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Investigation of biological, chemical and physical processes on and in planetary surfaces by laboratory simulation

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Abstract

The recently established Arkansas–Oklahoma Center for Space and Planetary Science has been given a large planetary simulation chamber by the Jet Propulsion Laboratory, Pasadena, California. When completely refurbished, the chamber will be dubbed Andromeda and it will enable conditions in space, on asteroids, on comet nuclei, and on Mars, to be reproduced on the meter-scale and surface and subsurface processes monitored using a range of analytical instruments. The following projects are currently planned for the facility. (1) amination of the role of surface and subsurface processes on small bodies in the formation of meteorites. (2) Development of in situ diment dating instrumentation for Mars. (3) Studies of the survivability of methanogenic microorganisms under conditions resembling the subsurface of Mars to test the feasibility of such species surviving on Mars and identify the characteristics of the species most likely to be present on Mars. (4) The nature of the biochemical "fingerprints" likely to have been left by live organisms on Mars from a study of degradation products of biologically related molecules. (5) Testing local resource utilization in spacecraft design. (6) Characterization of surface effects on reflectivity spectra for comparison with the data from spacecraft-borne instruments on Mars orbiters.

1. Introduction

Due to the success of the Discovery program and similar programs in Europe and Japan, enabling large number of missions to Mars and smaller solar system bodies, and the increase in the number of missions performing in situ studies and (potentially) sample return, we have constructed a multi-user facility for providing laboratory support by the simulation of the conditions on the surfaces of Mars, asteroids or comets. An environmental chamber was obtained from the Jet Propulsion Laboratory, Pasadena, California, and we have established a center for space and planetary sciences. Known as "Andromeda", the chamber will be made available to anyone interested in the investigation of conditions on planetary surfaces by laboratory simulation experiments. We believe that this will be the largest facility of its kind in North America, although a larger facility exists in Cologne, Germany. A review of the kind of work that can be performed in such chambers, at least for cometary studies, is provided by Sears et al. (1999).

2. The Andromeda planetary environmental chamber

The Andromeda chamber is a large stainless steel vacuum chamber constructed for comet simulations and recently used for simulating surface processes on Mars. The chamber is a vertical cylinder 2.2 m long and 60 cm in diameter inside a 4 m tall and 2 m × 2 m aluminum cabinet. The chamber is equipped with heating elements, cooling coils (liquid nitrogen, methanol–CO_2 slush, chilled-water) and thermal insulation (Fig. 1). The chamber contains eight lead-throughs for thermocouples, pressure

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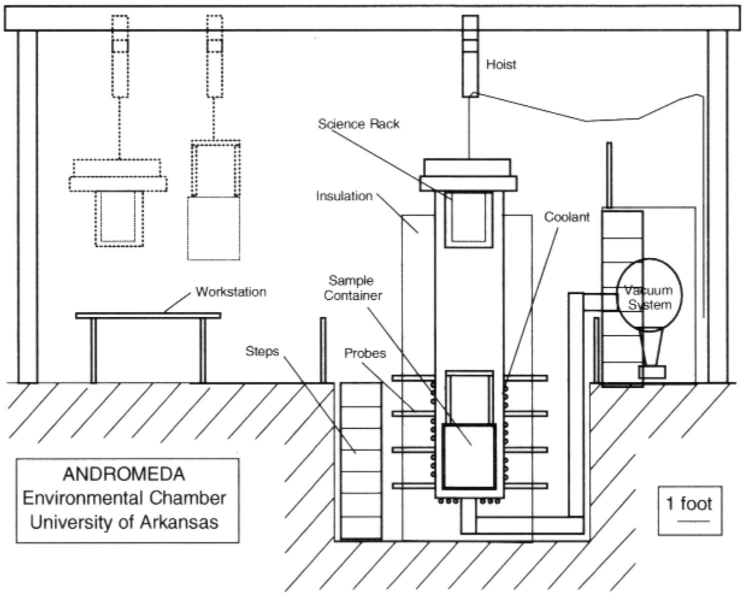

Fig. 1. Schematic diagram of the laboratory that houses the Andromeda planetary environmental chamber.

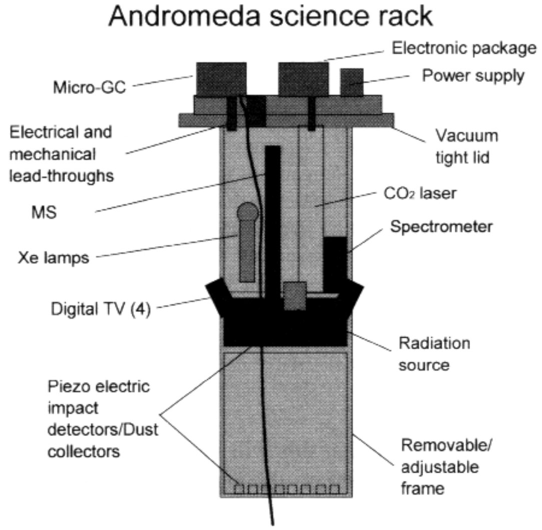

Fig. 2. The Andromeda Instrument Rack attached to the lid of the main chamber. A typical (and fairly full) suite of apparatus is show attached to the rack. This can be changed depending on the experimental requirements. Fill-coding reflects detection/collection instruments, sources, and support electronics.

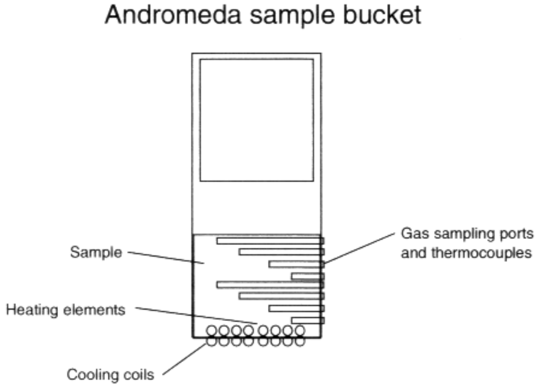

Fig. 3. The Andromeda Sample Container. The container is filled with soil simulant of the appropriate type and then lowered into the chamber with a hoist.

gauges, or other probes for access to the interior of the chamber.

A variety of containers contain asteroid, comet and martian analog materials of a wide variety of compositions and textures (Fig. 2). The containers are 50 cm in diameter and 50 cm deep and are lowered into the chamber by a hoist. The underside of the bucket contains a copper pipe through which coolant is pumped and the bottom of the bucket is lined with heating elements. Thermocouples, gas collectors or other probes can be placed throughout the sample.

Attached to the underside of the lid of the chamber is an instrumentation rack, onto which a number of environmental, detection and monitoring instruments will be placed (Fig. 3). The rack will typically contain Xe lamps and radiation sources, a high-powered laser, a gas chromatograph (GC), a quadrapole mass spectrometer, and dust collectors and detectors. Visible and IR spectrometers can also be included. A micro-GC is housed outside the chamber, and has 13 capillary tubes to sample the soil and the atmosphere inside the chamber. Some apparatus will be placed inside the chamber. The chamber can be evacuated to 10^{-6} T sufficient to simulate the vacuum in space, and atmospheric composition can be adjusted with a large vacuum reservoir and various gas supplies.

3. Currently planned projects

3.1. Surface and subsurface processes on small bodies and the formation and history of meteorites

Asteroids and comets have unique scientific interest in that they are primitive residues from the formation of the solar system. Comets form in the outer solar system and asteroids form in the 2.0–3.0 AU region. Comets are deflected into the inner solar system, undergoing evaporation, crust formation and many internal changes, and some fraction evolve into asteroidal orbits. Studies of comets and asteroids have used ground-based and space-based telescopes, and there have been several spacecraft fly-bys and recently, the NEAR-Shoemaker spacecraft orbited Eros for a year and finally soft landed, but samples are yet to be returned.

Laboratory samples are available in the form of meteorites, mostly asteroidal fragments, that suggest a number of chemical fractionations during formation. Some questions can be addressed with theoretical models, but there is a lack of "ground truth" laboratory observation. Most laboratory simulation efforts relevant to these issues have either used water-rich starting materials appropriate to comets but not asteroids, or they have been done in a highly simplified fashion on the millimeter to centimeter scale, with minimal monitoring of the process in real time.

We plan to simulate devolatization and its effects on the unconsolidated regolith of these bodies under high vacuum and on the meter scale, continuing from the Kometen Simulation (KOSI) experiments performed in support of the Rossetta mission (Sears et al., 1999). Analogs will be placed in the vacuum chamber and exposed to a solar spectrum of radiation at about 1 solar constant at temperatures appropriate for the asteroid belt (Table 1). Vaporization of volatiles will cause the ejection of particles from the surface, size sorting of materials remaining in the surface, and development of a subsurface stratigraphy. The large chamber size will enable in situ monitoring of the process in real time with video cameras and gas chromatograph-mass spectrometer. We will also model hypervelocity impacts in our simulations, since impacts are a possible means of disrupting the crust.

Heating by internal radioactivity or impact probably lead to vaporization of water and carbon dioxide and to size and density sorting of components in the regolith. The regolith may have provided sufficient insulation for metamorphism chondrites to form in the near-surface environment (Akridge et al., 1998). Slight variations in initial composition and parent body size could explain the full diversity of chondrite types and classes, without need to appeal to unusual processes in the early solar nebula. Previous work investigated size and density sorting of particulates using fluidization columns filled with mixtures of quartz and iron (Huang et al., 1996; Akridge and Sears, 1999). We need to extend these measurements to pressures more appropriate to asteroids and the solar nebula and Table 2 lists the particle details for our proposed experiments.

The chamber lends itself to wet asteroid/comet simulation experiments in which H_2O/CO_2 ice and dust mixtures can be evaporated and the entrainment of dust in the gases studied, much as was done in the KOSI experiments (Sears et al., 1999). In fact, the experimental setup is similar to that required for the Mars polar simulations discussed below.

3.2. In situ optical dating of martian sediments

Analysis of data from orbital spacecraft clearly reveals that the martian ice caps exhibit stratification. Meaningful interpretation of data stored in these strata will require absolute dates in order to provide a temporal framework for the climatic processes. The stratification in the polar caps of Mars arises, at least in part, from the incorporation of various amounts of eolian (wind blown) material into the ice. Active eolian processes are also exhibited near the poles and other regions of the martian surface in the form of dune fields, and these features are also potential candidates for the luminescence dating techniques to be developed in this project.

At the moment, the only available absolute chronological estimates for the main geomorphological structures are based on crater counting. Only one method has been discussed in the literature for dating the sedimentary layers

Table 1
Proposed wet asteroid simulation experiments

	1	2	3	4	5	6
Sample composition (wt%)						
Silicates	70	70	80	40	40	60
Iron	10	10	5	20	0	0
Sulfide	0	5	0	15	0	0
Matrix	0	5	5	5	40	20
H_2O	20	10	10	10	20	10
CO_2	0	0	0	10	0	10

Table 2
Proposed metal–silicate fractionation experiments at low pressures

Run	Quartz (wt%)	Iron (wt%)	Quartz grain size (mm)	Iron grain size (m
1	100	0	0.15–0.25	—
2	100	0	0.30–0.43	—
3	100	0	0.60–0.71	—
4	90	10	0.15–0.25	0.15–0.25
5	90	10	0.30–0.43	0.15–0.25
6	90	10	0.60–0.71	0.15–0.25
7	80	20	0.15–0.25	0.15–0.25
8	80	20	0.30–0.43	0.15–0.25
9	80	20	0.60–0.71	0.15–0.25
10	70	30	0.15–0.25	0.15–0.25
11	70	30	0.30–0.43	0.15–0.25
12	70	30	0.60–0.71	0.15–0.25

The series of experiments will be run at 10^{-6}, 0.03, 0.3, and 3 Torr.

on Mars (Lepper and McKeever, 1998, 2000; Sears et al., 1999), which is the use of luminescence measurements to date mineral grains trapped within these layers. Both eolian and fluvial deposits would be suitable targets for dating in this manner. The necessary methods have been successfully developed for absolute age determinations for numerous Quaternary eolian deposits on Earth (McKeever, 1985; Wintle, 1997; Aitken, 1998). The event to be dated using luminescence is the last exposure of the sediment grains to solar radiation. Eolian sediments are suitable materials because they are well dispersed during transport and are therefore well exposed to solar radiation. This exposure resets the "luminescence clock". To calculate the age, the method uses the natural, radiation-induced luminescence from silicate grains to determine the natural dose of absorbed radiation since the sediment was deposited. By establishing the natural environmental radiation dose rate, the age may then be calculated from

$$\text{Age} = \text{Natural dose}/\text{Dose rate}.$$

The age range over which the technique works is expected to be ~ 100 to 10^6 years. This would be appropriate for studies of "recent" sedimentary processes. Greeley et al. (2001) recently reviewed aeolian processes and the chronology of Mars and lamented the complete paucity of quantitative information on the rates of erosion, burial and exhumation of landforms by aeolian processes. They argued that it should be the focus of future work.

A luminescence dating module compatible with a wide variety of platforms could be used on future missions to Mars and thereby provide the absolute ages. Furthermore, the radiation dosimetry necessary for luminescence dating also provides data on the radiation environment on Mars, both at the surface and at the 0.3–1.0 m depth of the samples extracted for dating. Comparisons of dose vs. shielding depth measurements made on Mars will provide the needed data to assess the validity and accuracy of ground-based experiments and model simulations.

Major uncertainties concerning the use of luminescence to date the deposits include the degree to which the luminescence signal is reset during solar bleaching on the martian surface and the degree to which radiation dose rate might be attenuated by the sediments themselves. Understanding this attenuation will enable better evaluation of the age range over which luminescence can provide dates.

The Andromeda chamber will be used to: (1) simulate solar resetting of the luminescence signal from sediments under conditions expected on the martian surface, and (2) perform measurements of the radiation attenuation expecte from water and carbon dioxide ice matrices. In both projec the Mars soil simulant JSC Mars-1 will be used. The JSC Mars-1 simulant is weathered, terrestrial volcanic ash from Hawaii prepared by Lockheed Martin Space Science Systems in collaboration with NASA and Geohazards Consultants International (Allen et al., 1998).

For the resetting experiments martian soil simulant (JSC Mars-1) can be initially irradiated and fans within the environmental chamber will simulate dispersed dust in the martian atmosphere at low temperatures and under solar simulation (using the solar lamps fitted in the chamber). The efficacy of bleaching will be examined by extracting the samples and reading the luminescence as a function of exposure time, dust storm severity, grain size and mineral type. Furthermore, the luminescence signal will be stimulated using a variety of stimulation sources, including thermal (i.e. thermoluminescence) and optical (optically stimulated luminescence, OSL). For the radiation attenuation experiment, frozen and unfrozen terrain (both expected at the martian poles) will be simulated. By placing dosimeters (TLDs) at strategic points within the matrix, the radiation attenuation will be examined using an internal 90Sr source inside the chamber. Furthermore, the difficulties which may be encountered on Mars when extracting the sediment from frozen layers will also be examined, including extraction of an ice core, followed by melting to extract the sedimen material, and subsequent testing for luminescence.

3.3. *The survivability of methanogenic microorganisms under conditions resembling the subsurface of Mars*

The Viking experiments have shown that martian soil has unusual chemical properties and that it is unlikely that life currently exists on the surface of the planet (Klein et al., 1992). Methanogens, microorganisms in the domain Archaea and which utilize the reaction hydrogen and carbon dioxide to produce methane, could be models for possible martian subsurface lifeforms, especially if water exists below the surface. Methanogens occupy just about every anaerobic habitat on Earth (DiMarco et al., 1990; Jarrell and Kalmokoff, 1987; Jones et al., 1983) and we now have a solid understanding of the activities of methanogens in our environment (Zinder, 1992).

The methanogens are thought to have played a crucial role in the early evolution of our biosphere. Micropaleontological evidence indicates that the first cells on planet Earth were prokaryotic. Oceans of "organic soup" under a reducing atmosphere could have resulted in the first cells being anaerobic heterotrophs which depended on the available organic molecules for their existence. But as cell populations increased and organic supplements were depleted introduction of autotrophy probably occurred, in which organisms such as methanogens required energy from chemical reactions. Many methanogens live at relatively high temperatures, not unlike those of the early Earth, and most can use H_2 as the reducing agent and thus energy source, a gas that was plentiful in the primordial atmosphere. Thus, methanogens may have been the first autotrophs to evolve (Ehrlich, 1990).

Although the growth of methanogens has been explored for a wide variety of terrestrial conditions, little or no work has been performed under conditions applicable to Mars, particularly under water-stressed conditions. The present work seeks to explore the range of conditions over which methanogenic microorganisms can survive in order to determine the likelihood of such organisms currently existing on Mars, to identify the conditions required for similar organisms to survive on Mars, and to lay a framework of understanding the likelihood of such organisms existing on Mars more than 3.5 Ga ago when conditions may have been wetter than at present (Fanale et al., 1992).

The Andromeda chamber will be used for four investigations. (1) Knowing that some methanogens will produce methane on a Mars soil simulant under water-stressed conditions, we want to determine the least amount of water that will support methane production and how environmental factors affect this response. (2) We want to determine how long these methanogens can survive on Mars soil simulant when the water stress is varied. (3) We want to pursue the first two objectives using carbon monoxide instead of hydrogen as an energy source. We also want to determine carbon monoxide thresholds under these conditions. (4) We propose to follow the carbon isotopic composition of the CH_4, CO_2 and biomass produced during the different experimental incubations described in the first three objectives.

Certain methanogens grow well on Mars soil simulant with carbon dioxide, molecular hydrogen, and very limited amounts of water (Kral and Bekkum, 1999a, b). If molecular hydrogen is present below the surface of Mars, with even small amounts of liquid water, then all requirements for methanogenic growth would seem to be present. Even if hydrogen is not present, carbon monoxide is known to be present, and some methanogens can use carbon monoxide instead of molecular hydrogen. Thus, studies to determine the minimal amount of water that will allow for growth on Mars soil simulant under various environmental conditions (pressure, temperature, pH, inoculum size, carbon monoxide as energy source) will have relevance to the possibility of life surviving on Mars, currently or in the past.

3.4. *The nature of the biological "fingerprints"*

While it seems unlikely that life currently exists on Mars, conditions were once more amenable (McKay and Stoker, 1989; McKay et al., 1992; McKay, 1997; Kieffer et al., 1992) and a method capable of detecting traces of extinct life is needed. Since it seems likely that if life ever existed on Mars it was in the form of microorganisms, it will likely prove difficult to detect evidence for such life by looking for macroscopic fossil remains. What we propose here is to develop methods for finding chemical evidence of life on Mars.

We start with the assumption that life on Mars will be similar to that on Earth. That is to say martian life was cellular with nucleic acids, proteins, and carbohydrates dissolved in water enclosed in lipid bilayer membranes. This is a major assumption, but seems a reasonable starting point. The question is how to detect the presence of such organisms that may have lived millions or even billions of years ago in Martian samples. It is possible to find specific "fingerprint" molecules even in complex mixtures by using analytical techniques like gas chromatography-mass spectroscopy (GCMS) and liquid chromatography-mass spectroscopy (LCMS). Such techniques have already been applied to samples from martian meteorites (Glavin et al., 1999). Molecules of biological origin have been found, but isotope ratios appear to indicate that these molecules were earthly contaminants (Brack and Pillinger, 1998; Jull et al., 1998).

Our interest is to further develop this technique's application to samples from extreme earthly and extraterrestrial environments. It is known that the environment in which the "chemical fossil" ages influences the types and distribution of molecules found. In short, each environment produces a distinct "fingerprint" of biochemical markers. It seems likely that the martian environment would do the same. The environment on Mars differs in many distinctive ways from that of Earth. First, the surface of Mars appears to contain a strong oxidant that is responsible for the destruction of organics. The atmosphere of Earth is much more oxidizing than the atmosphere of Mars, but biological activity means that there is also a prodigious source of reduced material on Earth. As a result on Earth we have simultaneous reducing and oxidizing environments present at the surface of the planet. However, the subsurface Mars may have relic reducing material. The martian environment is also much drier than that of Earth. Since water and oxygen are clearly involved in many of the reactions producing chemical fossils on Earth, it seems likely that types and distributions of molecules produced under Martian conditions will differ from those characteristic of life on Earth. Similarly, we expect that distinct patterns of chemical markers could be found for life that exists or might exist under extreme conditions.

The Andromeda facility will enable us to determine the likely identity of these "fingerprints". By placing purified proteins, carbohydrates, lipids and other molecules of biological origin under conditions that mimic the Martian surface or Earth's interior, perhaps at elevated temperature, to speed the kinetics of the chemical aging process, we can see how these materials age and evolve into new mixtures of materials. We would also examine mixtures of these materials as well as intact microorganisms under extreme conditions and see what molecules result relative to similar materials under Earth conditions. We expect to develop profiles of molecules and identify distinctive molecular species that will clearly indicate whether the genesis of the biological material is from the extreme environment or a contaminate.

3.5. To develop means of local resource utilization in spacecraft design

The ability to explore planetary surfaces will be greatly improved by the utilization of local resources. Plans for surface explorations often incorporate a significant number of inflatable structures, including communication antennas, solar concentrators, aeroshells, aerobots, landing systems, photovoltaic arrays for centralized power, storage and/or diagnostic facilities, solar shields or other robotic "habitats", and rover tires. Manned missions will find habitable inflated structures beneficial. In many of these applications, inflatables will be the only enabling technology, due to low mass, low stored volume, low cost, and high deployment reliability.

Planetary surface structures which operate in a local atmosphere may be able to utilize those local gases for both initial structure inflation and make-up gas, depending on the specifics of the mission. For these applications, gas capture systems capable of operating at very low atmospheric pressures need to be screened and evaluated. Additionally, in situ gas generation from available solids may be beneficial in some cases. The task, therefore, is to identify the optimum approach for producing inflation gases from locally obtained materials. Since the first target for these explorations is expected to be Mars, the Martian environment is currently of prime interest.

Two general categories of inflation gas may be identified. For the majority of the structures (antennas, solar panels, tires, etc.), inflation with the local atmospheric gases (predominantly CO_2) would be acceptable. For these applic tions, it is anticipated that either a mechanical compressor or an adsorption/desorption (A/D) system will be appropriate. A very promising approach to wide-area surface exploration is the utilization of lighter-than-atmosphere (LTA) aircraft, which (while solar heating of the envelope can be used to provide buoyancy) are best implemented by utilization of an inflation gas of low molecular mass. The in situ production of nitrogen, hydrogen, methane, carbon monoxide, or oxygen would provide a viable and valuable source of LTA gas.

We will identify the optimum approaches for delivering inflation gas, with total inflated volume, inflation pressure, and total system mass requirements as primary parameters. These studies will map the parameter space to aid in system selection for specific applications. Concurrently with these studies, basic science/technology evaluations for the use of local materials for gas generation will be initiated. The environmental chamber will be used for these assessments. In this program, testing of A/D candidate materials will be conducted under realistic surface conditions.

3.6. Quantitative analysis of in situ reflectance and emission spectroscopy of martian surface materials

Grain size and composition of regolith and crustal components provide information with which to assess ancient and modern environments on Mars that may have permitted the development of life. The most efficient techniques to constrain composition and size remotely are reflectance and emission spectroscopy. During the next decade, visible and thermal infrared spectra from 0.4 μm to 50 μm will be acquired from the martian surface by orbiting multispectral and hyperspectral instruments at pixel sizes < 100 m and ~ 2 km, respectively. According to a recent workshop report on spectroscopy of the martian surface held at the Lunar and Planetary Institute in 1999, successful pursuit of the NASA objectives depends critically on the development of accepted methodologies for the quantitative assessment of remotely sensed high-information spectra and on the availability of spectral libraries that contain measurements of the minerals, coatings, and particle sizes likely to exist on the martian surface. Numerous spectra of specific mineral particles in various size ranges have been collected (e.g. Bishop and Pieters, 1995; Christensen et al., 2000). Data for irregular surfaces, such as mixtures of dust, sand, and rock observed at the Pathfinder landing site and likely characteristic of most of the martian surface, however, are largely lacking.

The Andromeda facility will be used to collect reflectance and emission spectra of analogs of martian surface materials, such as JSC Mars-1, under atmospheric and temperature conditions similar to those on the martian surface. One of the important characteristics of the Andromeda chamber is the ability to collect data on dynamic processes, such as dust storms. Thermal infrared spectra of Mars, for example, dominated by strong absorptions from dust, CO_2, water vapor and water ice in the martian atmosphere. These conditions may be simulated in the chamber through the creation of dust clouds that can model certain aspects of martian dust storms and modification of the gas content to approximate the martian atmosphere. Reflectance and emissivity data may be acquired during periods of intense obfuscation of the martian surface by dust and then again as the dust settles and the atmosphere clears. The effects of the thickness of the dust layer and the orientation of dust particles on martian surface spectra can be assessed quantitatively. The polar regions of Mars, whose surface temperature is below 225 K, contain temporally and spatially varying amounts of water ice, CO_2 ice. The relative concentrations of these components are not well constrained (Cutts et al., 1979; Malin, 1986). In situ spectra will be acquired from samples containing different mixtures of water ice, CO_2 ice, and dust for use as a reference dataset against which to compare multispectral and hyperspectral data acquired by orbiting instruments. Other parameters, such as the viewing angle, will be varied within the Andromeda chamber to allow investigation of geometry-dependent reflectance properties of samples. Although the initial emphasis is on visible and near to mid-infrared reflectance, addition of a thermal emissivity instrument is planned for the near future.

In addition to our study of polar regions, we intend to investigate materials likely to occur in warmer high-albedo regions of Mars, which display a globally homogeneous, but non-diagnostic spectrum similar to martian atmospheric dust (McSween and Keil, 2000). The composition of dust is not well known, but may be chiefly palagonite or a mixture of montmorillonite and comminuted basalt (Clancy et al., 1995). Experiments to further constrain dust composition also are a priority. Recently, Ruff and Christensen (1999) proposed on the basis of emissivity data acquired by the thermal emission spectrometer instrument on mars global surveyor that the high-albedo regions are composed of fine-grained basaltic material. We will collect spectra for different basaltic particle size fractions, taking advantage of the general property of silicates that emissivity decreases at short wavelengths and increases at long wavelengths with decreasing particle size. Also useful is that the brightness of spectral reflectance also depends primarily on the size of the reflecting grains.

Last, another set of experiments will address the controversy surrounding the formation of young gullies in cliff faces on the martian surface imaged by the Mars Orbiter Camera (Malin and Edgett, 2000a). Two mechanisms have been proposed: liquid water derived from subsurface ice (Malin and Edgett, 2000b) and CO_2 suspended flow generated from dry ice buried at shallow depth. The latter invokes build-up of a liquid CO_2 aquifer behind and below a dry-ice barrier in the subsurface. Rapid release of liquid CO_2 occurs in response to heating of the martian surface by solar radiation. Escape and subsequent rapid vaporization of the liquid CO_2 yields a density flow that erodes the gullies and carries material downslope where it is deposited as the flow ceases. We plan to mimic this process in the Andromeda chamber to test its viability as a mechanism to erode channels, entrain particles, and deposit debris aprons. The key parameters of burial depths of dry-ice, slope angle, and solar radiation can be varied systematically until release of CO_2 from the subsurface occurs. Digital video cameras can image the process in real time and provide constraints on inputs for kinematic flow modeling. In addition, visible and infrared spectrometers will yield information as to the detectability of potential alteration products at the surface, generated by reaction of materials with escaping CO_2 for comparison with spectral data acquired by current and future Mars missions.

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