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Space Station Planetology Experiments (SSPEX)

Proceedings of a workshop held at
the U.S. Geological Survey
Flagstaff, Arizona
June 20-22, 1985

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Space Station Planetology Experiments (SSPEX)

Edited by
Ronald Greeley
Arizona State University
Tempe, Arizona

Richard J. Williams
Lyndon B. Johnson Space Center
Houston, Texas

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1.0 INTRODUCTION

Ronald Greeley

This document gives the results of a workshop on Space Station Planetology Experiments (SSPEX) held at the U.S. Geological Survey in Flagstaff, Arizona, June 20-22, 1985.

Following the initiative to establish a manned Space Station in Earth orbit by the mid-1990's, numerous studies have been undertaken to identify the potential science activities that could be conducted in the environment afforded by an Earth-orbiting Space Station. Activities related to planetary science that are being considered for the Space Station include using the station: 1) as a platform for planetary observations, 2) as a staging base for various lunar and planetary missions, 3) to collect "dust", and 4) as an environment for carrying out experiments; the latter topic was the basis for the SSPEX workshop. Many planetary environments involve gravitational accelerations less than Earth. The Space Station could enable experiments to be conducted in which gravity is a critical term in certain planetary processes, especially for planetary experiments appropriate for extremely low gravity environments such as comets and asteroids. In other experiments, "g" may not be a critical term for study, but its near-absence on Space Station may enable experiments to be conducted which cannot be done on Earth. Some of the general experiment areas that have been suggested include impact cratering, experimental petrology, and the formation and interaction of small particles (e.g. planetary ring dynamics).

The workshop provided a forum for discussing the full range of possible experiments, their science rationale, and the requirements on the Space Station, should such experiments eventually be flown. The workshop, sponsored by NASA through Arizona State University and the Lunar and Planetary Institute, was open to all interested scientists.

During the workshop, subgroups met to discuss areas of common interest (impact cratering, aeolian processes, particle formation and interaction, and planetary materials/miscellaneous). This report includes summaries of each subsection, abstracts of contributed papers, and a list of participants.

Acknowledgements

The organizers of the workshop, Ronald Greeley *(Arizona State University)* and Richard Williams *(NASA-Johnson Space Center)* wish to thank the participants at the workshop for their contributions and thoughtful discussions. We are grateful to the subgroup chairmen for providing a focus for interaction and for writing the summaries. We thank Pam Jones at the Lunar and Planetary Institute for arranging the announcements of the workshop. We are particularly grateful to Maureen Schmelzer for the logistical arrangements at the workshop and for the preparation of this document.

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2.0 SPACE STATION IMPACT EXPERIMENTS

Peter Schultz (Chairman), *Brown University;* Thomas Ahrens, *California Institute of Technology;* W.M. Alexander, *Baylor University;* Mark Cintala, *Johnson Space Center;* Donald Gault, *Murphys Center for Planetology;* Ronald Greeley, *Arizona State University;* B. Ray Hawke, *University of Hawaii;* Kevin Housen, *Boeing Aerospace Co.;* Robert Schmidt, *Boeing Aerospace Co.*

2.1 Introduction

The impact process is ubiquitous in the Solar System affecting planetary surfaces from the microscale (regolith evolution) to the megascale (planetary disruption). Over the last two decades research has largely focused on impact processes in which gravity plays a key role, whether in returning ejecta to the surface of the target body or in limiting crater growth. Ongoing research continues to provide fundamental new insights under such conditions. As earth-based observations and missions return new data about small bodies, however, we discover that our understanding of impact cratering under low-gravity conditions is severely limited not because of lack of interest but because of difficulty in removing this dominant variable in 1 g experiments. A Space Station Impact Facility would provide the unique opportunity to reproduce impact conditions unachievable on Earth and to explore parameters "masked" by the gravity term.

Four processes serve to illustrate potential areas of study and their implications for general problems in planetary science. *First,* accretional processes reflect the success of collisional aggregation over collisional destruction during the early history of the solar system. Asteroids and meteorites are relicts of this epoch, but many of the conditions leading to their formation and evolution cannot be achieved under terrestrial gravity conditions. *Second,* both catastrophic and less severe effects of impacts on planetary bodies surviving from the time of the early solar system may be expressed by asteroid/planetary spin rates, spin orientations, asteroid size distributions, and perhaps the origin of the Moon. Although theoretical models can be constructed to describe these collisional effects, they require both essential inputs and constraints that could be provided by experiments under low-gravity conditions. *Third,* the surfaces of planetary bodies directly record the effects of impacts in the form of craters; these records have wide-ranging implications. The size distribution of craters establishes the relative surface or resurfacing ages, and the morphology of craters provides clues to subsurface structure. The removal of the gravity term, however, results in craters much larger than those on a gravity-dominated surface, thereby modifying the recorded size distribution and the efficiency of crater destruction. Subtle forces may control final crater size and shape. Moreover, removal of the gravity term may help resolve fundamental issues for much larger craters on gravity-dominated bodies: for example, the origin of central peaks and the effect of gravity on the cratering flow field. Phobos, the Moon, and Mercury all have craters (basins) and antipodal patterns that may indicate near-destruction by a single event, but conditions favoring or limiting destruction remain poorly constrained. *Fourth,* regolith evolution of asteroidal surfaces is a consequence of cumulative impacts, but the absence of a significant gravity term may profoundly affect the retention of shocked fractions and agglutinate build-up, thereby biasing the correct interpretations of spectral reflectance data.

An impact facility on the Space Station would provide the controlled conditions necessary to explore such processes either through direct simulation of conditions or indirect simulation of certain parameters. The following discussion outlines a general plan for achieving this goal: 1) we propose a four-phased approach in implementing of both the facility and experimentation, 2) we review a tentative scenario for a Space Station Impact Facility with anticipated hardware requirements, 3) we identify possible commonality with other experiments, and 4) we offer recommendations.

2.2 Approach

A phased approach to microgravity impact experiments is necessary in order to refine specific experiment parameters and to gain practical experience. The subgroup identified four distinct phases: 1) Earth-based feasibility experiments; 2) STS (Shuttle) experiment package; 3) IOC (Space Station) experiment package; and 4) the Space Station impact facility. This phased approach will not only lead to further definition for the final goal--the Space Station Facility--but inevitably will also lead to new scientific results. Although the first three phases may be driven primarily by only a few research groups in order to maximize efficiency and minimize costs, an operational Space Station Impact Facility is envisioned as a national facility for a wide range of qualified users.

Earth-based Feasibility Studies

Constraints on the size of the impact chamber size restrict the range in micro-gravity experiments. Experience with existing low-gravity cratering data and extrapolations of data from higher g-levels indicate that crater dimensions and formation time increases dramatically under micro-gravity conditions. For example, at 1 g a 20-cm-diameter crater formed in a particulate target takes 0.2 seconds to form. If the current understanding of gravity effects is correct, then extrapolation indicates that at 0.001 g the crater will be 64 cm in diameter and take 10 seconds to form. The expected increase in crater size requires large containers; the increase in formation time would also permit numerous shock-wave reflections from container walls that could possibly affect crater growth. Consequently, the subgroup recognizes that initial experiments dealing with crater growth up through the IOC phase may be severely restricted and that the most promising results would first come from impact experiments focusing on free-floating targets. Further experience is needed, however, in order to assess the severity of such constraints and to identify the crucial parameters for specific IOC experiments. Such experience can only be gained from properly designed experiments at existing facilities (e.g., NASA-Ames Vertical Gun and Johnson Space Center Vertical Impact Facility) and exploratory low-gravity experiments at the Ames facility, the KC-135 Reduced Gravity Aircraft, and drop-towers. The latter two facilities also provide essential experience with target design, preparation, and design of the IOC Impact Facility.

STS Impact Experiment Package

This phase offers proof-of-concept and design resulting from earth-based feasibility studies. The subgroup recognized enormous benefits that would accrue from experience on the Space Shuttle. This experience includes problems in target preparation and handling (e.g., construction of particulate spheres, free-floating liquid targets) and in testing preliminary designs of the IOC package.

IOC Impact Experiment Package

The first phase of Space Station experiments most likely will concentrate on impacts of free-floating targets in order to better understand phenomena associated with collision processes. The subgroup presently envisions this facility to be equipped with an accelerator permitting impact velocities from 0.1 to at least 2.5 km/s, monitoring systems (launch diagnostics, film/video records, etc.), and an ability to prepare, analyze, and exchange targets. The IOC module will be a direct outgrowth of the STS package but with increased sophistication to anticipate requirements for a larger impact chamber and to ensure meaningful scientific results. An impact chamber size of at least 1.0 m^3 is required.

Space Station Impact Facility

Key requirements for this final operational phase include variable gravity levels (10^{-5} g to 0.2 g), a large impact chamber (4 m diameter minimum), full range of impact velocities (0.1 km/s to at least 6 km/s), variety of targets (particulate, liquid), and experimenter interaction. More specific requirements and descriptions are deferred to a subsequent section. The expanded dimensions and capabilities permit systematic analyses of crater scaling, crater flow fields, crater relaxation, regolith evolution, accretion studies, and more elaborate free-floating targets.

2.3 Space Station Impact Facility: A Scenario and Requirements

In order to visualize the ultimate configuration of this facility and to identify problem areas, a tentative scenario with hardware requirements was compiled. The reader is reminded that this is a *preliminary* view that will evolve with further experiments and experience gleaned from the phased approach. Five key requirements, however, have emerged: 1) variable g, 2) large impact chamber, 3) wide range in impact velocities, 4) flexibility in target composition and structure, and 5) "hands-on" experiment operation.

Impact Chamber

A large chamber is necessary in order to reduce reflections of shock waves from the walls of the target container, to contain/capture ejecta products, and to ensure a variety of more complex free-floating targets. A minimum chamber size of 4 m by 4 m by 4 m is envisioned. In early stages of implementation this might be achieved within the primary module; nevertheless, the *subgroup strongly urges the availability of airlocks at least 1 m in diameter* in order to accommodate an add-on chamber of larger size and an accelerator mount. We suggest that airlocks on opposite sides of the module be considered in order to anticipate possible extensions for advanced accelerator designs. It is virtually certain that the desired variation in gravity levels will be obtained through some application of centrifugal force. The geometry that would yield the lowest rotation rate--presenting the smallest induced Coriolis effects--would find the target chamber at one end of a free-floating habitable module. On the other hand, other arrangements might be more desirable. A set-up that would find the chamber and accelerator attached to the two airlocks or docking ports, for instance, might be handled better by spinning the module along its major axis, i.e., perpendicular to the axis running through the chamber and accelerator. The chamber should be capable of operating in conditions ranging from vacuum to ambient atmospheric levels. It is possible that the Impact Chamber would be used also as a target preparation area. The large size of this chamber may be useful for other experimenter groups.

Accelerators

In order to achieve the desired range in impact velocities (0.1 to 7 km/s), the subgroup presently envisions the use of light-gas gun, powder-gun, and air-gun technology. Light-gas gun technology has been used for over thirty years and could be adapted easily. The subgroup also recognizes, however, that new technological advances in rail guns, mass drivers, and electrothermal guns may provide feasible alternatives and must not be designed-out. Additionally, experiments involving low-yield explosives will be desired. Post experimental analysis envisions the need for holographic systems, binocular microscopes, still photography, mass determination, and sample curating. The subgroup envisions real-time telemetry of experimental data to the earth for analysis by ground-based personnel.

Instrumentation

Three primary groups of instrumentation support are envisioned: launch/environment diagnostics, impact recording instrumentation, and post-impact analytic diagnostics. Launch/environment diagnostic instrumentation includes computer-controlled gun operations/sequencer, projectile velocity, sequencer, flash x-ray generators and detectors, pressure and temperature transducers, and accelerometers. This instrumentation is necessary to record projectile velocity and integrity, to monitor conditions at impact, and to coordinate instrumentation and sequence of use. Impact recording instrumentation includes a range of film recording devices from 24 fps to 35,000 fps (movie and video), lighting, pressure transducers, ejecta sensors, computer-controlled 20 channel digital transient recorder, and holographic recording. Several experimental recording instruments will be integrally tied into micro-computers, and we envision that one of these will be used to program experimental theories and backup for each mission.

Target Preparation and Housekeeping

An assortment of additional requirements include target containers, molds, sieves, vacuum systems, target preparation equipment, small lathe and other power tools, "scales" for mass determination, microwave heater, transducers, ice-crusher/freezer, oven, and miscellaneous "furniture" (benches and accessories). We envision such materials to be needed by other experimenters and anticipate a mutually shared facility.

Personnel

In this advanced experimentation phase, we recognize the need for 2 payload specialists and 2 back-up specialists on the ground.

2.4 Summary

It must be emphasized that this scenario depicts a fully operating facility more than a decade in the future. Such an exercise was performed in order to envision more limited needs and requirements during earlier phases and to anticipate design requirements at much later phases.

Commonality

The large impact chamber, certain recording instrumentation (video, film recorders, microcomputer, etc.), and shop facilities all should be conducive to shared-use with other experiment groups, although not necessarily at the same time. The unique section of this facility is primarily the accelerator system; however, proper design should permit portability. It is possible that the accelerator system, however, may be useful for certain studies in shock dynamics (shock tube) in addition to the more typical impact experiments.

2.5 Recommendations

The Impact Experiment Subgroup recommends a phased approach in order to gain insight and experience with impact processes under low to micro-gravity conditions. This phased approach includes pilot studies and research involving existing impact facilities, the KC-135 Reduced Gravity Aircraft, and drop-towers. The subgroup feels that the most useful first experiments at micro-gravity (IOC) will involve impacts of free-floating targets in order to understand the effects of momentum transfer and disruption on realistic or modeled planetary bodies (e.g., regolith-covered bodies, fluid spheres, etc.). However, continued studies may identify additional configurations during the IOC phase.

The subgroup also recommends that additional studies involving meteorite impact detectors and cosmic dust collectors be encouraged since the results of such studies will be complementary.

3.0 SEDIMENT-TRANSPORT (WIND) EXPERIMENTS IN ZERO-GRAVITY

James Iversen (Chairman), *Iowa State University;* Dale Gillette, *NOAA;* Ronald Greeley, *Arizona State University;* Jeff Lee, *Arizona State University;* Ian Mackinnon, *University of New Mexico;* John Marshall, *Arizona State University;* William Nickling, *University of Guelph;* Brad Werner, *California Institute of Technology;* Bruce White, *University of California;* Steve Williams, *Arizona State University*

3.1 Introduction

Aeolian processes involve the movement of particles by the wind and include dust storms, sand storms, and erosion by the wind. At least Earth, Mars, and Venus are affected by winds and understanding the physics of aeolian processes is essential to the interpretation of the current and past modification of the surfaces of these planets.

On Earth, it is estimated that more than 500 x 10^6 metric tons of dust are transported annually by the wind. Dust storms reduce visibility on highways and are responsible for loss of life and property through many accidents each year. Atmospheric dust, whether raised by winds or injected into the atmosphere by volcanic processes, can also have a significant effect on temperature. Thus, windborne particles can have a direct effect on the climate. In addition, windblown sands cause abrasion and erosion of natural and manufactured objects and encroach upon cultivated areas, turning productive land to desert--a process termed *desertification*. The problem of desertification is enormous and is recognized on all inhabited continents of Earth. Agricultural land damaged by wind erosion in the United States alone varies from 400 to 6,000 km^2 per year.

The key to understanding problems associated with windblown sediments, including those aspects of desertification dealing with wind processes, is knowledge of the physics of windblown particles. Many parameters, such as grain size and wind speed, must be considered in assessing the entrainment and transport of windblown grains. Beginning with research in the 1930's, numerous investigators have used wind tunnels to analyze particle entrainment. Wind tunnels have the advantage that individual parameters can be closely controlled and isolated for study and analysis. Gravity is one of the most critical parameters in the analysis of windblown sediment movement; however, there is no effective means for isolating and assessing its effect during experiments conducted on Earth. Hence, a space station would afford an opportunity to conduct experiments in zero-gravity and variable-gravity environments. Such experiments would enable not only this parameter to be assessed, but through its elimination as a factor in the experiments, other critical parameters could be evaluated as well.

Approach

We propose to fabricate an experimental facility that can simulate the movement of particles by the wind, or in other turbulent-fluid environments. We could use a "phased" approach in which experiments would be flown initially on board the KC-135 aircraft for "proof of concept" and to assess potential problems, as may occur in handling particles and in recording appropriate data. The second step might be to fly an experiment on board Shuttle, followed by a fully operational facility on Space Station.

The wind tunnel proposed (termed the *Carousel Wind Tunnel,* or CWT) consists of two concentric rotating drums. The space between the two drums comprises the test section. Differential rates of rotation of the two drums provide a wind velocity with respect to either drum surface. A zero-gravity environment results in a space station laboratory by rotation of only the inner drum. Rotation of the outer drum provides a "pseudo gravity" for particles resting on the inner surface of the outer drum. In order to test the concept of the design, 1/3 and 1/5 scale model CWTs have been constructed and calibrated. Calibrations show that a Prandtl logarithmic boundary layer exists adjacent to the inner surface of the outer drum, a necessary requirement for the simulation of an aeolian saltation layer on a planetary surface. An interesting and quite satisfying characteristic of the CWT is that the so-called "fetch-length" (after initial start-up time) is infinite.

3.2 Experiments

We envision several types of experiments to be conducted, as described below.

Threshold Experiments

Threshold defines the minimum wind speed (or friction speed u_{*t}) required to initiate particle motion and is a fundamental factor in aeolian processes. The prediction of threshold speed involves assessment of the forces acting on the resting particles, including aerodynamics lift and drag, weight, cohesive force between particles, and perhaps force due to impact from another already moving particle. Elimination of the particle weight in the threshold force equation—as in a weightless environment—would enable more accurate assessment of the cohesion and aerodynamic forces. In particular, the cohesive force is currently much in question as to its magnitude and origin. Threshold experiments conducted at one g in a range of atmospheric densities indicates that the cohesive force is at least approximately proportional to the particle diameter, as predicted by the Van der Waal's force, although the coefficient of proportionality is much smaller than the Van der Waal's coefficient, at least for particles between 30 and 100 microns in diameter.

Is the source of the cohesive force primarily electrostatic? If so, the CWT would be a good tool for studying this phenomenon because of three factors: (1) the cohesive force is the only retarding force on the particle in the zero-g environment, (2) the electrostatic forces could be altered by using particles of differing electrical properties (i.e., conducting and non-conducting particles, clays of differing mineralogy, etc.), and (3) providing electric potential difference between the outer and inner drum surfaces (drum surface electrical conduction property can also be changed). It will be necessary to establish an appropriate matrix of experimental conditions before final space laboratory CWT design.

Ripple Experiments

The CWT may be used to performed critical experiments that will provide insight into the relationship between the saltation path length and surface bedform structures such as ripples, waves, dunes, etc. The CWT can provide controllable saltation path lengths by adjusting the rotation rate of the outer drum of the CWT. Thus, saltating particles relative to an observer positioned on the outer drum moving with it, may be made to have positive, negative or neutral (a purely electrical) jumps. Experiments then may be performed where the only variable in the saltation process could be the path length or jump length of the particle (i.e., the D_p, ρ_p, p, g, ρ are held constant while u_* is adjustable by fixing different rates of outer drum rotation). Hence, a direct assessment of saltation path length of wave lengths of surface structures (i.e., ripples, etc.) could be made.

Varying the position at which a particle lands with respect to the position from which it lifted off will provide the only direct method of finding the relationship between path length and ripple frequency. Researchers have not resolved this problem since Cornish first considered bed formation in 1903.

A second application of the controllable path length would be the study of the physics of particle interactions with the surface. This may be accomplished by varying the impact angle of the saltating particle which thus enables direct control of particle velocity with respect to the bed, i.e., control of both magnitude and direction of individual particle momenta. This is directly applicable to the understanding of initiation of particle motion by impact, i.e., how momentum is transferred between an incoming particle and stationary material on the surface. This latter aspect is important for understanding how particles and rock surfaces become abraded during transport and for determining the real ~ coefficient of restitution between colliding particles in the natural environment.

Saltation Induced Emission of Fine Particles vs. Direct Suspension of Fine Particles

Fine particles that are suspended by the turbulent motions of the air may be defined as particles whose setting velocity is some small fraction of the scale of vertical turbulence (alternately fluid friction velocity, u_*). These particles are emitted by direct suspension (Owen and Gillette, personal communication, 1985) or by the sandblasting effect of saltation. The proportion of the flux by sandblasting to direct suspension is unknown and is probably a function of the state of sediment in the soil. For example, a soil composed of loose particles, all of which would go into suspension for a given wind, would have fine particle emissions dominated by direct suspension. For the more usual (for earth) case of a soil composed of a mixture of particles the suspendable fraction having higher threshold velocities and the saltation-sized-particles having a lower threshold velocity we would suspect that both sandblasting and direct suspension would be producing particles. The fraction of particles produced by sandblasting to those produced by direct suspension is not known, however.

The above ratio can be determined, however for a given soil by changing gravitation so that the entire soil mixture goes into direct suspension (low g) or that it displays saltation mode for coarser particles and direct suspension is possible for finer particles (higher g).

The ratio of sandblasted to direct suspended particles is the ratio of concentration of suspended particles for the saltation run reduced by the concentration of particles of the same size for direct suspension divided by the same concentration.

i.e.

$$\frac{\text{particle mass produced by sandblasting}}{\text{particle mass produced by direct suspension}} = \frac{\text{c (saltation)} - \text{c (direct suspension)}}{\text{c (direct suspension)}}$$

where c (saltation) is the concentration of suspended particles in the saltation experiment and c (direct suspension) is the concentration of particles of the same size interval as suspended particles produced in the saltation experiment.

The experiment should use a wide variety of soil types. The practical use of such experiments would come in the prediction of flux of suspended particles. If the suspended particle flux can be shown to be dominantly produced by sandblasting, then relationships of suspended particle flux to saltation flux can be developed. Applications could come in agriculture (long term loss of soil nutrients), acid rain (production of suspended alkaline particles), planetary geology (martian dust storms), and possibly other fields.

Solar Nebula Formation

From the broadest perspective, the Carousel Wind Tunnel in zero-g provides a baseline for fundamental experiments in particle dynamics. This situation can best be perceived with the notion that at zero-g, particle-surface interaction is negligible (apart from "interparticle" attraction effects for particles physically located on or near a drum surface). Thus, particles within the central (experimentally well-characterized) portion of the wind tunnel can be placed in a flowing atmosphere which can be at a continuous or variable rate. With appropriate scaling this condition may be analogous to portions of an evolving solar nebula. The existence and the importance of turbulence and mass flow within solar nebula formation models are well-documented (Morfill, 1983; Kornacki and Wood, 1984); other, non-equilibrium particle-gas flow dynamics could be envisioned in the controlled environment offered by CWT. These experiments could involve variations in micro-g and the effects of turbulence which can be induced (and adequately compared) by differential rotation speeds of the carousel drums. Carousel Wind Tunnel experiments of this type may provide clues to a number of fundamental dust-gas interaction questions and include:

a. What grain characteristics (size, shape, charge, composition) influence grain growth (or aggregate dispersal) in a given flowing atmosphere (e.g., O-rich, He-rich, C-rich)?

b. Do grains aggregate in a steady mass flow (turbulent-free) environment over time?

c. At the onset of turbulence, or at particular levels of turbulence, will interparticle attractions predominate? If so, for what particle size range?

Additional refinements may be included in a series of dust-gas flow experiments with the application of an ionizing atmosphere. This could be induced throughout the experimental apparatus or within a given phase (a rough analogy to the latter case would be an ionized atmosphere/dust flow in the ecliptic of an evolving solar nebula). These experiments may be especially fruitful if mixed grain characteristics (e.g., spheres and laths; clays and silica; organics and graphites) were introduced to a given run.

A simple, IOC level experiment might be performed to test the survivability of certain grains in flowing atmospheres by placing well-characterized aggregates (e.g., refractory condensates made by Nuth or others) in the Carousel Wind Tunnel at zero-g. These aggregates would be in a suitably scaled atmosphere in the CWT and with drum rotation, grain (or gas) motion to desired volatiles may be obtained. The CWT can then be sampled at appropriate time intervals to determine whether these open fluffy refractory aggregates remained or were disaggregated.

Requirements:

Zero-g (±1%) for periods of approx. 24 hours
CWT atmosphere intake and outlets
Operator intervention (by remote sample collector) every 3 hours
Optical and/or laser monitoring of grain characteristics (nephelometry) on continued, automated basis

3.3 Instrumentation

In order to assess experiment results, it is necessary to measure particle velocities and fluxes. The nature of particle movement at threshold can be evaluated by the use of a laser monitoring system. The present single-beam system used by Nickling (1984, 1985) can be modified for CWT and could be adapted for tests on the KC-135. The system uses a 5 mW He-Ne laser, high response photo-diode, filtering circuits and a high speed pulse counter/microprocessor. This monitoring technique overcomes many of the problems of visually detecting the initial movement of isolated grains over a relatively large surface area. In addition, the system characterizes the change in particle motion from fluid to dynamic threshold. The point of full saltation flow is also indicated when the beam becomes continuously broken.

In its present form, the threshold monitoring system requires continuous input of velocity data from which shear velocity is calculated. If velocity probes are not used in the Carousel Wind Tunnel, drum velocity or g level (KC-135 tests) could be used as input data and shear velocity calculated indirectly. This system can be improved by using a thin, wide sheet of laser light rather than a single reflected beam. At present, the recorded total grain count is really a measure of grain activity and not an absolute measure of the number of grain movements, since a single grain can break more than one beam. A sheet of light produced by appropriate lenses could be placed horizontally over the surface or vertically as a curtain in front of the sample bed. Using this method an individual spike would be recorded for each grain passage unless two or more grains passed through the beam simultaneously.

A velocimeter probe would also be extremely useful especially in the grain trajectory tests. This could be done using traditional probes or by some modification of the threshold monitoring system. For example, the width of the "spike" produced when a grain passes through the laser beam is a function of the grain velocity (and particle diameter). By using a pulse analyser, the time required for the grains to pass through the beam can be compiled and individual grain velocities calculated. This would require some assumptions in the grain diameter and the beam widths.

The development of any threshold monitoring system is contingent upon the final design of the Carousel Wind Tunnel. Of primary importance will be whether or not the sides of the wind tunnel will revolve with the outer drum. This will probably have ramifications for any other instrumentation that might be used in the tests.

As was shown in the presentation of Gillette and Owen (this volume), a flat plate sensor using the piezoelectric principle could be a useful tool in measuring mass flux, momentum flux, and kinetic energy flux of particles hitting the floor. This sensor has the advantage of not disturbing airflow in the carousel wind tunnel and not having optical surfaces which could become dirty. The measurements of relevant fluxes in the wind tunnel could serve as an important system to provide primary information or as confirmation of other measurements.

3.4 Summary and Conclusions

Interparticle Force

The CWT wind tunnel can be a significant tool for the determination of the nature and magnitude of interparticle forces at threshold of motion. By altering particle and drum surface electrical properties and/or by applying electric potential difference across the inner and outer drums, it should be possible to separate electrostatic effects from other forces of cohesion.

Grain Threshold Criteria

The researchers contributing to this summary represent a significant fraction of the world's experience at determining particle threshold and the techniques involved should be readily adaptable to the CWT.

Other Applications

As with many new kinds of research laboratory devices, the applications which present themselves in addition to the original purpose continue to increase. Besides particle trajectory and bedform analyses, new suggestions for research investigators include particle aggregation in zero- and sub-gravity environments, effect of suspension-saltation ratio on soil abrasion, and the effects of shear and shear-free turbulence on particle aggregation as applied to evolution of solar nebula.

Commonality with Particle Group Experiments

In addition to some common interests with particle group experimenters, the aeolian and particle groups should be able to share particle storage, particle insertion and transport techniques, instrumentation (such as photography, nephelometry, lighting equipment, electrical equipment), and cleaning equipment.

4.0 PARTICLE FORMATION AND INTERACTION

Steven Squyres (Chairman), *NASA Ames Research Center;* George J. Corso, *Northwestern University;* Lynn Griffiths, *MATSCO;* Ian Mackinnon, *University of New Mexico;* John Marshall, *NASA Ames Research Center;* Joseph A. Nuth III, *NASA Headquarters;* Brad Werner, *California Institute of Technology;* John Wolfe, *San Jose State University*

4.1 Introduction

A wide variety of experiments can be conducted on the Space Station that involve the physics of small particles (μm to cm in size) of planetary significance. Processes of interest include nucleation and condensation of particles from a gas, aggregation of small particles into larger ones, and low velocity collisions of particles. All of these processes could be investigated with a general-purpose facility on the Space Station for study of the physics of small particles. The microgravity environment of the Space Station would be necessary to perform many experiments, as they generally require that particles be suspended for periods substantially longer than are practical at 1 g. Only experiments relevant to planetary processes will be discussed in detail here, but it is important to stress that a particle research facility will be useful to a wide variety of scientific disciplines, and can be used to address many scientific problems. We will also discuss briefly some experiments that would not utilize such a facility. More detailed descriptions of some specific experiments are presented in the workshop abstracts.

4.2 Background and Scientific Rationale

Some of the most fundamental processes involved in the origin and evolution of the Solar System concern the condensation of solid matter from a gas, the aggregation of small particles to form larger particles, and the collisional interaction of particles over a range of sizes. Understanding particle condensation is critical to understanding the earliest stages of solar system formation. Classical nucleation theory is inadequate to predict the condensation of circumsolar grains from the early solar nebula. Experiments have been performed in terrestrial laboratories to duplicate the nucleation and condensation of planetary particles from the solar nebula, but such experiments suffer from convective instabilities induced in the gas from which the condensation takes place. In a microgravity environment, it will be possible to conduct condensation experiments with more quantitative accuracy, and to extend experiments to much more refractory materials. Experiments extended to low temperature condensation will also be able to investigate formation of icy grains that went into accretion of the outer planets, their satellites, and comets.

Once grains formed by condensation in the early solar nebula, they underwent aggregation into planetesimals. This process is poorly understood, particularly in the scenario where significant amounts of gas are still present. Particle aggregation is also an important part of any process that injects large amounts of comminuted material into a planetary atmosphere. Three such processes are dust storms, explosive volcanic eruptions, and large impact events. For example, it has been hypothesized that a large impact could have caused substantial atmospheric dust loading on Earth and subsequent faunal extinctions. Such hypotheses are dependent on the efficacy of dust aggregation and the rate at which particle aggregates settle from the atmosphere. Aggregation rates also play a crucial role in calculations of "nuclear winter" scenarios, and control the lifetime of some volcanic plumes and large dust storms. Some laboratory experiments suggest that aggregation, at least under some conditions, is surprisingly effective, but all aggregation experiments are severely restricted in duration by rapid settling in a 1 g gravitational field. The microgravity environment on the Space Station will allow the process of particle aggregation to be studied in great detail under a wide range of conditions. Specific parameters that need investigation include aggregation rates, the size distribution of aggregates, the dependence of aggregation efficacy on material properties, etc.

Immediately after the first stages of particle aggregation in the solar nebula, planetesimal formation probably involved collision of particles at relative velocities of a few m sec^{-1} or less. The detailed dynamics of such collisions are poorly understood, including particularly the nature of the conditions necessary for particles to adhere together after a collision. Factors that affect collision dynamics probably include particle composition, relative sizes, spin, and ambient gas pressure. The effects of all these factors are poorly known. Low velocity particle collisions also take place in planetary ring systems. Collisions result in an effective viscosity for the rings, and development of diffusional instabilities that are manifested as intricate small-scale structures. In this case the important parameter to understand is the coefficient of restitution, which describes the inelasticity of collisions. Attempts have been made to study low velocity particle collisions by suspending particles from pendula, but such experiments suffer severely from the restriction of particle motions to two dimensions. Full three-dimensional interactions, including interaction of more than two particles, can be conducted in a microgravity environment.

4.3 Hardware Concept

The high cost of experimentation on the Space Station provides a strong motivation to develop orbital laboratory facilities that will be capable of addressing as wide a range of problems as possible, rather than highly specialized facilities applicable to only one narrow problem. In principle, all of the investigations outlined above could be conducted in a chamber in which particle formation and interaction could be induced and observed. One possible concept for such a facility will be described below. A critical task to be carried out in the near term is determination of which investigations can be conducted in a general particle research facility, and which require more specialized facilities. The general objective will be to design a facility that is as flexible as possible, admitting as many high-priority investigations as is feasible without compromising the science. The design discussed here is very preliminary, and will be subjected to substantial review, refinement, and revision.

The basic facility is envisioned as residing in a glove box in one of the Space Station laboratory modules. It is felt that the glove box approach is necessary to ensure against contamination of the module interior with particles. The glove box must be at least the size of a double rack (38 inches wide) in order to accommodate the necessary equipment. It should be as voluminous as possible, and include internal power outlets and attachment to a thermal control system. The experimental chamber itself would be mounted inside the glove box. It should also be as voluminous as possible while allowing space for external attachments within the confines of the glove box; for a double rack glove box, an experiment chamber 24 inches on a side might be appropriate. All faces should be readily accessible to an experimenter outside the glove box, and the positioning of the chamber within the glove box should be adjustable. The chamber should be pressure tight, and at least one face should be completely removable. Each face should be equipped with a general-purpose port to which investigators may attach equipment. Some standard pieces of equipment should be provided as part of the facility. These might include illumination sources, still or motion picture cameras, laser nephelometers, or photometers. In the case where an investigator could not build a piece of equipment that would be compatible with a general-purpose port, the investigator could provide an entire removable face of the chamber to which his or her equipment would be attached. In the extreme case where the chamber itself is unsuitable for an investigator, it should be possible for the investigator to remove the chamber and insert a specialized one that meets his or her requirements.

The amount of crew interaction that will be required by these experiments will of course vary from one experiment to the next. In general, however, it is expected that most will require the close attention of at least one individual, either the investigator or a trained crew member. A particle research facility shares the need to effectively handle significant quantities of small particles with a number of other possible Space Station experiments, including impact experiments and a wind tunnel. This common need suggests that a standardized procedure for transporting and handling particles should be established. Equipment developed for particle transportation, handling, and storage should be as general as possible.

Several of the particle-related experiments described in the abstracts could not be accomplished in a facility within the Space Station, but could be conducted outside the Station. These include experiments to collect micrometeorites, and experiments to study the orbit properties of colliding, co-orbiting bodies. Facilities for the conduct of these experiments might be constructed outside the Space Station, or could perhaps be accommodated on free-flying spacecraft.

4.4 Recommendations

A particle research facility should be developed for the Space Station and maintained as a national facility for research involving the physics and chemistry of small particles in microgravity.

A multi-disciplinary workshop will be conducted to define clearly the scientific rationale for the particle research facility, establish the desired capabilities of the facility, and establish a strawman design. This workshop will be conducted at Ames Research Center on August 22-24, 1985. A major focus of the workshop will be to establish the degree to which widely differing investigations can share the same facility, and how many specialized chambers are actually necessary.

The results of this workshop should be incorporated in a report that is provided to the appropriate individuals at Johnson Space Center, Goddard Space

Flight Center, and, especially, in the Office of Space Science and Applications at NASA Headquarters. The report should define the need for the facility and its configuration as fully as possible. The report should be completed as soon as possible, and well before the Space Station Interface Requirements Review in January, 1986.

An effort should be made to obtain funding for the facility at a level sufficient for completion at the time the Space Station reaches its Initial Operating Capability (IOC). Potential funding sources include the Astrophysics, Planetary Science, and Life Sciences programs in the Office of Space Science and Applications, as well as the Space Station Office itself.

The Space Station should be constructed in a manner that allows the development of large particle collection and interaction experiments outside the main Station structure.

5.0 REPORT ON OPPORTUNITITES AND/OR TECHNIQUES FOR HIGH-CALIBER EXPERIMENTAL RESEARCH (OTHER) PROPOSALS FOR SSPEX

Joseph A. Nuth (Chairman), *NASA Headquarters;* George Corso, *Northwestern University;* Donald DeVincenzi, *NASA Headquarters;* Al Duba, *Lawrence Livermore Laboratory;* John Freeman, *Rice University;* Ramon Lopez, *Rice University;* James Stephens, *Jet Propulsion Laboratory;* Ian Strong, *Los Alamos National Laboratory;* John Wolfe, *San Jose State University*

5.1 Introduction

Unlike the previous summary reports, the only unifying factor among the experiments discussed in this section is that they are all unique Opportunities and/or Techniques for High-caliber Experimental Research (OTHER!). Many of the investigations discussed in this report were submitted to the SSPEX workshops as abstracts, although several additional experiments have been added as a result of workshop discussions. Despite the enormous diversity of the investigations proposed, several common concerns have emerged regarding the availability of "standard" items.

Several people expressed a desire for one or more windows. These can be located either in the lab module, as a transparent hatch cover or in the habitability module. In general, these would *not* be in constant use -in fact they probably would be used only rarely. Windows should "look" both "upstream" and "downstream" from the station and should also be available for Earth and "deep space" views. Because they would be used only occasionally, positioning behind mobile equipment racks in the lab module could be considered.

Another requirement of several of the proposed investigations is the development of automated tether systems; if possible, small (<500 m) tether systems should be able to travel along tracks spanning much of the station. Another possibility is the attachment of small tethers to one or more remote manipulator arms(s) or to one or more deployable booms. A boom which can hold a shield several hundred meters "in front of" the station (or above it) in order to avoid local contamination is a necessity for several experiments. Of course, investigators assume some astronaut EVA time for limited servicing, equipment and/or sample changes, as well as deployment or retrieval of the experiment.

One additional factor which requires thought is the degree of overlapping needs or use of common equipment for very different experiments. For example, the experiment proposed by Walker could provide a very large shield to create the ultra high vacuum required by Duba or Nuth (see abstracts). Could such an ultrahigh vacuum facility be useful to a larger community? Could the small tethers required by Lopez be used to deploy and retrieve Stephens' artificial comet? Could the rail gun proposed for the cratering experiments be used to fire projectiles into the atmosphere at speeds greater than 25 km/s and thus create an artificial meteor? Could the dust collectors proposed by Corso be mounted on *all* tethered upper atmospheric research satellites?

Along these same lines, mutual interferences among experiments--or Space Station operation--must be considered. As examples, could particles released by Strong or Stephens interfere with the collection efforts of Walker? How many tethers could be deployed around the station, and in which directions, before they constitute a navigational hazard? How large a disturbance to microgravity experiments would result by firing projectiles into the upper atmosphere (or doing cratering studies)?

Many of the experiments described in the abstracts are in the "formative" stage of development. Still, all of the proposals utilize the space station environment for investigations which could never be performed on Earth. None are suitable for flight on the KC-135, although several could be developed as Shuttle experiments. In some cases (e.g. Strong (12) and Williams (8)) development of Shuttle experiments is under way.

The following includes brief descriptions of 13 experiments; 9 of these were presented to workshop participants. Another is mentioned in the "Banks" Report as a candidate for IOC. Two more experiments were discussed by participants at the workshop, as an outgrowth of other experiments already under discussion. A final "calibration" experiment was discussed by Boynton at an earlier meeting. Considering the number and variety of Planetary Science experiments which keep emerging these should be considered as the vanguard of many more proposals.

5.2 Specific Experiments

Ultrahigh Vacuum Petrology Facility

Duba proposes placing a large (>3 m diam.) shield in front of (or above) the Space Station. The region behind the shield would experience a very low pressure due to the shield "sweeping" ambient gas away as it travels at orbital velocity (8 km/s). Pressures of 10^{-15} torr of H and He seem possible, while atom partial pressures less than 10^{-20} torr could be obtained. In this very low pressure region Duba proposes to study the high temperature metamorphism of carbonaceous chondrites. In particular he proposes to measure the variation in the electrical conductivity of the sample as a function of both time and temperature in order to test the theory that the observed differences in composition of asteroids (as a function of their orbital semi-major axis) could be due to electromagnetic heating during the early history of the solar system.

Artificial Comet-Free Flyer

Stephens proposes placing several large "chunks of ice" into orbit in which finely dispersed dust particles and several radio thermometers have been frozen. The object of the experiments is to determine the dependence of the temperature structure within the comet on both the composition and concentration of the dust. In particular, he wants to test the hypothesis that a significant quantity of volatiles could be trapped inside of "dead" comets and protected by a highly efficient insulating layer of "hardened", extremely porous dust.

Artificial Comet - Tethered

In this experiment Stephens proposes to tether materials similar to those described in (2) in order that the "comets" can be recovered for later study on earth. In this way the thickness of the insulating layer, as well as its structure could be determined and correlated with its "insulating efficiency".

An additional advantage of tethered comets is observation of the development of the dust plume as a function of exposure to various levels of solar insulation.

Cosmic Dust Detector

Wolfe proposed placing a relatively large (1-2 m^2) acoustic impact detector on the space station in order to measure the long term anisotropy of the flux of cosmic dust particles. Using acoustic spectral analysis he feels that it is possible to derive some compositional information about the impacting particle as well as its directions and momentum. In this way, information about both the flux and composition of asteroidal, cometary and interstellar particles might be gained.

Cosmic Dust Collector

In this experiment, Wolfe proposes placing an electrostatic decelerator on the space station. The detector is capable of decelerating particles entering the collector with velocities as high as 25-30 km/s, and will simultaneously reject relatively slow moving debris in the vicinity of the station. Periodic return of the collector surface would allow the recovery of pristine cosmic dust samples which have not been contaminated by the earth's atmosphere. Such materials would constitute an extremely valuable resource to the exobiology community.

Dust Collection using Tethered Satellites

Corso proposed outfitting satellites lowered into the Earth's upper atmosphere with cosmic dust collectors. In this way he hopes to collect large numbers of relatively uncontaminated particles soon after their arrival. In fact, using this method it could be possible to determine to within a few hours the time of arrival of particular particles and thus correlate them with known meteor showers. Such a collection would be complementary to both the stratospheric and space station efforts.

Artificial Magnetosphere

Lopex proposes suspending a strong magnet from a tether approximately 200 m or so above the space station in order to create an artificial magnetosphere. Diagnostic probes could be suspended on mobile tethers downstream from this magnet to probe its interaction with the ambient plasma. In addition ionic tracers such as Barium could be released "upwind" at will. A series of non-tethered experiments might also be necessary to probe the effect of the tether on the plasma sheath.

Micro-gravity Petrological Studies

Williams and Lofgren have constructed a highly efficient furnace system which accurately controls the redox conditions under which the experiments are performed. They propose to fly this system aboard space station in order to study the effect of cooling rate on the resulting texture of chondrule-like materials. Efforts to study this problem in 1 g are frustrated by the settling of early condensates from the melt and, in some cases, by buoyancy driven convection.

Slitless UV Spectrometer (Construction and Calibration)

Wdowiak, et al. have proposed the construction of a Slitless UV Spectrometer to obtain meteor spectra, and especially to determine the relative ratios of the biogenic elements in these meteors. If the cratering community (or SDI) places a rail gun (or similar facility) into orbit it might be possible to fire projectiles of known composition into the earth's atmosphere along well determined trajectories at speeds approaching 25 km/s. Such a facility not only could be used to accurately calibrate the spectrometer but could also be used to test models of atmospheric entry phenomena.

ODACE - Orbital Determination and Capture Experiment

Walker proposed building a large dust collector (10 m x 10 m) with the capability to determine the velocity of the impacting particle. When "interesting" particles are observed the small cell (10 cm x 10 cm) containing the particle would be returned to earth for study. At this time it might be possible to precisely determine the orbital parameters of the particle as well as a significant amount of compositional and structural information. A cosmic dust collector is mentioned in the Bank's Report as a high priority item for IOC.

High Velocity Sputtering of Amorphous Silicates

This experiment grew out of discussions with Al Duba and others at the workshop. If we put a hole in the middle of Al Duba's shield (which could be closed off -of course) then this would be an excellent source of 7-8 km/s oxygen, nitrogen, helium and hydrogen atoms with which to carry out sputtering experiments. It might also be possible to charge these atoms using an electron gun so that one could electromagnetically separate the beam into its atomic components. This device could serve as a useful experimental facility for material science experiments. In particular, Nuth wants to study the metamorphism of amorphous iron and magnesium silicates exposed to such a beam in order to better understand the processing of these materials via shocks in the interstellar medium.

Particle Release Experiments

Strong and coworkers have not yet established a definitive set of particle release experiments to be performed from the space station, in part because they have not yet carried out a planned series of releases from the space shuttle. These experiments will take advantage of the unique observational capabilities of the AMOS Facility in Hawaii in order to measure various properties of the released particles such as the scattering, absorption and extinction efficiencies as well as the speed with which the particles become aligned in the earth's magnetic field. The results of these early shuttle experiments will determine the particular experiments which best utilize the unique opportunities afforded by the space station.

Calibration of Gamma and X-ray Remote Sensing Probes

Boynton mentioned this possibility at a previous meeting and it is included here for completeness. He suggests that the best place to calibrate a remote sensing tool such as a gamma ray or x-ray fluorescence spectrometer is in the space environment. On earth, only single line gamma ray sources are available for use as excitation probes for natural samples. Similarly, no continuous "natural" x-ray spectra are available with which to calibrate x-ray fluorescence detectors. Much better instrument calibrations would be available if one could observe transported natural samples such as basalts, granites and various ices - or even observe various parts of the station itself prior to launch to their ultimate planetary targets.

6.1 CONTRIBUTED ABSTRACTS

A PLANETARY ULTRA HYPERVELOCITY IMPACT MECHANICS AND SHOCK WAVE SCIENCE FACILITY

Thomas J. Ahrens, Seismological Laboratory 252-21, California Institute of
Technology, Pasadena, CA 91125

Macroscopic experiments in which the amount of shock-induced melting, vaporization and ionization produced during impact of projectiles at speeds from 8 to 15 km/sec have never been conducted. Experimentation with ~10 m diameter range projectiles, have been of great value for interpreting the results of micrometeorite, cosmic and cometary dust space-flight experiments and for ground-based research on zodiacal light. The small projectile experiments have uncovered several new physical processes which could never have been discovered via only numerical calculations. Radiant energy losses from impacted regions occur so rapidly in this size regime that these affect the cratering morphology and undoubtedly chemical processes, such as incongruent vaporization and impact-induced ionization. Because impact experiments carried out with light gas gun are limited to achieving the range of shock pressures (2 Mbars) inducing melting, but not copious vaporization in silicates, there are virtually no experimental insights into such currently controversial issues in planetary science as

1. The physics of "after burn" for oblique impact on the earth and the possible formation of the moon.

2. The amount of production of very fine vaporized ejecta condensate from large impact of such as from the hypothetical K-T bolide.

3. The nature of incongruent vaporization of minerals and the possible impact devolatilization of the moon. This requires data on the speciation in the impact induced vapor.

4. The production of impact-induced vapor plumes, upon oblique impact onto various planetary targets and the possible relation of this process to sampling, via impact ejection, of different planets (e.g. Mars).

Using the concept of intercepting orbits from a pair of Space Station serviced free-flyers, a new class of impact and shock wave experiments pertinent to planetary science can be carried out. One proposed free-flying vehicle (A) is an impactor dispensor, and the second free-flyer (B) is an impact laboratory. How collision is achieved by utilizing essentially twice orbital velocity is demonstrated in Fig. 1. Vehicle A contains a series of small (1 kg) flyer plates or other projectiles which are launched into the trajectory of Vehicle B at appropriate points. Vehicle B is a large impact tank similar to those in terrestrial gun laboratories, except it contains a supply of targets and instrumentation such as high speed cameras, flash x-ray apparatus and digital recorders. As indicated in Fig. 2 shock and isentropic pressures of up to 20 Mbar are achievable with such a system which provides 15 km/sec impact velocities for precisely oriented projectiles. Future augmentation with other devices, now being developed e.g. rail guns, can, in principle, boost performance and the ability to obtain high precision data to carry out pioneering research at even higher pressures in the future.

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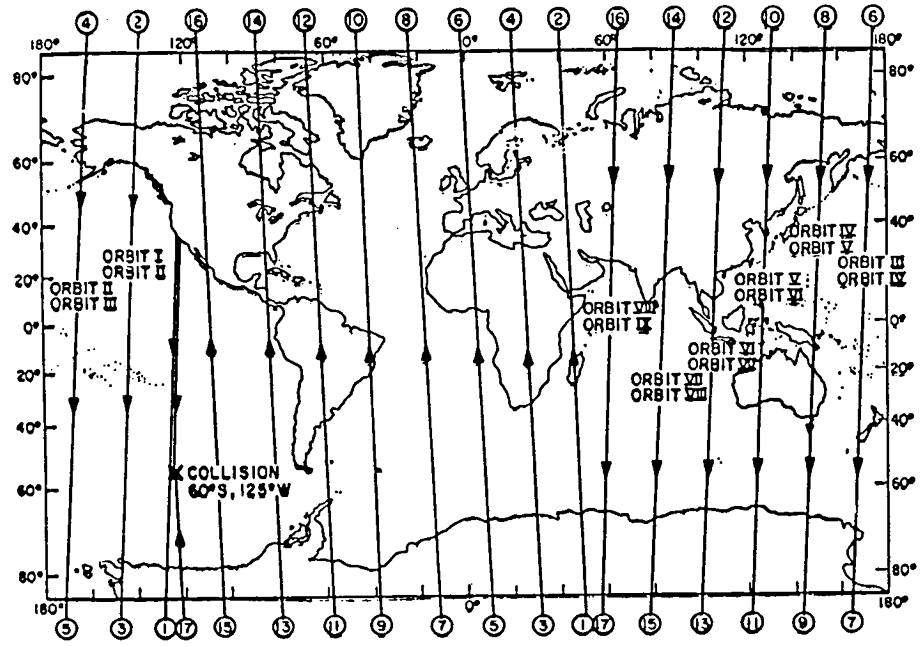

100 naut. mi. circular orbit
Orbit period 88.2 min.
2nd vehicle launch occurs after
8.16 orbits of 1st vehicle

Fig. 1 - Ground track of vehicle launched due south from Vandenburg AFB, into 100 nautical mile elevation polar orbit, demonstrating how a second vehicle launched 8.16 orbits after first vehicle will give rise to a collision over 60°S, 125°W.

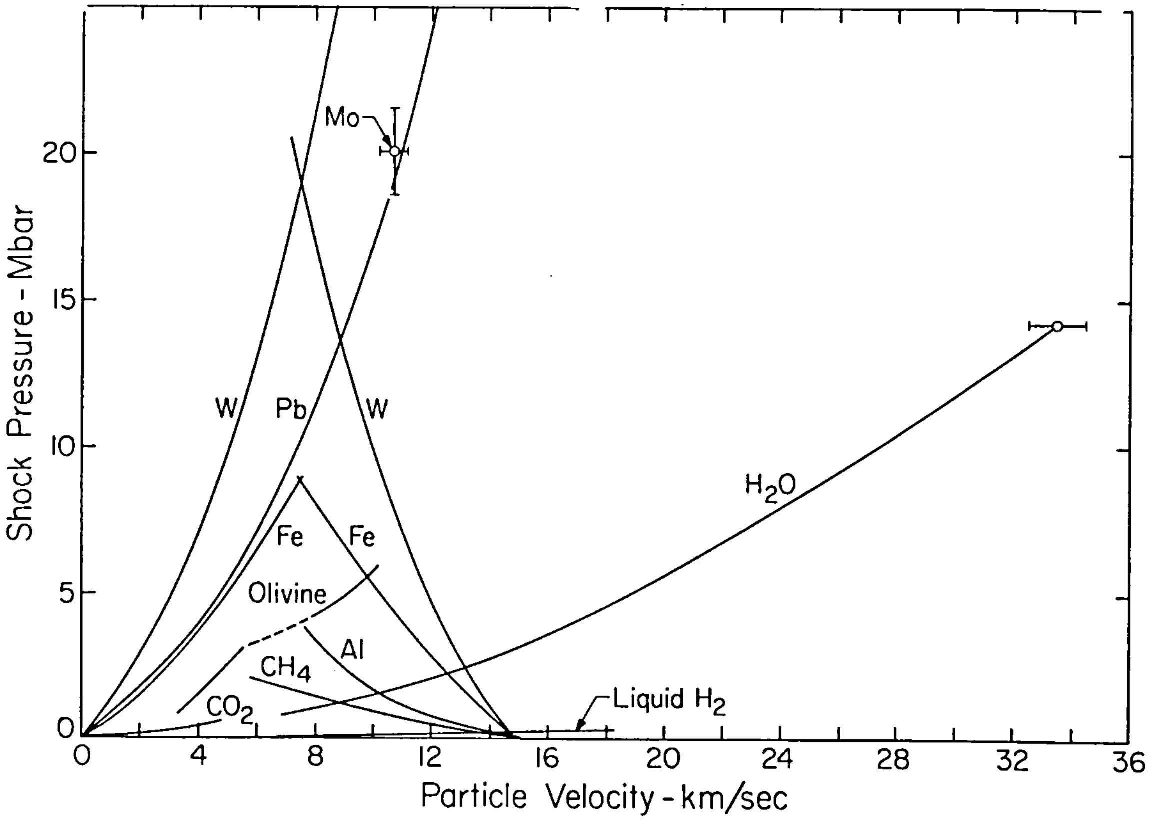

Figure 2 – Pressure-particle velocity plane for various materials, impacting at 15 km/sec. Shock pressure found by intersection of pressure-particle velocity curves, centered at 0 and 15 km/sec, e.g., ∼19 Mbar for W impacting W; ∼13.6 Mbar for W impacting Pb; 1.6 Mbar for Al impacting H_2O. Specific data for Mo and H_2O, with experimental errors shown, are from Ragan et al. (1977) and Podurets et al. (1972), both obtained using nuclear explosives. As can be seen from the figure, by choosing impactors and target materials a wide range of very high pressures may be achieved via a single available impact velocity.

PROPOSED EARTH BASED CRATERING EXPERIMENTS AT LOW G IN HARD VACUUM

Thomas J. Ahrens, Seismological Laboratory 252-21, California Institute of Technology, Pasadena, CA 91125

In order to address the questions of whether the cratering scaling which has been developed by Holsapple and Schmidt (1980,1982) and Housen et al. (1983) can be extrapolated to low velocity encounters, of planetesimals appropriate for the conditions appropriate during accretion of the planets and the impact mechanics of encounters of both asteroids and the solid objects which comprise the rings of the outer major planets, a series of experiments at low g and at high vacuum are proposed. Specific issues which could be addressed include

1. What is the effect of very low g on cratering efficiency and final crater shape in unconsolidated media at low g? At what g and vacuum levels do scaling laws become affected by surface and/or electrostatic forces? Are ejecta curtains different at very low g? Could these possibly give rise to the striae seen on the surfaces of Phobos and Deimos? Is a regime achieved such that all impact ejecta escape and the projectile erodes the target and falls aways from the target?

2. What are the dynamics of impact into a strengthless spherical and ellipsoidal "liquid" targets? Is impact into a liquid sphere a viable fragmented asteroid model? What controls spall, ejecta size, mass and velocity in such a situation?

As a precursor to experiments on a space station, impact experiments employing drop towers on earth could play a useful role. Experimental facilities at NASA/Lewis and Marshall Space Centers can be employed in both developing instrumentation and obtaining preliminary impact data on geologic materials at low and very controlled g levels in hard vacuum.

Constraining likely experiments are both the size of chambers available in drop towers and their drop time. The Lewis Research Center has the world's largest such facility. It has the capability of launching a 1 meter diameter x 3.4 meter long hollow container, in which the proposed impact experiment is placed, into a vertical ballistic trajectory and thus obtain virtually zero g for ten seconds. If the container is just dropped from the top of the 145 m high tower, 5 seconds of test-time is available at various low g levels. Another facility which is a simple (100 m) drop tower is available at Marshall Center. This has a 0.9 m diameter test container. Using the formulas in Holsapple and Schmidt (1980, 1982), expected crater sizes and crater formation times were calculated for impact into Ottawa sand. Useful bounds on the crater sizes (Fig. 1) and crater formation times (Fig. 2) can be obtained by assuming the lowest and highest energy impactor which could conceivably be launched are a 0.01 g, 10 m/sec and a 1 gm, 10 km/sec plastic and iron projectile, respectively. As can be seen from Fig. 1, the 145 m tower will just barely contain the 100 cm diameter crater expected at 10^{-5} g for the 1 g - 10 km/sec projectile. Fig. 2 demonstrates that the 12 to 200 second crater formation times are much too long for the 3 to 10 second test times available from drop towers. Ejecta absorbing or catching internal walls would be required for drop tower experiments to be conducted to final crater dimensions. Moreover, although both facilities have apparatuses for decelerating payloads, because craters in unconsolidated media in vacuum are fragile, it is unlikely that good recoveries will always be obtained. Both onboard video recording and acceleration versus time recording appear to be important ingredients in obtaining high quality data in this environment.

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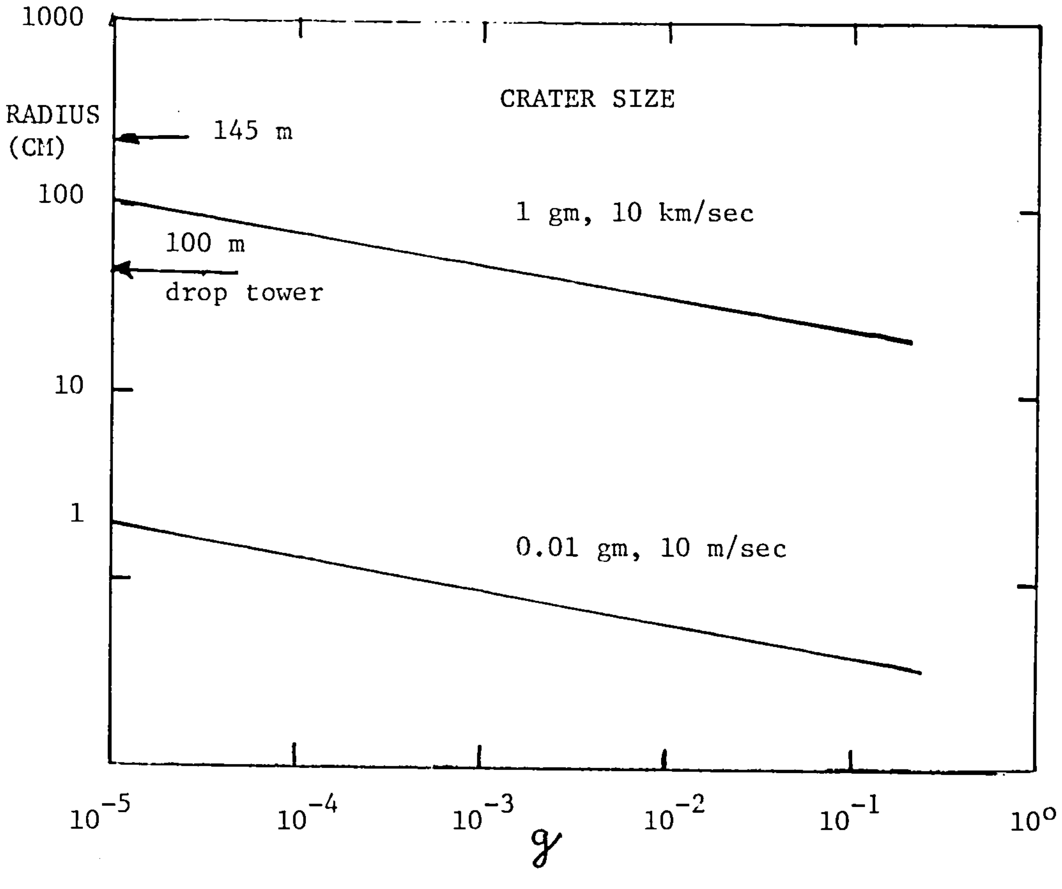

Figure 1. Calculated Ottawa sand crater diameter at different g levels for a 1 gm iron projectile impacting at 10km/sec and a 0.01 gm plastic projectile impacting at 10 m/sec. Available drop tower dimensions are indicated.

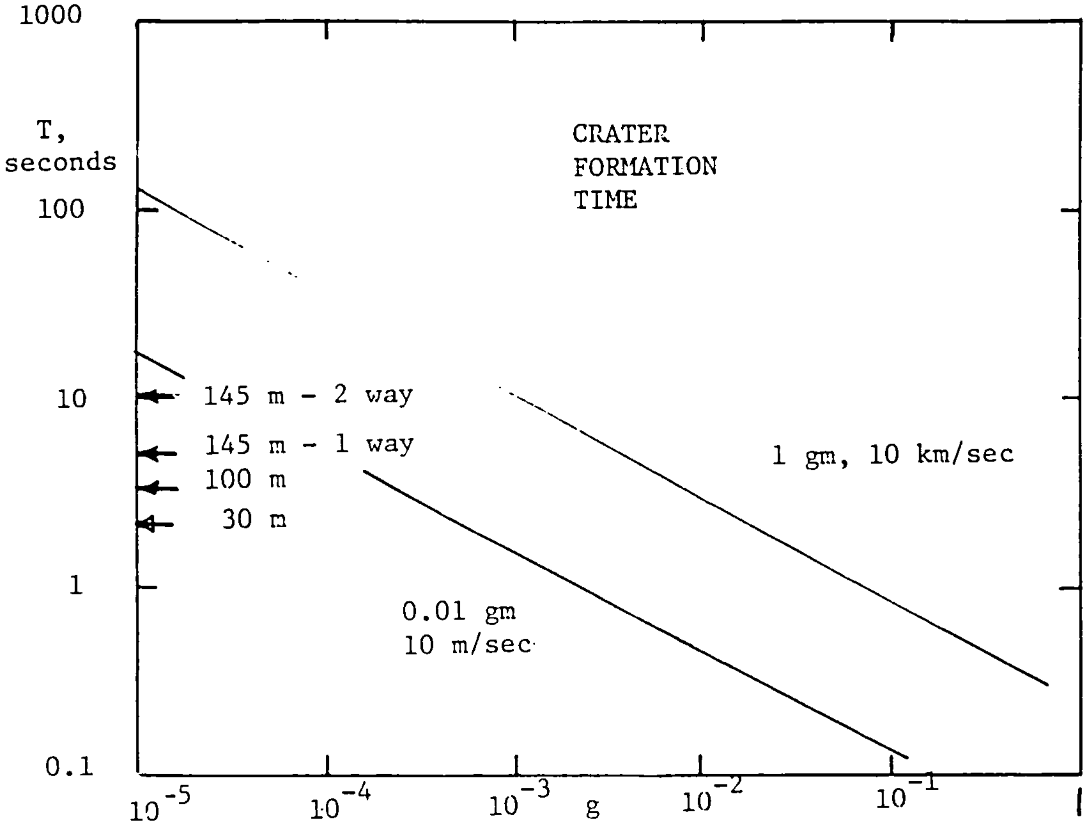

Figure 2. Calculated Ottawa sand crater formation times at different g levels for the two projectiles of Fig. 1. Drop tower test times are indicated.

MASS LOADING OF THE EARTH'S MAGNETOSPHERE BY MICRON SIZE LUNAR EJECTA-- I: EJECTA PRODUCTION AND ORBITAL DYNAMICS IN CISLUNAR SPACE

W. M. Alexander, W. G. Tanner, P. D. Anz and A-L Chen;
Department of Physics, Baylor University, Waco, Texas.

Investigations in progress have focused on particulate matter possessing lunar escape velocity which may be sufficiently perturbed to enhance the cislunar meteoroid flux. Extensive studies have been devoted to the examination of the interplanetary flux, while lunar ejecta created by the impact of this material on the lunar surface only now is being thoroughly examined. Of primary importance to this study is the production of ejecta at the lunar surface by hypervelocity impacts. Examination of the production mechanisms of lunar ejecta requires that one define the principal parameter of the hypervelocity impact event, i.e., the interplanetary meteoroid flux. To this end, two recently reported flux models /1, 2/ are employed to calculate the total mass impacting the lunar surface due to the sporadic meteor flux. However, when the moon intersects the orbit of shower meteoroids, additional matter will be injected into selenocentric space and consequently will increase the cislunar meteoroid flux. The increase is primarily due to an augmentation of lunar ejecta.

Hypervelocity meteoroid simulation experiments /3, 4, 5/ have provided ratios relating the mass of the impacting particle to the mass of ejecta produced. In order to discover that ratio, the effects of particle density as well as impact angle of incidence have been examined. Schneider /4/ has found that a 10 mg particle with a velocity of 4 km/s impacting at normal incidence would produce ejecta which represented 7.5×10^{-5} the mass of the incident particle and had a velocity greater than 3 km/s. Alexander /5/ has shown that under similar initial conditions the ejecta mass ratio, e, would be higher by an order of magnitude ($e = 5. \times 10^{-4}$). A recent study by Zook et al /6/ reported that oblique angle impacts would produce 200 to 300 times more microcraters (diameters = 7 μm) on ejecta measuring plates than would be produced by normal incidence impacts. Given that 7 μm diameter microcraters correspond to particles with $m \cong 10^{-12}$ g /7/ and that the impact velocity was 6.7 km/s, one may infer that the fraction of ejecta mass with lunar escape velocity would also increase by 200 to 300 times ($e = 1.5 \times 10^{-2}$). These three values for the "ejecta to incident particle mass" ratios will be employed to establish the total lunar ejecta mass after the interplanetary flux at 1 AU has been determined.

Two distinct dust flux models are used to carry out the calculations in this paper. The first model originates in McDonnell /8/ and then is updated in Alexander /1/; the second one is that of Grün et al /2/. Both interplanetary flux models rely exclusively upon the data gathered from in-situ experiments and thus will be represented by an empirical equation of the form

$$\Psi = \xi(m)\, m = A\, m^{1-\alpha}\, dm. \tag{1}$$

Hughes /9/ reports that this equation describes the cumulative flux of particles on a surface (per unit area per unit time) having a mass greater than m. Table 1 presents the values for α in each regime of mass value for each model.

TABLE 1

	$m \leq 10^{-14}$(g)	10^{-14}(g) $\leq m \leq 10^{-9}$(g)	$m \geq 10^{-9}$(g)
McDonnell	0.33	0.303	1.22
Grün	0.85	0.36	1.34

Using equation (1) and the two models for interplanetary flux, the total mass flux of sporadic meteoroids impacting the lunar surface can be calculated. If one assumes the sporadic meteoroid flux is isotropic and impacts the lunar surface with an average speed of 20 km/s, then the spatial mass density near the lunar surface can also be calculated, using an equation from Grün et al /2/,

$$S\ (m) = \frac{k\Psi}{\bar{v}} \qquad (2)$$

where $k = 4$ for isotropic impacts and $\bar{v}$ is the average meteoroid impact velocity at the lunar surface.

TABLE 2

	Lunar Mass Flux (g/m^2 sec)	Total Mass Lunar Surface (tons/day)	Spatial Mass Density (g/m^3)
McDonnell	2.5×10^{-12}	8.72	5.0×10^{-16}
Grün	1.04×10^{-13}	0.74	2.1×10^{-17}

These two models determine the upper and lower bound for the sporadic meteoroid flux at the lunar surface.

There exist a few notable examples /10/ of experiments which have measured the physical and dynamic properties of the ejecta. However, only a few experiments /4,5/ have investigated the dynamics of that portion of the ejecta which has achieved lunar escape velocity (2.4 km/s). An additional ejecta parameter that is common to the studies /4, 5, 6/ is an estimate of the cumulative size distribution for high velocity micron size ejecta from which the important parameter α, the mass distribution index, can be determined. Such an index can be inferred from the information Schneider reported /4/. Table 3 gives the values for α for each reported instance.

Table 3

Mass Distribution Index	
Schneider /4/	0.64
Alexander /5/	0.83
Zook, et al /6/	0.81

Given the total ejecta mass of interest ($v = 2.4$ km/s), the mass distribution index, and the ejecta mass ratio e for each study, one can determine the cumulative flux for the ejecta leaving the moon's sphere of influence.

Table 4 presents the Total Ejecta Mass Flux corresponding to each ejecta mass ratio for the two interplanetary flux models employed in this paper. (All values have the units g/m^2 sec.).

Table 4

	Ref /4/ (7.5×10^{-5})	Ref /5/ (5.0×10^{-4})	Ref /6/ (1.5×10^{-2})
McDonnell	1.9×10^{-16}	1.3×10^{-15}	3.8×10^{-14}
Grün	7.8×10^{-18}	5.2×10^{-17}	1.6×10^{-15}

The ejecta spatial density near the lunar surface is given in Table 5 for comparison with that of the interplanetary dust flux in Table 2. (All values have the units g/m^3).

TABLE 5

	Ref /4/	Ref /5/	Ref /6/
McDonnell	2.5×10^{-19}	1.7×10^{-18}	5.0×10^{-17}
Grün	1.04×10^{-20}	6.9×10^{-20}	2.1×10^{-18}

The above results show that the lunar ejecta spatial density near the lunar surface differs from the interplanetary dust spatial density by three orders of magnitude for Ref /4/, by two orders of magnitude for Ref /5/, and by one order of magnitude for Ref /6/. The variation between each spatial density value originates with the ejecta mass ratios which express the fraction of the incident particle mass with escape velocity. The lunar ejecta spatial density due to sporadic meteoroid flux at 1 AU remains essentially constant.

When the earth-moon system intersects the orbit of annual meteoroid showers, the interplanetary flux near these orbits significantly increases. Taking into account, the cumulative mass distribution and the energy of the meteoroids of the stream, one can calculate the cumulative mass flux of the particular shower. As the sporadic flux, one may then use the ejecta mass ratios to ascertain the lunar ejecta cumulative mass flux /11/. For two representative annual meteoroid streams, i.e., Quadrantids and Geminids, the lunar ejecta cumulative mass flux values are $4. \times 10^{-15}$ and $3. \times 10^{-15}$ (g/m^2 sec), or three times the upper bound value for the lunar ejecta mass flux created by the sporadic meteoroid flux in Table 4.

CONCLUSIONS

There is ample evidence to support the contention that the sporadic interplanetary meteoroid flux enhances the meteoroid flux of cislunar space through the creation of micron and submicron lunar ejecta with lunar escape velocity. During annual meteoroid showers there will be a significant increase in the lunar ejecta cumulative flux which will augment the cislunar meteoroid flux for the mass range $m \leq 10^{-9}$g by as much as an order of magnitude.

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MASS LOADING OF THE EARTH'S MAGNETOSPHERE BY MICRON SIZE LUNAR EJECTA--II:EJECTA DYNAMICS AND ENHANCED LIFETIMES IN THE EARTH'S MAGNETOSPHERE

W. M. Alexander, W. G. Tanner, P. D. Anz and A-L Chen;
Department of Physics, Baylor University; Waco, Texas.

Extensive studies have been conducted concerning the individual mass, temporal and positional distribution of micron and submicron lunar ejecta existing in the earth-moon gravitational sphere of influence. Initial results of these studies have been reported/1, 2, 3, 4/ and show a direct correlation between the position of the moon, relative to the earth, and the percentage of lunar ejecta leaving the moon and intercepting the earth's magnetosphere at the earth's magnetopause surface, EMPs. The current studies reveal the following information concerning the general transport characteristics of the ejecta (lunar phase angle, LPA, defined as the angle of the moon in earth orbit with 0° at full moon or anti-solar position):

1. The percentage of lunar ejecta entering the earth's magnetosphere varies between 65% and 85% for ejecta with radii between 0.05µ and 0.6µ and LPA between 60° and 180°;
2. the ejecta LPA release positions for maximum percentage flux at the EMPs varies with the particle mass;
3. the transport time of the ejecta from the lunar surface to the EMPs also varies with the particle radii; and
4. with the preceding data, the lunar ejecta cumulative flux, LECF, at the EMPs for conditions of maximum ejecta in-put during one lunar orbit is determined and the result is a lunar ejecta pulse for masses less than 10^{-9} g entering the EMPs during a time period ≤ 48 hours, and this represents a focusing, by a factor ≥ 3, of the lunar ejecta flux into the earth's magnetosphere.

The pertinent data relating to LPA and % of LEF at EMPs is presented in Tables 1 and 2. The information in Table 1 shows four ejecta sizes, the range of LPA for enhanced lunar ejecta flux at the EMPs, the LPA for % Max LEF and the % Max LEF at the EMPs, but gives the range of LPA as the Max % LEF arrive at the EMPs and the LPA at % Max LEF at the EMPs.

Table 1
EJECTA AND MOON POSITION PARAMETER ASSOCIATED WITH EJECTA
MOON-EARTH TRANSPORT TIMES AND POSITIONS

Particle Radii	Range of LPA	LPA at % Max	% Max LEF at EMPs
0.6µ	40°--140°	90°	72
0.3µ	50°--160°	110°	85
0.1µ	80°--180°	130°	65
0.05µ	100°--200°	150°	62

Table 2
RANGE OF LPA AND % MAX LPA AT ARRIVAL OF LEF AT EMPs

0.6µ	150°--260°	205°	72
0.3µ	135°--255°	195°	85
0.1µ	130°--250°	190°	65
0.05µ	135°--240°	188°	62

The above information uses the LPA as a time indicator. For example, the transport time for 0.6μ ejecta is 115° LPA (8.9 days); 0.3μ ejecta is 85° LPA (6.6 days); 0.1μ ejecta is 60° LPA (4.7 days); and 0.05μ ejecta is 38° LPA (2.9 days). The result is the arrival at the EMPs of the Max % LEF for each size within 32 hrs, or essentially at the same time. The LEF and Lunar Ejecta Space Density, LESD, has been estimated for the sporadic interplanetary dust particle flux and examples of the same quantities associated with two representative meteor streams /5/. Thus, a pulse of lunar ejecta into the earth's magnetosphere for each lunar cycle is indicated from these studies.

An additional factor of major importance to this work is that of lunar longitude at the time of impact of a primary particle. While the LPA is the major determing lunar position factor, the combination of LPA and longitude produces the maximum LEF onto the EMPs surface. This is demonstrated in Table 3 where all percentages are calculated for the LPA range (in 10° steps) from 10° to 160° /6/.

TABLE 3

Lunar Longitude Quarter	Average % EMPs Intercept	Max % EMPs Intercept	LPA°
1st	20	64	100
2nd	27	78	90
3rd	38	94	110
4th	33	90	110

The most important factor regarding sensitivity to longitude is the occurrance of non-random impact flux events. This is quite noticeable for the periods known as major shower periods. Initially, the LPA will determine if these ejecta will be transported to the EMPs surface. For an optimal LPA, the maximum LEF will occur when the lunar quarter (by longitude definition) is in the most favorable impact position with respect to the meteor shower radiant. From Table 3, a shower radiant that was essentially normal to the 3rd and 4th quarter with an LPA near 110°, would result in greater than 90% of the produced ejecta intercepting the EMPs surface.

When the dynamics of micron and submicron particles are being studied, several forces other than gravitational have to be considered. Radiation pressure is the major additional force which causes the lunar ejecta-magnetosphere pulse effect. The force due to convective drag becomes significant in cis-lunar space for the smallest of particles ($r \leq 0.1u$) because this is a force essentially normal to the ecliptic plane of such a magnitude (= to radiation pressure force) that many particles miss the magnetosphere even during the favorable LPA pulse portion of the lunar cycle.

The magnitudes of some of the nongravitational forces inside the earth's magnetosphere become vastly different from that of interplanetary space at 1 AU. The Lorentz type forces represent the greatest change as the radiation pressure is the same and the coulomb drag type forces are near the same because, though the velocity of the solar wind is much higher, the increase of electron densities in the magnetosphere as compared to interplanetary space effectively compensates for the velocity difference.

The Lorentz Force is much more significant inside the magnetosphere because the earth's magnetic field is greater than the magnetic field of interplanetary space and the charge on a particle is also much greater inside the magnetosphere. It is found that the Lorentz Force can be greater than the earth's gravitational force inside the magnetosphere.

Table 4 presents a comparison of gravitational and Lorentz forces inside the earth's magnetosphere. These values are calculated for spherical particles of tektite material that have been charged to a potential of -1000 volts or to the break-up potential, whichever has the lowest value. The Lorentz Force is greater than the gravitational force for particles of one micron and less radii.

Table 4 /6/

Particle Radii(u)	Particle Mass(g)	L=1.5 FG (dy)	L=1.5 LF (dy)	L=3 FG (dy)	L=3 LF (dy)	L=6 FG (dy)	L=6 LF (dy)
10	1.5×10^{-8}	6.4×10^{-6}	2.8×10^{-6}	1.6×10^{-6}	2.5×10^{-7}	4.0×10^{-7}	2.2×10^{-8}
1	1.5×10^{-11}	6.4×10^{-9}	2.8×10^{-7}	1.6×10^{-9}	2.5×10^{-8}	4.0×10^{-10}	2.2×10^{-9}
0.1	1.5×10^{-14}	6.4×10^{-12}	2.8×10^{-8}	1.6×10^{-12}	2.2×10^{-9}	4.0×10^{-13}	1.9×10^{-10}

Table 5 gives the particle radii for which the Lorentz Force exceeds the gravitational force by the factor γ.

Table 5 /6/

γ = LF/FG	L=1.5	L=3	L=5
1	8.3 μ	3.9 μ	2.7 μ
10	2.1 μ	1.2 μ	0.9 μ
100	0.7 μ	o.4 μ	0.3 μ

It is seen that the Lorentz Force dominates all other forces, thus suggesting that submicron dust particles might possibly be magnetically trapped in the well-known radiation zones. For stable trapping to occur, 3 conditions must be satisfied. The Lorentz Force must be large compared to any other force acting on the particle. Second, the particle's cyclotron gyro-period must be small compared to the corotation of the earth's magnetosphere. Third, the magnetic field must be approximately constant over distances comparable to the particle's cyclotron gyro-radius. Even if these 3 conditions are not met and no durable trapping occurs, important magnetic focusing effects may still be present. Conditions do exist where micron and submicron lunar ejecta meet the three criterion; thus, magnetically trapped or focused lunar ejecta can exist. An observable enhancement of these particle fluxes with in-situ impact experiments will occur only if the spatial density of these particles is significant in comparison to the spatial density of interplanetary dust at 1 AU. This indeed appears to be true.

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LOW-GRAVITY IMPACT EXPERIMENTS: PROGRESS TOWARD A FACILITY DEFINITION.

Mark J. Cintala, Code SN12, NASA Johnson Space Center, Houston, TX 77058.

Innumerable efforts have been made to understand the cratering process and its ramifications in terms of planetary observations, during which the role of gravity has often come into question. Well-known facilities and experiments both have been devoted in many cases to unraveling the contribution of gravitational acceleration to cratering mechanisms. Included among these are the explosion experiments in low-gravity aircraft performed by Johnson et al.(1), the drop-platform experiments of Gault and Wedekind(2), and the high-g centrifuge experiments of Holsapple and Schmidt.(3,4) Considerable insight into the effects of gravity, among other factors, has been gained through studies exemplified by those cited above. Even so, other avenues of investigation have been out of reach to workers confined to the terrestrial laboratory. It is in this light that the Space Station is being examined as a vehicle with the potential to support unique and otherwise impractical impact experiments. This report summarizes the results of studies performed by members of the planetary cratering community; their names and affiliations are listed below.

Scientific Rationale and Experiment Types -- The microgravity environment is useful in two basic ways. First, with some coaxing, it can permit direct experimentation at the gravity levels characteristic of the vast majority of planetary objects in the Solar System. Second, virtual weightlessness is a factor that enables the execution of experiments that are inordinately difficult or practically impossible to accomplish in a constant 1-g environment. Thus, there are three basic types of impact experiments that could be performed in a Space Station-supported laboratory: direct simulation (of asteroidal regoliths, for instance), process studies (e.g., collisional disruption of weakly bound, free-floating objects), and examination of scaling relationships (the control of crater size and geometry, for example, by forces that are safely negligible in higher gravity fields, such as electrostatic attraction). It must be kept in mind that the overwhelming majority of experimental data have been collected at 1-g. Empirical estimates of ejecta-deposit thicknesses, for instance, rely primarily on terrestrial impact- and explosion-cratering data.(5,6,7) On the other hand, theoretical predictions exist (8,9), but they remain to be tested at different gravity levels.

The Space Station Impact Facility -- The design of an impact facility for the Space Station is being pursued within the framework of the desired capabilities and goals of experimentation that would be performed with it. Among the requirements imposed by the group are

- High impact velocities (at least 6 km/s)
- As large an impact chamber as possible (to accommodate, for instance, the large craters that would be formed at low gravity levels)
- A variety of data-gathering methods (film, video, oscillograph, digital)
- Maximum flexibility in accommodating targets of different types (ranging from massive containers of noncohesive material to solid, free-floating objects)
- Peak electrical power capability of ~25 kW (necessary for short periods of time for chamber lighting and high-speed camera operation)
- Ability to support acceleration levels over the range of 0-0.2g.

SPACE STATION IMPACT FACILITY
Mark J. Cintala

Discussion -- These were levied with minimal restriction of the definition process to detailed Space Station capabilities as currently envisioned. Thus, it is a virtual certainty that actual vehicle performance will result in some rethinking of these and other requirements. In this vein, the Initial Operational Capability (IOC) version of the Space Station will be considerably more spartan in its ability to support the sort of facility described above. Nevertheless, a variety of very interesting experiments could still be performed; in particular, those not requiring variable gravity levels would be well-suited to the IOC facility. Not only would they provide new scientific data, but they would also serve to establish experimental procedures in the Space-Station environment. This experience would then provide a valuable foundation for operations with the expanded facility on the post-IOC Station.

At this early stage in the definition of the facility, the type of projectile accelerator is uncertain; rapid advances in railgun and other related technologies portend a precarious future for light-gas guns, especially in terms of the potential for high velocities exhibited by the former. (Should the electromagnetic accelerators be incorporated, their penchant toward high-velocities might permit their use in meteor studies, in which projectiles of various physical properties would be launched into the atmosphere. The resulting artificial meteors would then be examined simultaneously from below and above.)

The requirements of a large target chamber and variable gravity are somewhat uncompromising in an engineering sense. It is likely that centrifugal force would be employed to yield the desired accelerations in the post-IOC version, but the large volume required essentially eliminates simple centrifuges as candidate mechanisms. It is suggested instead that a detachable module or modular array be included as part of the post-IOC the Space Station, carrying its own guidance and propulsion capability. It would then separate from the Station to a safe distance and "spin up" to generate the desired g-level. Numerous experiments needing variable accelerations would benefit from this capability.

A number of technical areas have been identified which could provoke some difficulties unless studies are undertaken to determine remedial solutions or procedures. Target preparation and handling, for instance, especially in the case of fragmental or liquid materials, will pose some challenges; not only would it be a more difficult matter to fabricate a target of sand or some other fragmental material in low to zero gravity, but the floating silicates would pose a nontrivial health hazard. The absolute size of the target chamber is still somewhat in question, since theoretical predictions and extrapolations of experimental data are the only sources of information on crater size at the low g-levels that would be employed. The issue is complicated somewhat by the likelihood that stress waves reflected from the walls of the target containers could be relatively more severe than their generally ignorable counterparts in the terrestrial laboratory.

Many of these technical challenges could be approached through judicious experimentation on the NASA KC-135 Reduced Gravity Aircraft and/or the large NASA drop towers. These facilities can provide support over a wide range of experiment conditions and gravity levels, permitting engineering, procedural, and, most significantly, scientific questions to be addressed in some detail. With the benefit of such experiences, planning for the Space Station facility could be carried out with substantially more confidence.

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Microgravity Impact Working Group

T.J. Ahrens (Cal. Inst. of Tech.)
M.J. Cintala* (NASA JSC)
S.E. Dwornik (Ball Aerospace)
D.E. Gault (Murphys Center for Planetology)
R. Greeley (ASU)
R.A.F. Grieve (Bur. of Energy, Mines, and Resources, Canada)
B.R. Hawke (Univ. of Hawaii)
F. Hörz (NASA JSC)
D.L. Orphal (Cal. Research and Technology)
D. Roalstad (Ball Aerospace)
D.J. Roddy (USGS, Flagstaff)
R.M. Schmidt (Boeing Aerospace)
P.H. Schultz (Brown Univ.)

* Chairman

COSMIC DUST COLLECTION WITH A SUB-SATELLITE TETHERED TO A SPACE STATION

G.J. Corso, Indiana University Northwest, Gary, Ind.46408 and the
Lindheimer Astronomical Research Center, Northwestern Univ., Evanston, Ill

The number concentration and density of 1 micron and submicron sized grains in interplanetary space, as well as their relation to the larger zodiacal dust particles, and the importance of the Beta meteoroid phenomenon are currently being questioned (1,2).

Current stratospheric collection with balloons and high altitude aircraft has resulted in the accumulation of several hundred (perhaps a thousand) extraterrestrial particles larger than 10 microns; however, there are inherent problems with using this collection technique for the smallest particles less than 1 or 2 microns in size:

1) Strong contamination from small terrestrial particles in the stratosphere
2) Loss of time resolution and mixing of particles from different sources resulting from the long settling times of the particles as they fall slowly into the stratosphere from the upper atmosphere where they are decelerated

Attempts to obtain samples of the smallest micron and sub micron sized cosmic dust particles in space with collectors on board the space shuttle or satellites such as the Long Duration Exposure Facility (LDEF) are subject to two major difficulties:

1) Contamination by shuttle debris, rocket exhaust, and other orbiting man made debris
2) Hypervelocity impact speed on the order of tens of km/sec. resulting in destruction of the smallest particles with only small amounts of chemically fractionated impact debris remaining around impact craters.

A superior approach to the problem of how to collect large numbers of intact micron and sub micron sized cosmic dust particles in real time while avoiding terrestrial and man-made contamination would be to employ a tethered subsatellite from a space station down into the earth's upper atmosphere. In this way orbital contaminants from the space station could be avoided and advantage could be taken of the gradual deceleration of the hypervelocity particles by the earth's upper atmosphere.

Such a sub satellite tied to the space shuttle by a 100 km long tether is being developed by the Marshall Space Flight Center for the acquisition of upper atmospheric data. The author has previously proposed that cosmic dust collectors be affixed to the outside of such a sub satellite tethered to the space shuttle (3,4,5). However the maximum duration of deployment into the upper atmosphere is likely to be on the order of only a few hours, which is much shorter than what would be possible (several days) if the sub satellite were tethered to a space station maintaining altitude indefinitely. The number of particles collected intact or nearly so in this fashion should be at least a factor 10 greater than from the space shuttle. It is also possible that a permanent space station would allow the use of a tether even longer than the 100 km. long one scheduled for use on the space shuttle. This would allow even deeper penetration into the earth's upper atmosphere allowing for even more deceleration to be imposed on the hypervelocity particles before impact onto the collectors. Of course the relative impact velocity is not likely to be less than the orbital velocity of the sub satellite except for those particles within two cones of solid angle alpha, one in the forward direction and one to the rear, whose cosmic velocity vectors are essentially parallel to and within a few km/sec of the satellite's. Laboratory impact simulation experiments have shown that high density particles impacting with velocities on the order of a few km/sec can survive impact intact or nearly so in appropriate target materials.

It should be noted that the same tethered collectors could also be employed to study the composition and flux of man made earth orbiting debris in any direction within 100 km. or so of the space station. This would make it possible to monitor the build up of any debris belt in low earth orbit.

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SPACE STATION SCIENCE LAB MODULE

D.L. DeVincenzi, NASA Headquarters, Washington, DC

The Science Lab Module (SLM), a key component of the proposed Space Station (SS) orbiting complex, is undergoing intensive study during the project design phase which is currently underway. The SLM is one of two laboratory modules (the other is for materials processing) which, together with two habitation modules, comprise the core elements of the SS reference configuration.

Current project emphasis is to configure the SLM as a national science laboratory module facility which would have four major functions: maximize life sciences research potential, support operations of attached payloads, provide shirtsleeve environment for other payload instrument servicing, and support "other" science requirements. Included under "other" science are, for example, exobiology, planetary sciences, Earth observations, etc.

Conceptually, the design studies are focusing on outfitting a common module basic design to accommodate the four specific functions identified above. The common module is expected to be a 35 foot long, 14 foot diameter spacelab-like structure carried to orbit in the cargo bay of the Space Shuttle. Basic subsystem support provided by the common module design includes distributed data, power, thermal, communications, environmental life support, and storage. Science- or discipline-specific equipment will be designed, developed, and provided by the science users (i.e., NASA's Office of Space Science and Applications and its user community).

Although design work for outfitting the SLM for life sciences research is underway, science requirements for the other sciences and functions indicated above are not as well developed. A SLM Users Working Group has been convened to advise the project on the extent to which science requirements across all disciplines and functions are being accommodated by the SLM outfitting project design activity.

ELECTRICAL CONDUCTIVITY OF CARBONACEOUS CHONDRITES AND ELECTRIC HEATING OF METEORITE PARENT BODIES

Al Duba, Lawrence Livermore Laboratory, P.O. Box 880, Livermore, CA 94550

The electrical conductivity of samples of the Murchison and Allende carbonaceous chondrites is 4 to 6 orders of magnitude greater than rock forming minerals such as olivine up to 700 C. The remarkably high electrical conductivity of these meteorities is attributed to carbon at grain boundaries. Much of this carbon is produced by pyrolyzing hydrocarbons at temperatures in excess of 200 C. As temperature increases, light hydrocarbons are driven off and a carbon-rich residue or char migrates to the grain boundaries enhancing electrical conductivity.

Assuming that carbon was present at grain boundaries in material which comprised the meteorite parent bodies, we have calculated the electrical heating of such bodies as a function of body size and solar distance using the T-Tauri model of Sonett and colleagues (1970). Input conductivity data for the meteorite parent body were the present carbonaceous chondrite values up to about 800 C and the electrical conductivity of olivine above 800 C.

The results indicate that bodies up to 500 km in diameter would be heated to 1100 C (melting point of basalt) out to about 3 AU in times of one million years or less, the hypothesized length of the T-Tauri phase of the sun (Sonett et al, 1970). The distribution of asteroid types as a result of these calculations is consistent with the distribution of asteroid compositional types inferred from remote sensing (Gradie and Tedesco, 1982): carbonaceous chondrite asteroids peak at about 3 AU, more siliceous asteroids peak at about 2.4 AU.

One concern with these calculations is the use of olivine conductivity data at temperatures in excess of 800 C. We were required to use olivine conductivity at these temperatures because the conductivity of all carbonaceous chondrite samples decreased percipitously toward the olivine values. Two factors could be responsible for this decrease: oxidation of carbon in the CO_2/CO gas mixture or volatility of carbon. We are unable to separate these effects in gas mixing systems, vacuums, or inert gases because of the extremely low oxygen fugacity- less or equal to about 10^{-15} Pa- required to prevent the oxidation of carbon at 800 C. In addition, the precipation of carbon from the more reducing CO/CO_2 gas mixes required to produce this low oxygen fugacity interferes with the conductivity measurement.

The environment in the wake of the space station can be exploited to produce oxygen fugacities less than 10^{-15} Pa (Oran and Naumann, 1977). An experimental package consisting of a one square meter shield attached to a 15 cm diameter by 40 cm long furnace and tied to a conductance bridge, furnace controller, and digital voltmeter inside the space station via umbilical cable could make the required measurements. Since heating rates as low as 0.1 C/hour are required to study kinetics of the pryolysis reactions which are the cause of the high conductivity of the carbonaceous chondrites, experimental times up to 3 months will be needed.

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THE ORBIT PROPERTIES OF COLLIDING CO-ORBITING BODIES

John W. Freeman, Department of Space Physics and Astronomy, Rice University, Houston, Texas 77251

It is generally assumed that an ensemble of small bodies located in similar Keplarian orbits will, because of collisions, tend to disperse into more and more dissimilar orbits. For example, it is thought that the asteroids may represent the remnents of a few larger bodies that broke up or failed to fully accrete. Alfvén and Arrhenius (1976), Alfvén (1971), and Baxter and Thompson (1971,1973) and others have challanged this. Alfvén (1971), maintains that for the case where the time between collisions is longer than the orbit period and the collisions are essentially inelastic the orbits and velocities will become more similiar. This gives rise to the concepts of negative diffusion and jet streams. Figure 1 taken from Alfvén and Arrhenius (1976) illustrates the problem: Does the arrow of time lead from figure a. to b. or vice versa.

We propose that this question might be investigated experimentally using the space station. An ensemble of small bodies or particles might be released gently from a central location in a large chamber, much like the breaking of billiard balls (see Figure 2). The particles would then co-orbit and occasionally collide. Their subsequent behavior could be monitored by several video recorders, their linear and angular velocities before and after collisions calculated and their general behavior studied. The experiment might be varied by using particles of varying elasticities (coefficient of restitution), varying masses, and different initial relative velocities. The particles would be colored to make it easy to follow their motion and could be spherical or irregular shaped and smooth or rough. Their size might be approximately that of billiard balls. Materials could be found which would break up on collision and the fate of the collision products followed and the size distribution studied. U.V. lights and gas could be introduced to simulation charging and drag conditions found in space or near a primordial planet.

Figure 3 illustrates the possible relative motion of two bodies released in this fashion. The expected ultimate configuration for this simple case is that the bodies line up again at rest in the center of the chamber.

The proposed experiment requires a large spherical or cylindrical chamber about 14 feet (4.66 m) in diameter with three cameras looking into the chamber along three orthogonal axes. The particles will be in free orbits about the center of the chamber, therefore, the vertical or horizontal motion of the chamber, due to loss of altitude from drag or thrusting must not exceed 3 feet (1 m) in 10 orbits (~15 hours). The experiment may need to run for as long as 50 orbits. It requires only initiation and periodic checks by the crew to insure the cameras are operating. Power is required to operate the cameras and lights, 50 watts with a 10% duty cycle, and to initiate release of the particles, 5 watts for 5 seconds.

This experiment could yield results of fundamental importance for theories of the origin of the planets, the asteroids, comets and probably ring systems.

CO-ORBITING BODIES
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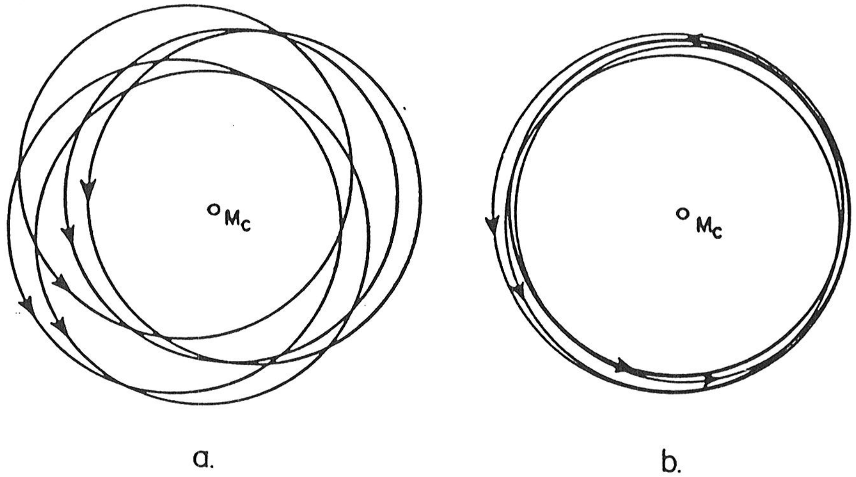


a. b.

Figure 1

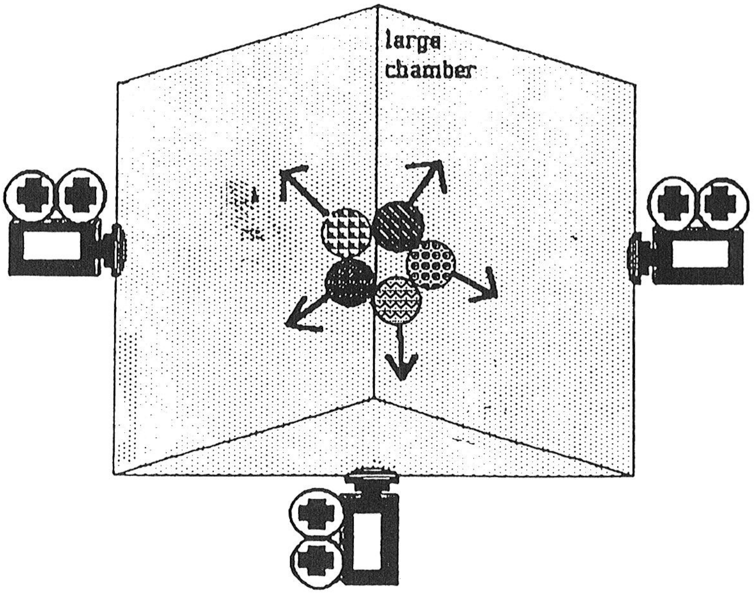
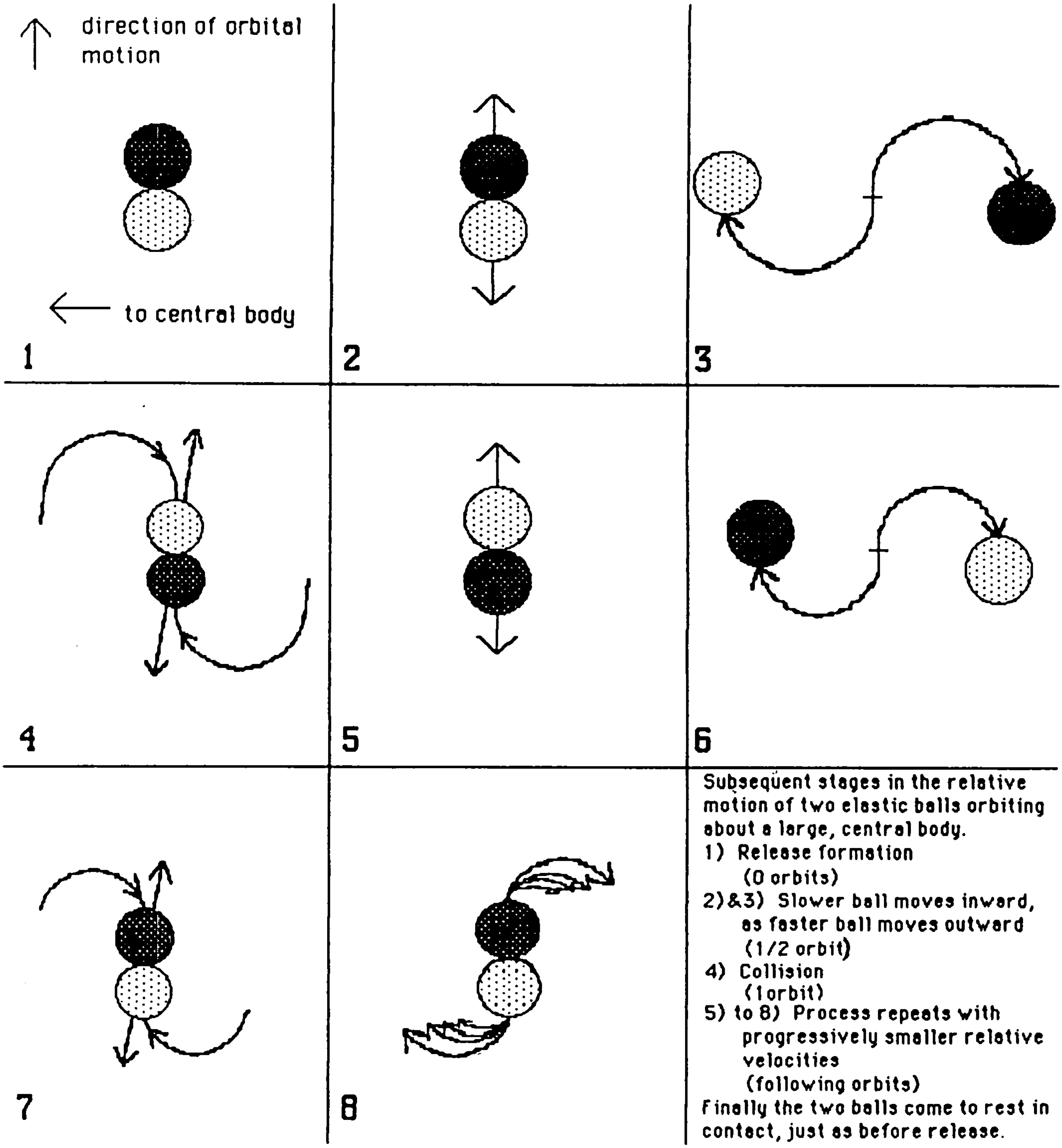


Figure 2



Subsequent stages in the relative motion of two elastic balls orbiting about a large, central body.

1) Release formation
(0 orbits)

2)&3) Slower ball moves inward, as faster ball moves outward
(1/2 orbit)

4) Collision
(1orbit)

5) to 8) Process repeats with progressively smaller relative velocities
(following orbits)

Finally the two balls come to rest in contact, just as before release.

Figure 3

SMALL LINEAR WIND TUNNEL SALTATION EXPERIMENTS: SOME EXPERIENCES

D. A. Gillette and P. R. Owen, FRS, GMCC/ERL/ARL/NOAA and the Imperial College of Science and Technology

Since the wind tunnels proposed to be used for the Space Station Planetology Experiments are of a rather limited size, some experience and techniques used for saltation experiments in a small linear wind tunnel may be of interest. Three experiences will be presented. The first concerns a length effect of saltation mass flux in which the size of the wind tunnel exaggerates the physical process taking place. A second experience concerns a non-optical technique that does not interfere with flow and by which momentum flux to the floor may be measured. The technique may also be used to calculate saltation flux (using appropriate assumptions). The third experience concerns the use of the momentum equation to estimate momentum fluxes by difference.

1. A length effect exaggerated by wind tunnel dimensions.

A feedback mechanism that increases mass flux of saltating particles with distance exists for sufficiently fast moving air passing from a smooth floor to a surface of erodible sand. Absorption of momentum by sand starting to move in saltation increases the apparent aerodynamic roughness height. This increase of roughness height corresponds with increased momentum flux from the air which makes a larger saltation mass flux possible. P.R. Owen theoretically showed this feedback mechanism to be exaggerated by the presence of a wind tunnel cieling. His theory agrees quite well with experimental results of a small cross section linear wind tunnel.

2. An approximate method for fast response measurement of saltation particle flux.

A fast time response sensor may be used to count the number of impacts on an area of floor as well as measure the momentum flux from impacts. It has the capability of furnishing data to a method by which the horizontal flux of mass moving in saltation for monodisperse particles can be estimated. The sensor has a large advantage in that it does not interfere with the flow in the wind tunnel. A disadvantage of the estimation method is that it must assume a relationship of saltation trajectories to convert the signal into mass flux information. The method uses the assumption for monodisperse particles that saltation length is proportional to particle speed at impact with the surface. The mean particle speed at impact with the surface is assumed to be proportional to the momentum flux divided by the mass flux. It is assumed that mass flux is proportional to number of impacts times the mass of each particle.

SOME EXPERIENCES WITH A SMALL LINEAR WIND TUNNEL

D. A. Gillette and P. R. Owen

The method giving a fast response mass flux for saltating particles shows for a typical run a rapid increase of particle mass flux corresponding to increase of air speed after turning on the wind tunnel fan, followed by a period of steady mass flux, followed by a decay of mass flux as the particles are depleted from the wind tunnel.

3. An attempt to use a direct momentum flux measuring device to evaluate momentum fluxes by using the momentum equation.

By measuring several terms of the momentum equation, momentum fluxes may be estimated by evaluating all but one of the terms of the momentum equation; the difference of terms is the quantity estimated. For example, the momentum equation was used to estimate the momentum flux to the floor of a rectangular wind tunnel as follows: Floor stress = upwind wind momentum flux - downwind wind momentum flux - cieling stress + pressure differential integrated over the wind tunnel cross section - downwind particle momentum flux. In the example, downwind particle momentum flux was measured using a direct momentum integration device. The method suffered, however in that the difference, the floor stress, was a small difference of large quantities all having experimental errors. Results show that the method is unreliable for distances smaller than 150 cm in a linear wind tunnel and that the estimate has large error limits. It was concluded that direct measurements were preferable where they can possibly be made.

IMPACT EXPERIMENTATION AND THE MICROGRAVITY ENVIRONMENT: AN OVERVIEW

Richard A.F. Grieve, Earth Physics Branch, EMR, Ottawa, Canada K1A 0Y3 for the Microgravity Cratering Working Group.

Impact is an ubiquitous physical process in the solar system. It occurs on all solid bodies and operates over a spectrum of scales, influencing geologic processes ranging from accretion, the early evolution of planetary bodies, the petrogenetic and spatial relations of lunar samples, the surface characteristics and interpretation of spectral data of asteroidal bodies, to the nature of some meteorites. Understanding impact phenomena is therefore paramount in constraining and underpinning a large number of research efforts into fundamental problems in planetary geology. Gravity is an important parameter in impact processes. For example, in cratering it affects the size of crater excavation, the post-excavation modification of the cavity by gravitational collapse, the spatial distribition of ejected materials, and the effectiveness of this ejecta in producing secondary cratering events. With few exceptions (Gault and Wedekind, 1977) previous experimental studies of cratering processes have been undertaken at gravitational accelerations of 1g or higher. These are not the gravity conditions occurring on most solid bodies in the solar system. The physical environment offered ultimately by Space Station represents an unique opportunity to extend the experimental aspect of impact studies into the microgravity (<1g) regime.

Previous and current experimental studies of impact phenomena address a variety of problems. The bulk of impact experimentation, however, has been concerned with crater growth and scaling. Experimental data have established that at impact energies above $\sim 10^{18}$-10^{19} ergs (equivalent to the impact of an iron meteorite in the meter-size range impacting at 20 km s^{-1} in a 1g environment), crater excavation occurs in the so-called "gravity regime", where target strength effects are unimportant (Schmidt, 1980). This condition is simulated experimentally by using low strength materials, such as sand or water, and by the use of elevated gravitational accelerations. The effect of elevated gravity is to displace the onset of the gravity regime to lower energies. Such experimentation has led to the development of scaling relations, where cratering efficiency is related to a dimensionless parameter which includes the effects of projectile velocity and size, and gravitational acceleration.

It has been sugggested recently that additional parameters such as the shape of the experimental projectile (Schultz and Gault, 1985) and variable energy losses due to waste heat in the target (Cintala and Grieve, 1984) are not fully accounted for in the current dimensionless parameters. Thus it is important to continue work in this area. The opportunity to conduct new experiments at gravities directly applicable to that of planetary bodies will contribute to determining and refining the relevant scaling relations for large craters. Apart from their importance in problems concerned with cratering mechanics, such relations are required to correctly relate crater densities on different solar system bodies to absolute surface ages (Basaltic Volcanism Study Project, 1981).

A further advantage of the microgravity environment is that, for a given impact event, reduced gravity increases the crater growth time. It will be possible, therefore, through high-speed photography to observe the crater growth and ejecta dynamics in considerably more detail than in previous 1g experiments. This will lead to a better understanding of the relative importance of rebound and collapse phenomena in crater formation and the nature of the ejecta plume as an erosional and depositional agent.

In the low strength materials used in impact experiments under terrestrial conditions, gravitational forces dominate other bonding forces, such as surface tension, electrostatic effects etc. This may not be the case under highly reduced gravity conditions, which prevail on small asteroidal bodies. Even if current dimensionless scaling relations are shown to be substantially correct for large planetary craters, they can not be applied to the energy regime associated with small cratering events. Cratering experiments at highly reduced gravities, corresponding to asteroidal bodies, will therefore provide basic and currently unavailable information on cratering and regolith development or lack of it on these bodies.

Previous experimentation provides little or no information on the spatial distribution, source region and physical state of ejecta under differenct gravity conditions. The few experiments designed to address these fundamental questions all have been undertaken at 1g (Stoffler et al., 1975). Similarly, the only direct observational data on these questions are from terrestrial craters. It is well-established that for a specific impactor size and velocity and target materials, crater size will increase with decreasing gravity. However, peak shock pressures and the spatial distribution of shock isobars in the target are not a function of gravity and will remain constant. They are a function of impact velocity, pulse length and target characteristics. The reduced gravity environment afforded in near-earth orbit provides an opportunity to consider the questions of ejecta source and shock state and its final distribution under varying gravitational accelerations. These questions are highly germane to problems such as the physical and thermal state of ejecta blankets and regolith development on both planetary and smaller bodies. These relate directly to questions in lunar sample and meteorite analyses and the interpretation of remotely-sensed spectral and geochemical data.

The microgravity environment also provides a new and potentially rewarding area of impact experimentation not previously possible. Through the use of free-floating targets, it may be possible to explore in detail phenomena associated with the collision of bodies. Such experiments can address questions regarding early and late accretional processes, catastrophic disruption and asteroidal evolution, as well as the effects of large impacts on the momentum and spin of the target bodies. The last question is of considerable topical interest with respect to the hypothesized origin of the moon by a Mars-sized impact on the early Earth.

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EXOBIOLOGY EXPERIMENT CONCEPTS FOR SPACE STATION

L.D. Griffiths, MATSCO, Washington, DC
D.L. DeVincenzi, NASA Headquarters, Washington, DC

The exobiology discipline uses ground-based and space flight resources to conduct a multidiscipline research effort dedicated towards understanding fundamental questions about the origin, evolution, and distribution of life and life-related molecules throughout the universe. Achievement of this understanding requires a methodical research strategy which traces the history of the biogenic elements from their origins in stellar formation processes through the chemical evolution of molecules essential for life to the origin and evolution of primitive and, ultimately, complex living species. Implementation of this strategy requires the collection and integration of data from solar system exploration spacecraft and ground-based and orbiting observatories and laboratories.

The Science Lab Module (SLM) of the Space Station orbiting complex may provide an ideal setting in which to perform certain classes of experiments which form the cornerstone of exobiology research. These experiments could demonstrate the pathways and processes by which biomolecules are synthesized under conditions that simulate the primitive Earth, planetary atmospheres, cometary ices, and interstellar dust grains. For some of these experiments, gravity is a critical factor. Others may require exposure to the ambient space environment for long periods of time. Still others may require on-orbit preparation, servicing, maintenance, fixing, and analysis of samples. The pressurized SLM provides sufficient duration in the space environment and the crew interactions needed to assure implementation of these investigations.

Exobiology experiments proposed for Space Station generally fall into four classes: interactions among gases and grains (nucleation, accretion, gas-grain reactions), novel high-energy chemistry for the production of biomolecules, physical and chemical processes occurring on an artificial comet, and tests of the theory of panspermia. Clearly, many of these simulations contain aspects of interest to the planetary sciences such that a close coupling between these disciplines will maximize science return and promote a more efficient use of resources.

SEDIMENT-TRANSPORT EXPERIMENTS IN ZERO-GRAVITY

James D. Iversen
Aerospace Engineering Dept., Iowa State University
Ronald Greeley
Dept. of Geology, Arizona State University

One of the important parameters in the analysis of sediment entrainment and transport is gravitational attraction. The availability of a laboratory in Earth orbit would afford an opportunity to conduct experiments in zero-gravity and variable-gravity environments. Elimination of gravitational attraction as a factor in such experiments would enable other critical parameters (such as particle cohesion and aerodynamic forces) to be evaluated much more accurately. A Carousel Wind Tunnel (CWT) is proposed for use in conducting experiments concerning sediment particle entrainment and transport in a space station. The type of wind tunnel we propose consists of two concentric rotating drums. The space between the two drums comprises the wind tunnel test section. Differential rates of rotation of the two drums provides a wind velocity with respect to either drum surface. Rotation of the outer drum provides a "pseudo" gravity ("pseudo" in the sense that a gravity force acts on the particle only when it is resting on the outer drum surface).

In order to test the concept of this wind tunnel design, a 1/3 scale model Carrousel Wind Tunnel (CWT) was constructed and calibrated. In this prototype, only the inner drum rotates, whereas in the final configuration, both drums would rotate at controllable, variable speeds. The outer drum is sealed along its periphery, but there is a small gap between the sides of the inner drum and the outer drum.

Threshold Experiments

Threshold (u_{*_t}) defines the minimum winds required to initiate particle motion and is the fundamental factor in aeolian processes. In the determination of a general expression of the threshold wind speeds for small (~sub-millimeter) particles, the effect of aerodynamic forces tending to dislodge a particle from a bed of loose granular material is equated to the effect of opposing forces, namely the particle weight (W) and interparticle cohesion (I). The relative magnitudes of these forces have been deduced only approximately from wind tunnel tests of threshold speed (Iversen et al., 1976; Greeley et al. 1980a, Iversen and White, 1982).

The elimination of particle weight in the threshold force equation--as could be accomplished by conducting experiments in a weightless environment--would enable a more accurate assessment of the other factors. The equation of equilibrium for a small particle at threshold is

$$Da + Lb + M = Ic + Wb \qquad (1)$$

Where D, L, and M are aerodynamic drag, lift, and moment, respectively, W is particle weight, I is cohesive force, and a, b, and c are distances from lines of action of the forces to the overturning point. Elimination of the weight term would aid in the determination of the form and magnitude of the cohesive force term at the moment of threshold.

All of the previous experiments have been conducted under conditions of Earth's gravity. It would be extremely valuable to extend the matrix of experiments to include values of artificial gravity above and below that experienced on Earth. This could be accomplished in CWT by placing a bed of particles on the inner surface of the outer drum and rotating the outer drum at different rotational speeds. The rotating outer drum provides an acceleration directed radially outwards, normal to the surface, thus creating artificial gravity. While rotating the outer drum at a constant rate to maintain a constant value of artificial gravity, the inner drum speed can be changed to increase the value of outer-drum wind-friction speed until the top layer of particles leaves the surface at which point the threshold wind friction speed can be ascertained.

Zero-gravity threshold experiments are valuable because of the elimination of the weight term in Equation (1). These experiments would be conducted by rotating only the inner drum, accelerating its speed until threshold is reached.

CWT Flow Characteristics

A series of experiments was conducted in a prototype carousel wind tunnel (CWT) to determine the flow properties. Taylor in 1935 hypothesized nearly potential flow between concentric rotating cylinders with the exception of boundary layers (governed by Prandl's mixing - length theory) near the outer and inner drum walls. Wind velocity profiles were obtained using a TSI Model 1010 hot-wire anemometer. The data show conformity to Taylor's hypothesis and good lateral uniformity of flow. Discrepancies between theory and experiment are due primarily to secondary flows in the wind tunnel cross section which seem to be concentrated near the inner drum. The flow is close to the desired two-dimensionality. Turbulence levels of 6% to 10% were measured within the inner and outer boundary layers. In CWT it is important that the mixing-length theory govern the boundary-layer flow adjacent to the curved cylinder wall surfaces because the same theory governs the flow adjacent to a plane surface and would be comparable to natural conditions and to conditions used in previous threshold experiments (Greeley et al., 1976, 1980b; Iversen et al., 1976). Experiments were performed in CWT to ascertain if these assumptions are correct and if Taylor's hypothesis is valid. For cases in which only the inner cylinder rotates (as in the prototype CWT) and assuming that the surfaces of the cylinder walls are aerodynamically smooth, the following equations for the flow between two infinitely long cylinders can be derived:

inner layer (Prandtl boundary layer)

$$U = R_i\omega - u_{*_i}\{2.5 \ln [(r - R_i)u_{*_i}/\nu] + 5.5\}$$

$$\text{for } R_i/R_o + (\nu/u_{*_i}R_o)e^{0.4R_i\omega/u_{*_i}} \leqslant r/R_o \leqslant r_2/R_o \tag{2}$$

central layer (potential inviscid layer)

$$U = KR_i\omega R_o/r$$

$$\text{for } r_2/R_o \leqslant r/R_o \leqslant r_1/R_o \tag{3}$$

outer layer (Prandtl boundary layer)

$$U = u_{*_o} \{5.5 + 2.5 \ln [(1 - \frac{r}{R_o}) R_o u_{*_o} / \nu]\}$$

$$\text{for } r_1/R_o \leqslant r/R_o \leqslant 1 - 0.1108/(R_o u_{*_o}/\nu) \qquad (4)$$

Preliminary results show uniform flow and boundary layer properties that are in agreement with theory. Experiments were conducted in the prototype to determine the feasibility of studying various aeolian processes and the results were compared with various numerical analyses. Several types of experiments appear to be feasible utilizing the proposed apparatus.

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DESIGN AND CALIBRATION OF THE CAROUSEL WIND TUNNEL

R.N.Leach[1], R.Greeley[1], J.Iversen[2], B.White[3], J.R.Marshall[1]
[1]Arizona State University, Tempe, Az. 85287, [2]Iowa State University, Ames Ia. 50010, [3]University of California, Davis, Ca. 95616

In the study of planetary aeolian processes the effect of gravity is not readily modeled. Gravity appears in the equations of particle motion along with inter-particle forces but the two terms are not separable. A wind tunnel that would permit variable gravity would allow separation of the forces and aid greatly in understanding planetery aeolian processes.

Wind tunnels suffer from several shortcomings in aeolian experiments, primarily due to limitations of size. The flow Reynolds Number is a function of the distance from the tunnel entry and for most experiments a long distance is desirable to obtain a sufficiently high Reynolds Number and corresponding fully developed turbulent boundary layer.

A uniquely designed carousel wind tunnel allows for a long flow distance in a small-sized tunnel since the test section is a continous circuit. It also allows for a variable psuedo gravity.

The carousel wind tunnel consists of two concentric drums, the space between the drums being the test section. A wind is generated by rotating the inner drum, which causes a velocity gradient in the air between the drums. This velocity is large enough to initiate movement of sand particles.

A prototype design has been built and calibrated to gain some understanding of the unique characteristics of the design and the results are presented. This prototype does not incorporate the variable psuedo gravity feature, but the design for this aspect is discussed. It is proposed to install this wind tunnel in the NASA KC135 aircraft used for zero g experiments. By comparing the velocity required to initiate saltation threshold at earth gravity, near zero gravity, and at or near 2g's we will be able to make an initial assessment of the effect of gravity on saltation threshold. It will also give us experience in working with this type of tunnel in variable gravity fields.

The experiment will be done in the following manner: A small quantity of sand of a given size will be placed in the test section. The inner drum will be brought to a speed below that required for particle threshold. The bed will be observed as the aircraft begins its manuever to reduce the apparent gravity and the gravity force at threshold will be recorded. This experiment will be repeated at different inner drum speeds and thus a curve of gravity force vs. particle threshold speed will be obtained. When the aircraft is performing its recovery manuever the gravity force will approach two g's. By observing the gravity level at which particle movement ceases for various inner drum speeds the relationship between particle movement and gravity force can be extended above 1 g.

Calibration was performed in the following manner: Using a photo-tachometer to determine drum speed, the drum RPM was correlated with the output from a magnetic pickup sensor displaying a digital readout proportional to drum speed. A TSI hot wire anemometer system was then used to obtain velocity profiles between the drums at five locations between the end walls. This was done for a "large" drum and a "small" drum, The large drum is two thirds the diameter of the outer drum and the small drum, is one-half the diameter of the outer drum. Having examined the data it has been determined that the large drum is more suitable for threshold experiments, while the small drum is better for examining particle trajectories. These data are presented as the ratio of the wind speed obtained to the rim speed of the inner drum vs. the percentage of distance to the outer drum. RMS values of the velocity fluctuations were also taken at selected locations to determine the turbulence level.

Tests were performed using sand of various sizes and thresholds were determined under laboratory conditions. These will be used as a data base to compare the flight data against.

In the final version of this tunnel both the inner and outer drums will rotate. This type of tunnel would be most useful in a zero gravity environment. It will permit a psuedo-gravity effect to be induced,i.e., by rotating the outer drum the particles will be held to the surface by centrifugal force while in contact with the drum. The movement of the drums can be so coordinated that a particle could lift off and return to the surface at the same spot or any chosen location. This would allow some interesting experiments that would shed light on the orgin and development of aeolian ripples and other bedforms.

A MAGNETOSPHERIC SIMULATION AT THE SPACE STATION

R. E. Lopez, J. W. Freeman, and F. C. Michel, Department of Space Physics and Astronomy, Rice University, Houston, Texas.

It is proposed that a strong magnet (terrella) be flown at or near the Space Station to create an artificial magnetosphere in a "laboratory" setting. The relative flow of the ionosphere past the terrella will constitute a plasma wind that will interact with the magnetic field of the terrella to produce a localized magnetosphere. This object could then be extensively studied using diagnostic probes attached to the Space Station, or with free flyers.

Although small in scale, such a magnetosphere would still be large compared to the gyroradius of the wind particles, as is the case in planetary magnetospheres. On the other hand the β of the plasma wind forming the magnetosphere would be much lower than the β of the solar wind for most planetary magnetospheres. Such a low β MHD interaction would expand the range of magnetospheric observations. In addition, the outside plasma flow is magnetically, rather than dynamically, dominated. This is very different from the earth's magnetosphere where the outside (solar wind) flow is dominated by the dynamic pressure of the flow. The terrella would provide our first example of such a system that we could study.

The support of the Space Station would allow all of the usual benefits to the experimenters of a laboratory; direct access to the experiment, availability of a suite of test equipment, computation and contemplation facilities, rapid turnaround and flexibility, etc. Moreover, the effects of unusual perturbations could also be studied, for example, the introduction of various heavy ions into the system. Another interesting possibility, not seen in planetary magnetospheres, is to charge the terrella to high potentials. Such an experimental setup could therefore do much to advance the general theory of magnetospheric physics.

The space and storage requirements would be minimal, since the experiment would be conducted outside the space station. The total equipment would consist of several terrellas (with varying surface conductivities), ~3 small magnetometer/plasma diagnostic packages, and several gas canisters for upstream "seeding". Power requirements would be ~60 watts. Several track-mounted tethers, each $\gtrsim$ 200 m in length, with the track parallel to the orbital motion and 100 m long, are also needed. Astronaut time needed would be minimal in the tethered configuration (~4 man hours/week). A free-flying configuration, while not needing the tether track, would require much more human interaction.

ELECTROSTATIC AGGREGATION OF FINELY-COMMINUTED GEOLOGICAL MATERIALS

J.R. Marshall and R. Greeley,
Department of Geology, Arizona State University, Tempe, Az.85287

Electrostatic forces are known to have a significant effect on the behavior of finely-comminuted particulate material: perhaps the most prevalent expression of this being electrostatic aggregation of particles into relatively coherent clumps. However, the precise role of electrostatic attraction and repulsion in determining the behavior of geological materials (such as volcanic ash and aeolian dust) is poorly understood. It may be an important factor in volcanic activity where the size of particles affects the behavior of eruption clouds during ash-fall or pyroclastic-surge, and it may also be important in affecting the threshold, transport, and deposition of aeolian particles. The effect of electrostatics on both pyroclastic and aeolian material could be important on Mars and Venus, as well as on Earth.

Electrostatic aggregation of fine particles is difficult to study on Earth either in the geological or laboratory environment principally because the material in an aggregated state remains airborne for such a short period of time. Also, aerodynamic forces acting on the clusters of particles during precipitation probably affect the aggregation process so that it is impossible to be certain about the respective roles of interparticle forces and aerodynamic forces in any experiment.

Previous studies with finely-comminuted (crushed) geological materials have shown that aggregation occurs very quickly after aerodynamic entrainment, that materials form a variety of aggregation products (one, two, and three-dimensional structures --filaments, flakes, and spheroids, respectively) and that aerodynamic forces during settling apparently modify the rate and nature of aggregation. The experiments also showed that the finest (clay-size) materials of the particulate mass were the primary contributors to aggregates.

Experiments conducted in the NASA/JSC - KC135 aircraft would shed some light on the aggregation process. Zero gravity would allow 1) a brief, but significant, time period for aggregation processes to be studied without settling of material, and 2) an environment in which electrostatic and aerodynamic forces could be separated.

The experimental variables for consideration would be the type of geological material, the method of comminution (aeolian attrition, glacial crushing, volcanic fragmentation, etc.), particle size and shape, and the atmospheric pressure (density) and temperature. The role of time cannot be studied in the KC 135 (except within a ~20 second period) and aircraft experiments are therefore seen as precursors to more elaborate and scientifically more comprehensive Shuttle or Space Station activities. For the KC 135, initial experiments would involve a simple glass case into which a particle cloud could be injected immediately prior to the zero-gravity maneuver. Photography would be the principal experimental record, but a framing rate of ~16 photos per second would be adequate for preliminary assessment of aggregation. In order to prevent contamination of the environment with the particles, the glass experimental chamber would be equipped as a standard glove box that would allow the total confinement of sample loading and chamber cleaning between experiments.

Although the proposed experiments are primarily aimed at aeolian and volcanic processes, the information obtained would be directly relevant to some of the more recent major issues of "nuclear winter" and the extinction of species in the geological record speculated to be caused by meteorite impact. Both hypotheses rely upon the role of atmospherically-suspended, finely-comminuted material.

THE INITIATION OF GRAIN MOVEMENT BY WIND

W.G. Nickling, University of Guelph, Guelph, Ontario, Canada.

When air blows across the surface of dry, loose sand, a critical shear velocity (fluid threshold, U_{*t}) must be achieved to initiate motion. However, since most natural sediments consist of a range of grain sizes, fluid threshold for any sediment can not really be defined by a finite value but should be viewed as a threshold range which is a function of the mean size, sorting and packing of the sediment. In addition these textural parameters can indirectly affect various interparticle forces such as capillary water tension and electrostatic charges which tend to bend individual grains together, thereby increasing fluid threshold and decreasing the supply of grains to the air stream.

In order to investigate the initiation of particle movement by wind a series of wind tunnel tests was carried out on a range of screened sands and commercially available glass beads of differing mean sizes (range: 0.19mm to 0.77mm), sorting and shape characteristics. In addition, individual samples of the glass beads were mixed to produce rather poorly sorted bimodal distributions. In the wind tunnel tests a sensitive laser monitoring system was used in conjunction with a high speed counter to detect initial grain motion and to count individual grain movements. Test results suggest that when velocity is slowly increased over the sediment surface the smaller or more exposed grains are first entrained by the fluid drag of the air either in surface creep or in saltation. As velocity continues to rise, the larger or more protected grains may also be moved by fluid drag. On striking the surface saltating grains impart momentum to stationary grains thereby reducing the fluid drag necessary for entrainment (dynamic or impact threshold). As a result, there is a cascade effect in which a few grains of varying size, initially moving over a range of shear velocities (fluid threshold range) set in motion a rapidly increasing number of stationary grains. This transition occurs very rapidly and is affected by the sorting, packing and shape of the surface grains. The rapid progression from fluid to dynamic threshold, based on the number of grain movements, can be characterized by a hyperbolic function, the coefficients of which are directly related to the textural characteristics of the initial sediment. The data also indicate that predicted threshold values based on the modified Bagnold equation (Iversen et al, 1976) fall within the range of threshold values defined by the transition section of the grain movement/shear velocity plots. Moreover, the predicted values are very similar to the threshold values derived for the point of maximum inflection on the curves.

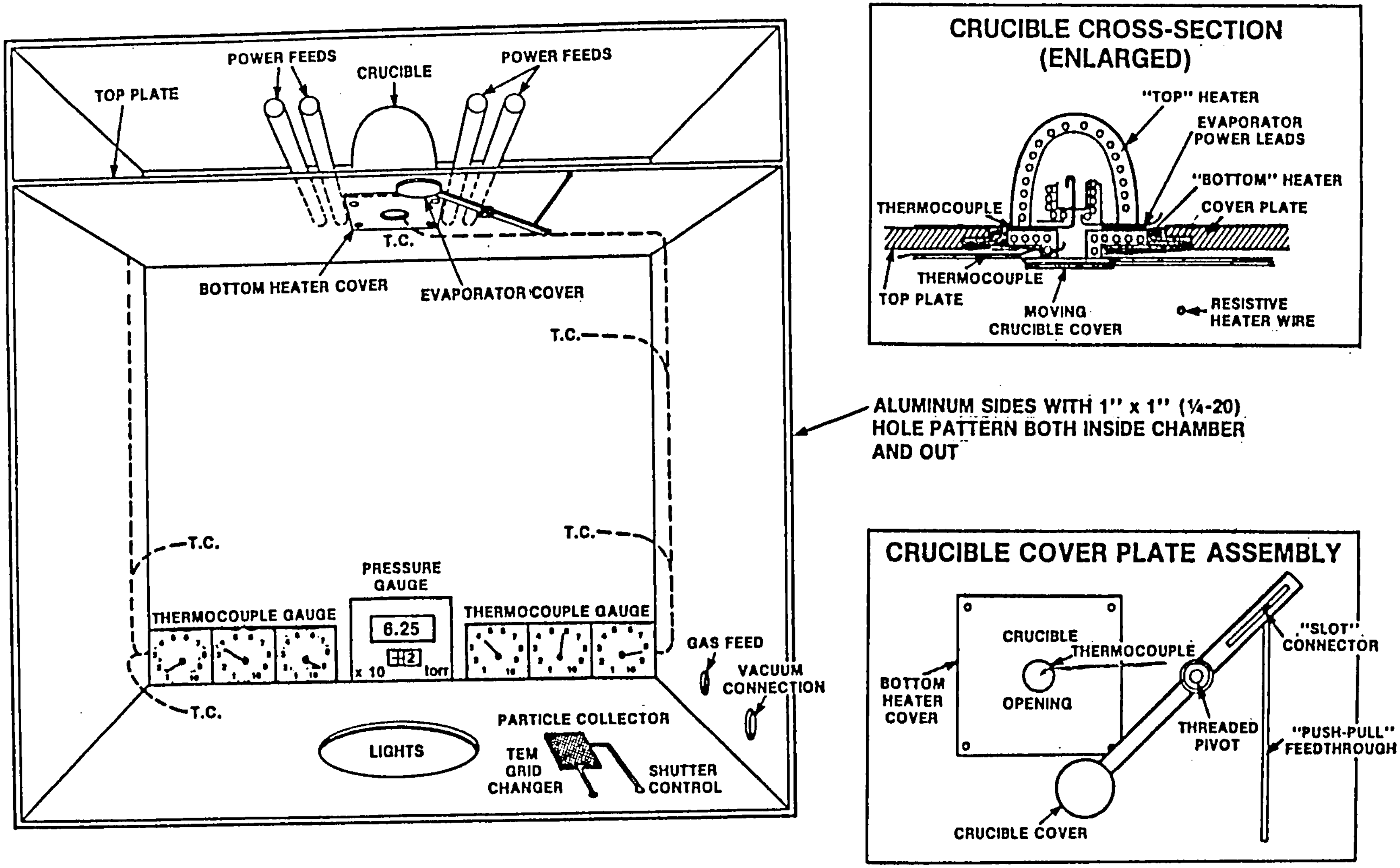
NUCLEATION EXPERIMENTS IN A MICROGRAVITY ENVIRONMENT

J.A. Nuth (NAS/NRC), J.E. Allen Jr. (GSFC), L.U. Lilleleht (U Va), I.D.R. Mackinnon (Microbeam, Inc.), F.J.M. Rietmeijer (LEMCO), J.R. Stephens (LANL)

A simple experimental apparatus (Figure 1) will be described in which a wide variety of vapor phase nucleation studies of refractory materials could be performed aboard NASA's KC-135 Research Aircraft. The chief advantage of a microgravity environment for these studies is the expected absence of thermally driven convective motions in the gas. The absence of convection leads to much more accurate knowledge of both the temperature distribution in the system and the time evolution of the refractory vapor concentration as a function of distance from the crucible.

We will describe the evolution of the apparatus as we gain more experience with the microgravity environment. Expected modifications include the addition of a programmable thermal gradient away from the crucible and a dye laser probe coupled with a detector system based either on a reticon array or a series of diodes. This latter system should make it possible to obtain a great deal of information not only on the conditions under which nucleation occurs, but also on the optical scattering and absorption characteristics of the particles produced in the experiments. These particles will be collected for SEM/TEM analysis. Comparison between the experimental results and the predictions of Mie theory for the measured particle size distribution will be made. In addition, an attempt will be made to measure the coagulation coefficient for a variety of materials and particle sizes by monitoring the time evolution of the size distribution.

We expect that a significant amount of nucleation data can be collected using the KC-135; considerably less information will be collected on the coagulation of the particles due to the short period of time in which the data can be obtained. Nevertheless, such experiments will be used to prepare for similar ones carried out aboard either the Shuttle or the Space Station where considerably longer duration experiments are possible.


POWER FEEDS
CRUCIBLE
POWER FEEDS
TOP PLATE
T.C.
BOTTOM HEATER COVER
EVAPORATOR COVER
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T.C.
PRESSURE GAUGE
THERMOCOUPLE GAUGE
6.25
x 10 -2 torr
THERMOCOUPLE GAUGE
GAS FEED
VACUUM CONNECTION
PARTICLE COLLECTOR
LIGHTS
TEM GRID CHANGER
SHUTTER CONTROL
CRUCIBLE CROSS-SECTION (ENLARGED)
"TOP" HEATER
EVAPORATOR POWER LEADS
"BOTTOM" HEATER
THERMOCOUPLE
COVER PLATE
THERMOCOUPLE
TOP PLATE
MOVING CRUCIBLE COVER
RESISTIVE HEATER WIRE
ALUMINUM SIDES WITH 1" x 1" (¼-20) HOLE PATTERN BOTH INSIDE CHAMBER AND OUT
CRUCIBLE COVER PLATE ASSEMBLY
CRUCIBLE
THERMOCOUPLE
"SLOT" CONNECTOR
BOTTOM HEATER COVER
OPENING
THREADED PIVOT
"PUSH-PULL" FEEDTHROUGH
CRUCIBLE COVER

Figure 1.

ULTRAVIOLET SPECTROSCOPY OF METEORIC DEBRIS: IN SITU CALIBRATION EXPERIMENTS FROM EARTH ORBIT

Joseph A. Nuth (NAS/NRC), Thomas J. Wdowiak (Univ. Alabama at Birmingham), William R. Kubinec (College of Charleston)

Introduction. We propose to carry out slitless spectroscopy at ultraviolet wavelengths from orbit of meteoric debris associated with comets. The Eta Aquarid and Orionid/Halley and the Perseid/1962 862 Swift-Tuttle showers would be our principal targets. Low light level, ultraviolet video techniques will be used during the night side of the orbit in a wide field, earthward viewing mode. Data will be stored in compact video cassette recorders. The experiment may be configured as a GAS package or in the HITCHHIKER mode. The latter would allow flexible pointing capability beyond that offered by shuttle orientation of the GAS package, and doubling of the data record. The 1100-3200 A spectral region should show emissions of atomic, ionic, and molecular species of interest on cometary and solar system studies.

A major problem at the present time is an inability to accurately convert observed meteoric spectral intensities into compositional information. This problem could be circumvented and a significant amount of data on fundamental meteoric phenomenon could be obtained by the high-velocity injection of well characterized projectiles into the earth's upper atmosphere. This could be accomplished quite easily if a rail gun were available on the space station as part of the microgravity cratering facility (or for other reasons). Projectiles launched from a rail gun in earth orbit could enter the atmosphere at velocities as high as 25 km/s. Optimal viewing of such artificial meteors could be achieved if the gun and detector systems were located on separate platforms several hundred kilometers apart.

Discussion. Analysis of middle to far ultraviolet spectral data of meteoric debris of cometary origin has yet to be carried out. Objectives of such a study include the observation of many atomic species, both neutral and ionized, including the strong feature due to MgI at 2850A and the strong blend at 2800A due to MgII and MnI. An interesting possible metal emission is that of BeI at 2349A.

Carbon is an expected constituent of comet-associated meteors. Though spectral features can exist in the visible region, carbon cannot be observed due to masking, principally by iron. The 1000-2000A region should be relatively free of FeI and FeII emission allowing observation of CI at 1193A, CI at 1330A, CI at 1561, and CI at 1657A. In addition, strong SiI and SiII emissions exist in the region suggesting determination of the C/Si ratio. Lines of SiO could also be observed at 1310A.

Lyman alpha emission occurs at 1215A due to hydrogen from dissociating H_2O and hydrocarbons. The video technique allows examination of the temporal development of the expected strong Lyman alpha emission from cometary sources. Sulfur lines occur at 1807A and 1820A; phosphorus lines occur at 1672A, 1675A, 1680A, and 1775A. Sulfur is a relatively abundant component of carbonaceous chondrites and its existence in cometary debris is of interest. The recent IUE observations by the Univ. of

UV SPECTROSCOPY OF METEORIC DEBRIS

J. A. Nuth, T. J. Wdowiak, and W. R. Kubinec

Maryland group, led by A'Hearn revealing dimer sulfur (S_2) emissions between 2820A and 3090A of comet IRAS-Araki-Alcock, makes the search for meteor sulfur all the more interesting.

Instrumentation. The experiment makes use of high speed (f ratio of 0.75) reflecting optics viewing a 12^{o} by 12^{o} field with an objective grating. The imaging detector is an intensified solid-state array having the following characteristics:

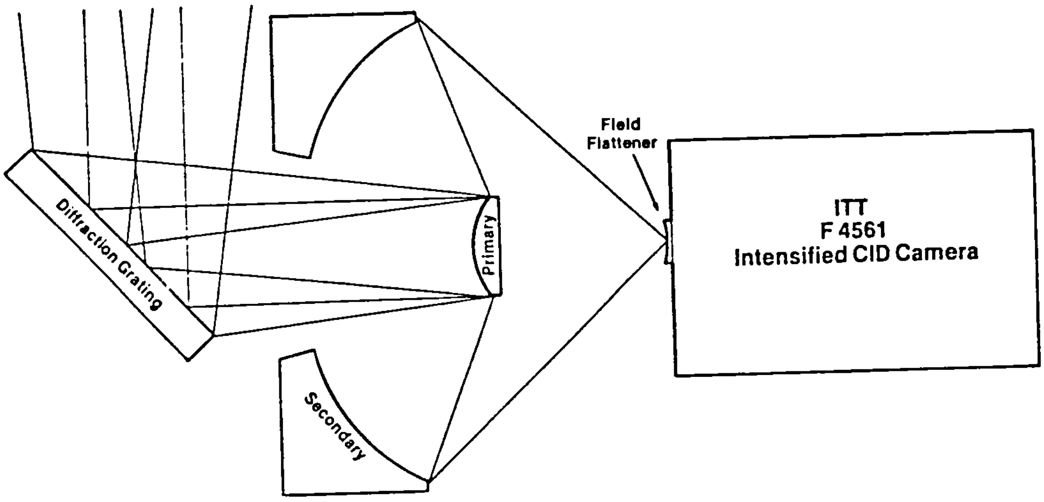
1100-3200A
UV intensified CID
244 x 388 pixels
8.7 x 11.4 mm

6 ma/watt sens. (1500A)
20 ma/watt sens. (2500A)
CsTe/MgF_2 p.c./wind.
ex. ITT F.4561

The dispersing element would be a 300 l/mm grating blazed for first order with a 250 A MgF_2 protective coating. Fig. 1 displays the proposed optical configuration.

In the GAS configuration, video data will be stored in a stack of up to four compact video cassette recorders. Depending upon recording speed, a total record duration for the four-stack would be eight to twenty-four hours. Because data is recorded for approximately twenty minutes per orbit, data would be gathered over twenty-four to seventy-two orbits. Control would be by microprocessor and total power required would be less than 1.2 KWH from a battery pack of less than 1 ft^3 and 100 lb.

A HITCHHIKER configuration would allow greater volume by utilizing shuttle power and additional GAS type containers for data storage. The optics/detector could then be gimbeled to allow some pointing capability.



LOW GRAVITY FACILITIES FOR SPACE STATION PLANETOLOGY EXPERIMENTS

Paul A. Penzo*, Jet Propulsion Laboratory, Pasadena, CA.

For experimentation, space offers a unique environment which is unobtainable on Earth. One characteristic is a gravity force less than 1 g, where g is the mean Earth gravity acceleration of 9.8 m/s^2 .

A near-zero g level is easiest to obtain, since orbiting spacecraft are in free fall. This condition, which is desired for many science and engineering applications, is referred to as microgravity. Total elimination of acceleration is difficult since perturbing forces, such as atmospheric drag, expulsion of mass, and disturbances, will contaminate the gravity environment. The purity of zero g is specified by some level of noise, such as 10^{-4} g; however, no single number can really indicate the true nature of the noise, which may be high frequency, low frequency, or intermittent.

Producing uniform gravity levels above zero g in space is quite different than producing microgravity. Here, a constant force must be produced over long periods of time. Thrust may be applied to spacecraft to produce low gravity, but this is not very practical, except perhaps with solar sails. For Earth orbital facilities, two methods are possible: (1) centrifugal force through rotation, or (2) gravity gradient force using long tethers. Which approach should be used depends on many factors, both from the standpoint of user requirements, and from design, implementation, operation and cost considerations. This presentation identifies the major parameters which should be considered in any design. It also presents some basic characteristics of rotating and gravity gradient tethers, and evaluates possible conceptual designs.

For planetology experiments, providing gravity in space will make it possible to more nearly simulate conditions on natural bodies. Its presence may be unnecessary for simulation of comet surfaces, since gravity is of the order of 1×10^{-5} g; however, for other bodies, it may be important. In terms of Earth gravity, the g-levels are:

larger asteroids:	0.01 - 5%
Moon, Io, Titan:	15 - 20%
Mars, Mercury:	35 - 40%
Venus, Saturn, Uranus:	80 - 100%

The types of planetology experiments which may be conducted under these g-levels may be impact, flow transport, and chemical reactions with solids, liquids, or gases. Also, using scaling laws, it may not be necessary to use one-to-one correspondence of the g-level with the planetary body of

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*Section Staff, Mission Design. Currently on assignment at NASA, Office of Space Flight, Advanced Programs, Washington, D.C. The research described in this paper was performed by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Adminstration.

interest. Very likely, with each experiment, some minimal g-level will be necessary.

The g-level is but one parameter involved in the design of a specific experiment. Other requirements may be:

1. g-level range
2. g-level tolerance value
3. Coriolis tolerance value
4. Volume requirement
5. g-level duration
6. Power and materials for experiment
7. Automated operation or man-tended

These requirements, and certainly others, will dictate the type of facility which should be considered. At one extreme, the requirements may be modest, and a certrifuge within a manned module may suffice. For example, a one meter radius centrifuge with rotation period of six seconds will produce about a 10% g-level. The Coriolis effect will naturally be high, and the usable volume small, which may or may not be a problem.

On the other hand, the planetology experiments may be such that they could only be done in a Spacelab environment; i.e., large volume, long duration, man operated, and low Coriolis effects. This may best be done by tethering a manned module from the Space Station; or by a large rotating structure not attached to the Space Station.

The larger facility, manned or unmanned, is the type being considered in this presentation. By the time that the Space Station is in operation, many tether experiments would have been done in space using the U.S. - Italian Tethered Satellite System on the Shuttle. On the second experiment, the Italian subsatellite will be tethered 100 km below the Shuttle. It will experience a g-level of about 5%. A similar tether system could be designed for use on the Space Station.

Concerning large rotating systems, the capability which must be developed for constructing the Space Station itself can be directly applied here. Also, many of the Station subsystems can be used. One configuration might be to have two laboratory modules, one at each end of a long beam structure. A hub at the center of this structure could contain a platform with required subsystems. This could also be an arrival and departure point for crew and supplies. An elevator on the structure could provide transportation from the hub to the modules at the ends.

A structure 200m long could be set rotating using thrusters at each module. A velocity of 7 m/s would provide a 5% g level. Increasing this to 20 m/s would produce 40%. The periods of rotation would be 1.5 min. and 30 sec., respectively.

Many other configurations are also possible, and a final selection will depend on many factors including user requirements.

DEBRIS-CLOUD COLLISIONS: ACCRETION STUDIES IN THE SPACE STATION

P.H. Schultz, Department of Geological Sciences, Brown University-Box 1846, Providence, Rhode Island 02912. D.E. Gault, Murphys Center of Planetology, Murphys, California.

Background: The growth of planetesimals in the Solar System reflects the success of collisional aggregation over disruption. It is widely assumed that aggregation must represent relatively low encounter velocities between two particles in order to avoid both disruption and high-ejecta velocities (1,2). Such an assumption is supported by impact experiments (3) and theory (4). Experiments involving particle-particle impacts, however, may be pertinent to only one type of collisional process in the early Solar System. Most models envision a complex protoplanetary nebular setting involving gas and dust. Consequently, collisions between clouds of dust or solids and dust may be a more realistic picture of protoplanetary accretion. Recent experiments performed at the NASA-Ames Vertical Gun Range (5) have produced debris clouds impacting particulate targets with velocities ranging from 100 m/s to 6 km/s. The experiments produced several intriguing results that not only warrant further study but also may encourage experiments with the unique impact conditions permitted in a microgravity environment.

Collisions Between Debris-Clouds and Particulate Surfaces: Impact experiments at the NASA-Ames Vertical Gun Range have assessed differences between clustered and single-body impacts on particulate surfaces. The primary goal was to examine the effects of atmospheric entry on cratering and possible implications for secondary cratering processes (5). Impacting debris clouds were produced during passage of a brittle pyrex projectile through a thin sheet of paper or aluminum foil. At hypervelocities ($v > 5$ km/s), a 2.5 mil sheet of paper was sufficient; at supersonic velocities ($v \sim 2$ km/s), a 1 mil aluminum foil was used. Because the launch tubes are rifled in order to induce separation between the projectile and sabot, the effective dispersion of the debris cloud could be varied by changing the distance between the target surface and paper or foil. High-frame rate photographs recorded the resulting dispersion in the impacting debris cloud and thus the effective density at impact.

The experiments revealed a factor of 5 decrease in predicted cratering efficiency for an impact by a solid projectile of the same mass (m) and velocity (v). If the energy density of the impacting cloud is included (6) by using a dimensionless expression of cloud radius (r) divided by v^2, then cratering efficiency is only slightly decreased. As might be expected, the crater aspect ratio and morphology were significantly altered (5). As typical for laboratory experiments, however, several unexpected phenomena also occurred. First, the high frame-rate photographic record revealed an intensely luminous cloud immediately after impact (7). The early stages of ejecta-plume growth were characterized by an amorphous cloud rather than the systematic expansion of a funnel-shaped curtain typical for single-body impact. Second, unusually large (1-5 cm across) fairy-castle aggregates were produced. Many of these aggregates had low-ejection velocities. An impact by a 0.2 g/cm^3 cloud at 4.1 km/s produced an unusually large aggregate extending from the floor to above the crater rim. The exact nature of such aggregates is not yet known; they appear to be melt-welded target material. We also do not yet know for certain if melt production increased relative to a single-body impactor. The early-time film record showing a bright luminous cloud and the slight decrease in cratering efficiency, however, may be indicating greater partitioning into internal energy losses. These preliminary results would indicate that collisions between two debris clouds might produce aggregates, thereby increasing particle sizes, whereas a single particle impacting a particle results in disruption and comminution. Such an experiment could provide new insight for early planetary growth processes and for interpreting the record of this stage (e.g., 8,9).

Possible Space Station Experiments: The microgravity environment of a Space Station would allow detailed studies of the competing processes of aggregation and disruption using conditions more appropriate (or at least scalable) for an evolving protoplanet. A cloud of impactor fragments can be readily produced in a manner already performed on Earth, but of different density, composition, and initial size distribution. Of specific interest would be the change in size distribution, shock state, velocity distribution, mixing, and the possible production of chondrite breccias (10). The formation of chondrules is more equivocal (10) but objections could reflect an incomplete experimental simulation. Collisional velocities would range from values expected for collisions in a nebular disk (< 100 m/s) to values possible from the early stages of planetesimal growth (<6 km/s). Perhaps the most intriguing aspect is the capability of repetitive collisions and more unusual conditions, e.g., passage of a larger projectile through a suspended debris cloud. The latter experiment could be performed over long path lengths by tubular extensions from the proposed impact facility.

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IMPACTS OF FREE-FLOATING OBJECTS: UNIQUE SPACE STATION EXPERIMENTS

P.H. Schultz, Department of Geological Sciences, Brown University-Box 1846, Providence, Rhode Island 02912. D.E. Gault, Murphys Center of Planetology Murphys, California.

The transfer of momentum and kinetic energy between planetary bodies forms the basis for wide-ranging problems in planetary science ranging from the collective long-term effects of minor perturbations to the catastrophic singular effect of a major collision. In the former case, we can cite the evolution of asteroid spin rates and orientations (1,2,3,4)) and planetary rotation rates (5). In the latter case, we include the catastrophic disruption of asteroids (3,6,), sudden but lasting changes in planetary angular momenta (7,8), and the near-global disruption of partially molten planets (9,10). Although the collisional transfer of momentum and energy has been discussed over the last two decades, major issues remain that largely reflect current limitations in earth-based experimental conditions and 3-D numerical codes. Two examples with potential applications in a Space Station laboratory, are presented below.

Asteroid Spin Rates and Orientations: Understanding the transfer of impactor translational momentum to target angular momentum is fundamental to understanding the present-day spin rates, orientations, and spin-limited disruption of asteroids (e.g., see 3). The efficiency of angular momentum transfer is typically expressed as a factor (ζ) ranging from 0 for purely elastic collisions to 1 for inelastic collisions with no ejecta loss (3). Although ζ is usually adopted as unity, Harris (4) prefers a value closer to 0.5 corresponding to a moderate forward-scattering of ejecta. Davis *et al.*, (3) suggest that ejecta are uniformly distributed -- even for low-angle impacts; consequently values of ζ closer to 1 might be justified. Such estimates, however, are largely based on intuition. For vertical impacts into basalt, ejecta carry away 4-6 times the original impactor momentum; therefore, the azimuthal distribution of these ejecta is crucial. For very low-angle impacts, the impactor is ricocheted down-range and carries with it considerable momentum (11). These results would indicate a value of ζ significantly less than 1. Even lower values may occur for curved surfaces. Recent experiments in easily volatilized material (12) reveal significant differences in the partition of energy at low-impact angles. Such differences might lead to differences in impact-induced spin rates between comets and asteroids (13).

Thus a wide range of values in ζ that depend on impact velocity and target composition/strength can be justified. Experiments are needed wherein free-floating non-spinning and spinning objects of varying strength, porosity, volatility, and strength are impacted at varying impact velocities and angles. A Space Station provides a unique and ideal environment for performing such experiments.

Planetary Disruption/Spin-Rates: The existing rotation periods and total angular momenta of gravitationally bound planets and planet-satellite systems may provide a fundamental link between the accretion and post-accretion stages of planetary evolution. The Moon and Mercury preserve a record of impacts of sufficient energy to produce possible antipodal disruption of the surface as indicated by observations and simplified calculations (9). More sophisticated 2-D axisymmetric finite-element codes reveal that a molten interior enhances disruption.

Taken to extreme, a collision-vaporization model of the Earth-Moon system has been recently revived with vigor and substance (14,15). Although preliminary calculations have been made to describe the impact-induced vaporization of the early terrestrial crust and the transfer of angular momentum (16), such models are limited by necessary simplifying assumptions including 1-D and 2-D descriptions of a 3-D event. It is unlikely (albeit fortunate) that a directly scaled event will occur. A space station platform, however, provides a unique opportunity to test important facets of such models by allowing freely suspended spherical targets of varying viscosities, internal density gradients, and spin rates. Although a centralized gravity term cannot be introduced or completely simulated, such limitations are far outweighed by variables that can be readily introduced and controlled.

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HOW TO MAKE A COMET

James Stephens, and R. Stephen Saunders, Jet Propulsion Laboratory;
and
Fraser Fanale, University of Hawaii

The primary mandate of NASA is the study of the nature and origin of the solar system. The study of comets provide us with unique information about conditions and processes at the beginning of the solar system. Short period comets and their relatives, the near Earth asteroids may prove to be second only to the sun in importance to the long term survival of civilization for two reasons. They are a possible candidate for the cause of mass extinctions of life on Earth; and they may provide the material means for the expansion of civilization into the solar system and beyond. They almost certainly represent the most primitive material of the solar system, still tantalizingly unavailable until space craft bring us first-hand information. In the meantime we must study comets by remote means. Laboratory investigations using synthetic cometary materials may add to our knowledge of these interesting objects.

Comets are presumed to be made of ices with noncontacting dispersions of micron and sub-micron sized particles (Whipple, F.L., Ch.1, Comets, page 67 in McDonnell.J.A.M., Cosmic Dust, New York, NY, Wiley & Sons, 1978). The most difficult physical characteristic to simulate is the dispersion of particles in ice in a way that prevents them from touching one another. This requirement is crucial because if the particles touch one another they are unlikely to be separated by the fluid dynamic forces (or electrostatic forces) at the subliming ice surface and the observed free flowing dust plume (comprising the comet's tail) will not be possible. It is possible, however, that even if the particles are not touching in the ice they may not escape the subliming surface and thus may form a mantle under some low rate of solar insolation. It is the study of these two processes, dust and mantle formation, that is the objective of this ongoing laboratory experimental investigation.

If a dispersion of particles in liquid water is frozen by ordinary means the freezing ice crystals push the particles ahead of the freezing solid-liquid interface. The particles are trapped in the ice where the ice crystals collide with one another. In the materials purification industry this phenomenon is referred to as zone refining. This phenomenon must be avoided if particle contact is to be prevented. In synthesizing comet ices we tried several methods of high-speed freezing the liquid dispersions of particles to obtain the requisite noncontacting particle dispersions in ice.

The most reliable means of freezing required that we spray a very dilute dispersion (100:1) of montmorillonite clay in water into liquid nitrogen through a very small nozzle (< 10 microns) at high pressures (500 psi). The nozzle must be within a few milimeters of the surface of the liquid nitrogen so that the droplets hit the liquid at high velocity and are frozen quickly. Because the orifice is nearly as small as the particles, means must be provided for continuously unplugging the nozzle. This was accomplished by using an adjustable coaxial needle valve orifice that could be continuously vibrated to remove any plugs produced by the submicron montmorillonite clay particles.

A slurry of water ice particles was formed in the liquid nitrogen. The liquid nitrogen was decanted and the concentrated slurry was poured into two stainless steel hemispherical salad bowls. A fine wire thermocouple was inserted into a small hole in the center of one hemisphere of the consolidated slurry. The other hemisphere was then joined to the first to form a spherical body of weakly sintered ice particles.

This "snow ball" (0.3 gm/cm3) was then suspended in a fine nylon hair net from a small spring scale. The entire assembly was then hung inside a cryotrapped, diffusion-pumped high-vacuum chamber. The chamber was pumped down to (10 -4 Torr) before all of the absorbed liquid nitrogen evaporated. The thermocouple indicated that some of the liquid nitrogen was in fact frozen during pumpdown.

This miniature "comet" sublimed away its water ice over the next seven days while the vacuum pressure, ice temperature and the weight of the body were recorded periodically. At the end of the experiment the sublimate residue that was left formed a sphere nearly the same size and shape as the original snow ball (.009gm/cm3).

Three slightly different "comet" sublimation experiments were performed in which the dust compositions (graphite was added) and concentrations (500:1) were varied. The sublimate residue spheres formed were similar in most respects (the 50% graphite made a weaker gray residue). They all took 7 to 8 days to sublime completely. The lowest temperature recorded after the solid nitrogen had sublimed was in the range of -60^0 C. The ice probably reached lower temperatures near the end of the experiment but, because the thermocouple lead conducted a significant amount of heat into the ice body the ice probably sublimed away from it early in the experiment. The vacuum chamber pressure continued to drop during the sublimation period (final pressure was 10-7Torr). This indicates that as the sublimate residue became thicker its insulating properties increased and the ice temperature dropped thus reducing the water vapor pressure in the chamber.

During the pumpdown small pieces (< 1 mm) of ice were ejected from the surface of the spherical body. These pieces of "snow" sublimed very quickly once they came in contact with the room temperature floor of the vacuum chamber. No indication of any free dust coming off the ice or from the sublimate residue was observed. The 300K walls of the vacuum chamber apparently did not produce enough radiation load onto the ice to produce a dust plume or the dust plume was so tenuous that we could not observe it. Future experiments using a solar simulator may be able to produce dust plumes. Some form of nephelometry will be used in these subsequent experiments to observe the dust if it is released. The amount of electrostatic charging produced due to the sublimation and the effect of induced electrostatic charge will also be measured.

GRAIN DYNAMICS IN ZERO GRAVITY

B. T. Werner and P. K. Haff, Division of Physics, Mathematics, and Astronomy, California Institute of Technology, Pasadena, CA 91125

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[1,2] 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 collisional 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 as well as by 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 (see Figure 1a). Correspondingly, as illustrated in Figure 1b, 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.[3]

We propose a basic experiment to be performed on the Space Station which would 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 we are presently developing. 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.[4] 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.

GRAIN DYNAMICS EXPERIMENTS IN ZERO GRAVITY

Werner, B. T. and Haff, P. K.

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FIGURE CAPTIONS

Fig. 1. One wall of a box partially filled with inelastic grains is heated (the left wall in the figure). A kinetic theory of grain dynamics is used to calculate the dimensionless density (a) and the dimensionless thermal velocity (b) as a function of position in the box for seven sets of parameters. Note that for run (g), the far wall is cool but not cold.

Run	% free space in box	thermal conductivity coefficient	coefficient of restitution
a	10	1	.9
b	10	10	.9
c	50	1	.9
d	50	10	.9
e	50	1	.6
f	90	1	.6
g	90	10	.6

GRAIN DYNAMICS EXPERIMENTS IN ZERO GRAVITY

Werner, B.T. and Haff, P.K.

Figure 1a.

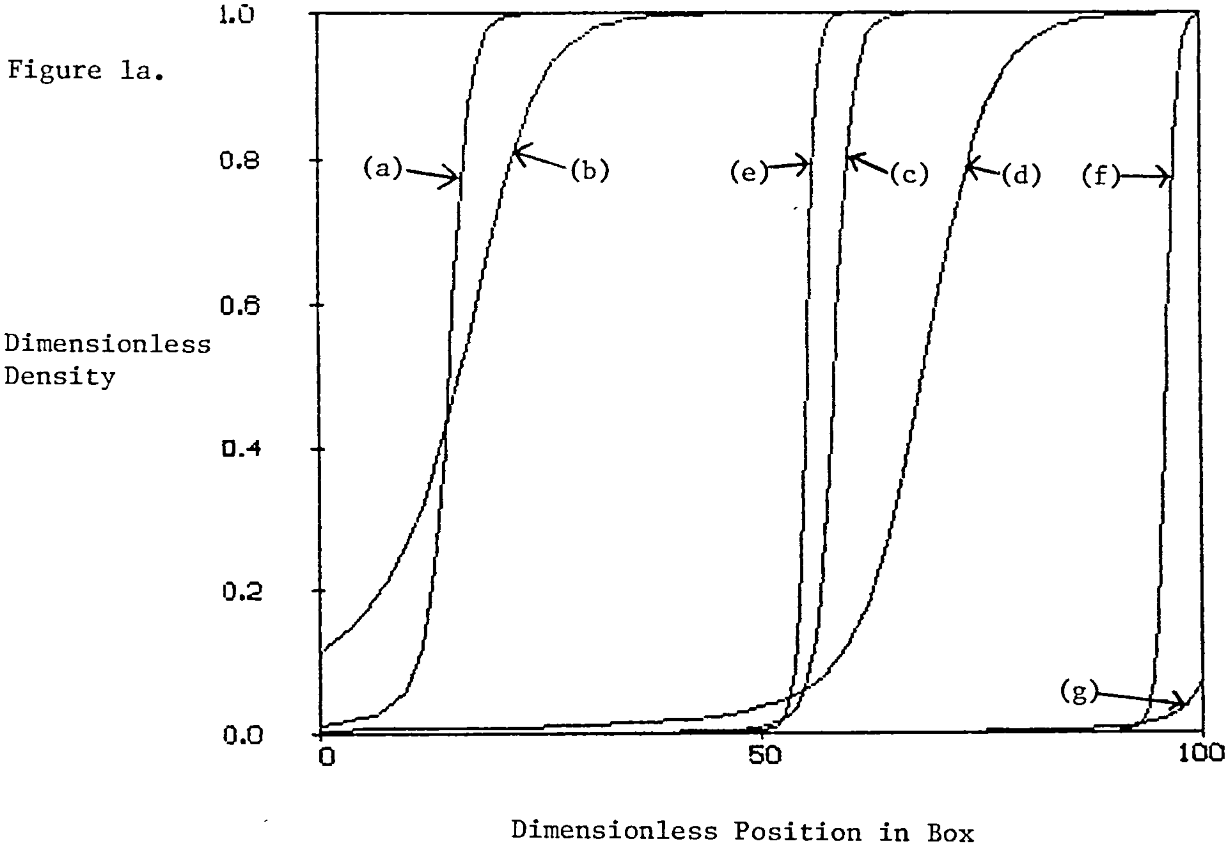
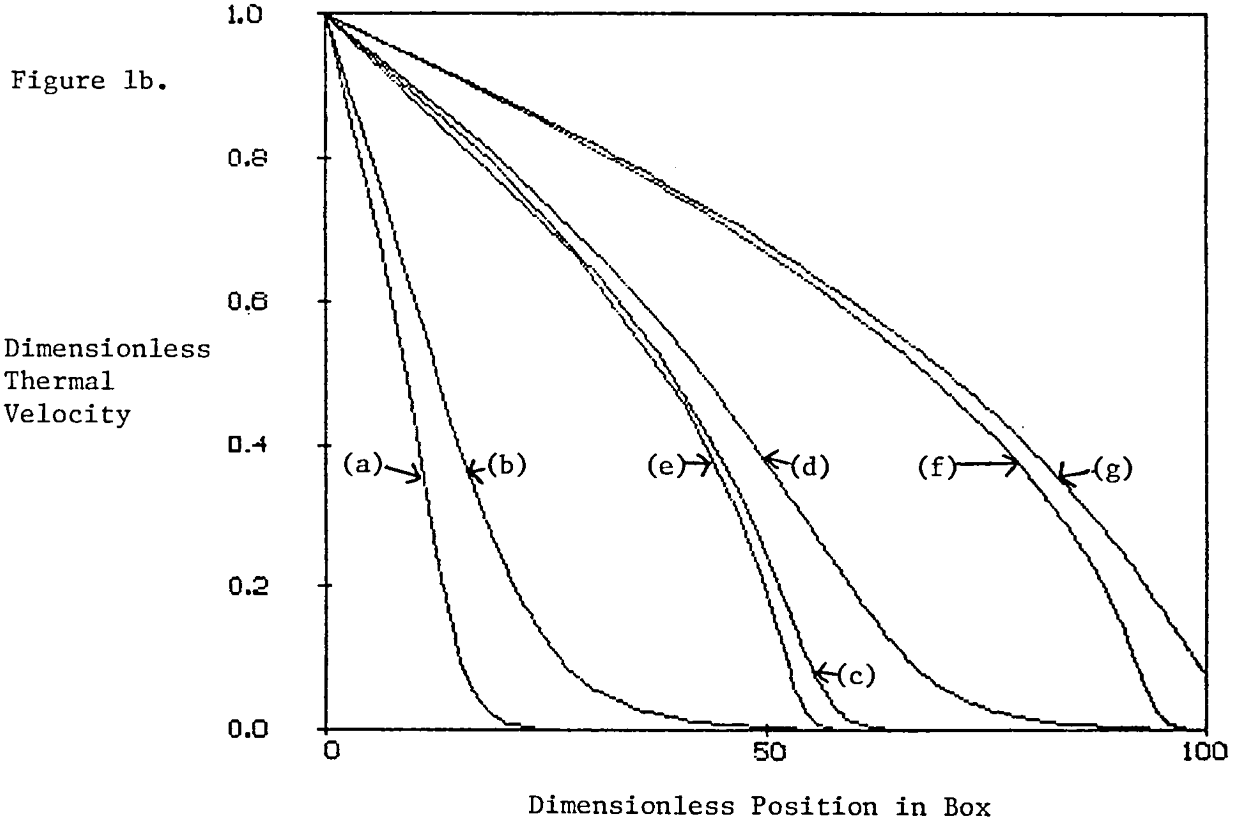


Figure 1b.



AEOLIAN PROCESSES ABOARD A SPACE STATION: SALTATION AND PARTICLE TRAJECTORY ANALYSIS

B. R. White, University of California, Davis; R. Greeley, Arizona State University; J. D. Iversen, Iowa State University; and R. N. Leach, University of Santa Clara

The type of wind tunnel we propose to use to study aeolian processes aboard a space station consists of two concentric rotating drums. The space between the two drums comprises the wind tunnel test section. Differential rates of rotation of the two drums would provide a wind velocity with respect to either drum surface. Rotation of the outer drum provides a "pseudo" gravity ("pseudo" in the sense that a gravity force acts on the particle only when it is resting on the outer drum surface). This type of wind tunnel is hence referred to as a Carrousel Wind Tunnel (CWT). Preliminary results of measured velocity profiles made in a prototype (CWT) indicate that the wall bounded boundary-layer profiles are suitable to simulate flat plate turbulent boundary layer flow.

Once particles are airborne, the forces acting on individual grains in their trajectories are the particle weight and the aerodynamic lift and drag. The two-dimensional flat-plate Cartesian coordinate equations of motion of a particle moving through the air can be written as

$$\frac{4}{3}\frac{\rho_p}{\rho} D_p \ddot{x} = \dot{y} V_r C_L - (\dot{x} - u) V_r C_D \tag{1}$$

$$\frac{4}{3}\frac{\rho_p}{\rho} D_p \ddot{y} = -(\dot{x} - u) V_r C_L - \dot{y} V_r C_D - \frac{4\rho_p g D_p}{3\rho} \tag{2}$$

$$V_r^2 = (\dot{x} - u)^2 + \dot{y}^2 \tag{3}$$

The last term in Equation 2 is the weight factor. Experimental and calculated trajectories for zero and one-gravity conditions have been calculated. With the elimination of the weight factor under zero-gravity, the only forces remaining are aerodynamic. Thus, experiments conducted in zero-gravity would enable direct assessment of aerodynamic lift and drag.

In order to assess the suitability of CWT in the analysis of the trajectories of windblown particles, a series of calculations was conducted comparing cases for gravity with those of zero gravity. The equations of motion for an airborne particle, assuming no lift force, are (in a polar coordinate system, Greeley and Iversen, 1983),

$$\ddot{r} - r\,\dot{\theta}^{2} - g\cos\theta + \left(\frac{3\rho C_D \dot{r}}{4\rho_p D_p}\right) V_r = 0 \tag{4}$$

$$r\,\ddot{\theta} + 2\,\dot{r}\,\dot{\theta} + g\sin\theta - \left(\frac{3\rho C_D}{4\rho_p D_p}\right) [U(r) - r\,\dot{\theta}]\, V_r = 0 \tag{5}$$

$$V_r = \{\dot{r}^{\,2} + [U(r) - r\,\dot{\theta}]^2\}^{1/2} \tag{6}$$

Equations 4, 5, and 6 were solved for several example cases. The drag coefficient, C_D, is a function of Reynolds number, assuming a spherical particle (White et al., 1975). Figure 1 illustrates particle trajectories in CWT for zero-gravity atmospheric-pressure conditions. The coordinate system is fixed to the particle launch point and rotates with the outer cylinder. In inertial space the trajectories are straight lines, but relative to an observer standing on the launch point of the rotating outer drum, as plotted, the trajectories are curved. The initial inward radial velocity of the particle is assumed to be equal to the surface friction speed of the outer cylinder. The assumed wind speed profile for the calculation was taken from prototype velocity profile measurements. Since the only force acting on the particle in CWT is aerodynamic, significant differences between trajectories with and without gravity should enable much more accurate determination of the aerodynamic forces (drag and lift) than is possible in an Earth-based facility. We conclude that the CWT can yield significant data on the trajectories of windblown particles impossible to acquire under the effect of gravity.

Analyisis of particle trajectories in a zero-gravity environment would enable the determination of the aerodynamic forces on windblown particles by using high-speed motion picture obtained during the experiments. The lift and drag forces would be determined by measuring particle accelerations, particle speeds, and wind speeds, and applying Equations 4, 5, and 6 to the results.

In conclusion, results from our calculations demonstrate that a wind tunnel of the carrousel design could be fabricated to operate in a space station environment and that experiments could be conducted which would yield significant results contributing to the understanding of the physics of particle dynamics.

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White, B. R., J. D. Iversen, R. Greeley and J. B. Pollack, 1975. Particle motion in atmospheric boundary layers of Mars and Earth: NASA TMX-62463, 200 pp.

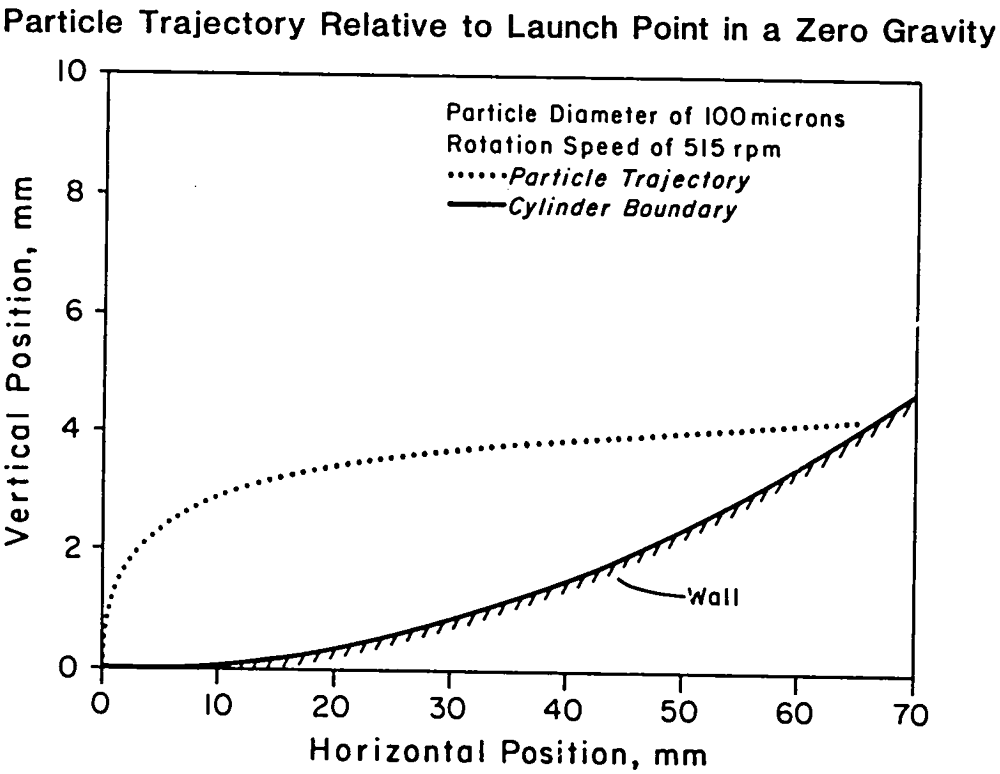


Figure 1 Calculated particle trajectory in zero-gravity, with one atmosphere of air, based on assumed drag characteristics. The outer cylinder is not rotating and the coordinate system is fixed to it at the launch point. The initial inward radial velocity of the 100 μm diameter particle is assumed to be 32.6 cm/s, the friction speed of the flow near the outer cylinder.

A SYSTEM FOR CONDUCTING IGNEOUS PETROLOGY EXPERIMENTS UNDER CONTROLLED REDOX CONDITIONS IN REDUCED GRAVITY

Williams, R. J., SN12, NASA-JSC, Houston, TX 77058

The Space Shuttle and the planned Space Station will permit experimentation under conditions of reduced gravitational acceleration offering experimental petrologists the opportunity to study crystal growth, element distribution, and phase chemistry under new conditions. In particular the confounding effects of macro and micro scale buoyancy-induced convection and crystal settling or floatation can be greatly reduced over those observed in experiments in the terrestrial laboratory. Also, for experiments in which detailed replication of the environment is important, the access to reduced gravity will permit a more complete simulation of processes that may have occurred on asteroids or in free-space. This latter aspect may be particularly relevant to studies of petrogenesis of chondrules and other meteorite components.

Most of the geologically interesting systems contain significant amounts of redox-sensitive ions - - Fe, Ti, Cr, etc. - - and thus studies of phase relations and crystallization require control of the oxygen fugacity during the experiment. Sophisticated but rather standardized techniques have been developed to control, measure, and manipulate oxygen fugacity in the terrestrial laboratory. Gas mixing is the major technique used in the study of one atmosphere igneous processes; unfortunately, it is not directly adaptable to use in space experimentation, because large quantities of gas must be flowed over the sample to maintain the oxygen fugacity. It is the purpose of this paper to describe a newly developed technique that can be used to control, measure, and manipulate oxygen fugacites with small quantities of gas which are recirculated over the sample. This system should be adaptable to reduced gravity space experiments requiring redox control.

System Description

The system employs a single solid ceramic oxygen electrolyte cell for both control and measurement of the oxygen fugacity. This is possible because the electrolyte cells can be used as oxygen pumps to adjust the CO_2/CO ratio in the gases that are used to impose redox control in gas-mixing systems electronically.

The system consists of a furnace surrounding a closed-end alumina muffle which surrounds a closed-end oxygen electrolyte tube that is platinized on both sides. A sample is suspended inside the electrolyte tube. Seals separate the gas in the alumina tube from the inner side of the electrolyte tube and isolate both from the laboratory atmosphere. Electrical feed-throughs connect the inner and outer electrode contacts to a DC power supply. The space between the aluminum muffle and the electrolyte cell is filled with oxygen gas (1 atmosphere pressure at $1200^{o}C$) and sealed. The inner side of the electrolyte cell is filled with a 1:1 mixture of CO and CO_2; (again at 1 atmosphere at $1200^{o}C$).

This mixture is sealed off and recirculated by a small pump. The oxygen fugacity is manipulated by applying a voltage to the cell and transferring oxygen to or out of the interior volume depending on the condition desired. The oxygen fugacity can be cycled between those of the quartz-fayalite-magnatite and quartz-fayalite-iron buffers in about 30 minutes at 1200°C, maintained to within 0.05 log units of a preset value over day-long periods, or changed in a controlled manner as function of temperature so that it replicated a preselected pattern during cooling or heating. The oxygen fugacity is measured by turning off the electrolysis voltage and recording the EMF with a high inpedance DC millivolt meter.

A high efficiency (approximately .2 watts/°C) furnace has been specially designed to operate on 28 VDC. At 1200°C, the hot zone is 2 inches long. The power supply to the furnace is controlled using a standard thermocouple as a sensor. It will maintain the temperature to within less than 1°C of a preselected temperature and can cool the system at controlled rates between 0.5° to 100°C per hour; heating rates of up to 1000°C/hr are possible. The maximum operating temperature is 1350°C for the current furnace.

A micro-computer is used to control both temperature and oxygen fugacity, both of which can be changes independently as a function of time. The computer also performs data acquisition tasks, and switchs between the measurement and oxygen pumping modes of operation.

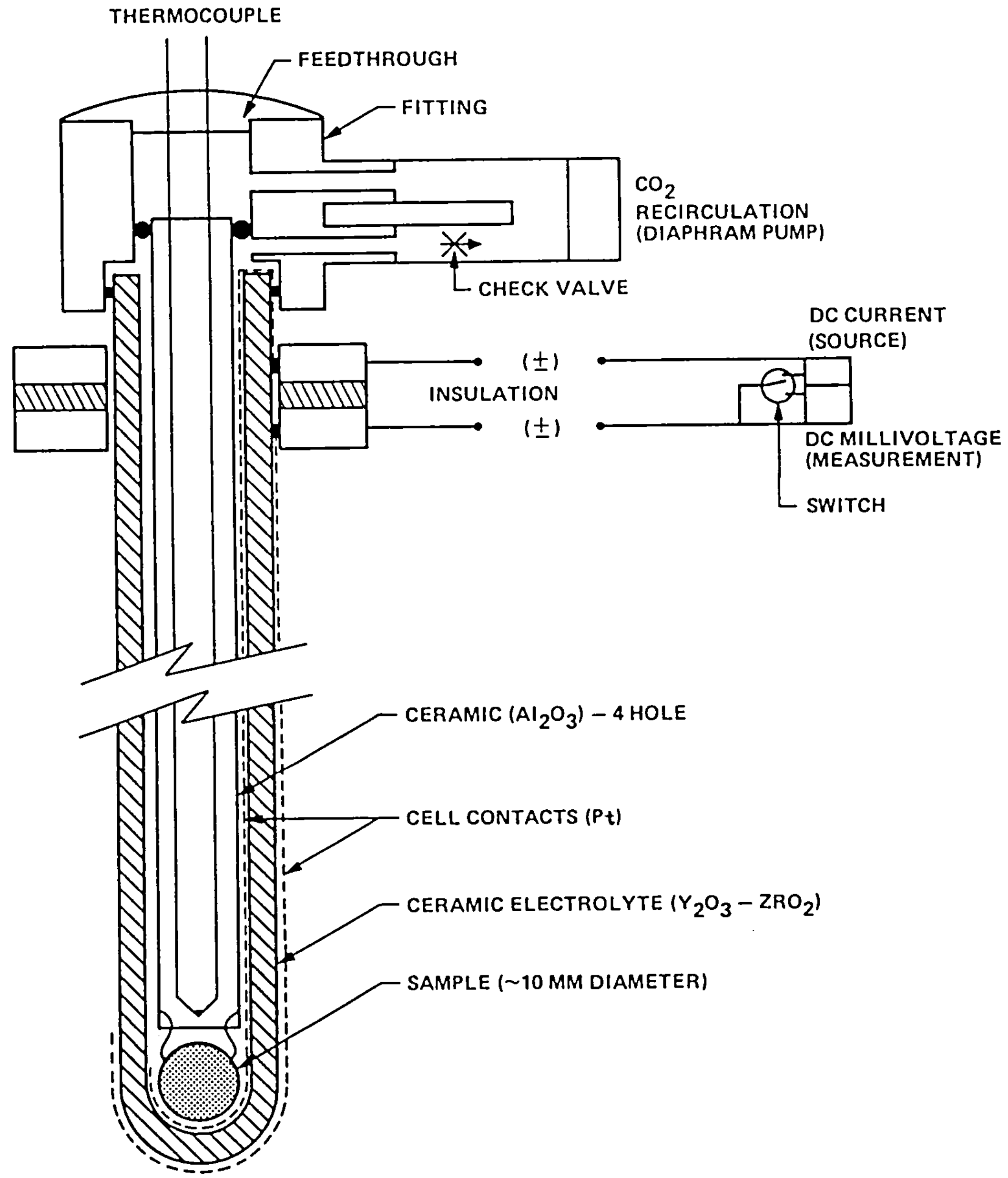
Experiments done conventionally and those done using this system yield identical results in a one-gravity field.

The total system (exclusive of the computer use for laboratory control) is 4 cubic feet; it uses about 500 watts. Except for the gas used to charge the system (approximately 30 cc at STP), no gas is used during the experiment. Although water cooling is now used to control the temperature of the furnace seals, forced air cooling is probably possible.

Summary

A system directly adaptable for use in controlled oxygen fugacity experimentation on Shuttle or Space Station has been designed, built, and tested. It should permit reduced gravity experiments which require such control to be undertaken.

REDOX CONTROL SYSTEM
(Cell Detail)



NEW TECHNIQUES FOR THE DETECTION AND CAPTURE OF MICROMETEOROIDS

J. H. Wolfe, San Jose State University, San Jose, CA 95192

In order to understand the origin and distribution of the biogenic elements and their compounds in the solar system, it will be necessary to study material from many classes of objects. Chemical, elemental, and isotopic measurements of returned samples of comets, asteroids, and possibly extra-solar system dust clouds would provide information on a particularly important class: the primitive objects. Extraterrestrial micron-sized particles in the vicinity of Earth are one source of such materials that might otherwise be inaccessible. The Space Station appears to be an eminently suitable platform from which to collect and detect these various particles. The primary challenge, however, is to collect intact, uncontaminated particles which will be encountered at tens of kilometers per seconds.

A concept for a micrometeoroid detector that could be deployed from Space Station has been developed which uses a large area detector plate implanted with acoustic transducers. When an impact event occurs, the resulting signal is subjected to spectral analysis providing positive detection, momentum information, and angle of incidence. The primary advantage of this detector is the large area which increases the probability of measuring events. A concept of a nondestructive micrometeoroid collector for use from Space Station has also been developed. The collector utilizes input port charging of the incoming particle followed by staged high voltage deceleration for nondestructive capture. Low velocity particles (local contamination) would be rejected due to insufficient energy and only uncontaminanted micrometeoroids would be collected. Particles so collected would then be returned to Earth for subsequent analysis.

MAPPING EXPERIMENT WITH SPACE STATION

Sherman S. C. Wu, United States Geological Survey, Flagstaff, AZ 86001 USA

Mapping the Earth from space stations can be approached in two areas. One is to collect gravity data for defining a new topographic datum using Earth's gravity field in terms of spherical harmonics. The geoid produced by this experiment may be much closer to the reality of Earth's equipotential surface than that which is currently used. Due to the fact that the Earth is both longitudially and latitudially asymmetric as indicated in the results of gravity studies by Votila (1962), this proposed experiment may be useful for a new generation of Earth mapping. The other, which should be considered as very significant contribution from the space station, is to search and explore techniques of mapping Earth's topography using either optical or radar images with or without reference to ground control points. Without ground control points, an integrated camera system can be designed. The system, in addition to the imaging camera, will consist of a stellar camera, radar altimeter and an inertial platform such as the one which was installed on the AN/USQ-28 Mapping and Survey Subsystem (Livingston et al., 1980). With ground control points, the position of the space station (camera station) can be precisely determined at any instant. Therefore, terrestrial topography can be precisely mapped either by conventional photogrammetric methods or by current digital technology of image correlation.

At an altitude of 300 km, the space station can view an area on the surface of Earth, that is intersected by a cone with a solid angle of 34.5° with respect to the Earth's center. Theoretically, if a total of 44 permanent ground-control points can be ideally distributed on the Earth's surface such that: 12 points along the equator with longitude increment of 30°; 18 points along latitude + and - 30° with longitude increment of 40°; 12 points along latitude + and - 60° with longitude increment of 60°; and 1 point at each of the two poles, then at least 3 ground control points can be viewed by the space station at any instant and its position (camera station) can be determined by resection with electronic ranging measurements. But, practically, permanent ground-control points in oceans are difficult to be established, distribution of permanent control points have to be adjusted on continents and islands. Geodetic position of ground control points can be predetermined by the Global Positioning System (GPS). In order to continue the radar experiment of the planned SIR-C mission, corner reflectors of right-angle tetrahedron can be installed at all ground control points.

With a radar altimeter on board, profiles traced along tracks of the space station can be utilized for constraints in addition to the determined position of the space station for photogrammetric processing.

For the mapping experiment with the space station, I propose to establish four such ground control points either in North America or Africa (including the Sahara desert). If this experiment should be successuflly accomplished, it may also be applied to our defense charting systems.

Sherman S. C Wu

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Appendix A: AGENDA

June 20, Thursday

8:00 Registration

9:00 Welcome, announcements, etc.

9:15 Introductory Session

SSPEX up-date (R. Greeley)

Space Station status (D. Thompson)

Johnson Space Center SSPEX activity (D. Roalstad)

Low gravity facilities for space station planetology experiments (P. Penzo)

11:00 Technical Session Aeolian Processes (J. Iversen, Chairman)

Sediment-transport experiments in zero-gravity (J. Iversen)

Aeolian processes aboard a space station: Saltation and particle trajectory analysis (B. White)

12:00 Lunch

1:00 Technical Session Aeolian Processes

The initiation of grain movement by wind (W. Nickling)

Small linear wind tunnel saltation experiments: Some experiences (D. Gillette)

Design and calibration of the Carousel Wind Tunnel (B. White)

3:00 Break

3:15 Sub-group meetings

5:00 Adjourn

June 21, Friday

9:00 Space Station lab module status (D. DeVincenzi)

9:30 Technical Session Impact Cratering (P. Schultz, Chairman)

Impact experimentation and the microgravity environment: An overview (R. Grieve)

Impacts of free-floating objects: Unique space station experiments (P. Schultz)

Proposed Earth based cratering experiments at low G in hard vacuum (T. Ahrens)

Low-gravity impact experiments: Progress toward a facility definition (M. Cintala)

Debris-cloud collisions: Accretion studies in the space station (P. Schultz)

A planetary ultra hypervelocity impact mechanics and shock wave science facility (T. Ahrens)

Mass loading of the Earth's magnetosphere by micron size lunar ejecta - I: Ejecta production and orbital dynamics in cislunar space (W. Alexander)

Mass loading of the Earth's magnetosphere by micron size lunar ejecta - II: Ejecta dynamics and enhanced lifetimes in the Earth's magnetosphere (W. Alexander)

12:30 Lunch

1:30 Technical Session Particle Formation/Interaction (S. Squyres, Chairman)

Planetary particle experiments on the space station: An overview (S. Squyres)

Electrostatic aggregation of finely-comminuted geological materials (J. Marshall)

Nucleation experiments in a microgravity environment (J. Nuth)

Grain dynamics in zero gravity (B. Werner)

Cosmic dust collection with a sub satellite tethered to a space station (G. Corso)

New techniques for the detection and capture of micrometeoroids (J. Wolfe)

Exobiology experiment concepts for space station (L. Griffiths)

3:30 Break

3:45 Sub-group meetings

5:00 Adjourn

June 22, Saturday

9:00 Technical Session Experimental Petrology, Planetary Materials, Other Experiments (J. Nuth, Chairman)

A system for conducting igneous petrology experiments under controlled redox conditions in reduced gravity (R. Williams)

The orbit properties of colliding co-orbiting bodies (J. Freeman)

How to make a comet (J. Stephens)

Planned observations of simulated interplanetary dust and cometary materials released from small satellites (I. Strong)

A magnetospheric simulation at the space station (R. Lopez)

12:00 Lunch

1:00 Sub-group reports

3:00 Summary

4:00 Adjourn

APPENDIX B: WORKSHOP PARTICIPANTS

Dr. Thomas Ahrens
Seismological Laboratory 252-21
California Institute of Technology
Pasadena, CA 91125
(818) 356-6906

Dr. W.M. Alexander
Department of Physics
Baylor University
Waco, TX 76798
(817) 755-3405

Dr. Robert Allen
Physics Department
Cowley Hall
University of Wisconsin
La Crosse, WI 54601
(608) 785-8669/782-7267

Mr. Phillip Anz
Department of Physics
Baylor University
Waco, TX 76798

Dr. Raymond Batson
U.S. Geological Survey
2255 N. Gemini Drive
Flagstaff, AZ 86001
(602) 527-7260

Dr. Carol Breed
U.S. Geological Survey
2255 N. Gemini Drive
Flagstaff, AZ 86001
(602) 527-7196

Mr. Yuan-Liang Chen
Department of Physics
Baylor University
Waco, TX 76798

Dr. Mark Cintala
Code SN12
NASA Johnson Space Center
Houston, TX 77058
(713) 483-3951

Dr. George J. Corso
Dearborn Observatory
Northwestern University
Evanston, IL 60201
(312) 476-0068

Dr. Donald DeVincenzi
Code EBR
National Aeronautics and Space Adm.
Washington, D.C. 20546
(202) 453-1525

Dr. Al Duba
Lawrence Livermore Laboratory L208
Livermore, CA 94550
(415) 422-7306

Dr. John Freeman
Dept. Space Physics, Box 1892
Rice University
Houston, TX 77251
(713) 527-4944

Dr. Don Gault
P.O. Box 833
Murphys, CA 95247
(209) 728-2191

Dr. Ronald Greeley
Department of Geology
Arizona State University
Tempe, AZ 85287
(602) 965-7045

Dr. Dale Gillette
R/E/AR4, 325 Broadway
Boulder, CO 80303
(303) 497-6653

Dr. Lynn Griffiths
MATSCO
600 Maryland Ave., SW
Washington, D.C. 20546
(202) 646-5074

Dr. B. Ray Hawke
Planetary Geosciences Division
HIG, University of Hawaii
Honolulu, HAWAII 96822
(808) 948-6488

Dr. Kevin R. Housen
Boeing Aerospace Co.
Mail Stop 13-20
P.O. Box 3999
Seattle, WA 98124

Dr. J. D. Iversen
304 Town Engr. Bldg.
Iowa State University
Ames, Iowa 50011
(515) 294-5157

Dr. Ramon Lopez
Dept. of Space Physics and Astronomy
Rice University
Houston, TX 77251
(713) 527-8101 x3504

Dr. Ian Mackinnon
Department of Geology
University of New Mexico
Albuquerque, NM 87131
(505) 277-7536

Dr. John R. Marshall
NASA Ames Research Center
MS 242-6
Moffett Field, CA 94035
(415) 694-6427

Dr. David McKinnon
U.S. Geological Survey
2255 N. Gemini Drive
Flagstaff, AZ 86001
(602) 527-7162

Dr. W. G. Nickling
Department of Geography
University of Guelph
Guelph, Ontario CANADA, N1G 2W1
(519) 824-4120 x3529/2171

Dr. Joseph A. Nuth III
Code EL
NASA Headquarters
Washington, DC 20546
(202) 453-1598

Mrs. Bonnie O'Hara
NASA-Ames Research Center
Mail stop 239-12
Moffett Field, CA 94035
(415) 694-5770

Mr. Dean O'Hara
NASA-Ames Research Center
Mail stop 245-5
Moffett Field, CA 94035
(415) 694-6277

Dr. Paul A. Penzo
NASA Headquarters, Code MT
600 Independence Avenue, S.W.
Washington, D.C. 20546
(202) 453-2543

Dr. David Roalstad
Ball Aerospace
P.O. Box 1062
Boulder, CO 80306
(303) 939-4789

Dr. Robert Schmidt
Boeing Aerospace Co.
Mail Stop 13-20
P.O. Box 3999
Seattle, WA 98124
(206) 655-9070

Dr. Peter H. Schultz
Department of Geological Sciences
Brown University
Box 1846
Providence, RI 02912
(401) 863-3546

Dr. Steven Squyres
National Aeronautics and Space Adm.
Ames Research Center
Mail Stop 245-3
Moffett Field, CA 94035
(415) 694-5491

Dr. James Stephens
MS 183-501
Jet Propulsion Lab
4800 Oak Grove Drive
Pasadena, CA 91109
(818) 354-3310

Dr. Ian B. Strong
Los Alamos National Laboratory
Mail Stop D-436
Los Alamos, NM 87545
(505) 667-4823

Dr. Gordon A. Swann
2255 N. Gemini Drive
Flagstaff, AZ 86001
(602) 527-7190

Mr. William G. Tanner, Jr.
2611 Lasker Ave.
Waco, TX 76707

Dr. Larry Taylor
Department of Geological Sciences
University of Tennessee
Knoxville, TN 37996
(615) 974-2366

Dr. David Thompson
Code PD
Johnson Space Center
Houston, TX 77058
(713) 483-6541

Dr. Wes Ward
U.S. Geological Survey
2255 N. Gemini Drive
Flagstaff, AZ 86001
(602) 527-7167

Dr. Brad Werner
301-38 Caltech
1201 E. California Blvd.
Pasadena, CA 91125
(818) 356-4649

Dr. Bruce R. White
Department of Mechanical Engineering
University of California
Davis, CA 95616
(916) 752-6451/0580

Dr. John Wolfe
457 Oliver St.
Milpitas, CA 95035
(408) 262-4283

Dr. Sherman S. C. Wu
U.S. Geological Survey
2255 North Gemini Drive
Flagstaff, AZ 86001
(602) 527-7248

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15. Supplementary Notes

Ronald Greeley: Arizona State University, Tempe, Arizona.
Richard J. Williams: Lyndon B. Johnson Space Center, Houston, Texas.

16. Abstract

A meeting of 50 planetary scientists considered the uses of the Space Station to support experiments in their various disciplines. Abstracts (28) present various concepts for impact and aeolian processes, particle formation and interaction, and other planetary science experiments. Summaries of the rationale, hardware concepts, accommodations, and recommendations are included.

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