

## Chapter 2

# Astrophysics and the Solar Nebula

J. Nuth (Chairman), W. Duley, J. Goebel, J. M. Greenberg, J. Kerridge, D. Lin, I. Mackinnon, F. Rietmeijer, J. Stephens, M. Tomasko

### 2.1 Introduction

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

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

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

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

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

## **2.2 Suggested Experiments for Space Station**

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

### **2.2.1 Microgravity Nucleation Experiments**

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

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

### 2.2.2 "Vacusol" Measurements

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

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

### 2.2.3 Coagulation of Interstellar Dust

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

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

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

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

## 2.2.4 Chondrule Formation via Electrical Discharge

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

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

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

## 2.2.5 Solar Nebular Turbulent Coagulation

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

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

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

## 2.2.6 Single Particle Measurements

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

## 2.3 Required Capabilities of an Orbital Facility

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

### 2.3.1 Optical Measurements

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

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

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

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

In order to provide sufficient data to allow particle dynamics to be monitored, wavelength, angle, and polarization-resolved scattering data are required. Rapid modulation of the light source polarization and intensity coupled with phase sensitive detection will allow high sensitivity detection of scattered light. For

multiple wavelength scattering measurements, multiple wavelength lasers or white light sources can be used in conjunction with wavelength resolved detection techniques, including multiple photodetectors or detector arrays. A computing controller must monitor the system's physical and chemical parameters including pressure and temperature and provide automatic or semiautomatic experiment operation. The controller must be capable of performing system calibration and operation as well as data reduction and display in real or near-real time for the local operator, and allow some system diagnosis and experiment summary to ground based experimenters.

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

### **2.3.2 Sample Collection and Analysis**

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

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

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

### **2.3.3 Hardware and Facilities**

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

experimenters will probably wish to build their own chamber, optimized for their own specific needs, but which will take advantage of certain standard capabilities.

Space Station provides the following to the facility:

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

The facility provides the following to experimenters:

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