ARES

Astromaterials Research & Exploration Science

BI-ANNUAL REPORT 2007–2008

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Astromaterials Research and Exploration Science Directorate

Eileen K. Stansbery, Ph.D.

The Astromaterials Research and Exploration Science (ARES) Directorate has a unique role within NASA by leading the Orbital Debris Program and providing curatorial responsibility for all NASA-held extraterrestrial samples. In addition, ARES scientists and engineers conduct research in basic and applied space and planetary science in addition to providing support to the human and robotic spaceflight programs with expertise in science planning and operations, analysis of micrometeoroid/orbital-debris risks to spacecraft, image analysis, and earth observations. The ARES scientific staff represents a broad diversity of expertise in the physical sciences (physics, chemistry, geology, astronomy), mathematics and engineering organized into three offices (see Figure 1), Astromaterials Research (KR), Astromaterials Acquisition and Curation (KT), and Human Exploration Science (KX).

Scientists within the Astromaterials Acquisition and Curation Office preserve, protect, document and distribute samples of the current astromaterials collections. This capability at JSC originated during the Apollo program with scientists who were responsible for the science planning and training of the astronauts for the lunar surface activities. Since the return of the first lunar samples, ARES has been assigned curatorial responsibility for all NASA-held extraterrestrial materials (Apollo lunar samples, Antarctic meteorites—some of which have been confirmed to have originated on the Moon and on Mars, cosmic dust, solar wind samples, comet and interstellar dust particles, and space exposed hardware). The responsibilities of curation consist not only of the long term care of the samples, but also the support and planning for future sample collection missions and research and technology to enable new sample types. The foundation of which is the research into the samples that allows ARES scientists to provide a basic characterization of each sample and a fundamental understanding of the entire collection as a service to the external research community who rely on access to the samples. The Lunar Sample Facility and other curation cleanrooms, data center, laboratories, and associated instrumentation are unique NASA resources.

The curation efforts are greatly enhanced by a strong group of planetary scientists who conduct peer-reviewed astromaterials research. Astromaterials Research scientists conduct peer-reviewed research in planetary science (e.g., cosmochemistry, origins of solar systems, planetary geology and geophysics) and participate as Principal or Co-Investigators in many of NASA's robotic planetary missions. Since the last report, ARES has achieved several noteworthy milestones, some of which are documented in detail in the sections that follow. The discovery of a new mineral and the recognition from the International Mineralogical Society with naming privilege for "Brownleeite" proves the value of the extremely high resolution instrumentation for precision analysis that was acquired and described in the previous Bi-Annual Report. ARES scientists continue to identify grains of interstellar origin in cosmic dust and now also in the Stardust samples. The landing and

our real-time support to the Mars Phoenix mission was a logical extension of our other Mars mission support and data analysis including the MER Spirit and Opportunity rovers. ARES scientists have unique expertise in "ground truth" relevant to the kind of rocks expected to be studied on Mars, making ARES a unique contributor to instrument development and calibration for the Mars Exploration Program. The Lunar and Planetary Institute (LPI) and ARES harnessed a long and successful history of collaborative research and exploration activities that began with the Apollo program to be selected as an integral part of the NASA Lunar Science Institute (NLSI). During this period ARES continued to modernize our analytical capability and acquired two new state-of-the-art instruments – a Focused Ion Beam (FIB) and an Inductively Coupled Plasma Mass Spectrometer (ICPMS).

ARES is a world leader in orbital debris research, including modeling and monitoring the debris environment, designing debris shielding, and policy development to control and mitigate the orbital debris population. ARES has aggressively pursued refinements in the knowledge of the debris environment and hazards that it represents to spacecraft. One of many recent activities included ARES researchers participating in the ATV-1 Jules Verne reentry observing campaign in collaboration with ESA by providing a low-light "intensified" video system to analyze fragmentation of the ATV breaking up as it enters the Earth's atmosphere and then use that information to verify computer models and enhance safety assessments of reentries of spacecraft. Additionally, the ARES Image Science and Analysis Group (ISAG) has been recognized as world class as a result of the high quality of near real time analysis of ascent and on-orbit inspection imagery to identify debris shedding, anomalies, and associated potential damage during space shuttle missions. ARES earth scientists manage and continuously update the database of astronaut photography that is predominantly from Shuttle and ISS missions, but includes the results of 40 years of human space flight. One of these photos, Atafu Atoll [ISS018-E-18129 acquired on January 6, 2009], was selected as 3rd place in the Earth Observatory 10th Anniversary Favorite Image contest. The Crew Earth Observations web site (http://eol.jsc.nasa.gov/Education/ESS/crew.htm) continues to receive between 10 and 20 million hits per month. ARES scientists are influencing decisions in the development of the next generation of spacecraft and missions through lab tests on optical qualities materials for windows, MMOD shielding technology, and analog activities to assess surface science operations.

ARES serves as host to numerous students and visiting scientists as part of the services provided to the research community and conducts a robust education and outreach program. ARES scientists are recognized nationally and internationally by virtue of their success in publishing in peer-reviewed journals and winning competitive research proposals. ARES scientists have won every major award presented by the Meteoritical Society, including the Leonard Medal, the most prestigious award in planetary science and cosmochemistry, the Barringer Medal, recognizing outstanding work in the field of impact cratering, and the Nier Prize for outstanding research by a young scientist. ARES has established numerous partnerships with other NASA Centers, universities, and national laboratories. ARES scientists serve as society officers, journal editors, and members of advisory panels and review committees.

This Bi-Annual Report summarizes a subset of the accomplishments made by each of the ARES offices and highlights participation in the support of on-going human and robotic missions as well as development of new missions and planning for the eventual return of humans to the Moon and on to Mars or other destinations beyond low Earth orbit.

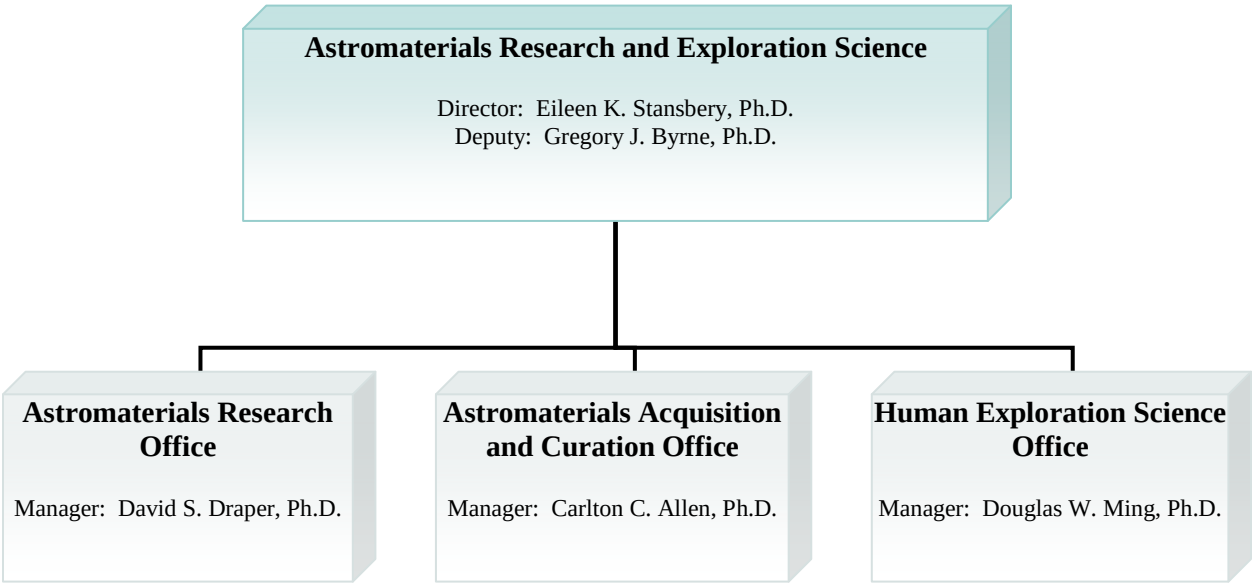


Figure 1.– ARES Organization Chart

Overview: Astromaterials Research Office (KR)

David S. Draper, Ph.D., Manager
http://ares.jsc.nasa.gov/AstroResearch/intro.html

The staff of the Astromaterials Research Office conducts peer-reviewed research in astromaterials and astrobiology. Scientists are funded through basic science disciplines of the NASA ROSES NRA (viewable from http://nasascience.nasa.gov/planetary-science), including Cosmochemistry, Origins, Exobiology, Planetary Geology, and Planetary Astronomy. Further funding comes from planetary missions, instrument development, and data analysis programs.

The fundamental goals of our research are to understand the origin and evolution of the solar system and the nature and distribution of life in the solar system. Our research involves analysis of, and experiments on, astromaterials in order to understand their nature, sources, and processes of formation. Our state-of-the-art analytical laboratories include four electron microbeam labs for mineral analysis, four spectroscopy labs for chemical and mineralogical analysis, and four mass spectrometry labs for isotopic analysis. Other facilities include the experimental impact laboratory and both one-atmosphere gas mixing and high-pressure experimental petrology labs. Recent research has emphasized a diverse range of topics, including:

- Study of the solar system's primitive materials such as carbonaceous chondrites and interplanetary dust
- Study of early solar system chronology using short-lived radioisotopes
- Study of large-scale planetary differentiation and evolution through study of siderophile and incompatible trace element partitioning, magma ocean crystallization simulations, and isotopic systematics
- Study of the petrogenesis of martian meteorites through petrographic, isotopic, chemical, and experimental melting and crystallization studies
- Interpretation of remote sensing data, especially from current robotic Mars missions, through study of terrestrial analog materials
- Study of the role of biological systems in evolution of astromaterials

The following reports give examples of astromaterials research done by members of this and other ARES offices.

Paul Niles, Douglas Ming, Richard Morris, and Brad Sutter

Mars Phoenix Lander

Launched Aug. 4, 2007, Phoenix landed May 25, 2008 in the north polar regions of Mars. Almost immediately it confirmed the presence of water-ice in the near subsurface of Mars. This verified the discovery of large subsurface concentrations of hydrogen in the region by NASA's Mars Odyssey orbiter in 2002. Phoenix is the first lander since Viking to feature intricate analytical chemistry instruments designed to measure the martian soil characteristics in detail.

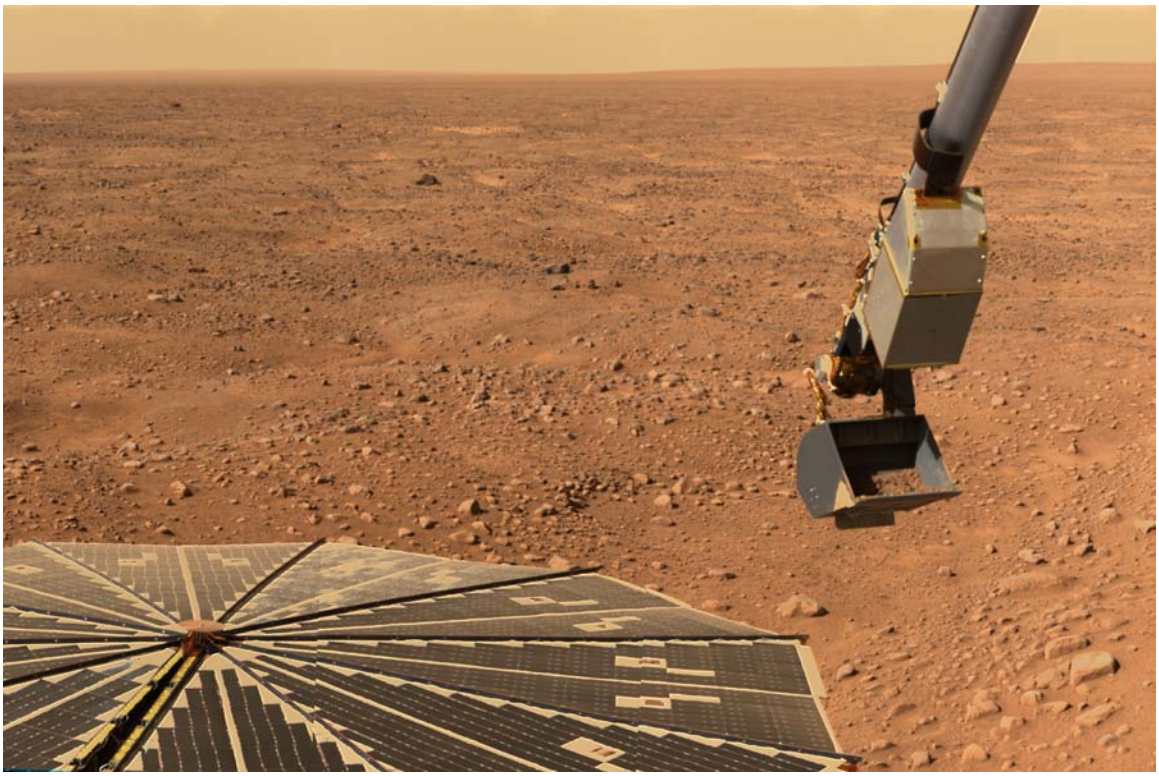


Figure 1.– This image shows NASA's Phoenix Mars Lander's solar panel and the lander's Robotic Arm with a sample in the scoop. The image was taken by the lander's Surface Stereo Imager looking west during Phoenix's Sol 16 (June 10, 2008), or the 16th Martian day after landing. The image was taken just before the sample was delivered to the Optical Microscope.

Figure 2.– This image was taken by the Phoenix lander's Robotic Arm Camera (RAC) and shows material collected during a test dig and dump on Sol 7 (June 1, 2008). The white material revealed in the right side of the image could either be ice or salts that have precipitated in the soil from water activity in the past.

Phoenix's preliminary science accomplishments advance the goal of understanding the history of water at the landing site. These initial findings include documenting a mildly alkaline soil; observing snow descending from clouds; discovering perchlorate salt, which has implications for ice and soil properties; and finding calcium carbonate, a marker for the presence of liquid water.

ARES has played a vital role in the Phoenix discoveries. The Thermal and Evolved-Gas Analyzer (TEGA) instrument on the Phoenix lander consists of ovens with thermal analysis capabilities and a mass spectrometer capable of analyzing the chemical and isotopic composition of the martian atmosphere and gases thermally evolved from martian soil samples. ARES has put together a TEGA-testbed laboratory which consists of 3 thermal analysis instruments and 5 mass spectrometers. One of the mass spectrometers is a near duplicate of the mass spectrometer flown with the TEGA instrument.

The discovery of carbonates in the martian soil was directly based on analyses performed in the TEGA-testbed laboratory. In addition, continuing work in the TEGA-testbed laboratory will support future discoveries and results from the Phoenix data set. This includes work on understanding the stable isotopic composition of CO_2 in the martian atmosphere and work on determining whether or not organic compounds are present in the martian soils.

Mars Science Laboratory

Scheduled to launch in the fall of 2011, Mars Science Laboratory (MSL) is part of NASA's Mars Exploration Program, a long-term effort of robotic exploration of the red planet. The main science goals of the lander revolve around the issue of "habitability" or whether or not the Martian surface can or ever could support environments favorable for life. The rover will carry the biggest, most advanced suite of instruments for scientific studies ever sent to the martian surface. The rover will analyze dozens of samples scooped from the soil and drilled from rocks. Two of the main instruments of this mobile analytical laboratory are the Sample Analysis for Mars (SAM), and Chemistry and Mineralogy X-Ray Diffraction (CheMin), a miniaturized x-ray diffraction instrument.

The SAM instrument features ovens and elaborate gas analysis tools including a mass spectrometer. The ovens will heat martian samples to create thermally evolved gases that can be analyzed to discover the chemical and isotopic composition of the gases. The CheMin instrument uses the technique of x-ray diffraction to characterize the mineralogy (or atomic structure) of the samples. Both of these analyses will provide new and exciting insights into the history of Mars, and will move us another large step in the direction of understanding the planet's past and present habitability.

ARES scientists are heavily involved in the MSL mission as members of the instrument teams. Building on the Phoenix experience, ARES has been developing test-bed laboratories that will provide data on analog samples that will be useful for calibrating and characterizing the SAM and CheMin instrument payloads on the MSL lander. Similar to Phoenix the results from the ARES laboratories will also be vital for understanding results returned from Mars.

The Last Two Years of Mars Exploration Rover Science

David W. Mittlefehldt, Douglas W. Ming, and Richard V. Morris

Introduction

The *Spirit* rover (MER-A) landed in Gusev Crater on 4 January 2004. Three weeks later, the *Opportunity* rover (MER-B) landed on Meridiani Planum on the opposite side of Mars (Fig. 1). Full mission success criteria included surface operations at each site for at least 90 sols (Mars days) and total traverse of 600 meters for at least one rover. As of 15 June 2009, *Spirit* is conducting science activities on sol 1937 and has 7730 meters on the odometer, while *Opportunity* is doing sol 1917 activities with 16569 meters under its belt. The three of us are members of the MER Athena Science Team, working principally with the Mössbauer Spectrometer and Alpha Particle X-ray Spectrometer (APXS) instruments. These instruments quantify the types of iron-bearing minerals present and the major and minor element compositions of rocks and soils.

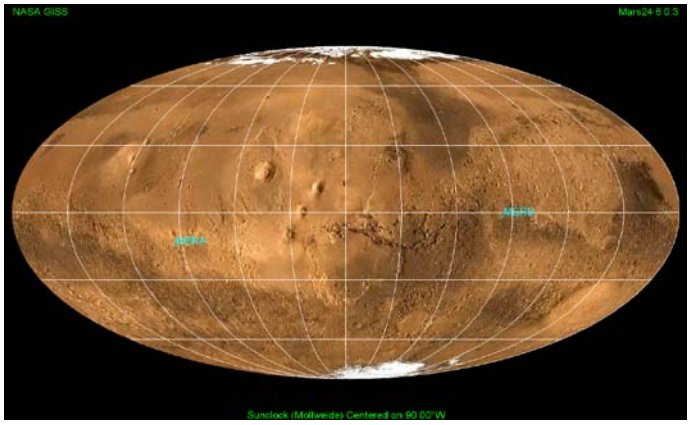


Figure 1.– Mollweide projection of Mars centered on longitude 90ºW showing the locations of the rovers.

Spirit *in Gusev Crater*

Gusev Crater was chosen as one of the landing sites in part because of morphologic evidence that suggested the crater was partially filled by waterborne sediments brought in via Ma'adim Valles from the south. This was in keeping with the NASA Mars Mantra "Follow the Water." Reality was quite different. Upon first look, *Spirit* saw a dusty plain littered with angular, dark rocks. Upon examination by the full panoply of instruments, these rocks proved to be volcanic, olivine-basalts similar in composition to known martian meteorites. Water was not important in forming the plains rocks in Gusev Crater.

The mission team decided to take full advantage of the rover's capabilities and strike out for the Columbia Hills rising above the plain 3-4 km away. As any field geologist would do, *Spirit* ascended one of the highest peaks, Husband Hill, looked around, and descended the other side. For the last two years, *Spirit* has been working in a region informally known as the Inner Basin south of Husband Hill in the vicinity of a topographic feature we call Home Plate.

Spirit lost the use of one wheel in March 2006, and now drags this almost useless appendage along wherever she goes. Although no longer a wheel, it has turned out to be a fabulous trenching tool. Using this new asset, *Spirit* has uncovered materials in the inner basin that show evidence of alteration by aqueous fluids. Most notably, *Spirit* has uncovered soils and rocks with distinctive light-toned colors that are very different from the normal, reddish martian soils and rocks (Fig. 2).

Southeast of Home Plate *Spirit* ran into soft soil in an area we named Tyrone, and nearly embedded herself in it. A look back after leaving showed an abundance of light-toned soils in variegated colors (Fig. 2). We dared not return to this trap to do *in situ* measurements on this interesting target, but some of these light-toned soils were dragged by the dead wheel for several tens of meters. We were able to use the Mössbauer Spectrometer and APXS on one of these soil-droppings. The results show that the light-toned soil is enriched in sulfur and that the largest fraction of the iron is tied up in a ferric sulfate phase. These results imply that aqueous alteration, more specifically acid-sulfate alteration, was likely responsible for the formation of these light-toned soils. Acid-sulfate solutions dissolved primary rock, bringing many cations into solution. As a result of changing conditions, sulfates and other salts were precipitated from the solutions, forming the minerals in the light-toned soils.

On the eastern margin of Home Plate *Spirit* ran into distinctive light-toned knobby rocks in the valley floor (Fig. 3). The rover spent a considerable amount of time driving up-and-down the Eastern Valley studying these materials. The rocks have the highest silica contents of any rocks studied by *Spirit* while the nearby soils have the highest silica contents of any materials analyzed on Mars and are enriched in titanium as well. Our working hypothesis for the origin of these unusual compositions is that they were formed by aqueous leaching of basaltic precursors under acid sulfate conditions, leaving insoluble silica and titanium behind.

Spirit also examined Home Plate in detail. This feature is visible from orbital images as a bright ring roughly 80 m in diameter. Home Plate is composed of laminated rocks fining upward with microscopic and macroscopic textures that suggest an origin as air-fall volcanic ash (Fig. 4). Compositionally, the rocks are unusual in being rich in some of the more volatile elements chlorine, bromine, zinc and germanium. Similar volcanic structures on Earth are often formed when magma erupts through water-saturated rock. A leading hypothesis for the origin of Home Plate is that magma ascended through rock saturated with brine – salt-rich water. The high volatile element contents of Home Plate rocks then are due to interaction with the briny water. We noted systematic variation in the chemistry and mineralogy of the rocks across Home Plate. This evidence led us to hypothesize that there were different localized alteration regimes on Home Plate; low temperature aqueous alteration on the eastern side and a higher temperature aqueous alteration on the western side.

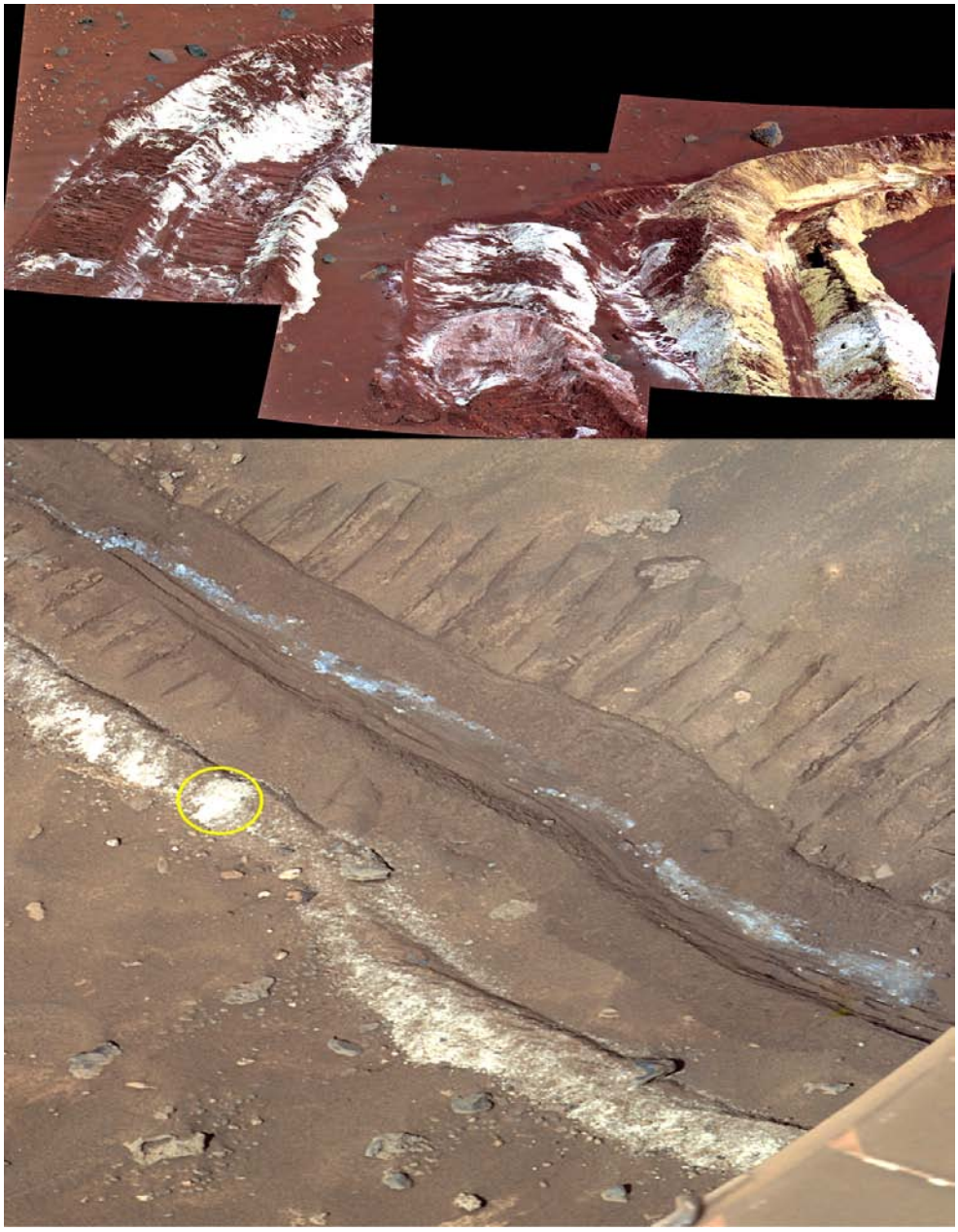


Figure 2.– Portions of Panoramic Camera false-color mosaics of regions southeast of Home Plate. Upper: Light-toned soil named Tyrone churned-up by Spirit's *wheels. These light-toned soils are rich in sulfates formed by aqueous alteration of rocks and soils in the local vicinity. Images taken on sol A788. Lower: Wheel tracks made after leaving Tyrone. A healthy wheel's cleat marks are in the upper right. Drag marks from the dead wheel diagonally cross the image. The whitish materials on the left side of the drag mark are salts dragged from Tyrone and that encircled was analyzed by the Mössbauer and APXS instruments (in yellow circle). This is part of the McMurdo panorama taken over sols A814 to A932. These and all Pancam images used here are from the Pancam team's website: http://pancam.astro.cornell.edu/pancam_instrument/index.html.*

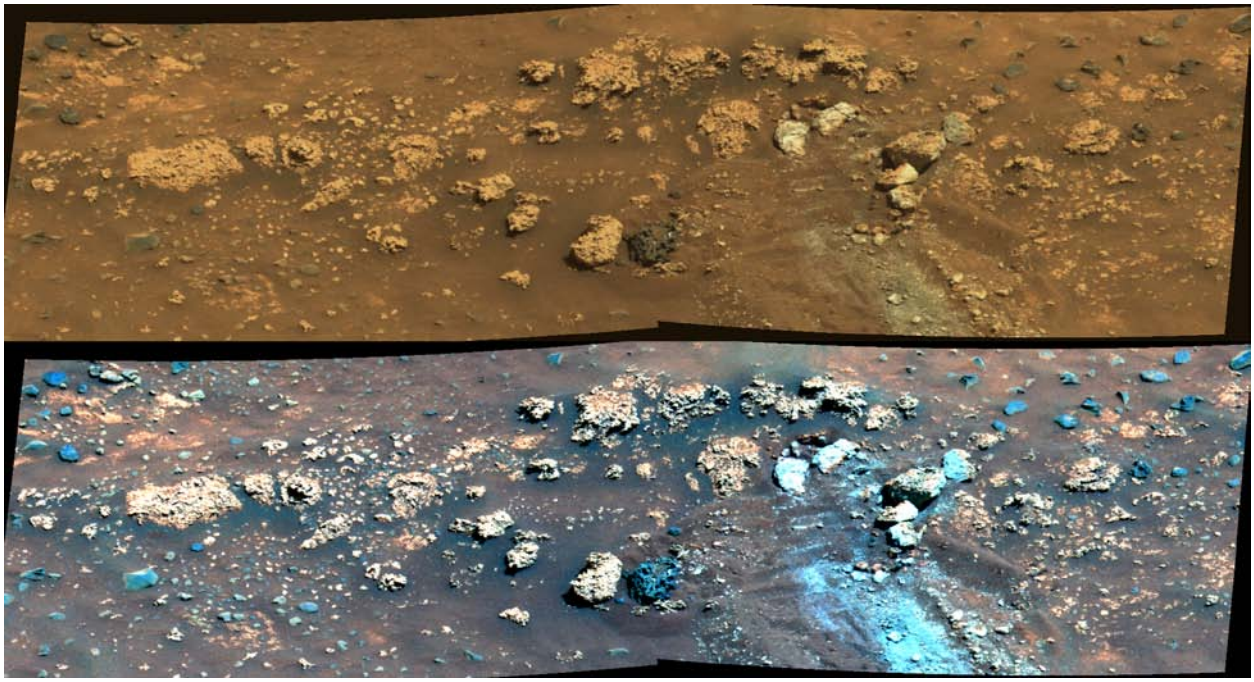


Figure 3.– Knobby, light-toned, silica-rich rocks in the Eastern Valley near Home Plate. Upper, approximate true color Pancam image. Lower, false-color Pancam image. The images were taken on sol A1234.

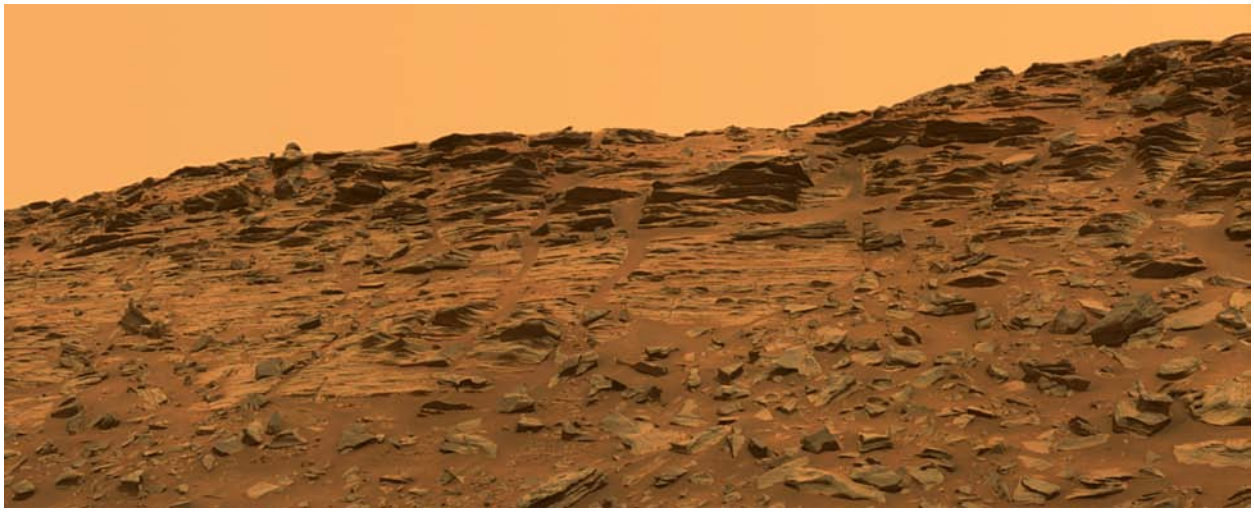


Figure 4.– The rocks of Home Plate are interpreted to be volcanic deposits similar to tuff rings on Earth. Portion of a Pancam approximate true color mosaic taken on sol A1886.

Opportunity *on Meridiani Planum*

Meridiani Planum was chosen as a landing site in part because orbital spectroscopic study had shown that this region was rich in the ferric iron mineral hematite, Fe_2O_3, which forms in oxidizing aqueous environments. *Opportunity*'s first look showed a terrain quite different from that at Gusev Crater. The region is composed of bright-colored, flattish, layered rock outcrops and dark drift sand. This terrain occupies the entire area *Opportunity* has traversed. Because we have examined rocks in cross section within craters, and laterally across Meridiani Planum, we have been able to develop a fairly detailed picture of the geologic history of these units.

The outcrops are composed of sedimentary rocks containing three main components; silicate sands, evaporite mineral sands, and hematite concretions. The first two components are reworked clastic materials; mineral and rock fragments from older rock units including weathered basalt and evaporites. Structures in the outcrops show that these sands were moved by wind, the same process that creates sand dunes and some types of sandstone on Earth. The upper part of the rock sequence was formed in wetter conditions; structures in the rocks suggest deposition in moving water. The minerals present in the rocks show that this water was oxidizing and quite acidic; otherwise the ferric sulfate mineral jarosite that is a key component of the sandstones would have dissolved away. The hematite concretions were formed *in situ* in the sediments by deposition from oxidizing aqueous fluids.

The key findings above were based on studies done of the interiors of small- and moderate-sized craters near the landing site, and on rocks exposed at the surface. In the last two years, *Opportunity* has been studying the rim and interior of a large crater, Victoria Crater, roughly 7 kilometers south of the landing site (Fig. 5). These studies have demonstrated that conclusions regarding the aqueous history of Meridiani Planum reached earlier in the mission can be extended over scales of many kilometers.

One key finding of our studies in Victoria Crater is that the diagenetic boundary we first observed in the rock section explored 1700 sols ago is also present 7 kilometers to the south. Diagenesis is a process whereby sedimentary rocks have their primary mineralogy, textures and compositions changed by interaction with groundwaters. In Endurance Crater we discovered that changes in rock color and texture at depth were accompanied by changes in composition, especially a large change in chlorine content. We hypothesized that these were indicators of interaction with groundwater. We have found a very similar set of changes with depth in Victoria Crater, leading us to conclude that the fluctuating water table was a regional phenomenon, not just a localized one.

Figure 5.– Upper panel: A portion of HiRISE image TRA_000873_1780 showing Victoria Crater, an 800 meter diameter impact crater. Lower panel: Portion of the Pancam false-color Duck Bay mosaic of the interior of Victoria Crater taken over sols B952 to B953.

Summary

One key goal of the NASA Mars exploration program is to determine the role of water in early Mars history, and the nature of aqueous environments that could have been hospitable to life. The MER rovers have done an admirable job of working towards that goal. They have shown that differing degrees of involvement of water are recorded, from just small amounts of alteration indicating low water/rock ratios, to sedimentalogical evidence for flowing water on the surface. In all cases, however, the solutions were oxidizing and acidic. The data returned by the rovers provide important information for assessing the potential for life on Mars, and give important evidence regarding the current environmental conditions on Mars that inform us of some of the challenges that await any future manned mission to that planet.

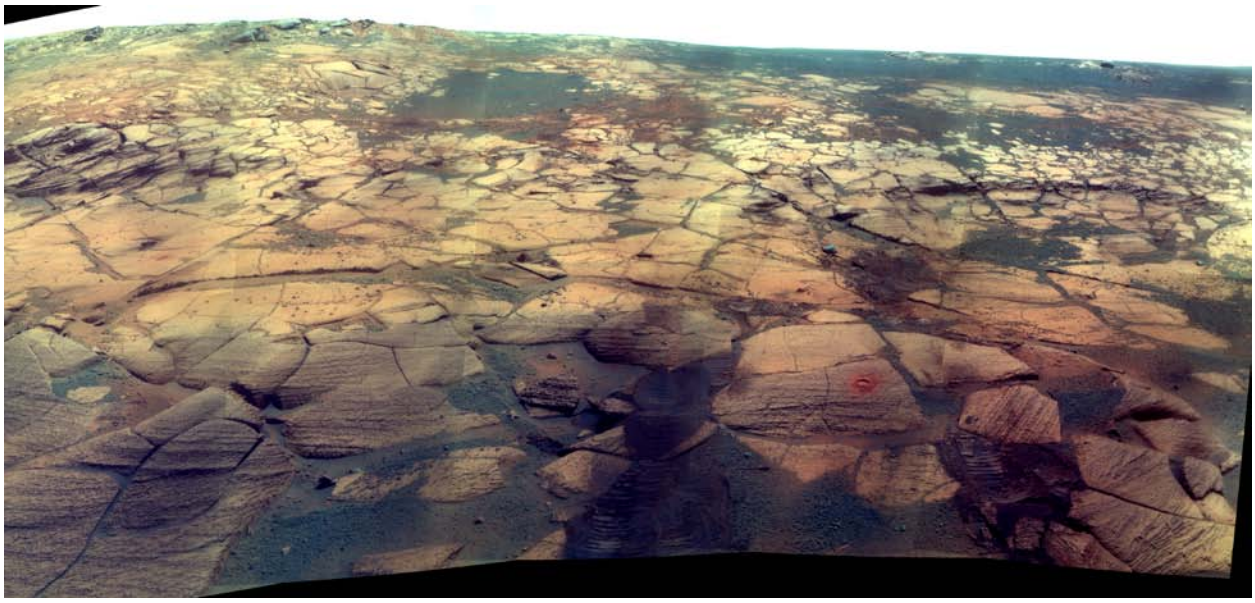


Figure 6.– Portion of a Pancam false color mosaic of the rock section studied in detail in Duck Bay of Victoria Crater. Image taken on sol B1423.

ARES High-Pressure Laboratory

Kevin Righter, Lisa Danielson, and Kellye Pando

The JSC High Pressure laboratory houses two non end loaded piston cylinder apparatuses and two multi-anvil apparatuses. The combination of these four pieces of equipment enables scientists in ARES to attain pressures between 0.5 and 25 GPa, and to simulate the conditions deep within planetary interiors such as the center of the Moon (4.5 GPa, the core mantle boundary of Mars (~22 GPa), or the upper-lower mantle boundary in the Earth (25 GPa). Since 2006, the facilities have been used to explore a variety of topics in earth and planetary science including the conditions of planetary mantle melting, the origin of volatiles (H, C, O, S), the conditions during accretion, the

origin of the Earth and Moon, and finally simply being able to synthesize high pressure phases that do not exist at ambient laboratory conditions. Two examples of research being undertaken in the JSC high pressure lab include studies bearing on the origin of volatiles and water in Earth, and the origin of the large amount of sulfur on the surface of Mars.

The origin of water on the Earth has three different kinds of models (Fig. 1). Traditionally its origin has been attributed to comets or another kind of volatile-bearing body that arrived late and well after accretion is complete. A second idea is that water arrived just at the end of accretion, after the Earth's huge metallic core finished forming. And a third idea is that the Earth acquired its water early, during the accretion process. The second hypothesis is linked to a class of elements called the highly siderophile elements (HSE) that are thought be reside mainly in the Earth's core, but are present in the mantle at concentration levels that are similar to that expected if small amounts of chondritic material were added to the mantle after the core formed. Because of this, the HSEs and the volatiles have commonly been linked in formation models for the Earth. However, the model was originally proposed in the 1970's at a time when relevant high PT data were not available. In order to test this idea more thoroughly, we have studied the distribution of the HSE palladium (Pd). The results, at pressures up to 15 GPa (published in Nature Geoscience, 2008) have shown that the concentration of Pd in Earth's mantle can be explained by high PT distribution between core and mantle early in Earth history. The implications are that late additions of (water- and HSE-bearing) material are not necessary, and that water and HSE concentrations in the Earth's mantle were established very early during accretion. Other elements such as Au, Pt, Ir and Rh are being investigated to see if they are also compatible with this simple and early origin of water on Earth.

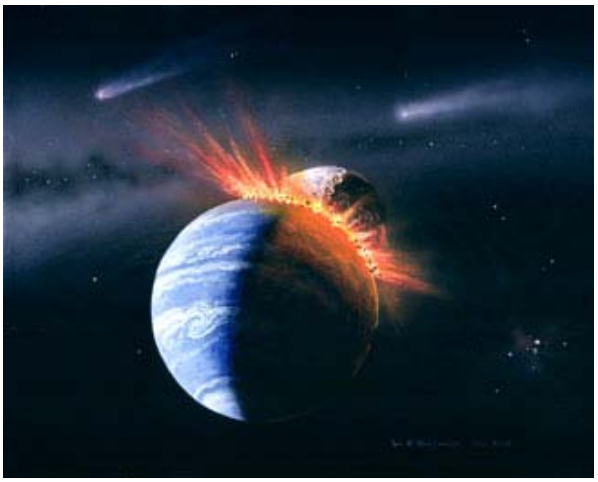


Figure 1.– Did Earth have water early, or did it acquire it later from comets? How did water survive a giant impact?

The surface of Mars has been known to contain sulfur for some time, but the diversity and distribution of sulfates around the surface has been only more recently appreciated. The origin of the sulfur is thought to be from interior degassing, but this idea has not been rigorously tested with experimental or more recent spacecraft data. If the sulfur comes from the interior the main vehicle for transport would have to be magma, which is capable of dissolving significant amounts of sulfur. Although this is well known for Earth basalts (such as mid ocean ridges and Hawaii), it is relatively poorly understood for martian basalts such as the shergottites or those erupted from Olympus Mons (Fig. 2). Because magma generation in Mars likely takes place at pressures accessible in the JSC high pressure lab, we have undertaken a study of S solubility in martian magmas that includes the melting process in the mantle, as well as later differentiation at shallower conditions at or near the surface. The results so far indicate that models based on terrestrial compositions and applied to martian systems are inadequate for predicting S in magmas. The solubility of sulfur in martian

magmas is perhaps 2x higher than that predicted by Earth-based models. The results of this study will have fundamental implications for the total S budget of Mars, as well as the understanding of sulfur inputs into the martian atmosphere and the control of elements in the martian interior by sulfides.

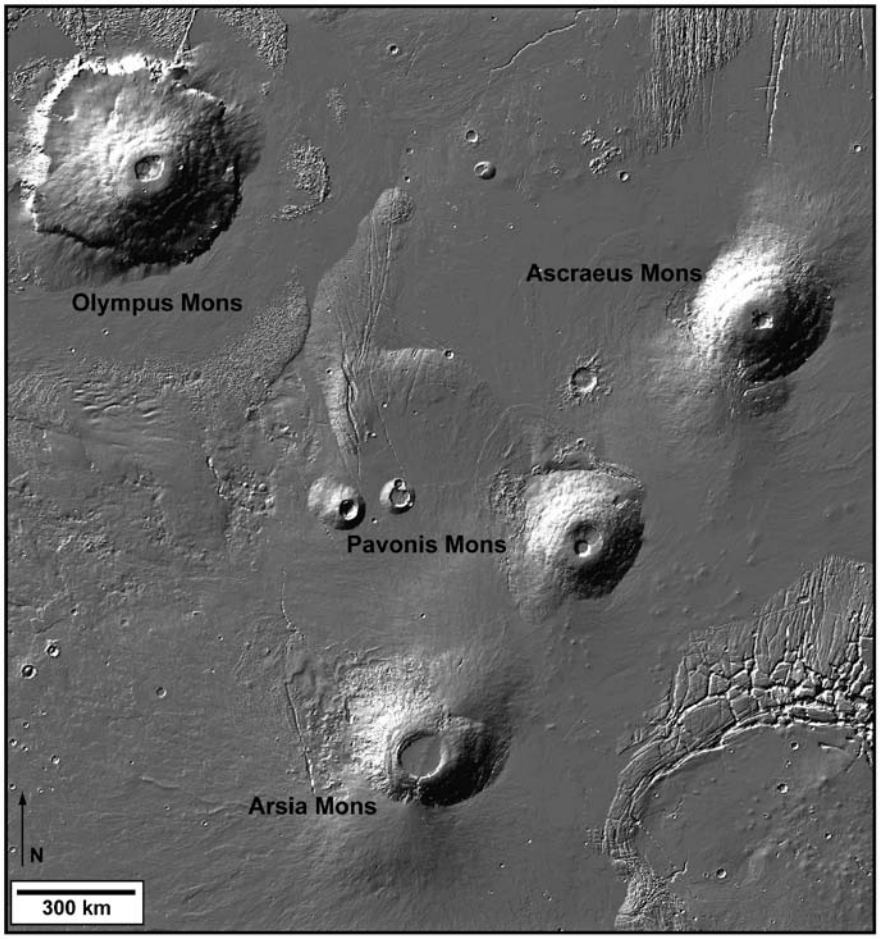


Figure 2.– Did all the sulfur on the surface of Mars come from volcanic eruptions such as from Olympus Mons?

Discovery of a New Mineral from a Cometary Particle

Keiko Nakamura-Messenger, Lindsay P. Keller, Simon Clemett, John Jones, Michael E. Zolensky, and Scott Messenger

There have been 4324 minerals officially recognized by the International Mineralogical Association (IMA). A team lead by ARES scientists added one more to the list, the first new mineral ever found in a cometary specimen. The new mineral, a manganese silicide (MnSi), named “Brownleeite” was

discovered within a cosmic dust particle that likely originated from a comet, perhaps comet 26P/Grigg-Skjellerup. The Earth accretes about 30,000 tons of dust particles from space each year, originating from the disintegration of comets and collisions among asteroids. This cosmic dust is a subject of intense interest because it is made of the original building blocks of our Solar System, the planets and our own bodies. Since 1982, NASA has routinely collected cosmic dust with high-altitude research aircraft. However, the sources of most cosmic dust particles have been difficult to pin down because of their complex histories in space.

A new opportunity to collect cosmic dust from a specific source was suggested by ARES space scientist Scott Messenger. He showed that comet 26P/Grigg-Skjellerup was a source of dust grains that could be collected in the Earth's stratosphere at a specific time of the year. In response to his prediction, NASA performed stratospheric dust collections, using an ER2 NASA high altitude aircraft to collect cosmic dust particles from this particular comet dust stream in April of 2003. The new mineral was found in one of the particles collected during this special collection.

In 2005, a powerful new transmission electron microscope (TEM) JEOL STEM2500SE was installed at the ARES E-beam facility. Because of the exceedingly small size of individual cometary dust components, we used state-of-the-art nano-analysis techniques in the TEM to measure the chemical composition and crystal structure of the new mineral. It turns out that one of the dust particles from comet 26P/Grigg-Skjellerup collection contains three tiny grains (100, 250, 600nm in size) of an exotic phase that has never been found in nature before. In fact, this phase was not predicted either to be a cometary component or to have formed by condensation in the solar nebula.

Recent analysis of material returned from comet Wild-2 by the NASA Stardust mission has shown that cometary components originated in a wide range of astrophysical environments, including refractory minerals formed at high temperature in the inner solar system; low temperature organic material from the outer reaches of the solar system or from interstellar molecular clouds; and dust grains from evolved stars whose origins predate the solar system. This new mineral must have formed under rather reducing, oxygen-depleted conditions, but no more so that the average for our early solar system. Alternatively, manganese silicide may have condensed within the high temperature and chemically heterogeneous ejecta of a supernova explosion. Mineral grains from supernovae have previously been identified in meteorites and cosmic dust particles, and they are identified on the basis of their exotic isotopic compositions. We may be able to determine if Brownleeite came from a supernova source by future silicon isotopic measurements using the ARES NanoSIMS 50L.

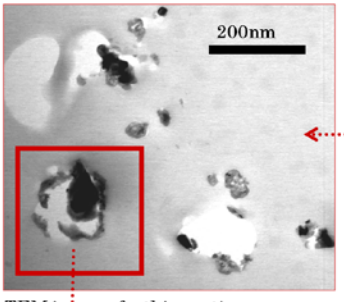
The IMA approved new mineral, Brownleeite, is named after Donald E. Brownlee, a professor of astronomy at the University of Washington, Seattle. Prof. Brownlee founded the field of cosmic dust research and is PI of the Stardust mission. Of all current sampling techniques, that developed by Prof. Brownlee, in the Earth's stratosphere is the superior way to obtain the least altered cosmic dust samples. The current view and understanding of the early solar system established from cosmic dust studies would not exist without his efforts.

Brownleeite has been synthesized and studied by materials scientists as a new generation semiconductor, but it has never been found in nature. Somewhere in the universe, there are places producing Brownleeite and it is supplied to Earth little by little as cosmic dust enters our atmosphere.

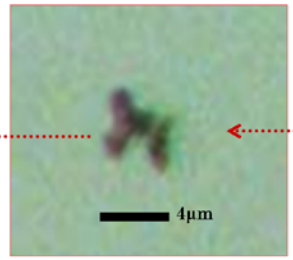
Brownleeite Discovery Flowchart

NASA ER-2 high altitute aircraft
collecting stratospheric dust particles for a total of 7.9 hours April 2003, over the southwestern USA. The altitude was between 63,500 ft and 65,000 ft

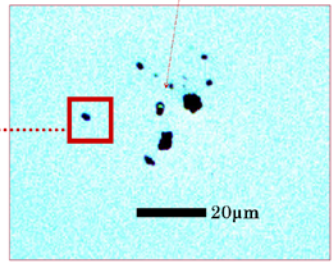
Dust Collector
attached to ER-2 aircraft. The particles are collected upon inertial impact surfaces suspended from the underside of the wings of NASA ER-2.



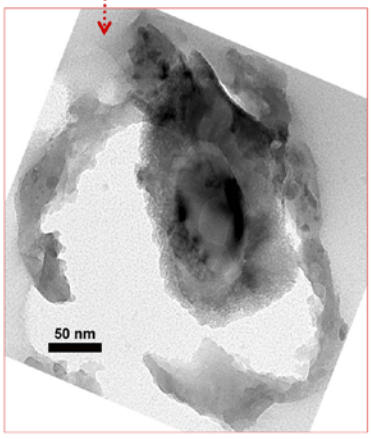
TEM image of a thin section
of the cometary particle where one of the Brownleeite grains was found



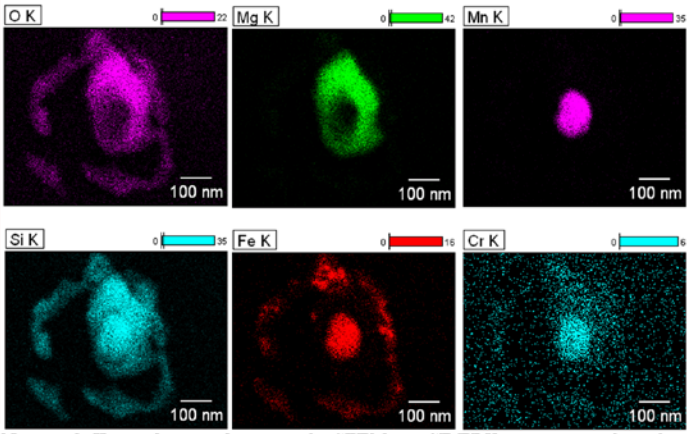
The dust particle sample we analyzed in this study
The particle was then sliced into 20 thin sections with 70nm thickness using ultramicrotomy.



Cometary Cluster particles
splashed onto the Dust Collector
Jack Warren from ARES Cosmic Dust curation team picks up these dust particles one by one.



Brownleeite crystal in the core
Poikiolitically enclosed by LIME olivine mantle.



Nanoscale X-ray elemental imaging by STEM2500SE EDX system revealing that the brownleeite grain (left) is free of O and Mg, but contains Mn, Si, Fe, and Cr.

Astromaterials Acquisition and Curation Office (KT)

Carlton C. Allen
http://curator.jsc.nasa.gov/

JSC and the Curation Team are responsible for the curation of NASA's current collection of astromaterials that includes lunar samples collected by the Apollo astronauts, meteorites collected in Antarctica, cosmic dust collected in the stratosphere, solar wind samples collected by the Genesis spacecraft, comet and interstellar dust particles collected by the Stardust spacecraft, and hardware exposed to the space environment. JSC has been designated as the U.S. curation site for a small amount of the asteroid samples collected by the Japanese Hayabusa spacecraft. JSC is responsible for curation of extraterrestrial samples collected on all future NASA missions.

Curation comprises initial characterization of new samples, preparation and allocation of samples for research and education, and clean, secure storage of samples at JSC or remote sites. The foundations of our curation are the specialized cleanrooms (class 10 to 10,000) for each of the specific types of materials, the supporting facilities, and the people, many of whom have been doing detailed work in ultraclean environments for many years.

The following reports give updates on curation of current astromaterials collections and plans for future collections.

Lunar Samples

Gary E. Lofgren, Andrea B. Mosie, Linda A. Watts, and Roger S. Harrington

During the Apollo Program, astronauts collected 2196 Moon rock and soil samples having a total mass of 382 kg. These are the only documented samples yet returned from another body in the solar system. The JSC Astromaterials staff curates this national treasure in the Lunar Sample Facility, a suite of class 1000 cleanrooms and secure vaults constructed in 1979. The collection now comprises approximately 100,000 subsamples, many of which are located in research laboratories and museums worldwide. The bulk of the collection, including pristine samples and material returned following analysis, is stored at the JSC facility. A remote storage facility at another NASA location stores a representative set of lunar samples.

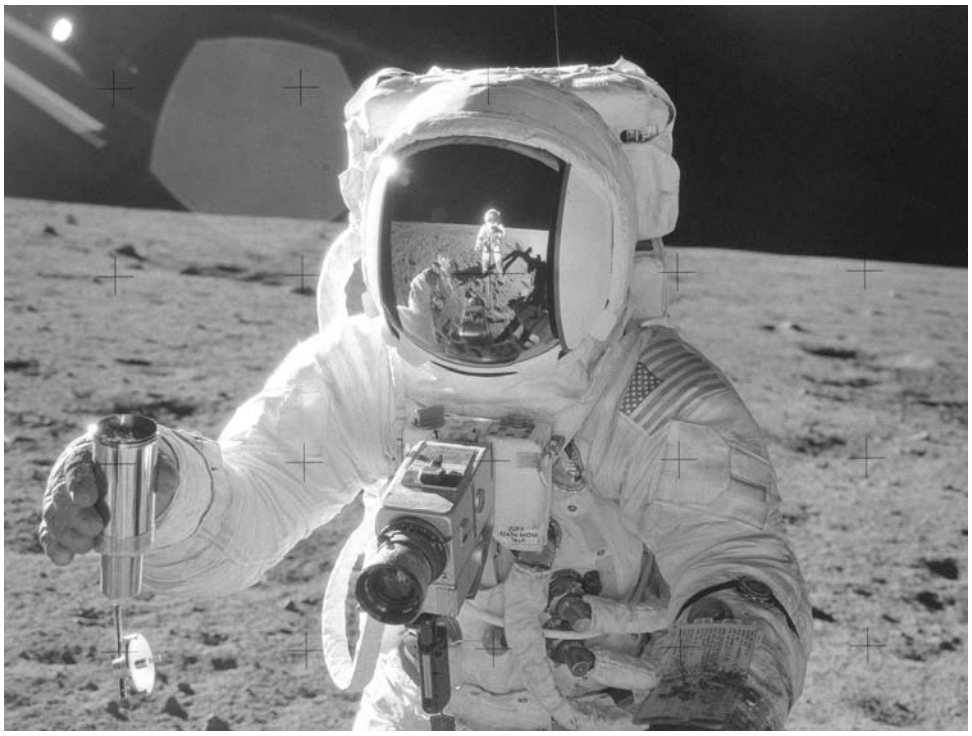
Even 36 years after the final Apollo mission, lunar sample research is active, with new techniques yielding new insights into the history of the Earth-Moon system. The Lunar curation team allocates samples on a regular basis to a large number of researchers. During 2007-2008, 401 samples were

allocated to 35 research groups and an additional 1200 samples were distributed for educational activities. Research is most prevalent using new kinds of analytical techniques that produce data not obtainable previously. This kind of research has contributed most directly to our understanding of the early history of the Moon, and to its formation as a result of the collision of the Earth with a Mars sized body shortly after accretion.

The upgrading of the Lunar Curation Facility has continued. A new liquid nitrogen tank and supporting system to supply clean gaseous nitrogen gas for the processing and storage cabinets were installed. This system replaced the 1979 original tank and an underground 2" supply line which was in danger of rupture from almost 30 years of tree root growth. New air handlers are in the process of replacement with completion expected in 2010.

Another milestone was the replacement of the 30 year old lunar database. The original database was tied to an obsolete VAX computer that was near failure and very outdated. The new database is a derivative of the original database, but has the advantage of being operated with desktop personal computers and can be accessed via the internet. Improvements to the database will continue including placing a searchable version of the database online for scientists to use in preparing lunar sample requests.

Apollo astronaut collection lunar soil



Antarctic Meteorites

Kevin Righter, Cecilia E. Satterwhite and Kathleen McBride

Meteorites are rocks from space that have fallen on Earth. Since 1976, the U.S. has sent yearly expeditions to Antarctica to recover meteorites. (Glacial movement concentrates meteorites on icefields near mountain ranges.) The Antarctic Meteorite Program is a collaboration between the National Science Foundation (NSF), the Smithsonian Institution (SI), and NASA in which NSF is responsible for collection and NASA and SI share curation duties. ARES' role is initial description, temporary storage, and distribution of samples to investigators. This is performed in a dedicated suite of class 1000 cleanrooms. The meteorites are eventually sent to the Smithsonian Institution for permanent storage after demand for an individual sample has decreased, but JSC curates over 4,000 specimens at any one time. The number of new samples collected by a single field team and delivered to JSC each year has ranged from approximately 200 to well over 1000, including meteorites from Mars and from the Moon. The collection currently includes ~ 17,000 samples, and includes pieces of the Moon, Mars, and asteroids.

Meteorite collecting in Antarctica

Cosmic Dust

Michael E. Zolensky and Jack L. Warren

Microscopic particles of comets and asteroids, captured by the Earth and suspended in the stratosphere, are collected by dedicated equipment on two NASA aircraft. The collectors are prepared at JSC, and returned to the JSC Cosmic Dust Laboratory, a class 100 cleanroom, where individual particles are retrieved, documented, and distributed to researchers. The Cosmic Dust program has operated since 1981.

NASA ER-2 at Dryden Flight Research Center, used for cosmic dust collections

Genesis — Solar Wind Sample Return

Judith H. Allton, Michael Calaway, Melissa Rodriguez, and Patti J. Burkett

Goals of the Genesis mission were to collect samples of the solar wind, return them to Earth and use these samples to accurately determine the composition of the Sun. The Sun contains 99.9% of the matter in the solar system. Scientists measure tiny differences between planets, comets, asteroids and interplanetary dust to reveal tantalizing hints about early solar system history, using primitive meteorite (CI chondrite) composition as a proxy measure for the original solar nebula. And now, with Genesis solar wind samples, all those tiny differences can be compared to the real thing! Emerging Genesis science results are challenging our views about conditions in the solar nebula – like the distribution of oxygen isotopes with distance from the Sun. Clues to solar system formation

are held in the Sun's isotopic composition of oxygen, Mg, Ca, Ti, Cr, and Ba. Clues to the evolution of planetary atmospheres are held in solar isotopic nitrogen, noble gases and carbon. ARES curation personnel are essential members of the Genesis Science Team, providing to the Science Team characterization of available samples, advice in sample selection, and cleaning and preparation of specimens.

Seeking the science… a tale of preparation and perseverance. Prior to launch, due to the extreme cleanliness required for assembly of the collector payload, the JSC Genesis team built two ultraclean ISO class 4 (Class 10) cleanrooms, NASA's cleanest laboratories for spacecraft assembly. The staff maintains this expertise in cleanroom operation and cleaning of spacecraft parts for flight using ultrapure water. After its August 2001 launch, the Genesis spacecraft began its journey sunward. In a stable orbit about 1 million miles on the sunward side of the Earth, collectors opened, "sunbathing" for two years, collecting atoms from the solar wind in very pure surfaces of silicon, gold, sapphire, diamond and other materials. The return to Earth in 2004 was more exciting than planned, as the parachutes failed to open and the capsule hit the ground hard. The recovery team placed the badly damaged spacecraft and samples in a temporary cleanroom at the landing site at the Utah Test and Training Range, where Science and Curation team members worked tirelessly for a month documenting, preserving and packaging samples for shipment to JSC. The very same Genesis ISO Class 4 cleanroom curation facility, in which the collectors were prepared for launch, now serves to curate the returned solar-wind-laden collectors. The solar wind samples are stored under nitrogen when not being examined with optical microscopes, an ellipsometer or the Fourier Transform Infra-Red spectrometer. These instruments are used to characterize the material, size and condition of the collector fragments. Ultrapure water and UV ozone are used for cleaning contamination from collectors. Samples are shaped to investigator requirements using a laser cutter. From 2004 to 2008, 1500 collector fragments, representing 18% of the total area have been cataloged and 350 samples allocated to investigators.

Michael Calaway, Melissa Rodriguez and P. J. Burkett characterize solar wind collector fragments in the Genesis Curation Facility, an ISO Class 4 cleanroom.

Stardust — Comet and Interstellar Sample Return

Michael E. Zolensky

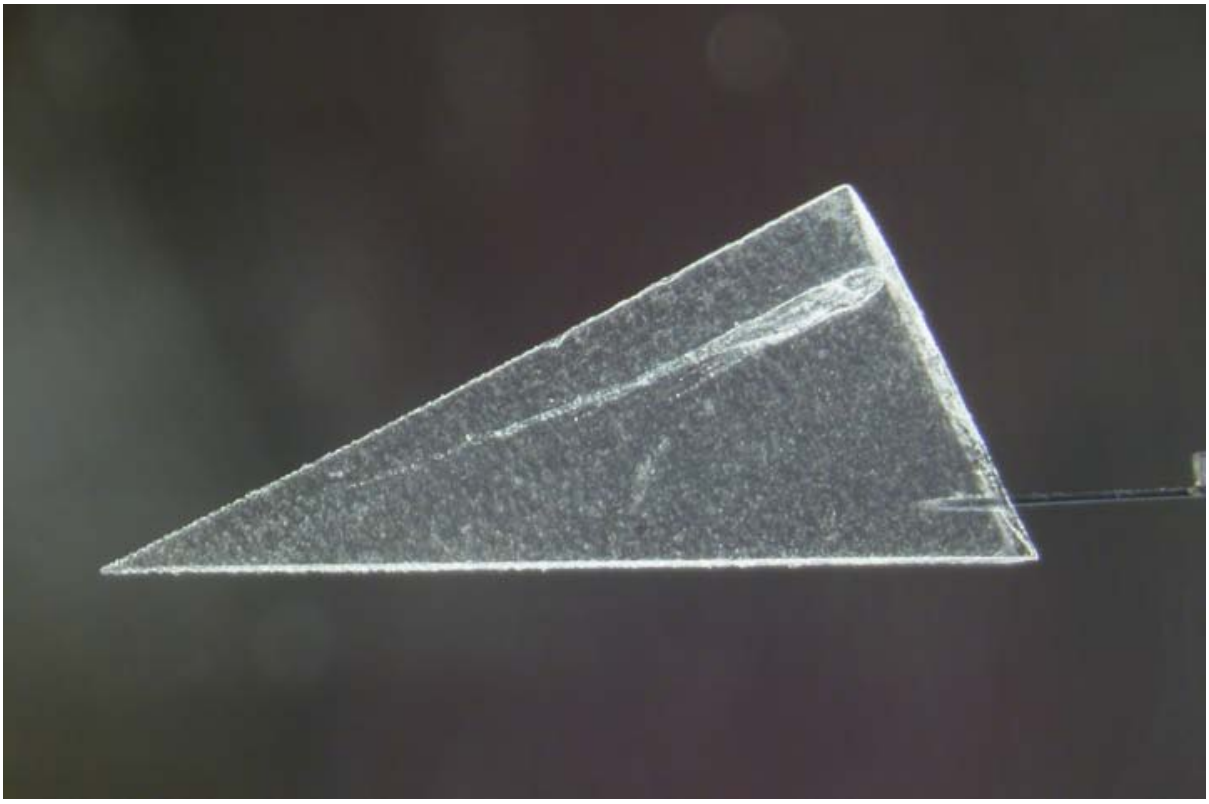
Comets are believed to be the oldest, most primitive bodies in the solar system, possibly comprised of some of the basic building blocks of life. They contain the remains of materials from the formation of stars and planets, holding volatile, carbon-based rich elements that are likely to provide clues about the nature of early solar system. Comets may have been the major source of water on the Earth, Mars and other worlds, making life possible.

With the prospect of comets offering this treasure house of ancient information, there is significant anticipation about what findings scientists will be able to extrapolate from a firsthand examination of cometary materials. Because the Stardust spacecraft has now returned samples of material from a comet's dusty coma, and provided real-time in-flight data about what it encountered, there is a real possibility of scientific findings that will change the way we view our origins.

The Stardust spacecraft was launched in February 1999. In January 2004, Stardust flew approximately 200 km in front of the nucleus of Comet Wild 2, through the halo of gases and dust. During this passage the spacecraft collected dust and volatiles. The comet samples are thought to consist of ancient pre-solar interstellar grains and nebular condensates that were incorporated into comets at the birth of the solar system.

The Stardust spacecraft returned to Earth in January 2006. Reentry and recovery were perfect, and the spacecraft and its precious samples were soon transported to the Curation labs at JSC. The Science Team and Curation Team worked diligently to prepare and analyze the comet particles, and the first scientific results were reported within two months. In 2007 and 2008 a total of 549 samples of comet dust was allocated to researchers around the world.

In addition to the cometary samples, the spacecraft also collected interstellar grains during the cruise phase of the mission. This material flows into our solar system in a great river of dust and gas. Analysis of this material will permit us to greatly expand our knowledge of the evolution of stars, the birth of the chemical elements, and the history of our galaxy. A dedicated effort is now underway to locate and identify the extremely small and rare interstellar grains.

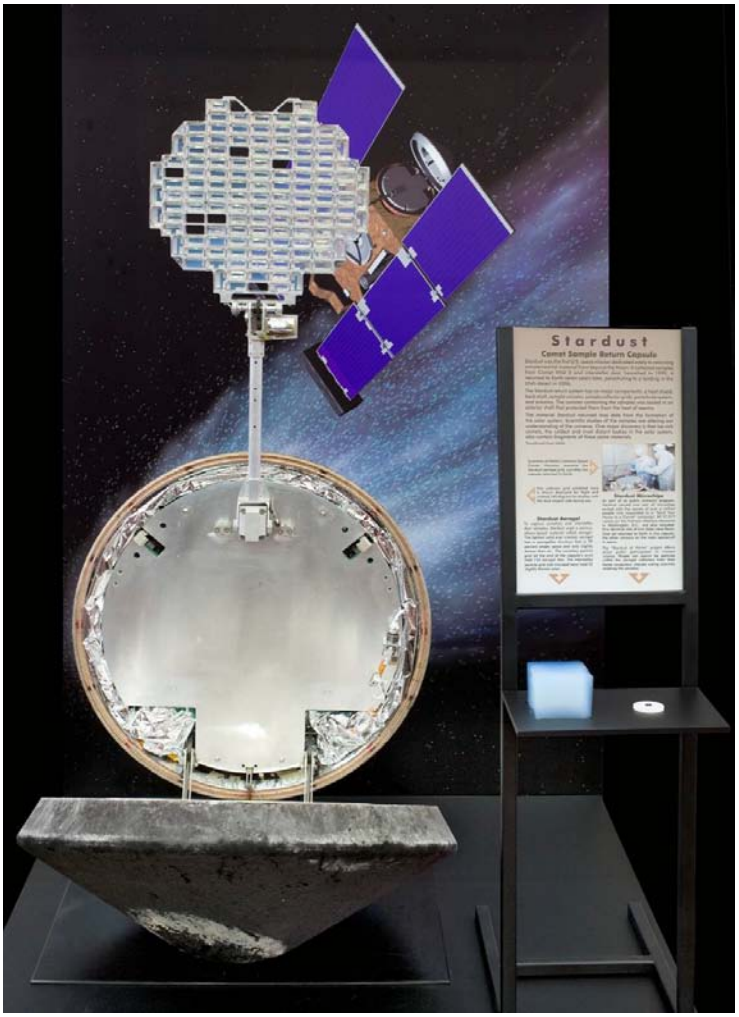


Stardust aerogel with the track of a comet dust particle

Space-Exposed Hardware

Michael E. Zolensky, Jack L. Warren, Thomas H. See, and Karen M. McNamara,

Since 1970, JSC has prepared and distributed a diverse collection of materials that have been exposed to the space environment. These have included pieces of the Surveyor 3 spacecraft returned by the Apollo 12 astronauts, the Long-Duration Exposure Facility, several commercial satellites retrieved by the Space Shuttle, materials from the Mir space station, and the Genesis solar wind sample return spacecraft. Documentation, sampling and storage of these materials is done in the new Space-Exposed Hardware Laboratory. The Stardust capsule, which was intensely studied in the JSC laboratory, was recently transferred to the National Air and Space Museum.



Stardust sample return capsule on display at the National Air and Space Museum

Hayabusa — Asteroid Sample Return

Michael E. Zolensky

The Hayabusa mission is the first sample return mission by Japan's space science agency, the Japanese Aerospace Exploration Agency (JAXA), and has been developed jointly with NASA and the Australian Academy of Sciences. The goal of the mission is to return regolith samples from the surface of a small near-Earth asteroid called Itokawa.

The spacecraft left Earth in May 2003, and rendezvoused with the near Earth asteroid in the summer of 2005. The entire spacecraft briefly touched down several times on the surface and attempted to collect samples, but the success of these efforts is unknown. In any case, on the order of 1g or less of regolith material may have been collected into a horn-shaped receptacle at one of the different sites.

In June 2010 the samples are due to be returned to Earth within a hermetically-sealed capsule, and flown to a laboratory in Japan for 1 year of preliminary investigation. Following this period the

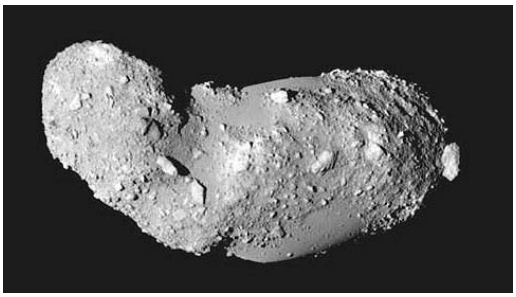
samples will be made widely available, with approximately 10% of the sample mass coming to JSC for curation and distribution. ARES scientist Michael Zolensky is a member of the Hayabusa Science Team and is involved in both sample curation and characterization of the target asteroid.

JAXA Sample Curation Facility in Sagamihara, Japan

Future Sample Return

Carlton C. Allen

The Curatorial team is preparing to curate the next generation of extraterrestrial samples. Missions have been proposed to sample previously unexplored areas on the Moon, several asteroids, and the surface of a comet. ARES is also involved in planning for post-mission sample handling and curation of samples returned by an international Mars mission as well as the future human exploration of the Moon.



Asteroids

Comets

Back to the Moon

On to Mars

Exploration Analog Missions

Mary Sue Bell

At the core of NASA's future space exploration is a return to the moon, and possibly to Mars and beyond. A sustainable long term human presence on the moon requires NASA to gain a deeper understanding of numerous system-wide and operational challenges that must be addressed to enable the joint human-robotic exploration of planetary surfaces. One method often employed in the development of hardware and operational scenarios involves testing concepts through field experimentation and demonstrations via analog missions and engineering evaluation and field tests. NASA has a history of analog missions and field tests, dating back to the Apollo era, that has advanced the development of mission hardware and operations. As it moves forward in the development of systems and operational concepts to accomplish the United States Space Exploration objectives, NASA will use a lunar analog strategy coordinated across the Agency to ensure the largest return on investment as possible.

NEEMO (NASA Extreme Environment Mission Operations)

During NASA Extreme Environment Mission Operations (NEEMO), a crew of six Aquanauts lives aboard the National Oceanic and Atmospheric Administration (NOAA) Aquarius Underwater Laboratory off Key Largo, Florida. The crew lives in saturation for a week to ten days and conducts a variety of undersea "moon walks" to test a suite of long-duration spaceflight medical objectives as well as concepts for future lunar exploration using advanced navigation and communication equipment in support of the Constellation Program planetary exploration analog studies. ARES

Curation personnel from JSC support the effort to produce a high-fidelity test-bed for studies of human planetary exploration and sample curation models including remote robotic sample collection, documentation and manipulation. During NEEMO 12 (2008), the world's first underwater geodetic marker was installed and surveyed by the US Geodetic Survey at the site of NOAA's Aquarius habitat - a concept conceived by ARES personnel to commemorate the continuing partnership between NASA and NOAA to conduct research and exploration in extreme environments.

Mary Sue Bell remotely operates a micromanipulator in the Aquarius habitat 62 feet below the sea off Key Largo, Florida from a surface laboratory during NEEMO 12 to demonstrate sample handling techniques that could be used by scientists on Earth to manipulate samples in a Lunar base laboratory.

NOAA Deputy Assistant Secretary for Oceans and Atmosphere Tim Keeney and Mary Sue Bell, Ph.D. scientist in ARES Curation holding the first undersea geodetic survey marker before its installation on the reef in the Florida Keys National Marine Sanctuary to commemorate the continuing cooperation of NASA and NOAA in exploration of extreme environments.

MARTE (Mars Astrobiology Research and Technology Experiment)

The MARTE project, an ASTEP field experiment, is exploring for a hypothesized subsurface anaerobic chemoautotrophic biosphere in the region of the Tinto River- or Rio Tinto- in southwestern Spain. Members of the MARTE Science team included ARES Curation personnel to help develop drilling, sample handling, and instrument technologies relevant to searching for life in the Martian subsurface, and demonstrate them in a field test at a site with a Mars-analog subsurface biosphere on Earth. The Mars drilling mission simulation included interpretation of drill mission results by a remote science team in a blind test. The MARTE robotic drilling mission was augmented by additional ground truth with a team in the field utilizing more conventional methods for drilling, sample handling, and laboratory analysis to explore for a subsurface biosphere at the field site. This field experiment serves as a good analog for the activities of a human crew on Mars

drilling in search of a subsurface biosphere. The MARTE project achieves exploration of an uncharacterized underground ecosystem of key relevance to Astrobiology and the search for life on Mars, while also developing and demonstrating technology needed in the next phase of Mars exploration.

The Rio Tinto mine, Spain is a massive sulphide deposit that has been continually operated for two thousand years. Water percolating through deposits like those at Rio Tinto create acidic environments so extreme that few organisms can tolerate such conditions. Conditions on Mars may be similar to the Rio Tinto and one might expect similar types of inhabitants to be present.

Human Exploration Science Office (KX)

Douglas W. Ming, Ph.D., Manager

The Human Exploration Science Office provides support for human spaceflight and conducts world-class research and technology development in the areas of space orbital debris, hypervelocity impact technology, image science and analysis, crew earth observations, and human and robotic exploration science.

NASA's Orbital Debris Program Office (ODPO) is housed in the Human Exploration Science Office. The ODPO provides leadership in orbital debris research, including the development of national and international space policy on orbital debris. The office is recognized internationally for research on measurements and modeling of the Earth's orbital debris environment.

The Hypervelocity Impact Technology (HVIT) project provides evaluation of the risks to spacecraft posed by micro-meteoroid and orbital debris (MMOD) impacts through laboratory testing and software modeling predictions. Research and technology development programs are underway to develop shielding to protect humans from MMOD during spaceflight missions. The project contributes to the safety of the crew on human spaceflight missions by identifying MMOD risks for each mission. Advanced shielding designs are being evaluated for future missions, including the Orion spacecraft.

NASA's Image Science and Analysis Group (ISAG) provides near, real-time imagery analysis of spacecraft flight (Shuttle, ISS, Hubble Space Telescope) to assess vehicle performance, debris shedding, and anomalies. Image analysis protocols are currently being developed to evaluate the performance and anomalies for future spacecraft, i.e., Orion. The Crew Earth Observations (CEO) payload onboard the ISS is a function of the ISAG. Earth imagery acquired by astronauts is catalogued and made available to the public through a web-based access site. ISAG scientists conduct research on the interpretation of the CEO imagery.

Human exploration science focuses on science strategies for future human exploration missions to the Moon, Mars, asteroids, and beyond. This function provides communication and coordination between the science community and mission planners in the Constellation Program. ARES scientists continue to support the operation of Mars robotic missions (i.e., Mars Exploration Rovers, Mars Phoenix Scout, Mars Science Laboratory) and contribute to the interpretation of data returned by these voyagers to the Red Planet.

Reports on several projects are given in the following pages.

Active Debris Removal – the Ultimate Solution to Preserve the Near-Earth Space for Future Generations

J.-C. Liou

The growth of the orbital debris population has been a concern to the international space community for decades. Many policies and procedures have been established to address the issue. A good example is the adoption of the space debris mitigation guidelines by the United Nations in 2007. However, recent numerical studies have shown that the debris environment in low Earth orbit (LEO, defined as the region up to a 2000 km altitude) has reached a point where the debris population will continue to increase, due to mutual collisions among existing objects, even if all future launches are suspended. In reality, the population increase will be worse than the "no future launches" prediction because satellite launches will continue and major breakup events, such as Fengyun-1C (FY-1C), Briz-M, and the collision between Iridium 33 and Cosmos 2251 may continue to occur. Even fully implementing the commonly adopted mitigation measures cannot stop the LEO population growth. To better preserve the near-Earth environment for future space generations, additional remediation measures, such as active debris removal (ADR), must be considered.

The NASA Orbital Debris Program Office initiated the ADR modeling study in late 2006 with a first effort focused on target selection criteria. Using a non-mitigation (sometimes referred to as the business-as-usual) scenario as the baseline for comparison, the study's main conclusion was that the product of the mass and collision probability of each object was an excellent removal selection criterion. Numerical simulations based on this criterion showed most objects in the critical inclination and altitude regimes had been identified and removed, and the LEO debris population growth, using the non-mitigation scenario as a benchmark, was significantly reduced. A second study completed in 2008 added the tracked FY-1C fragments to the initial environment for future projection and implemented a more realistic scenario based on the commonly adopted postmission disposal (PMD) mitigation measures for future launches. The second study's focus was to identify what would be needed to stabilize or even reduce the future LEO debris population.

The simulations were carried out using the NASA long-term orbital debris projection model, LEGEND. A scenario where, at the end of mission lifetimes, spacecraft and upper stages were moved to 25-year decay orbits (assuming a 90% success rate), was adopted as the baseline environment for comparison. Two annual removal rates and different ADR target selection criteria were tested, and the resulting 200-year future environment projections were compared with the baseline scenario. One hundred Monte Carlo (MC) simulations were completed for each scenario, and the averages were calculated for comparison. Figure 1 shows the main study results. The top curve is the projection for the 10 cm and larger objects in LEO. Even with a good implementation of the PMD mitigation measures, the population will still increase by about 75% in 200 years. However, a removal rate of 2 objects per year, starting from the year 2020, could reduce this population growth by half. In addition, the bottom curve indicates a removal rate of 5 objects per year could stabilize the future LEO environment. The trend also suggests that removing more than

5 objects per year could actually lower the future LEO debris population below what is in the current environment.

As the international space community working together to limit the generation of orbital debris, a more aggressive approach, active debris removal, must be seriously considered to remediate the environment. Based on the study results, ADR is an effective means to stabilize, or even reduce, the future LEO debris population. A combination of mitigation measures and active debris removal appears to be the only way to preserve the near-Earth environment. However, there are still many challenges ahead, such as performing detailed cost analyses, developing new ADR policies or guidelines in conjunction with developing viable removal techniques, identifying the source of funding needs, and addressing legal and liability issues.

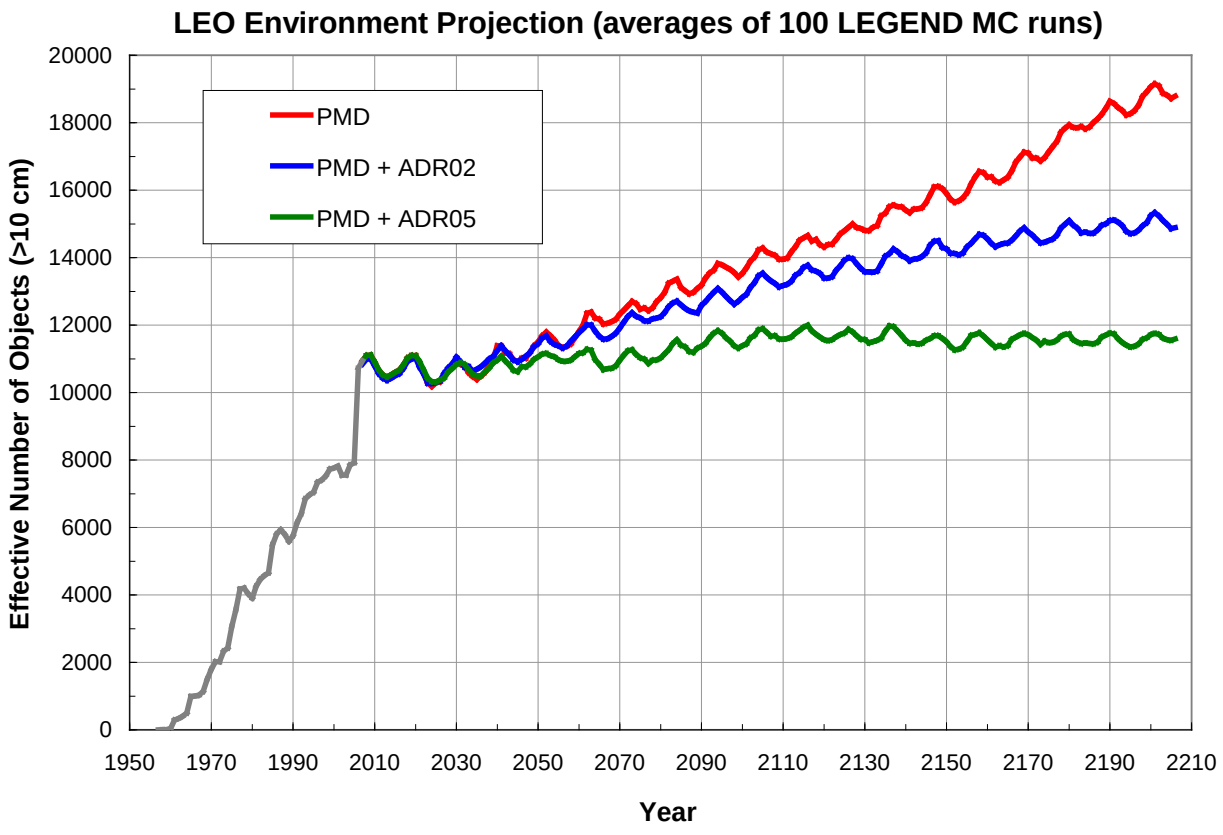


Figure 1.– Comparison of 3 different scenarios. From top to bottom: postmission disposal (PMD) only, PMD and ADR of 2 objects per year, and PMD and ADR of 5 objects per year, respectively.

Improving Access to Astronaut Photography Through Google Earth

William L. Stefanov

Images acquired by the ISS crew are downlinked to Johnson Space Center and delivered to the Crew Earth Observations team for geolocation and addition to the digital astronaut photography database. Descriptive metadata is generated, and together with the camera metadata for each frame, the image is added to a searchable online database - The Gateway to Astronaut Photography of Earth, http://eol.jsc.nasa.gov. This database is a highly valuable resource of historical and current imagery for researchers, government and nonprofit entities, planning and environmental professionals, educators and the general public in both developed and developing countries.

Through a collaborative team comprised of Ames Research Center, the Image Science & Analysis Laboratory, and Goddard Space Flight Center, selected astronaut photographs and descriptive content were included as a key component of the NASA content layer in the free geospatial browser Google Earth (http://earth.google.com). Initially released in 2007, astronaut photography comprises a distinct layer within the NASA grouping in Google Earth and is periodically updated with new content. Cataloged imagery in the Gateway to Astronaut Photography of Earth can also be viewed within the Google Earth environment using on-the-fly .kml file generation.

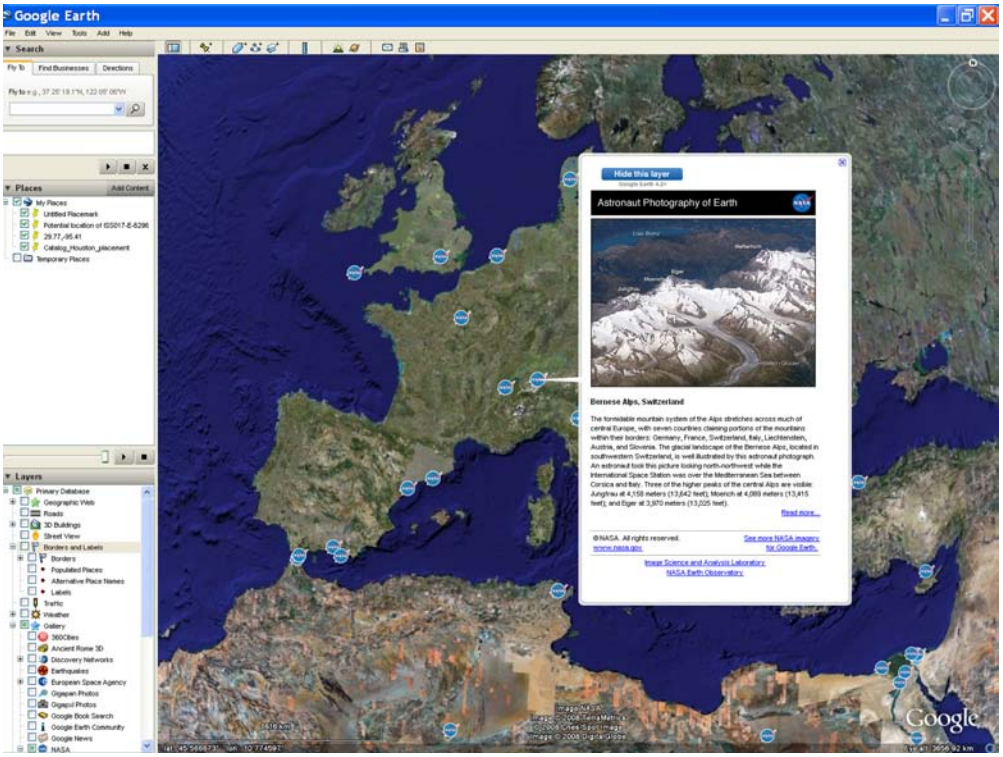


Figure 1.– Screen capture of Europe in Google Earth with the astronaut photography layer selected. NASA logos indicate locations of image content. One such content item—an image of the Bernese Alps in Switzerland—has been opened.

Geospatial browsers such as Google Earth are powerful tools for virtual geographic and geologic education. The ability of users to add geolocated placemarks and embed additional content such as images and html links, greatly enhances the potential for interactive geoscience education. A Google Earth-based series of geographic briefing modules have been developed by the Image Science & Analysis Laboratory for use in training International Space Station astronauts in recognition of major terrestrial features and landforms from low earth orbit. The modules are designed to accommodate both instructor-driven presentation and automated flyover tour modes and include direct query links to the online digital database of astronaut photographs of Earth.

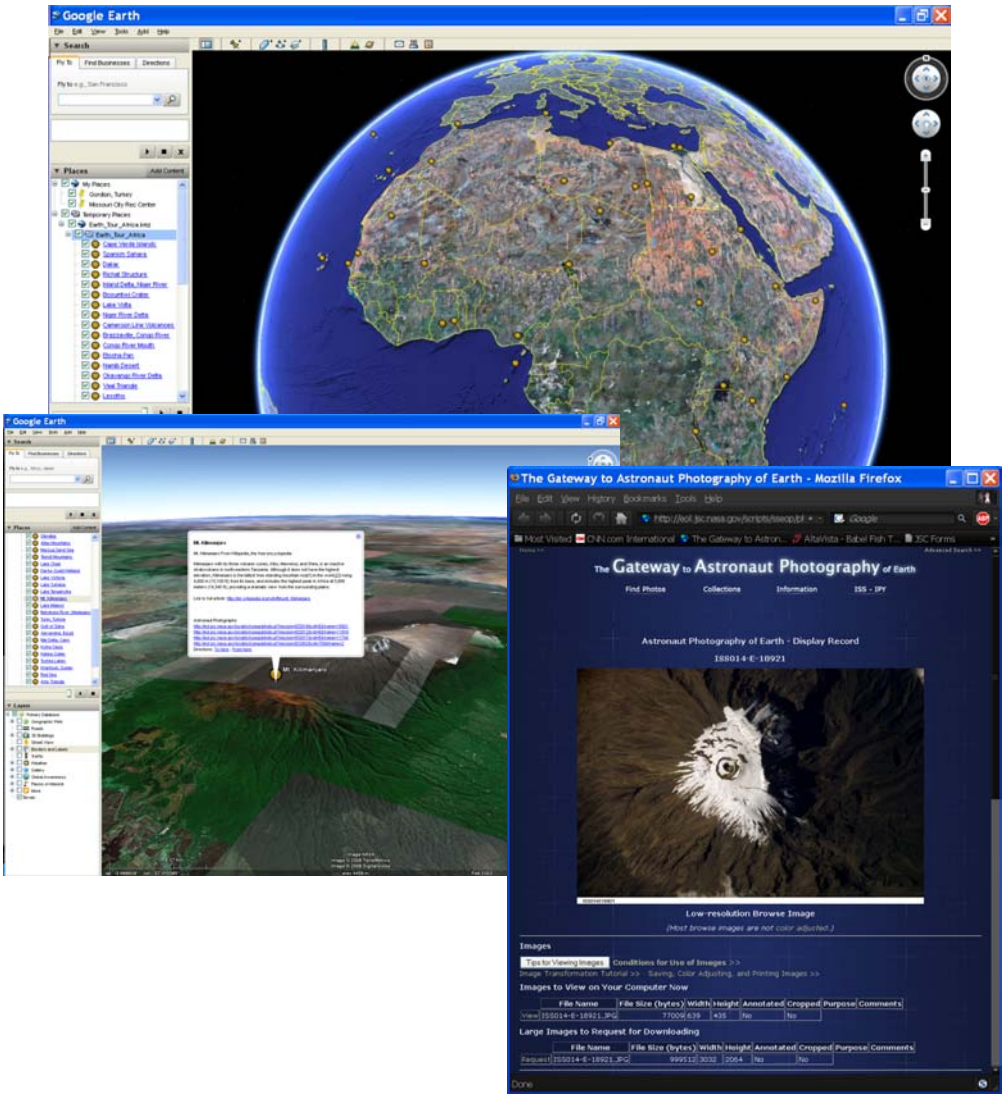


Figure 2.– Google Earth and the astronaut photography database make an effective tool for teaching general geography. This example from the Africa training module (top) illustrates the training entry for Mount Kilimanjaro (center), and a database entry page accessed through active links in Google Earth (bottom).

This direct query functionality provides a wealth of seasonal and multi-resolution imagery of selected locations that augments available Google Earth imagery, and is a useful data resource for more detailed geomorphology, structural geology, oceanography and ecology education. The training modules are presented to astronauts with a wide range of geographic knowledge, simulating exposure to a broad range of class levels. All components of the modules (Google Earth, Wikipedia, and the Gateway to Astronaut Photography of Earth) are freely available on the Internet, making this a robust and attractive approach to improving terrestrial geographic literacy. In addition, use of astronaut-acquired remotely sensed data for geoscience education - particularly K-12 - enhances interest in human space exploration and STEM career paths.

Investigation of Shuttle Radiator Micro-Meteoroid & Orbital Debris Damage

D. Lear, E. Christiansen, J. Hyde, J. Herrin, J. Kerr, F. Lyons, & S. Ryan

The space shuttle orbiter windows, radiators, wing leading edge, and nose cap are inspected for micro-meteoroid and orbital debris (MMOD) impact damage after each mission Over the past 125 missions, hundreds of MMOD impacts have been documented. The damage is measured and samples are obtained from the impact site to determine the likely impactor source (i.e., meteoroid or orbital debris), size of impactor, and impact velocity/direction. The impact samples are subjected to scanning electron microscope (SEM) energy dispersive spectroscopy (EDS) to determine elemental composition of impact debris. Hypervelocity impact (HVI) testing and the BUMPER-II MMOD risk analysis program are used to assess the size of the impactor and to compare actual to predicted damage. This article highlights the two largest shuttle radiator impacts observed to date, which occurred on STS-115 and STS-118.

Following the STS-115 mission of Atlantis in September 2006, an impact damage was observed on the aft right-hand side radiator aluminum honeycomb panel (figure 1). This was the largest of five total radiator MMOD impacts observed on this mission. The impact caused an entry hole of 3.2 mm x 2.7 mm (figures 2 and 3), delaminated a 22 mm by 28 mm region of the outer facesheet, destroyed or damaged approximately 31 of the internal honeycomb cells spanning 22 mm x 28 mm, and punched through the rear facesheet leaving a 0.79 mm diameter hole with a 6.8 mm long crack bulging 5 mm (figure 4). Based on impactor residue analysis and HVI testing, it is believed that the impactor was orbital debris, and consisted of a small fragment of fiberglass-epoxy electronic circuit board measuring approximately 1.25 mm in diameter. Figure 5 shows a SEM image of a fragment of the circuit board impactor taken from the impact residue sample. Based on BUMPER-II risk analysis results, the chance of a particle this size and larger impacting the radiators during a representative 12-day mission is 1.6%.

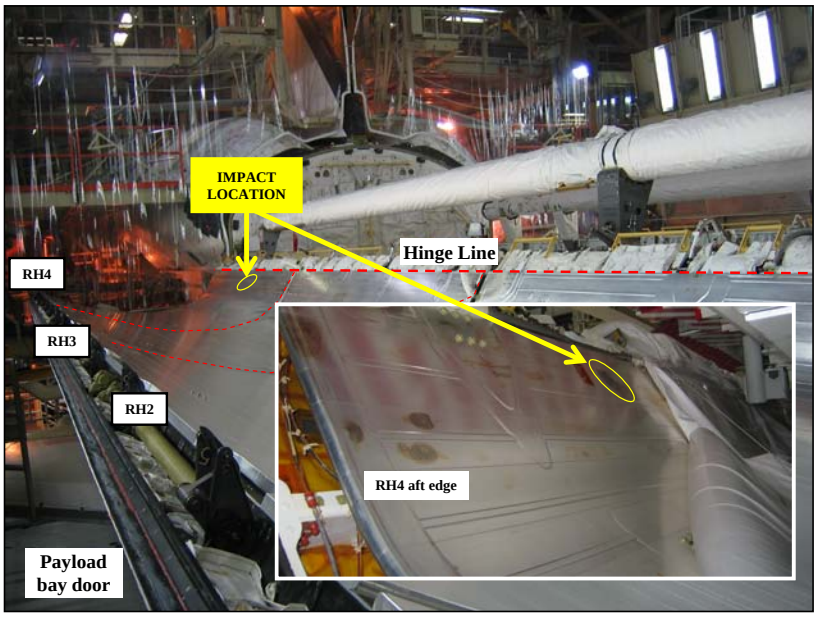


Figure 1.– STS-115 aft right-hand radiator panel impact location

Figure 2.– STS-115 radiator impact entry hole

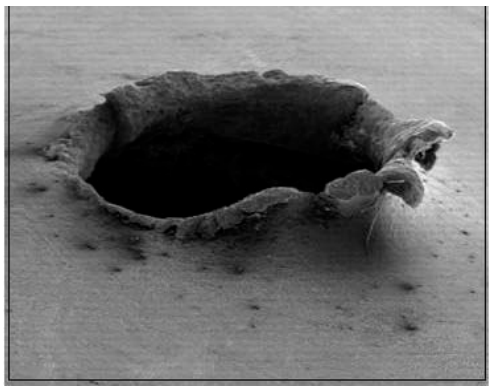


Figure 3.– STS-115 radiator entry hole side view using SEM

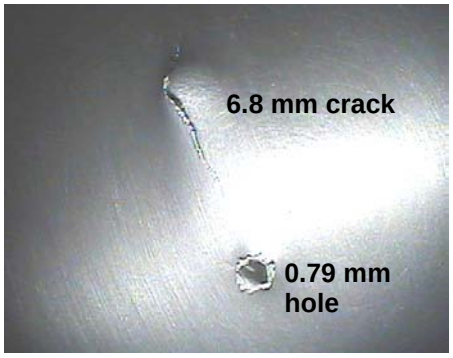


Figure 4.– STS-115 rear facesheet damage showing exit hole, crack, and bulge

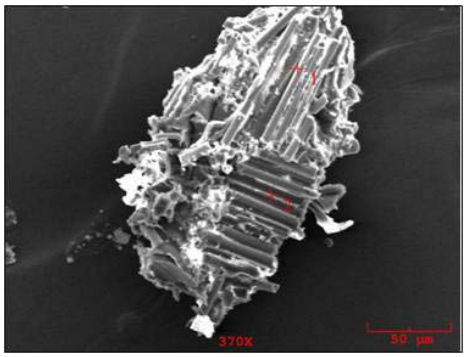


Figure 5.– STS-115 debris impactor fragment (circuit board)

An even larger radiator damage occurred to Endeavour during the STS-118 mission in August 2007. The impact occurred on the aft left-hand radiator aluminum honeycomb panel (figure 6), and was one of eleven radiator impacts on this mission. This impact penetrated completely through the radiator aluminum honeycomb panel, underlying thermal blanket, and left impact residue on the radiator door structure. The impact caused an outer facesheet entry hole of 5.5 mm diameter (figure 7), damaged or destroyed approximately 20 internal honeycomb cells, blew out the rear facesheet with a jagged hole measuring 19 mm by 12 mm (figure 8), then punched two holes 75 mm apart in the thermal blanket located 12.5 cm behind the rear facesheet (figure 9) and deposited residue on the graphite-epoxy payload bay door structure (figure 10). Based on impactor residue analysis and HVI testing, the impactor appears to have been a titanium-rich orbital debris particle containing traces of zinc and antimony and measured approximately 1.5 mm in diameter. Based on BUMPER-II results, the chance of a particle this size and larger impacting the radiators during a representative 12-day mission is 0.4%.

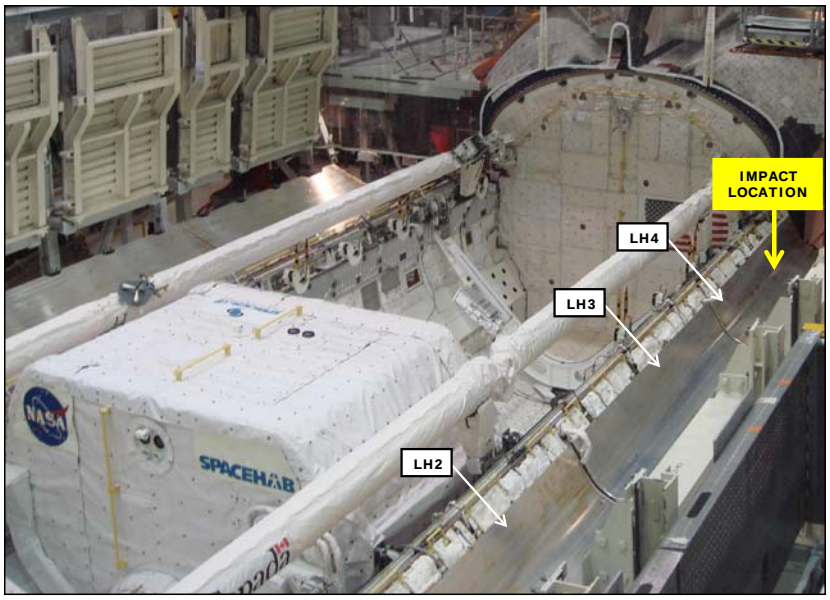


Figure 6.– STS-118 aft left hand radiator panel impact location

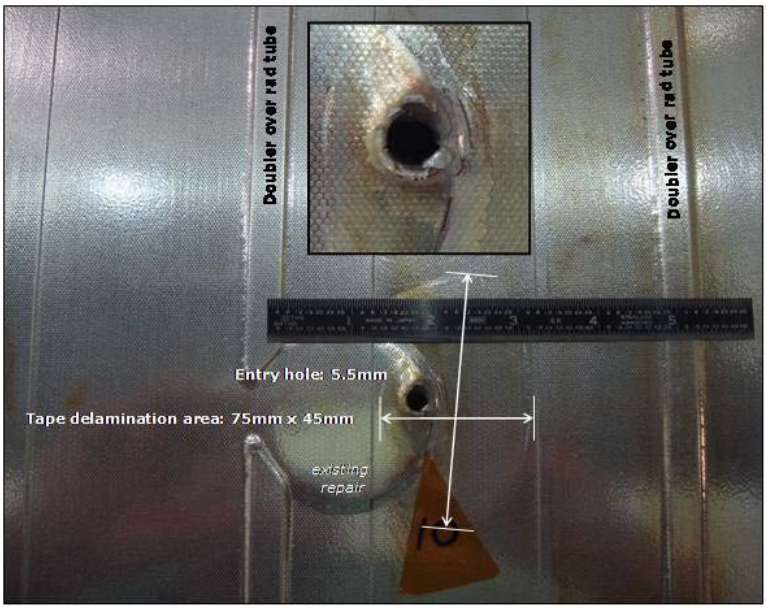


Figure 7.– STS-118 radiator impact entry hole

Figure 8.– STS-118 rear facesheet damage showing exit hole

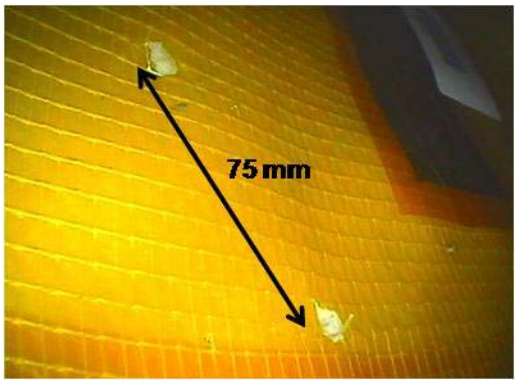


Figure 9.– STS-118 radiator thermal blanket holes

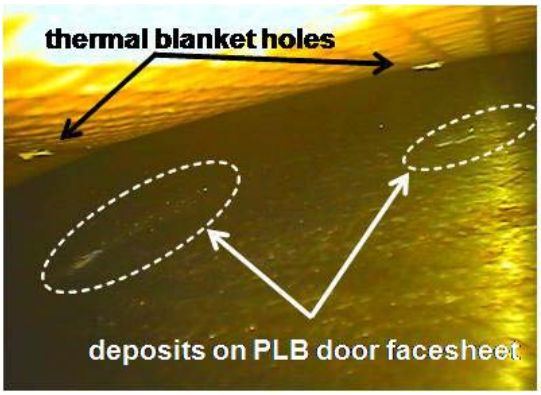


Figure 10.– STS-118 payload bay door graphite-epoxy structure showing thermal blanket holes and impactor particulate

After the Columbia accident, NASA implemented an alternate Space Station docking attitude strategy for the shuttle. With the intent of protecting the lower surfaces of the wing leading edge reinforced carbon-carbon (RCC) panels from MMOD damage, the shuttle/station stack is now rotated 180° about the station yaw axis (figure 11). While significantly reducing the loss of crew/vehicle risk while docked to station, the change from a “belly forward” attitude to a “belly aft” attitude orients the payload bay door radiators more directly into the orbital debris flux. This contributes to a higher impact risk for the upper surfaces of the vehicle including the radiators.

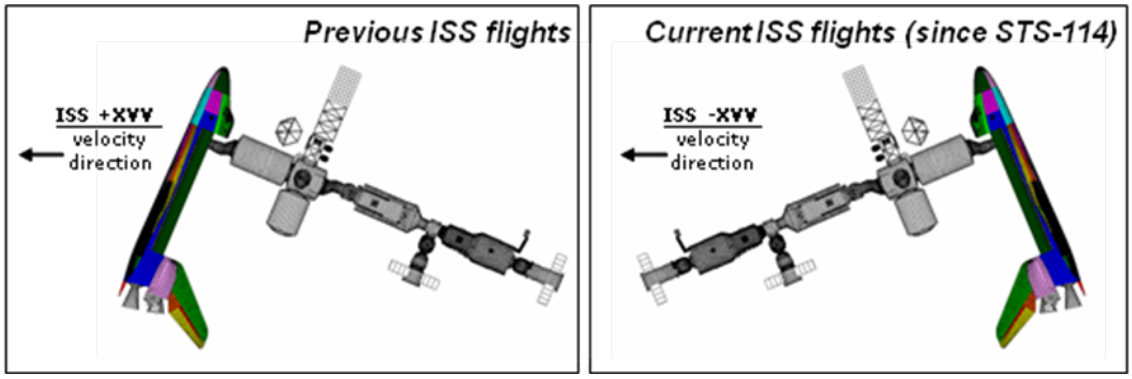


Figure 11.– Shuttle-ISS flight orientations before and after STS-114

The MMOD critical failure criteria for the orbiter wing leading edge and nose cap were updated for BUMPER-II flight readiness review risk assessments performed on STS-114 and subsequent missions after testing and analysis indicated that certain areas were more sensitive to hypervelocity impact damage. The highlighted red, orange, yellow and light green areas in figure 12 would have experienced critical damage if impacted by either the STS-115 or STS-118 radiator orbital debris particles. The damage taken to the radiators on flights STS-115 and STS-118 were both low-probability events, but occurred where we predicted the damage would occur if it happened and where we wanted the damage to occur (i.e., to non-critical surfaces), We believe that the vehicle orientation change made since STS-114 in turning the ISS-Shuttle stack backwards after dock has been very beneficial in improving crew safety by reducing serious MMOD damage to sensitive underside surfaces of the wing leading edge and nose cap.

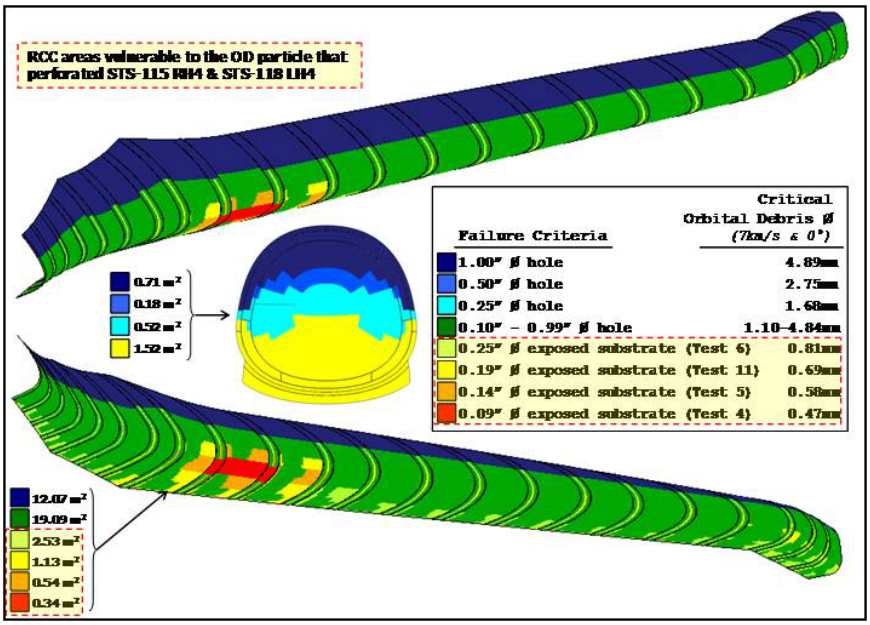


Figure 12.– MMOD loss-of-vehicle failure criteria for the wing leading edge and nose cap (Note that non-penetrating damage represented by red, orange, yellow and light-green colors are concentrated on lower surfaces of the wing leading edge and nose cap; various size through-holes are allowed in blue and dark-green areas)

Image Science Support of Constellation

Tracy Calhoun

The Image Science and Analysis Group (IS&AG) has provided image analysis services to the Shuttle and International Space Station (ISS) Programs for over two decades. This past year, IS&AG widened its customer base to include the Constellation (Cx) Program. The relationship between IS&AG and Cx is especially notable as it is the first time that engineering imagery has been consistently factored into a new vehicle's design and testing. Traditionally, vehicle imaging systems have been developed with public affairs as the key driver. While this type of imagery is vital for extending the spaceflight experience to the public, flight operations have evolved to depend heavily upon engineering imagery as a data source. The growing collaboration between Cx and IS&AG during vehicle development is a notable transition for the agency.

IS&AG supported Cx in 2008 with a wide range of services, from the development of imaging concepts and requirements to the analysis of imagery acquired during lab tests and flight tests.

Orion Window Photography Testing

Orion underwent a review that focused on vehicle mass, resulting in a window redesign that changed the glass pressure pane to a polycarbonate pane. As part of the polycarbonate evaluation, IS&AG was tasked to obtain and compare engineering photography through various Orion window configurations. Test photography using Orion window mockups and Shuttle window mockups revealed that a polycarbonate pressure pane will not support engineering image analysis photography using long focal length (400mm) lenses. The test did however reveal that window panes made of acrylic appear to have an optical quality comparable to the current Shuttle windows and could support long focal length photography. These findings served as the basis for an Orion Project directive to change the pressure pane material from polycarbonate to acrylic, with further acrylic testing planned in 2009.

Figure 1.– IS&AG and Engineering Directorate personnel conduct Orion window photography tests.

Imagery Analysis in Support of Flight Tests

IS&AG is supporting several flight test teams devoted to the field testing of vehicle and launch systems. The CEV Parachute Assembly System (CPAS) Cluster Development Test-2 (CDT-2) conducted at Yuma Proving Ground in July 2008 was the first parachute test supported by IS&AG. Ground tracking video of the test article, which experienced a failure of the programmer chute, was utilized to extract attitude and oscillation data in addition to building a failure event timeline.

Two upcoming test flights, Ares 1-X and Pad Abort-1 (PA-1) will also be supported by IS&AG. All ground and vehicle based video acquired during Ares 1-X will undergo screening and analysis using the techniques and tools utilized for each Shuttle launch. In addition to extracting vehicle performance information, Ares 1-X will afford the opportunity to assess how well the IS&AG

Shuttle processes and laboratory facilities support Ares. All PA-1 ground tracking camera imagery will be analyzed by IS&AG to compute attitude data and to assess system performance.

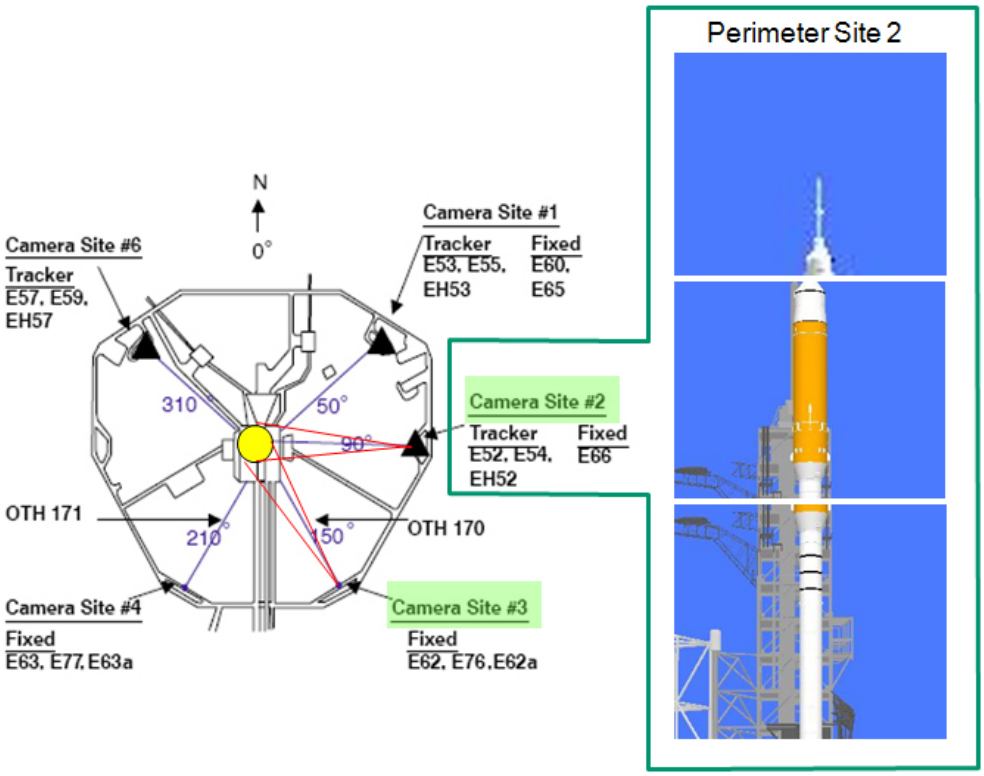


Figure 2.– An example of launch site camera planning for Ares 1-X.

Orion Thermal Protection System Inspection Capability Studies

IS&AG has extensive experience with on-orbit vehicle inspection using sensors and cameras to detect and measure structural damage from launch debris and on-orbit debris, referred to as micro meteoroid orbital debris (MMOD). The group's vehicle inspection skill set that was developed and honed for Shuttle is now being applied to Orion. Block 1 missions to ISS will require Orion to be docked to ISS for months, exposing the thermal protection system (TPS) to potential MMOD damage. A verification of TPS integrity prior to reentry will be necessary.

An IS&AG study revealed that existing ISS imaging resources are capable of detecting a surface feature that could be indicative of damage to the Orion TPS (assuming the currently predicted damage criteria). The group is now performing studies to identify an appropriate method of characterizing a tile cavity. 3D sensors from Shuttle are under evaluation as are new technologies currently in development. Additionally, photogrammetry techniques that extract depth data from multiple images obtained with a conventional 2D camera continue to be refined and considered. While imaging tools and techniques can readily be implemented while Orion is docked to ISS, the team is also considering how TPS inspection can be performed on Lunar missions that do not have the convenience of ISS resources.

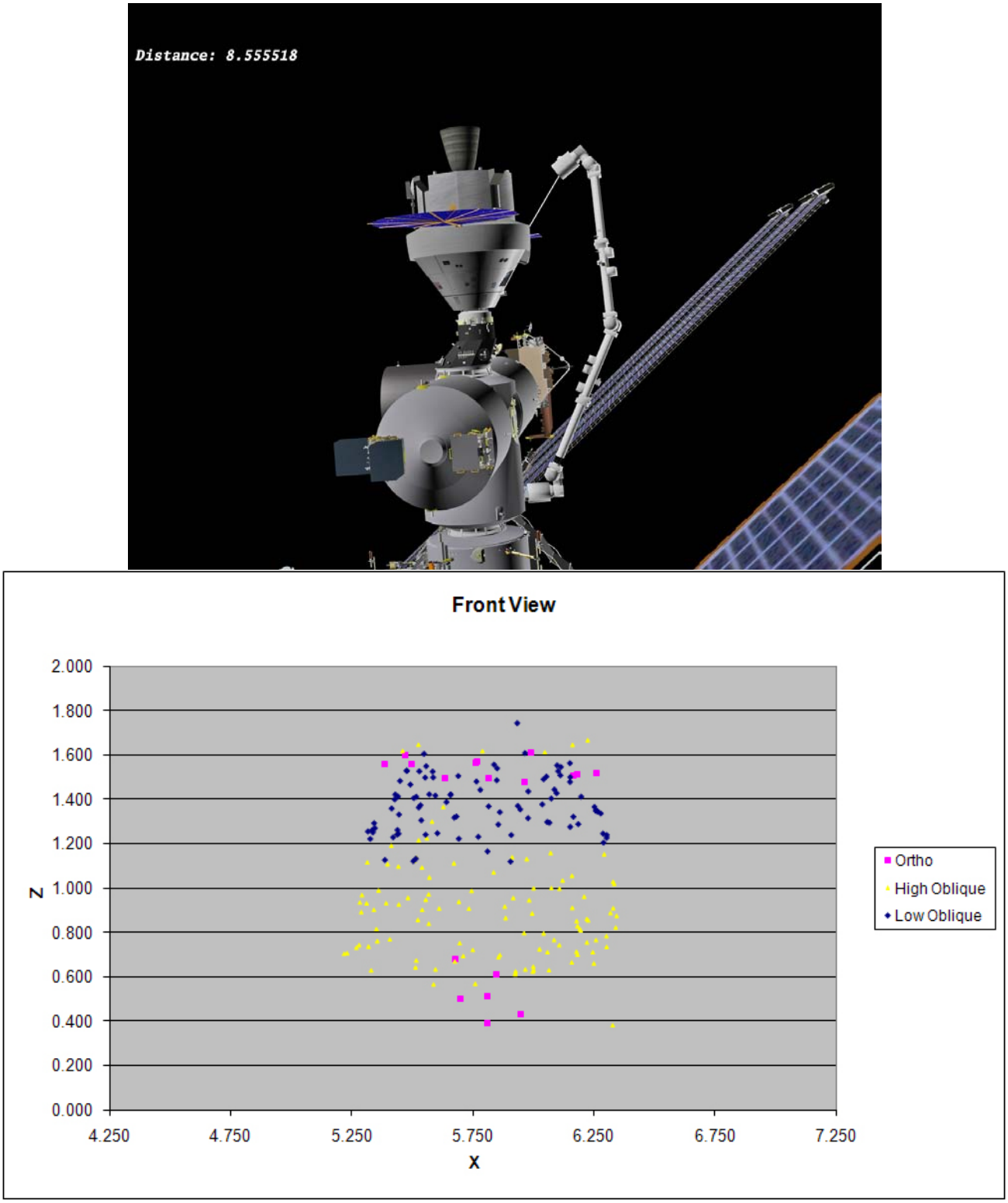


Figure 3.– An illustration of Orion inspection for TPS damage while docked to ISS Node 2 (top). 3D Orion tile cavity characterization using multiple images from a 2D sensor. The pink points map the periphery of the entry hole and the bottom of the cavity. The yellow points map the lower extent of the sides of the cavity (bottom).

Justin Wilkinson

Megafans are a new feature of geomorphic study, the significance of which was first revealed by astronaut handheld imagery. Research based on the first global study of these features has resulted in the following diverse research in the last two years.

Megafans as a New Explanation for Martian Landscapes of Sinus Meridiani

Explanations for the enigmatic geology of Sinus Meridiani—where the rover *Opportunity* still operates—are dominated by the common but restricted view that river channels only form in hilly country—i.e. channels are always confined within valley walls. Numerous megafans around the world show the following features that closely parallel Meridiani landscapes: (i) networks of stream channels which (ii) occupy vast plains, with (iii) the channels forming more resistant elements in the landscape (resulting in the classic sinuous "inverted" ridges of terrestrial and Martian landscapes). Libyan landscapes even show the detail of sinuous ridges interacting with circular craters, our most persuasive analog yet for the Meridiani Plains.

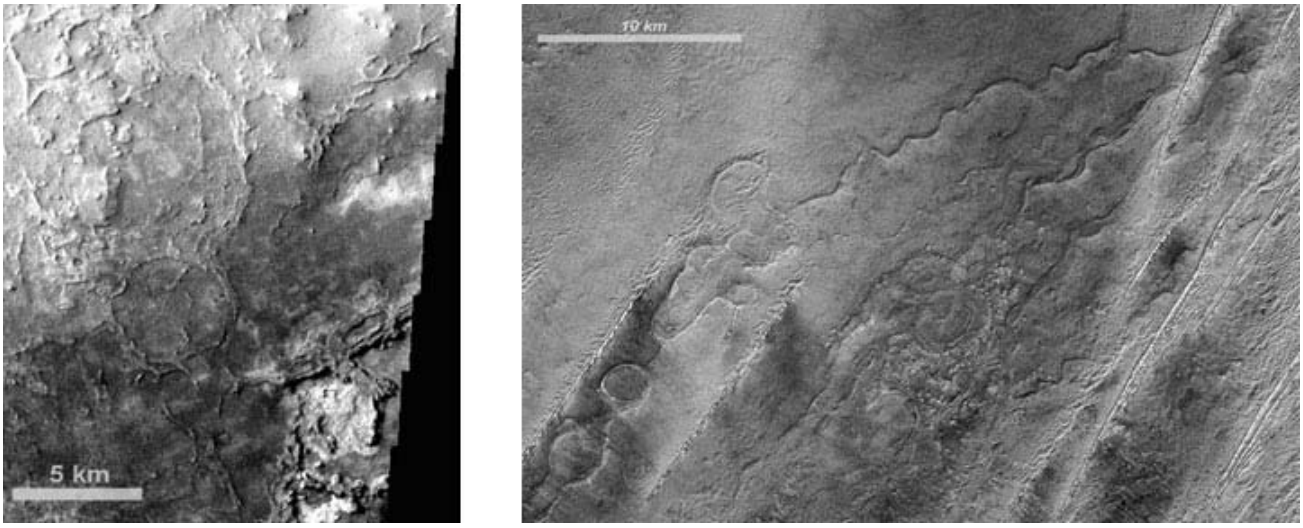


Figure 1.– Sinuous and partly circular (crater) features, Sinus Meridiani (top). Craters with indurated rims and numerous stream channels (flow direction is NE—towards top right), Libyan Sahara (bottom).

Megafans as a New Explanation for Kalahari Desert Landscapes of South-Central Africa

Maps of a series of megafans of the Kalahari basin provide a fundamental shift in understanding landscape evolution, biological evolution and water resources of the arid central Kalahari basin. A newly identified megafan on which the large Okavango River flowed alternately southward—into a basin in northern Namibia—and eastward, to the modern Okavango megafan hundreds of km downstream in northern Botswana. Paleontological data shows that this alternation operated until ~6 Ma when the Okavango River incised into the new fan, thereby causing the drying up of paleo-lake

Etosha. This drying has been ascribed to climate change, but likely relates to activity on faults of the Okavango Rift. Three geological publications have incorporated these new perspectives.

Megafans as a New Explanation for the Evolution of Modern Amazon Landscapes

Maps based on Mars topographic roughness algorithms were generated for South America. These reveal that (i) the very widespread megafan plains of Argentina likely extended far to the north and explain much of modern Amazonia in the later Neogene. (ii) Earlier work argued that megafans can act as *species pumps* for aquatic fauna aquatic fauna. Applying these arguments to Amazonia, we argue that paleo-megafans could well explain some of the fish biodiversity of western Amazonia where many species occupy the "megafan zone" against the Andes Mts.

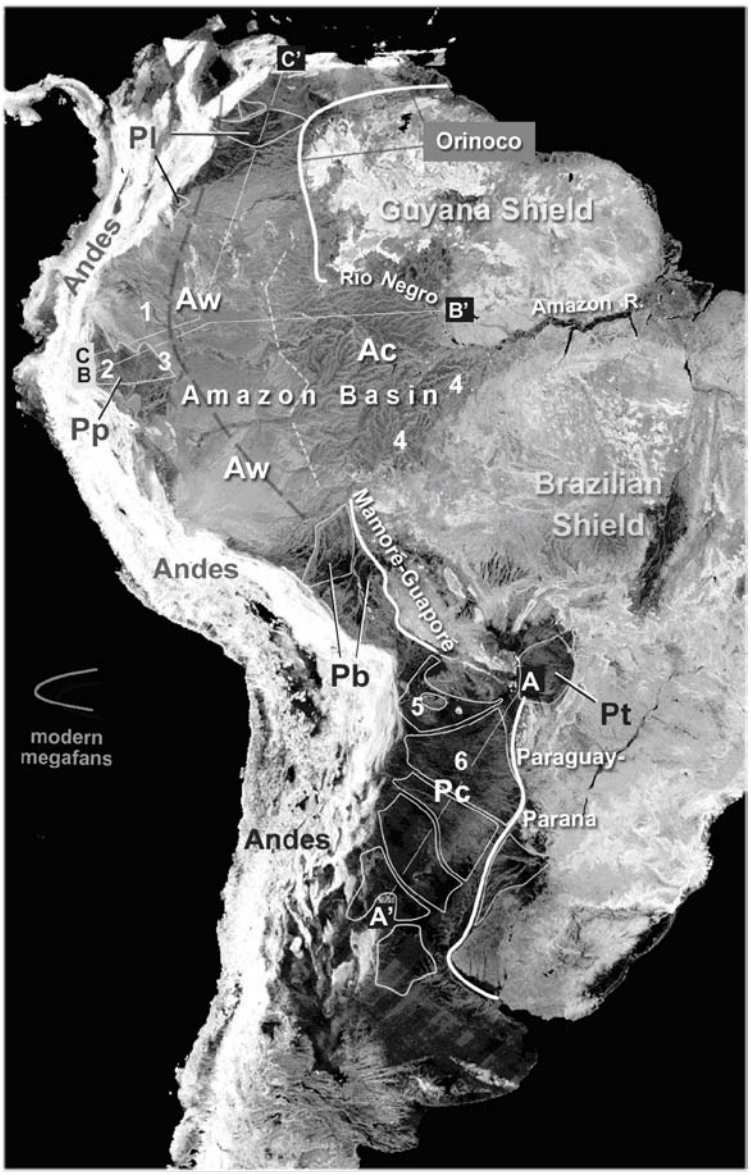


Figure 2.– Roughness map of South America. Darkest areas are lowest slope and smoothest landscapes, all dominated by megafans.

A New Biogeographic Boundary Coinciding with a Tectonic Plate Boundary

This study portrays one of the few known plate boundaries in Latin America that coincides with clear-cut distributional limits separating major biogeographic provinces. Costa Rica's Grande de Tárcoles River occupies the fault zone that defines the Costa Rica–Panamá microplate boundary. The Tárcoles River also marks an unusually clear biogeographic frontier between the Pacific dry forest (Mexican Pacific Coast Province) and the Pacific rain forest (Western Panamanian Isthmus Province).

Scarab Species Endemism and Diversity: Criteria for Conservation Priorities in Costa Rica

Species richness and endemicity maps for scarab beetles (probably representative of most insects) allowed definition of four priority levels of conservation area. The single most critical zone of landuse overlap is in the Central Valley of Costa Rica. This zone lies mostly *outside* protected zones in Costa Rica, where commercial agriculture landuse is dominant. This analysis has significant policy implications for a country in which the protection of biodiversity is a key tourist attraction.

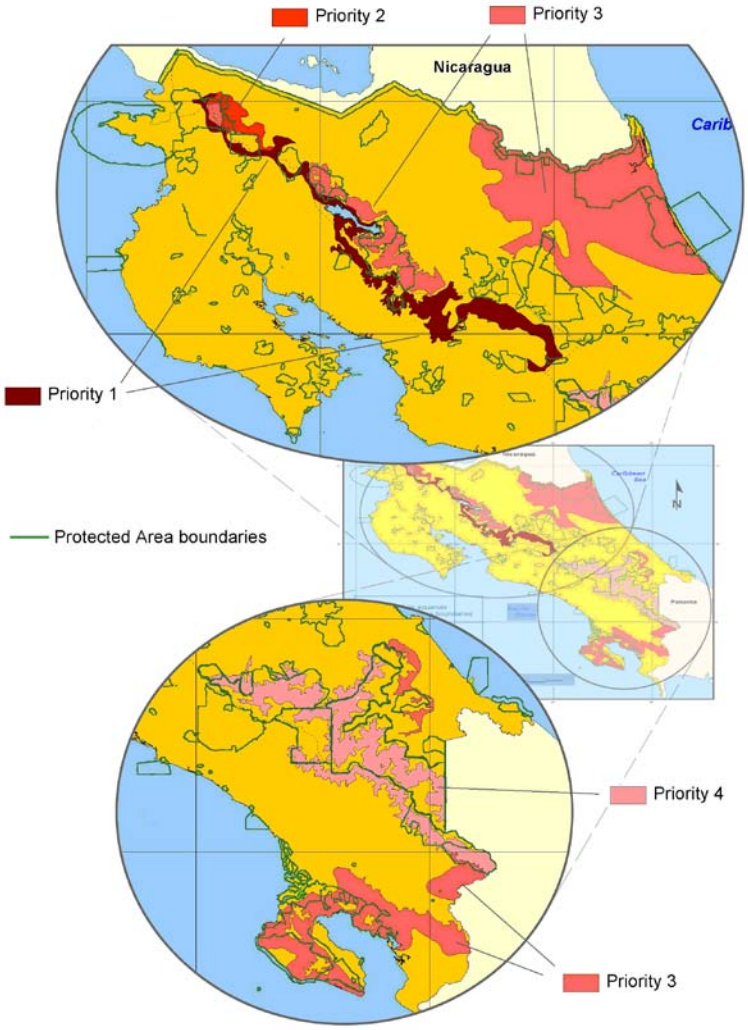


Figure 3.– Conservation priority zones.

Astrometric and Photometric Analysis of the September 2008 ATV-1 Re-Entry Event

Mark Mulrooney, Ed Barker, Paul Maley, Kevin Beaulieu, & Chris Stokely

The Orbital Debris Program Office (ODPO) at NASA-JSC was selected to participate in a campaign to observe the September 29, 2008 reentry and fragmentation of the first European Space Agency (ESA) Automated Transfer Vehicle (ATV-1) named "Jules Verne". Developed to service the International Space Station (ISS), the crewless ATV-1 (Figure 1) delivered supplies, was a depository for waste, and provided orbital re-boost to the ISS. At end-of-mission, the ATV-1 separated from the ISS, performed a de-orbit burn, and underwent a destructive reentry in the Earth's atmosphere.

Figure 1.– "Jules Verne" Automated Transfer Vehicle (ESA Graphic)

The final moments of ATV-1 were observed by a joint ESA-NASA Multi-instrument Aircraft Campaign or JV-MAC (see http://atv.seti.org/) coordinated by Dr. Peter Jenniskens of the SETI Institute. The spacecraft's reentry was recorded with a range of instruments aboard two aircraft to study the fragmentation process as ATV-1 passed through the Earth's atmosphere. The acquired data is being compared with modeled predictions of the fragmentation sequence with particular focus on the time and altitude of the primary fuel tank disruption. The data is also being analyzed to determine the individual behavior of the multitude of liberated fragments with comparisons to other break-up events. As a participant, NASA-JSC's ODPO supplied two image intensified video cameras and has performed photometric and trajectory analysis of the fragments separating and streaming from the vehicle. The two cameras were developed by Paul D. Maley of United Space Alliance. Each consists of a camera lens optically coupled to a Gen 3 micro-channel plate (MCP) with 400-800 nm (S20) response, and a commercial, low-light, off-the-shelf security camera. Output was recorded to analog Hi-8 tape and later digitized to DV format for processing. The cameras' 75 mm and 12 mm lenses yielded 8 and 20 degree fields of view respectively. Dr. Edwin Barker (ODPO Optical Lead) operated the cameras (called the JSCINT package) aboard the campaign's Gulfstream V aircraft (Figure 2). Having two cameras enabled a wide range in sensitivity and provided views of fragments close to the parent target as well as a larger scale assessment of the debris trail.

Airborne measurements were required to ensure timely access to the reentry corridor—the southern pacific ocean south of Tahiti. NASA's DC-8 was positioned near the end of the reentry path and the Gulfstream V (provided for this effort by Google Corporation) was positioned upstream at a point where the major disruption was predicted to occur. The Gulfstream V provided a platform that could turn to follow the ATV-1 as it moved across the sky. In addition to the JSCINT cameras, high-speed cameras, low-light spectrometers, near infrared and HD cameras were assigned to other windows in both aircraft (Figure 3). While several CCD video cameras recorded the reentry, the JSCINT system was one of two intensified systems whose goal was to image the fainter debris targets. Accurate timing and aircraft location was provided by distributed GPS systems on both aircraft.

Figure 2.– Dr. Ed Barker with the two low-light video cameras

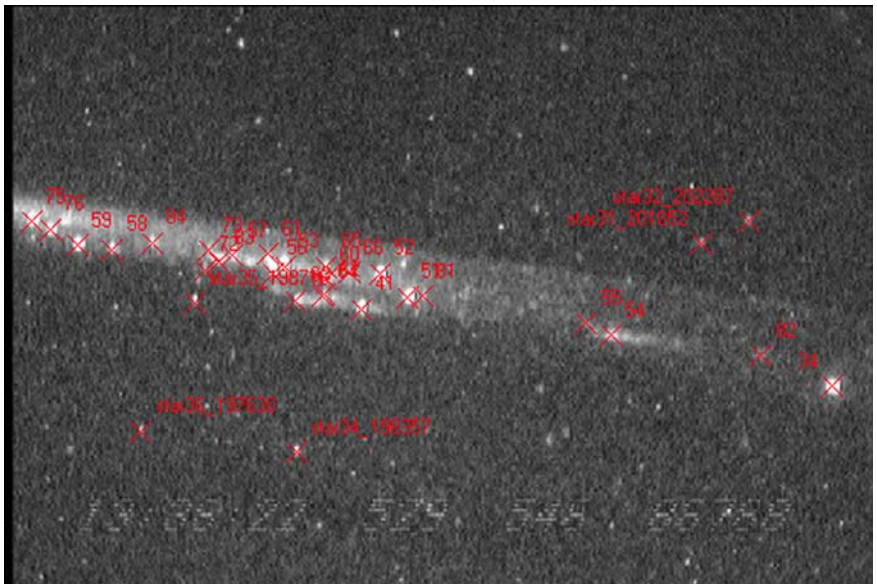
Figure 3– Instrument bays on the NASA DC8 aircraft

The ATV-1 reentry event was visible from the aircraft for approximately 3 minutes and its trajectory and arrival time were very close to those predicted. Barker successfully acquired the target a few seconds after it rose above the horizon and followed as it traversed the sky at a peak angular rate of about 3 degrees per second. The video data, although saturated in the immediate vicinity of the parent target due to its extreme brightness, is of sufficient quality to differentiate many of the fragments as they emerge from the saturated zone a few degrees aft along the trail (Figure 4).

Figure 4.– Digitized still frame of ATV-1 reentry stream (FOV 8 degrees). The 3 bright objects below the parent are reflections from the aircraft window.

As its primary scientific objective the ODPO undertook the assessment of the relative motions and brightness of the trailing debris fragments. This analysis first required identification of a series of reference stars with known brightness and positions to be used as photometric and astrometric fiduciaries. A minimum of four stars were needed per frame of video to obtain an accurate plate solution in the celestial (Right Ascension and Declination) coordinate system. After the reference stars were identified, measurements of the image coordinates and flux values of the stars and all detectable fragments were needed. With over 5000 frames of video data and dozens of stars and fragments per frame, a sophisticated software program called Trackeye (Photosonics, Inc.), traditionally used in the NASA-JSC Image Science and Analysis Laboratory (ISAL), was employed to facilitate measurements (Figure 5). After procuring software improvements, a frame-by-frame track and coordinate transformation (from Cartesian image to celestial) for each discrete fragment was performed (Figure 6). The sheer volume of data coupled with erratic motion induced by the aircraft, observer, and target, made a software solution essential. A total of 150 fragments and 66 reference stars were measured in the 3 minute video sequence with detailed analysis having thus far been performed on the first half (1.5 minutes).

Figure 5.– Digitized still frame of ATV-1 reentry stream (FOV 8 degrees) showing labeled tracked fragments and reference stars.



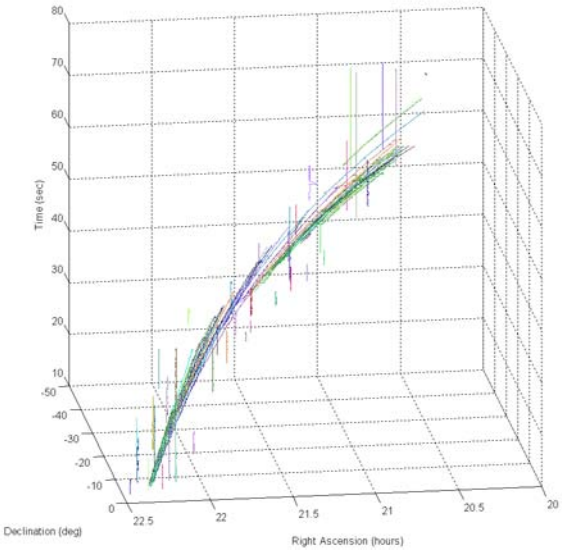


Figure 6.– Fragment and reference star trajectories in the first 90 seconds of the ATV-1 video sequence. Stars are fixed in RA/Dec space (vertical lines), while fragments follow curved paths.

With the astrometric positions determined and the astronomical brightness calibration performed, the time dependent trajectories and luminosities were analyzed to assess any patterns to fragment behavior. Interestingly, a clustering phenomenon was evident wherein several primary fragments separated into smaller pieces with each exhibiting differential motion (Figure 7). This motion is attributed to varying area-to-mass (A/m) ratios and corresponding drag coefficients among fragments.

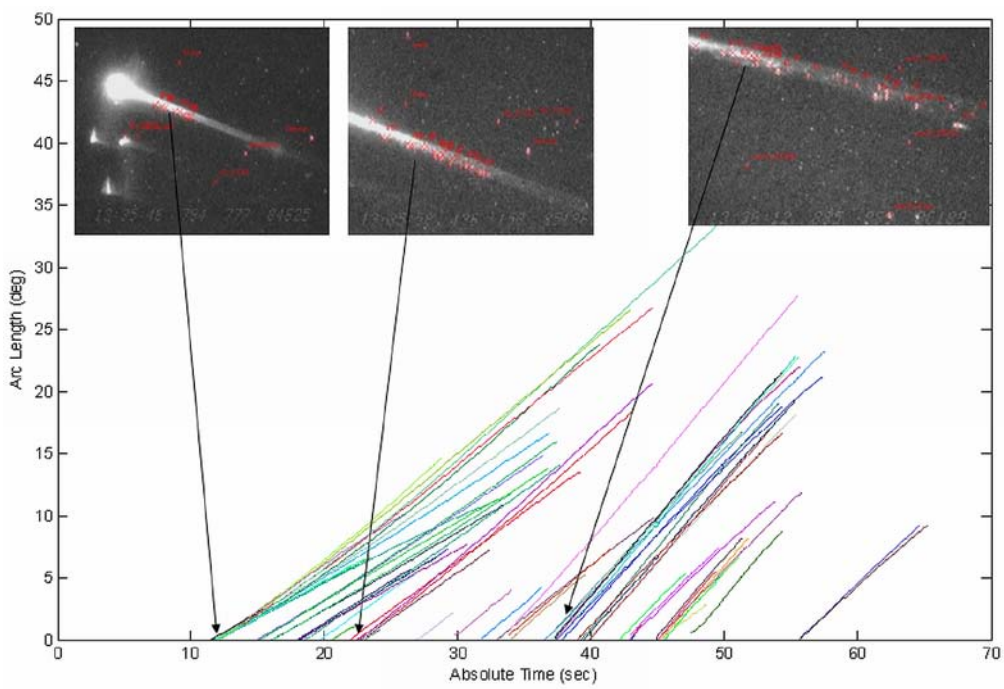


Figure 7.– Trajectory Length (degrees) versus Time (seconds). Several groups of fragments have a common origin. These clustering events result when a larger parent object breaks into smaller piece, each with its own differential motion.

Although the target luminosities exhibited significant noise (due to the analog nature of the video data), the fragment logarithmic brightnesses are observed to decay at fairly constant rates with about 25% of them briefly brightening before the onset of the decline (Figure 8). Further analysis will determine if this brightening correlates with the period of peak deceleration.

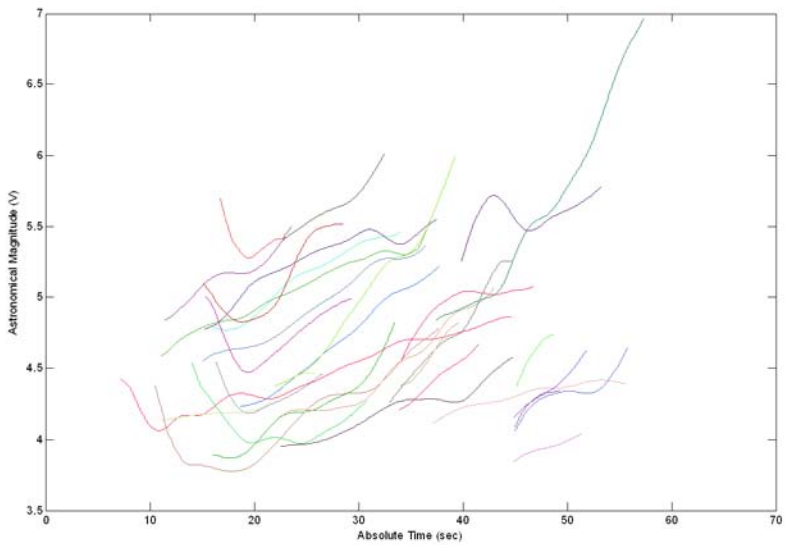


Figure 8.– Astronomical Magnitude (V Band) versus Time (seconds). Some fragments exhibit a brief brightening before declining in luminosity. This brightening may correspond with the period of maximum deceleration (energy deposition).

An accurate assessment of true fragment motion required removal of perspective effects. Thus transformation from the derived celestial to physical geocentric XYZ coordinates was necessary. JV-MAC participant Hans Nielsen (University of Alaska) performed this transformation with the NASA data so that physical trail lengths, velocities, and accelerations could be determined. The resultant altitude/ground track is shown in Figure 9. The demise of ATV-1 fragments in the 60-80 km altitude regime is consistent with prior empirical measurements and atmospheric re-entry models. Detailed analysis of the intrinsic fragment motions is ongoing.

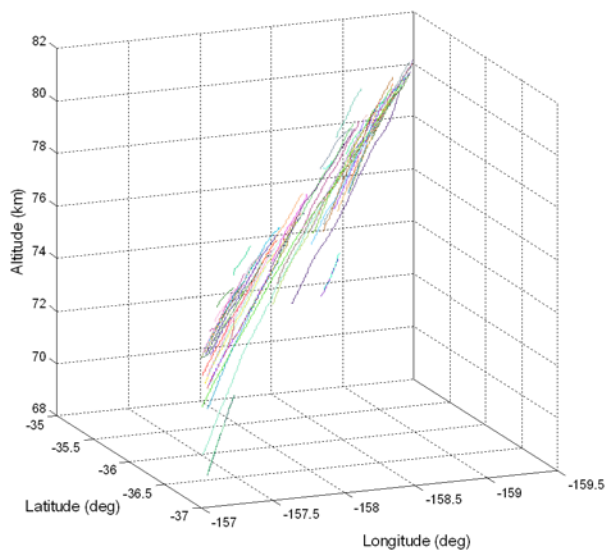


Figure 9.– Altitude (km) versus Latitude and Longitude (degrees) for the ATV-1 re-entry path.

The ATV-1 reentry presented a unique opportunity to study the dynamical evolution of a satellite atmospheric fragmentation event. The NASA-JSC ODPO implemented an observing procedure and acquired data that has yielded new insights into break-up fragment motion and luminosity variations during the re-entry process. Additionally, a data processing and analysis pipeline has been developed to support future re-entry observing campaigns.

Object-Based Image Analysis of Astronaut Photography

William L. Stefanov

High-resolution (4-10 m/ pixel) and freely available digital astronaut photography acquired from the International Space Station is a potentially useful dataset for ecologic, geologic and land use/land cover studies. The entire digital astronaut dataset is freely available from http://eol.jsc.nasa.gov. The dataset includes imagery from 1961 to present, and includes data for much of the Earth's surface. A collaborative data collection and research agreement between the Image Science & Analysis Laboratory (ISAL) and the National Science Foundation's Long Term Ecological Research (LTER) Network provides an ideal framework for assessment of the quantitative potential of digital astronaut photography. The LTER Network of 26 sites represent a wide range of biomes including temperate and tropical forest, deserts, grasslands, tundra and urban human-dominated ecosystems. This wide range of sites provides an excellent database for comparison of digital astronaut photography with remotely sensed data obtained from automated satellites (i.e. Landsat) as well as field-based validation and measurement data.

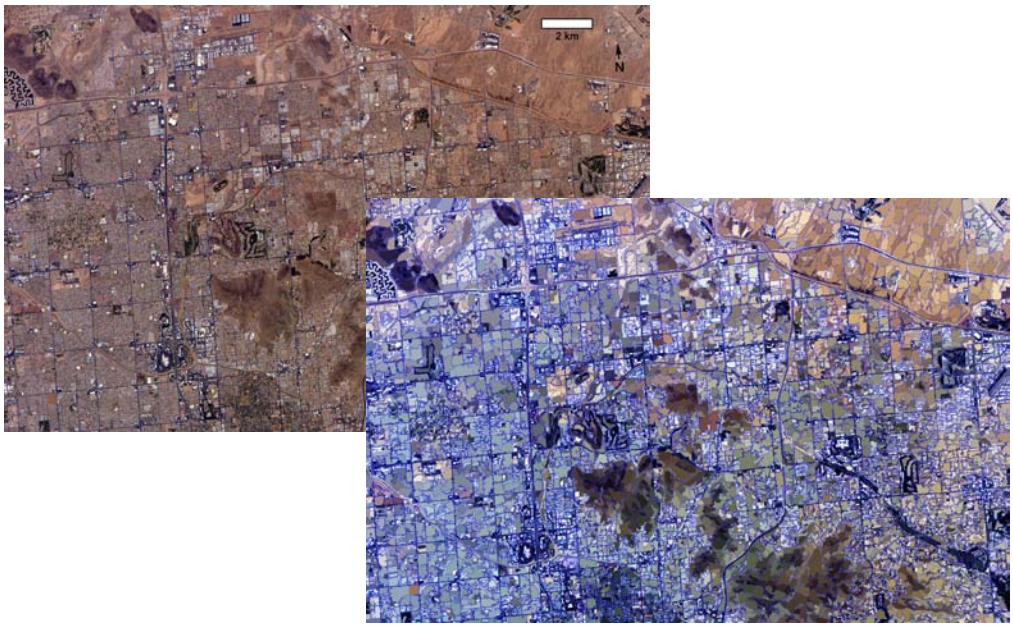


Figure 1.– Astronaut photograph ISS013-E-17386 of the Central Arizona–Phoenix LTER site (top). The image is segmented into homogenous polygons for object-based image analysis (bottom).

In contrast to traditional narrow bandwidth remote sensing instruments, digital astronaut photography is acquired using off-the-shelf digital cameras sensitive to the visible red, green and blue wavelengths; decisions to acquire imagery are made on-the-fly by the astronaut. The wide bandpasses of the camera make traditional classification approaches difficult as discrete spectral information is not typically obtained. A multilevel, object-based image analysis approach is being applied at the ISAL to high resolution digital astronaut photography of LTER sites representing a range of continental and island biomes. This approach emphasizes spatial relationships of similar pixels - through image segmentation - in addition to spectral information and takes advantage of the high density of spatial information captured in astronaut photographs. Used with remotely-sensed satellite and airborne data, digital astronaut photography can increase the temporal resolution of observed variables such as land cover, land use change, vegetation dynamics and surface soil processes.

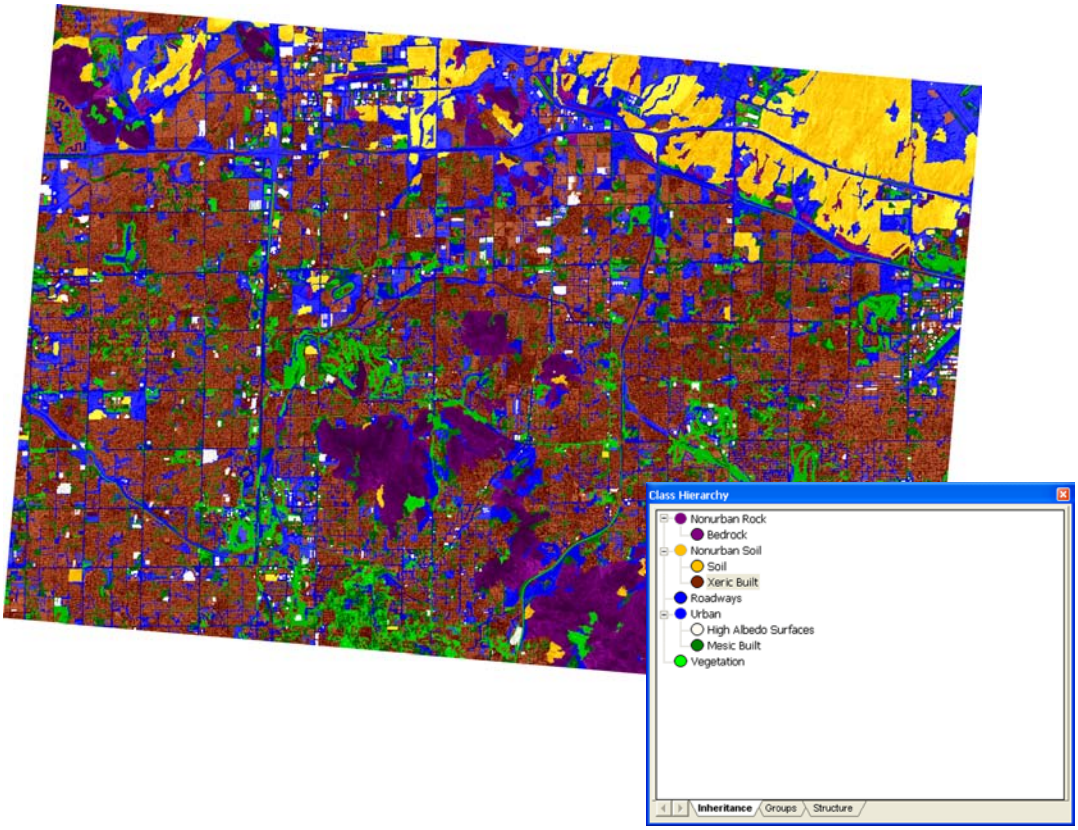


Figure 2.– Land cover classification of image ISS013-E-17386 using object-based image analysis (key at left). Image has been rotated to place north to the top. Application of this technique to high resolution astronaut photographs demonstrates the quantitative value of the dataset for a variety of terrestrial remote sensing applications, as well as future lunar and Martian digital photography.

Micrometeoroid and Orbital Debris In Situ *Measurement Activities at the NASA Orbital Debris Program Office*

J.-C. Liou

A good definition of the particle environment in space is needed for several applications: cost-effective satellite shielding design, reliable impact risk assessment, mission operations support, and planetary science. Micrometeoroids and orbital debris (MMOD) dominate the near-Earth environment. Around and on the surface of the Moon, micrometeoroids and lunar secondary ejecta (MMSE) are of particular concern. These populations follow different yet continuous size distributions, from sub-micrometers to meters. In order to fully characterize these populations, different observation techniques must be employed for particles in different size regimes.

The Orbital Debris Program Office initiated an effort to support the development of *in situ* instruments for the detection of the near-Earth MMOD particles in 2002. To support NASA's Vision for Space Exploration, the effort was later extended to include the detection of MMSE particles near the Moon. The majority of the projects are in collaboration with Naval Research Laboratory, the University of Kent at Canterbury (UK), the US Naval Academy, and Virginia Tech. The instruments being developed include impact acoustic, resistive grid, fiber optic displacement, and laser curtain sensors. These sensors rely on different mechanisms and principles for particle detection. A system consisting of these different sensors will collect data that are complementary to each other, and will provide a better description of the physical and dynamical properties of the particles in the environment. The three main development activities in 2007-2008 were Debris Resistive/Acoustic Grid Orbital Navy Sensor (DRAGONS), Fiber Optic Micrometeoroid Impact Sensor (FOMIS), and Impact Sensor for Micrometeoroid and Lunar Secondary Ejecta (IMMUSE).

DRAGONS

DRAGONS consists of Resistive Grid Sensors (RGS) and polyvinylidene fluoride (PVDF) acoustic sensors. A basic RGS unit is made of 75-μm wide resistive lines, lying in parallel and separated by 75 μm gaps, on a substrate circuit board (Figure 1). In the size regime for which the RGS sensor is designed (~50 μm to a few mm), one or more of the resistive lines will be destroyed as a result of a particle impact. By measuring the resistance increase of the sensor, the number of destroyed resistive lines and an estimate of the impacting particle's size can be obtained. The PVDF acoustic sensors, which are attached to the backside of the RGS board, provide additional impact momentum measurements. The capability of the system was successfully demonstrated through a series of hypervelocity impact tests on prototype DRAGONS units conducted at Kent in 2008.

The long-term goal of DRAGONS is to deploy a 1 m^2 system at an 800 to 1000 km altitude to measure the orbital debris population in the region. The project was proposed to the DoD Space Test Program in late 2007. It has been approved for a potential flight but not yet manifested on a specific spacecraft.

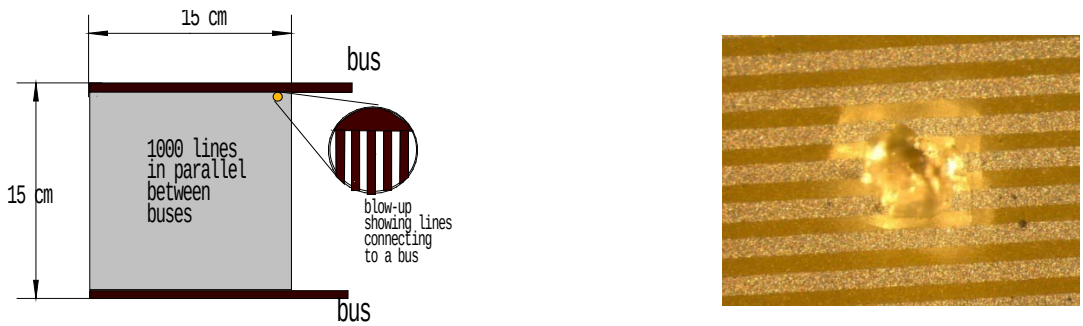


Figure 1.– Left: An illustration of the RGS system design. Right: Damage caused by a 100 µm glass particle at a 5 km/s normal impact on a test RGS unit.

FOMIS

The objective of FOMIS is to design and build prototype units that can be used as the building block of a large-area (tens of m^2 or more), low-cost, low-mass, and low-power-consumption MMSE impact sensor on the surface of the Moon. The basic structure of FOMIS is a 1 m^2 thin film, under tension, with multiple fiber optic displacement (FOD) sensors mounted below the surface. The FOD sensor has seven optical fibers with the central fiber serving as a light-emitting-diode (LED) transmitter and the other six functioning as receivers. When a particle impacts or penetrates the thin film, it causes the film to vibrate like a drum. The vibration is a function of particle size and impact speed. It is measured via the variation in intensity of the reflected light (Figure 2). Due to the high sensitivity of FOMIS, the measurable vibration amplitude is up to one cm with a better than one angstrom resolution. Successful hypervelocity impact tests on a small prototype FOMIS unit were also carried out at Kent in early 2008 to demonstrate the capability of the system. Large prototype units, up to 78 cm across with different shapes, are being constructed and will be subjected to both low velocity and hypervelocity impact tests in 2010.

FOMIS is funded by the Focused Investment Group of the JSC Mission Enabling Science Program. The near-term goal of the project is to advance the maturity of the system to a Technical Readiness Level of 6 by 2012 and to identify any possible lunar deployment opportunities in the future.

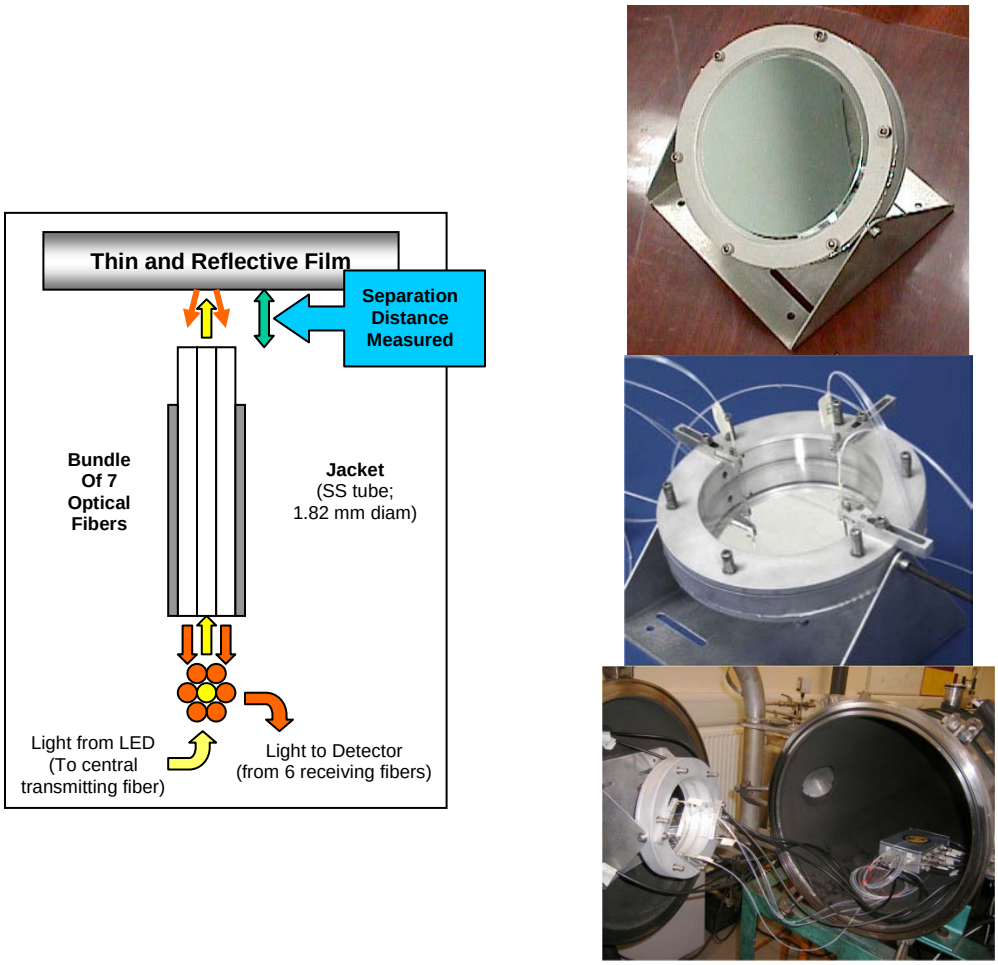


Figure 2.– Left: The detection principle of FOMIS. Right: The front (top) and back (middle) views of a small prototype FOMIS unit. The bottom image shows the unit and the electronics inside the two-stage light gas gun test chamber at Kent. Just before closing the chamber, the unit was turned 180° to allow the front side to face the incoming projectile.

IMMUSE

The IMMUSE system includes two components: (1) the Micrometeoroid Impact Detection System (MIDS) - a large area ($\geq$1 m^2) detector based on PVDF and FOD sensors and (2) the Secondary Ejecta Detection System (SEDS) - a 10 cm × 10 cm detector consisting of a dual-layer laser curtain and PVDF sensors.

The top portion of MIDS is similar to FOMIS while the bottom portion includes PVDF sensors attached to a substrate aluminum plate (Figure 3). The FOD sensors provide the first detection of a micrometeoroid as it impacts and penetrates the film. The thin film also filters out and prevents the much smaller secondary ejecta particles from reaching the base plate. As the micrometeoroid hits the aluminum plate, the impact momentum is recorded by the PVDF sensors. The SEDS component is a combination of a dual-layer laser curtain sensor and PVDF sensors (Figure 3). As a particle goes through the first and the second laser curtains, accurate impact speed and direction

measurements can be made. An estimation of the size of the particle is also possible based on the light scattering data. Impact acoustic measurements are obtained when the particle finally hits the base plate.

The IMMUSE project is funded by the NASA Lunar Advanced Science and Exploration Research Program through 2012. The project goal is to reach a Technical Readiness Level of 3 to 4 for both components within 4 years in preparation for a more advanced development beyond 2012.

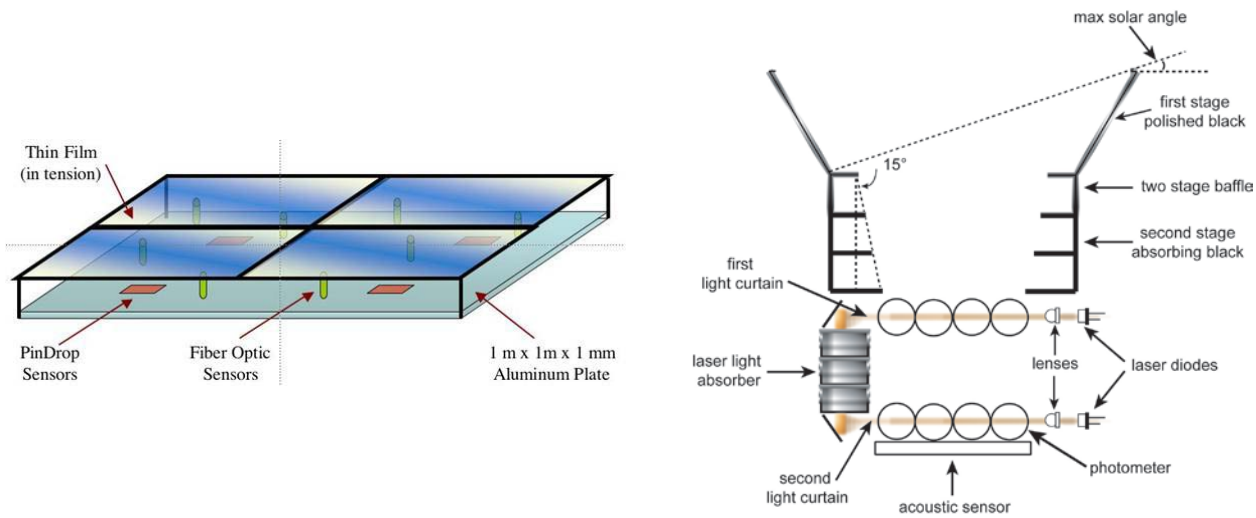


Figure 3. Illustrations of the basic configuration of the two IMMUSE components, MIDS (left) and SEDS (right).

ARES Education and Public Outreach

http://ares.jsc.nasa.gov/Educaton/outreach.htm

The ARES education team is charged with translating the work of ARES scientists into content usable in formal and informal education settings and to assist with public outreach. This is done through local efforts and national partnerships.

Local Efforts

Local efforts include partnerships with universities, school districts, museums, and the Lunar and Planetary Institute (LPI) to share the content and excitement of space science research. Through a NASA Minority University Initiative grant to the University of Houston-Downtown, ARES co-investigator staff trained student ambassadors, as well as Houston and Brownsville teachers in space science activities. Our strong partnership with LPI included a variety of solar system educator workshops at Texas science teacher conferences and Harris County Department of Education. We also teamed with LPI to provide space science events at LPI and Girl Scouts of San Jacinto venues. The ARES education team supports NASA JSC education workshops and the Texas Aerospace Scholars program with workshop presentations, speakers, and printed materials.

Locally the education team assists the ARES directorate in public outreach endeavors. Sharing our science with the public is an essential part of ARES programs in Earth and space science. As the small enclave of physical scientists at a NASA engineering and space flight center, our staff is frequently called upon to support science presentation and interview requests from the JSC public affairs or education offices. Scientists and staff are active volunteers in the JSC Speaker's Bureau, Digital Learning Network, and National Engineers Week programs. Scientists and staff also support local science fairs and give presentations at many local schools. Our scientists are frequent mentors for university faculty and students in programs sponsored by the NASA education and equal opportunity offices as well as the Lunar and Planetary Institute. ARES staff provides frequent tours of our research and curatorial laboratories for JSC personnel and visitors.

National Partnerships

Programs with a national reach are an important vehicle for ARES education and public outreach efforts. With funding from Mars Public Engagement, NASA Science Mission Directorate Solar System Education Forum, the Exploration Mission Directorate, and the Discovery Program, the ARES education team is an active and contributing member of the NASA space science education community. The team is involved in several national efforts to reach formal and informal educators.

- The ARES education team continues our affiliation with Girl Scouts GSUSA and the NASA Girl Scout Core Trainers. ARES Education staff trained a set of NASA Girl Scout Core Trainers to conduct Exploring the Solar System thematic workshops for all of the Girl Scouts of the USA.

- Through Mars Public Engagement Program's Imagine Mars project, our team assisted with major program design and curriculum development. ARES education personnel trained Housing and Urban Development staff to engage youth in Mars, Imagine Mars, and solar system activities.
- ARES education developed and facilitated a teacher training and school visitation event in conjunction with the Discovery @15 meeting in Huntsville, Alabama.

ARES education continued to have a presence at state and national venues for science educators and afterschool educators presenting workshops focused on Solar System Exploration including ARES research, Mars, and the Moon. The education team is advising the Out-of-School Time curriculum group working to adapt formal classroom activities for the informal, afterschool setting.

ARES Directorate has four continuing education programs that reach a national audience. The Earth Observations E/PO, the Educational Thin Sections program, and the Lunar and Meteorite Sample Education Disk Program continue to serve a large national audience; Expedition Earth and Beyond is a newly funded program that is in development for introduction in Fall 2009.

Earth Observations E/PO
http://eol.jsc.nasa.gov

Astronaut photography of Earth is extremely popular with students, teachers, and the general public, and this interest is used to leverage interest in science and exploration. ARES provides at least one human space flight image headline per week to "Earth Observatory," NASA's Earth science education flagship website (<<http://earthobservatory.nasa.gov>>). Over 500,000 astronaut photographs of Earth are downloaded each month by educators and the public from the "Gateway to Astronaut Photography of Earth," which has received numerous educational citations (<<http://eol.jsc.nasa.gov>>).

Expedition Earth and Beyond

Expedition Earth and Beyond is a newly-funded inquiry-based geosciences student involvement program being developed and led by the ARES Education Program. This new program will allow teachers and students to be actively involved in the excitement of exploration, discovery, and the process of science. Expedition Earth and Beyond is being designed to facilitate student-led, authentic research projects that promote the study of Earth and planetary body comparisons. Scientists within the ARES Image Science and Analysis Laboratory (ISAL) will play a major role in the facilitation of the program.

Expedition Earth and Beyond will use astronaut photography images which have been extremely popular with students, teachers and the general public. The program will provide an educational structure that will now allow teachers in grades 5-14 to have their students use these stunning images of Earth to conduct authentic research. Standards-aligned curricular guides will enable teachers to replace previously used classroom curriculum with a more engaging, relevant and inspiring curriculum that uses the excitement of current exploration as the hook. Students will also have the opportunity to submit science proposals to request new imagery to be taken on their behalf. ISAL scientists who train astronauts and send image requests to them on the International Space Station

will submit requests on behalf of student scientists participating in the program. Classrooms across the nation will also have the opportunity to connect with ARES scientists to increase their knowledge of Earth, planetary comparisons, and science being conducted within the ARES Directorate. Additionally, the program will provide a means in which students can present their research to their peers across the country as well as to ARES and other participating scientists using distance learning technologies.

Lunar and Meteorite Sample Education Disk Program

The Lunar and Meteorite Sample Education Disk Program is a consolidation of a long-established NASA education program that ARES will manage. This program is available to schools, libraries, museums, and planetariums throughout the country. Distribution of the disks has made it possible for millions of people to examine the precious Apollo lunar samples and meteorites. Educational materials including a teachers' guide and image support accompany the education sample disks.

An integral part of this program is the training and certifying of educators to borrow the disks. ARES Education team serves as trainers of trainers by designing and conducting workshops at JSC ARES that deliver the scientific background information, hands-on activities, and security information to NASA Aerospace Education Services Program (AESP) specialists and Educator Resource Center educators who prepare formal and informal educators to use the disks as they teach planetary science. Security and the loan system regulations will be shared with all NASA Center Disk Custodians through trainings in 2009.

The ARES Education Office in cooperation with ARES Curation Office currently manages the Lunar and Meteorite Sample Education Disk Program.

Educational Thin Sections

The NASA Educational Thin Section sets are available to colleges around the country. The lunar and meteorite thin section sets consist of 12 samples. The meteorite sets were prepared in collaboration with the Smithsonian Institution. Educational materials including a detailed booklet with background information and petrographic descriptions and a video or slide set with captions accompany the thin section sets.

The ARES Curation Office manages the NASA Educational Thin Section Sets program.

Publications

The ARES education team has developed and published activities and education packages. This work is the collaboration of ARES scientists and classroom educators. The hallmark of ARES education activities is accurate science presented in hands-on learning experiences that meet the needs of educators.

Exploring Meteorite Mysteries

http://ares.jsc.nasa.gov/Education/Activities/ExpMetMys/ExpmetMys.htm

Exploring the Moon (produced by University of Hawaii staff)
http://ares.jsc.nasa.gov/Education/activities/ExpMoon/ExpMoon.htm

Fingerprints of Life?
http://ares.jsc.nasa.gov/Education/websites/astrobiologyeducation/index.html

Space Rocks Tell Their Secrets—the slide show only
http://ares.jsc.nasa.gov/Education/spacerocks.htm

Destination: Mars! (Houston Museum of Natural Science publication)
http://ares.jsc.nasa.gov/Education/activities/destmars/destmars.htm

Modeling the Solar System
http://ares.jsc.nasa.gov/Education/modelingsolarsystem.pdf

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PESLIER, ANNE	KR	281 244 6714	31/134
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SATTERWHITE, CECILIA	KT	281 483 6776	31/258
SAYRE, MICHAEL	KA	281 483 8403	31/233
SCHARF, ROBERT	KX	281 483 2756	36/142A
SCHWARZ, CAROL	KT	281 483 5124	31/260
SEE, THOMAS	KR	281 483 5027	31/266
SHAFER, JOHN	KA	281 244 6923	31/128
SHEBALIN, JOHN *	KR	281 483 9446	31/136
SHIH, CHI-YU	KR	281 483 5024	31/154
SHOOTS, DEBRA	KX	281 483 5170	268/106
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