dust grains, which consist of typical ultramafic minerals such as olivine, should represent single ferroelectric domains. If so, an ensemble of freely suspended olivine grains is expected to orient in an externally applied electric field. The same is expected to hold when the grains move at a constant speed through a homogeneous magnetic field.

The fundamental interest in this phenomenon is that it may represent a mechanism by which interstellar dust grains are oriented in the galactic magnetic field. It is to be noted that olivine is probably quantitatively the most abundant silicate phase in the interstellar medium, forming either individual grains or acting as cores for composite grains. So far, there seems to be no valid concept of how interstellar dust grains can be oriented, unless they are ferromagnetic. Small iron or magnetite needles have been discussed, but it is questionable whether they are present in sufficient number to cause the observed degree of orientation. Olivine appears to fulfill the major requirements which are needed to produce oriented interstellar dust particles.

We are considering a research program for the study of the dielectric/ferroelectric properties of simulated interstellar dust grains. For ground-based experiments, in order to firmly establish the predicted ferroelectric response of fine-grained material, one would use loosely packed powders, or powders which are suspended in equal-density liquids. For a more advanced stage of the project one would set up an experiment under microgravity conditions. For this we would require a large vacuum chamber into which dust grains can be injected and studied under the influence of externally applied fields. The requirements for the chamber to conduct such an experiment are basically not different from those proposed by other interested parties for the study of freely suspended dust.

6.2.5 Supersonic Nozzle Beam

When a gaseous source at a pressure P_o is allowed to expand into a vacuum through a hole whose diameter is much larger than the mean-free-path of the gas (corresponding to the pressure P_o), the random translation motion of the gas is converted to directed motion thereby isentropically cooling the gas. Temperatures down to 30 millikelvin are possible. If the gas is molecular, rotational and vibrational temperatures are also reduced, but not as much as that of the translation. The temperature may drop sufficiently rapidly during the expansion to cause condensation producing clusters of the gas atoms or molecules in the region in the nozzle where the pressure is still sufficiently high to allow three-body collisions to occur. Eventually, of course, the expansion is so thorough that no further collisions occur and the cluster distribution (and rotational and translational temperatures) are "frozen in."

This technique is very well established and is commonly used to:

1. Cool molecules so as to minimize spectral congestion in a subsequent spectroscopic analysis.
2. Create reagents with known translational energies for chemical dynamical studies.
3. Make metal cluster beams in order to investigate the properties of clusters as a function of cluster size.

The most popular current technique generates clusters by entraining metal vapor which has been generated by laser-vaporizing a metal target in a helium atmosphere which is forced through a nozzle.

There are other techniques for vaporizing metal, such as hollow cathode sputtering which can generate orders of magnitude more metal flux. The requirements in pumping speed, however, make such an experiment costly and very cumbersome.

The large pumping speeds available in space make the cluster beam experiment a candidate for the Space Station. The size of the "vacuum chamber" on the station, which may be the outside of the station, make feasible such techniques for cluster beam separation as centrifugation, which cause clusters of different mass to deviate by a small angle from one another. These small angles may be translated into large displacements if the drift length for the beam was large enough, bringing up the possibility of collecting clusters of different size, trapping them, for example, in porous oxide supports for terrestrial investigation. In this way, the catalytic, structural and spectroscopic properties of clusters of metal atoms may be investigated as a function of cluster size.

In order to provide the pumping speed demanded by a system which produces clusters at a sufficient rate so that they may be separated and collected on earth, special pumps and chambers must be constructed at a cost that would likely surpass that of performing the experiment in space.

6.2.6 Some Astrophysical Cluster Experiments

Two sets of specific moieties that would be essential to study with the cluster techniques described above are silicon and carbon based species. The primary reason for the interest in these apart from the serendipitous aspect of discovering a new form of carbon and silicon with unusual electric and catalytic properties is that they make up the bulk of interstellar solid material that is produced in space. These, in turn, form the nucleation centers for other species and are the material from which comets, meteorites, planets and stars are formed.

The period of interest in stellar evolution is the epoch following the H and He burning phase of a star when the heavier elements, such as carbon and silicon, are produced. As this material is ejected as atoms into a circumstellar shell, refractive particles such as Si_nO_m, SiC, C_nH_m and "graphite" are believed to form.

The amount of each type is dictated by the amount of oxygen available relative to carbon. If oxygen dominates (the O/C ratio is greater than 1), silicon condenses out primarily as an oxide and carbon does not form particles but is tied up in the gas CO. If the oxygen to carbon ratio is less than 1, the silicon condenses out primarily as silicon carbide (SiC) and carbon particles are formed. Although there is no definite spectroscopic evidence strongly in its favor, carbon is believed to condense out as sheets of graphite on the order of 50 nm in size. There is recent, good spectroscopic evidence that a large fraction of the carbon is not in the form of graphite, but in the form of polycyclic aromatic hydrocarbons. Whether they are present as free molecules or as constituents of particles is not clear.

To date, there is no theory available that can describe how these particles are formed under the conditions prevalent in the circumstellar shell and no laboratory produced material can reproduce the spectroscopic signatures observed in detail. Thus, in addition to the other systems to be studied in microgravity particle chamber cluster experiments, silicon and carbon cluster formation experiments are extremely important as well. Naturally, in addition to characterizing the types of clusters formed, the optical properties from the ultraviolet through the infrared should also be determined. Without this type of information all that the best observatories and satellites can do is provide more uninterpretable data. Without a laboratory in which realistic samples can be produced, little progress will be made in these areas.

6.3 Required Capabilities of an Orbital Facility

6.3.1 Required Analytical Capabilities

An appropriate use of some of the space and resources allocated for particle research may include state-of-the-art surface chemical analysis capabilities and scanning electron microscopy with energy dispersed X-ray detector (EDX). These two capabilities would be routine tools for many experiments (high versatility and applicability) and should be designed in a flexible manner. They should be positioned near vacuum for high-speed pumping, and the surface analysis method should be provided with excellent UHV characteristics (proper material selection, and pumping in a constant wake). Space, weight, and power consumption should be modest, with power consumed only when doing the analysis (no pumps), possibly less than a few kilowatts when running.

Perhaps the most appropriate surface analysis method for the Space Station at the present time is the surface analysis by laser ionization (SALI) technique recently developed at SRI. This method has extreme sensitivity and is quantifiable, while being strictly surface sensitive, but useful for depth profiling as well. It also is valuable for gas analysis and studies of particle-induced desorption and evaporation from grain and material surfaces. The method is mass spectrometric, using time-of-flight mass spectrometry, and general and efficient ionization of sputtered or desorbed neutral atoms, molecules, and clusters by nonresonant laser radiation. It is reasonably likely that a commercial unit based on this method will be available before 1990, which along with an SEM instrument would alleviate the need for major special designing. It is worth noting that related uses of time-of-flight mass spectrometry are featured in two recent Soviet space probes, Halley's comet, and to Mars' moon Phobos.

Applications of SALI include, but are not limited to, the following types of experiments and characteristics: determination of mass spectra of molecules and microparticles up to weights of 10^4 to 10^5 amu; chemical mapping of surface composition of recovered extraterrestrial particles at a spatial resolution of 200 nm or less, to the 1% level; isotope analysis; measurements of the sticking coefficients of molecules during accretion; measurements of particle outgassing and particle and cluster fragmentation during collisions; study of the (organic) chemistry occurring on the surfaces of extraterrestrial and artificial grains; and monitoring of on-board gases.

6.3.2 Volume and Communications

With the exception of the molecular beam experiments, the 3 m^3 space discussed in some detail in Chapter 2 of this report, as well as the instrument lists compiled by the other subgroups, will suffice. For the beam experiments a nozzle that allows expansion of gases into space through an appropriate port and a manipulator that may sample the beam outside the station would be needed. In addition, we suggest the instrumental compliment discussed above.

It was also felt that it was crucial that the experimental design in the Station be such to allow the principle investigators to communicate in real time with the experimenters on board so as to be able to make follow-up decisions regarding subsequent phases of an experiment based on initial results.

Chapter 7

Conclusions and Recommendations

Given the constraints involved in development of flight experiments for the Space Station, it is desirable that experimental facilities developed *(a)* address scientific problems of fundamental importance, and *(b)* be useful to as broad a range of scientific disciplines as possible without detracting from their ability to meet specific important research goals. A wide range of fundamental scientific experiments can be conducted on the Space Station that involve microgravity studies of small particles. The range of particle experiments that require the Space Station covers many disciplines and involves a variety of methods and measurement techniques. However, these experiments share the common requirement of study of particles in an extremely low-gravity environment since, in general, they require that particles be suspended for periods substantially longer than are practical at 1 g. Because of this commonality, it is reasonable to suppose that a particle suspension chamber with adaptable configurations and measurement capabilities might provide a generic research facility. At the same time care must be taken to avoid development of a concept that is so adaptable that it is unable to meet many specific requirements of high priority experiments.

The results of the workshop indicate that the concept of a generic particle facility is viable, and a broad brush design has emerged. A Space Station Microgravity Particle Research Facility would require on the order of several cubic meters of space (about two racks) in a Space Station research module. The chamber would require a fairly sophisticated environmental control system capable of controlling internal gas composition, pressure and temperature. Access to the external space environment is not a strong design constraint except as a source of high vacuum. The key to the multi-disciplinary success of the chamber is its adaptability. In at least two important ways the chamber must be adaptable: particle production and handling equipment within the chamber, and optical ports and measuring equipment. Required g levels are $\sim 10^{-5}$ g for most experiments.

The desirable characteristics of an ideal microgravity particle facility have been outlined in this report. It will almost certainly be very difficult to accomodate all of these capabilities in a single facility. No attempt has been made here to identify which capabilities can realistically be supplied by such a facility, and which must be provided by individual investigators with more specific needs. Similarly, no attempt has been made to prioritize the value of the scientific experiments discussed.

It is the recommendation of this report that the concept of a facility for study of particle processes in microgravity on the Space Station receive further study. Two steps are necessary:

1. An engineering design study should be conducted in order to more fully define the nature of such a facility, and to realistically estimate its power, mass, volume, and maintenance requirements. This is necessary to support Space Station planning efforts. The study should be conducted on the basis of the scientific objectives and capabilities outlined in this report, tempered with the realization that not all of the suggested experiments can realistically be accommodated in a single facility.

2. An attempt should be made to prioritize the scientific objectives outlined in this report, as an aid to conducting the engineering study. Priority should be based on both the extent to which the possible investigation addresses fundamentally important scientific issues, and the technical ease with which the investigation can be conducted.

These two steps should be conducted concurrently, with the goal of developing a detailed plan for a facility that provides the optimum combination of high quality science and practical feasibility.

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16. Abstract

This document is a report of the Microgravity Particle Research Facility Workshop held at NASA Ames Research Center on August 22-24, 1985. The contents of the report outline the multidisciplinary science rationale for a dedicated adaptable facility (called the Gas-Grain Simulation Facility or GGSF) onboard the Space Station to conduct studies involving small suspended particles.

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