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# Chapter 3

# Planetary Science

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## 3.1 Introduction

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

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

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

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

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

## 3.2 Suggested Experiments for Space Station

### 3.2.1 Low Velocity Collisions Between Fragile Particles

Microgravity offers unique opportunities to simulate phenomena in the early solar nebula. One important area for study is the dynamics of collisions of weak, unconsolidated bodies at low relative velocities. Collisional behavior of grain aggregates may have indirectly controlled large-scale processes in the nebula. There

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is a class of nebular models that are convectively unstable, maintaining turbulence by a feedback mechanism involving viscous dissipation. Such models involve the redistribution of mass and angular momentum in the nebula disk, thereby establishing the general configuration of the solar system. A key assumption for convective instability is a high opacity of the nebular material; however, the dominant source of opacity is solid grains rather than gas. Thus, the possibility of convection depends on the concentration and size distribution of grains, and the degree to which they may form larger aggregates by coagulation.

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

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

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

### 3.2.2 Low Velocity Collisions of Ice Particles

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

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

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

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

### 3.2.3 Plasma-Dust Interaction

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

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

### 3.2.4 Aggregation of Finely-Comminuted Geological Materials

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

1. Volcanic eruptions (especially phreatomagmatic)

2. Aeolian entrainment (dust storms)

3. Meteorite impact.

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

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

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

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

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

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

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

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

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

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

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

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

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

A microgravity environment would permit the following:

1. Study of aggregation purely as a function of interparticle (principally electrostatic) attraction.
2. Study of virtually stationary subjects.
3. Sufficient time for useful observations to be made. Implicit in this is the ability to observe upper limits to growth. Larger samples also permit greater ease of observation.
4. Ability to collect suspended aggregates without disruption caused by impact with the ground.

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

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

The study would provide knowledge of the following:

1. Rate of aggregation.
2. Mode of aggregation (shape, packing density and particle orientation).
3. Size to which aggregates can grow within the confines of a fixed supply of dust.
4. Interaction of one aggregate with another.
5. Type and size of material most prone to aggregation.
6. Dependency of aggregation on initial dust-cloud density.
7. The role of the comminution process in aggregation (e.g., crushing versus explosive generation of dust).

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

1. To what extent does aggregation play a role in "closing-down" both martian and terrestrial dust storms?
2. Does aggregation cause the sudden and catastrophic collapse of volcanic eruption plumes (which ultimately gives rise to pyroclastic surges spreading great distances from the eruption site)?

3. Could meteorite impact or other explosions on a terrestrial body give rise to global shielding of solar input (with biological implications for Earth) or would aggregation tend to cleanse the atmosphere when critical dust densities were exceeded?
4. To what extent does the rate and nature of aggregation control the global distribution of loessic deposits on planetary bodies such as Mars and Earth?

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

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

## 3.3 Required Capabilities of an Orbital Facility

1. Volume: to accomodate an environmental chamber and supporting equipment. Two standard electrical rack volumes are considered adequate. One rack would be entirely devoted to the environmental chamber, its enclosing glove box, and attached thermal and optical probes *etc.* The second rack would contain power supplies, gas reservoirs, vacuum pumps, controls, indicators and gauges, sample storage, microscopes, *etc.*
2. Environmental Integration: The 2-rack facility has many power requirements that will generate heat. This must either be dissipated by the system itself, or accommodated by the environmental controls of the module. The facility also handles fine dust and (possibly) toxic gases, and must therefore be capable of confining potential environmental contamination without loss of technical flexibility.
3. Process Control: The facility must be capable of providing sustained microgravity of the order of $10^{-5}$ g with minimal perturbations. Samples under investigation must be suspended in a chamber of sufficient size to essentially eliminate the attractive or repulsive forces (*e.g.*, electrostatic) of the confining walls. The experimental process should be capable of generating temperatures between 600 K (for decontamination baking of the walls) and 80 K (for simulating the Space environment). The facility should support pressures ranging from vacuum to a few atm, and the capability to control the gas composition.
4. Production: Some materials such as fragile dust/ice balls will require *in situ* production with all the appropriate instrumentation (molds, manipulators, etc.)
5. Handling: The system must be capable of positioning, launching, manipulating and tracking fragile ice/dust composites and other materials with extreme precision. It must also be capable of injecting and controlling dust clouds in the environmental chamber.
6. Monitoring/Inspection: Samples in the environmental chamber must be monitored during an experiment which requires continuous illumination; cameras, lenses, and viewing ports capable of imaging fine dust and cm-size objects; and instrumentation provided with continuous output for temperature, pressure, gas content, sample position, sample concentration, gravitational (and other) acceleration, electrical fields, *etc.* Samples must also be removed from the chamber and examined with various instruments such as microscopes after experimentation, and this maneuver must also take account of the potential for environmental contamination.
7. Cleaning: The capability must exist for cleaning the experimental chamber, decontamination, and disposal of used gases and particulate samples.
8. Hardware Requirements:

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

Chamber characteristics:

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

(b) Support Systems

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

(c) Process Controls and Instrumentation

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

(d) Experiment-Specific Equipment

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

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