The Stuff of Other Worlds

By Alexis Glynn Latner and Eileen K. Stansbery

Extraterrestrial material eternally rains down on Earth. Meteorites flare in the night sky. Cosmic rays plow into Earth's atmosphere, creating invisible bursts of secondary particles. These processes began when the Earth formed in the primordial solar system and have continued ever since, indifferent to the exceedingly recent presence of human intelligence.

For us to seek out stuff of other worlds, in contrast, takes a great deal of determined ingenuity. First we have to send a spacecraft somewhere else in the solar system. Indigenous material has to be collected and then brought back to Earth without exposure to conditions that might significantly alter it. The material must undergo meaningful scientific analysis. Most important, part of the material is preserved intact for future investigations. Beginning with bringing back Moon rocks, and now moving onward in the form of new missions to capture the hot thin solar wind and cold thin atmosphere of comets, extraterrestrial sample return takes place on the cutting edge of scientific technology.

Sample return is also the fulcrum of an energetic debate about how to do planetary science missions. Scientists and engineers are debating whether to rely on remote sensing and in situ analysis, or to plan missions to undertake sample return. The latter is definitely more expensive on a per mission basis, and is usually technologically more challenging. But for an initially high investment of money and technology, bringing the stuff of other worlds back to Earth yields an incomparable return in scientific results.

Figure #1. Composite picture of Apollo astronaut, a Moon rock, and thin section of a lunar sample. (Courtesy NASA Johnson Space Center.)

LUNAR SAMPLE SCIENCE AND CURATION

Rocks, cores, and lunar regolith dust were brought back to Earth by NASA's Apollo Moon missions. The lunar materials remain in vaults in a nitrogen atmosphere at Johnson Space Center. About fifteen percent of the collection resides in a similar vault at Brooks Army Air Field in San Antonio, as insurance against disaster striking JSC. Samples are in the hands of researchers worldwide.

Johnson Space Center's fundamental purpose is twofold: manned space exploration and astromaterials. In addition to lunar samples, meteorites are curated. The collection includes meteorites that originated on the Moon and Mars. The famed "Mars-fossil" meteorite, ALH84001, was curated at JSC after being collected in the Allen Hills area in Antarctica. When researchers realized its potential significance, they asked for and duly received a piece of it from the meteorite collection. Also curated at JSC is cosmic dust, more precisely called interstellar dust particles (IDP's), collected on oil-glazed plates taken into the stratosphere by high-flying aircraft.

Some Moon rocks are still pristine; some core tubes haven't been opened. About eighty percent by weight of the Apollo lunar materials have not yet been analyzed. This is for excellent scientific reasons. There are analytic instruments now that did not exist 30 years ago. Subsequent decades will see new analytic equipment and new questions. The lunar collection is a reservoir for the future.

Researchers have been analyzing lunar samples for more than three decades, making a steady stream of discoveries not only about the Moon itself, but also about planetary processes and even the Sun. The Moon's top layer of dust and rocks -- the lunar regolith – is now known to contain the best and most attainable radiation history of the Sun, written in chemical element enrichment and implanted isotopes in the rocks and mineral grains. The Moon turns out to be a complex body. The lunar science community has benefited from being able to compare and contrast sample analysis with remote sensing data (such as photographic and radar images.) A combination of sample return and remote sensing is the best way to understand our deceptively familiar companion ~~planet~~, the Moon.

Figure #2. A graph of the number of samples of lunar material sent out to Principal Investigators per year from 1980 through August, 2000. (Courtesy NASA Johnson Space Center.)

SOLAR WIND SAMPLE SCIENCE AND CONTAMINATION CONTROL

The last Moon rocks came back 30 years ago. In great contrast, the next extraterrestrial sample return will consist of atoms.

A solar wind sample return mission, named Genesis, is set to launch early in 2001. The wind from the Sun, consisting of atomic particles, is largely deflected by the Earth's magnetic field. Prior to space exploration, the only attainable samples of solar wind were traces of noble gases found trapped in meteorites. Foils made of aluminum and platinum were unfurled for the duration of some of the Moon missions and brought back for analysis. Genesis builds on findings from the Apollo foils.

Parked for two years in a halo orbit around the Earth-Sun libration point L1, the dining-room-table-sized Genesis spacecraft will spread five immaculate arrays of collector material to catch the wind from the sun. It will shuffle the arrays to expose various surfaces depending on which regime of the solar wind is active. Besides mirrorlike silicon wafers, there are areas of sapphire, aluminum, gold, germanium, platinum, and vitreloy in the collector arrays. There is also a particle concentrator with such target materials as silicon carbide and CVD diamond.

Figure #3. Genesis array designed to sample the high-speed solar wind regime with various collector materials. (Courtesy NASA Johnson Space Center.)

In the end the spacecraft will repack itself, stacking its arrays back up inside a resealed science canister, and return to Earth. The science canister will plunge through the atmosphere on a parachute toward a dramatic retrieval by helicopters over the Utah Test and Training Range. There is a contingency plan in case the canister crash-lands and the brittle collector materials shatter. Each of the five arrays is a different thickness. If necessary, technicians can reassemble five puzzles containing ~~a~~ samples of the Sun.

Curated at JSC in a Class 10 clean room environment, the collector materials will be analyzed for embedded atoms of almost all elements in the Periodic table -- not the vastly abundant hydrogen and helium, but everything else from lithium to uranium. Of particular interest are isotopes of oxygen and nitrogen, the noble gases, and carbon.

The findings from solar wind sample return will illuminate and enhance the results from two other missions that are now underway, SOHO and ACE. The Solar and Heliospheric Observatory, sponsored by NASA and the European Space Agency, is observing the sun without interruption for at least two years. The Advanced Composition Explorer, ACE, captures low energy particles of solar origin, as well as high-energy galactic particles, for in situ analysis. SOHO and ACE are looking for different things than the Apollo foil experiments and Genesis. These are complementary approaches. As with the Moon, scientists who study the Sun and solar system evolution are best served by a combination of remote sensing and access to samples returned to Earth.

Whether returned samples are rocks, solar wind atoms, or something intermediate in size, the challenge is fundamentally the same. The difference is one of scale, above all else in the degree of contamination control required.

A trace of nitrogen or oxygen embedded in a silicon wafer could be from the solar wind, but it could also be a byproduct of the manufacturing process; spacecraft outgassing or thrusters; micrometeoroid impact; handling by technicians; or exposure to the Earth's atmosphere upon re-entry. Fortunately, most sources of contamination deposit atoms on the surface. Particles from the Sun will be embedded into the collector materials by the force of the solar wind.

Figure #4. Illustration of contamination deposition and depth of solar wind particles embedded in Genesis collector material. (Courtesy NASA Johnson Space Center.)

Contamination control is mission-critical for any extraterrestrial sample return mission. In the case of Genesis, contamination has to be stringently controlled all the way down to the atomic level. Among many bedeviling considerations is the fact that standard cleaning techniques such as sputter cleaning appear to embed 10 per cent of the atoms otherwise cleaned off. Genesis serves as a test bed for extreme limits of sample return and analysis.

PROVENANCE

For any extraterrestrial sample, the meaningfulness of scientific results depends on the certainty with which we know where it originated and what it may have been exposed to prior to analysis: the provenance of the sample. It must be certainly known where the sample came from -- from what area on a planet, from what part of space, during what solar event, and so on.

Establishing provenance dictates knowing whether a planetary sample might have been exposed to a plume of expended fuel propellant when the spacecraft landed. Subsequent exposure to heat, magnetic fields, ionizing radiation, pressure, and physical shocks such as g-forces must be minimized and documented. Then there are questions about the equipment used to collect, retrieve, and finally store the sample. Everything that touched the sample must be documented. This includes understanding the material composition of sampling devices, cutting tools, measuring devices, gloves and analytic equipment.

Storage and cataloging protocols are of utmost importance. The Moon rocks are catalogued so as to specify daughter fragments when a piece is split or sectioned. 296 original pieces of lunar material are now cataloged as about 100,000 samples. Even the fines from cutting processes are collected and catalogued. When the next generation of extraterrestrial samples are returned and curated, an equally rigorous system to account for every sliver will be in effect.

Without clear provenance, scientific results are disputable. Astromaterials curators must establish and provide an ongoing provenance for every original sample and every eventual subset thereof.

One of the hardest parts of establishing provenance is before a sample return mission ever leaves Earth. Most spacecraft design and development is highly focused on structure, mechanisms, and mission. Obtaining representative material coupons during the construction of a spacecraft requires unusual effort, but is extremely important. The coupons are archived and analyzed for detailed understanding of the material composition of spacecraft parts that might come into contact with the samples. In addition, spacecraft and especially the sample collection equipment must start out clean. There has always been concern to keep spacecraft clean until they launch: witness the Apollo-era technicians who wore coveralls and hair caps. But the definition of "clean" is orders of magnitude more exacting now.

Genesis started with silicon wafers manufactured to extreme standards of purity developed by the computer industry. Every thing else -- the metal array frames, the canister lid, the screws and other fasteners -- started out shockingly dirty, relatively speaking. Traces of lubricants or fastener staking compounds, substances which are ubiquitous in most machines, are highly problematic for future analysis of the solar wind sample.

In order for it to be a blank slate for the atomic isotopes of the solar wind, the Genesis science canister, developed by the Jet Propulsion Laboratory, came to Johnson Space Center to be disassembled, cleaned, and reassembled in July and August of 2000. Then it was sealed before being sent to be integrated into the spacecraft. It won't unseal and open until it reaches L1 in April of 2001. The cleaning process took place in a clean room built for this purpose. At Class 10 (meaning 10 particles per cubic foot of air), it is the cleanest such facility NASA has ever had. Surgical operating rooms vary from 1,000 to 10,000. The Apollo Moon rocks are in nitrogen cabinets within a Class 1,000 clean room, which was the state of the art in 1970. In addition to solar wind samples, Class 10 clean rooms figure into cleaning of future payloads and/or handling of samples returned from asteroids, comets, and conceivably Mars and Jupiter's moon Europa. Depending on the aim of the analysis, even some future lunar material would require Class 10 arrangements.

Figure #5: Class 10 clean room in use at JSC. (Courtesy NASA Johnson Space Center.)

Given the extreme difficulty of sample return, contamination control, and establishing clear provenance through a long chain of events, one might wonder why not just do it all remotely or in situ. The answer, as becomes more apparent with every advance in planetary science, is that both approaches are essential.

SAMPLE RETURN VERSUS IN SITU ANALYSIS AND REMOTE SENSING

As new planetary and space science missions are planned within tight budgetary constraints, people engage in heated discussion about sample return versus in situ or remote sensing approaches. There are very real risks of losing samples in transit. The complexity of robots that can undertake the sampling and make their way home is a serious concern. And the issue of expense is omnipresent.

Without doubt, some things can only be done in situ: measuring atmospheric pressure, wind, and volatiles, for example.

On the other hand, the work done with the meteorite ALH84001 highlighted a critical fact: unless it is much more conspicuous than the evidence in Martian meteorites, fossil life on Mars might be impossible to detect in situ, much less remotely. The analytic instruments brought to bear on ALH84001 (inconclusively, so far) are big, delicate and expensive machines: thermal ionization mass spectrometers, transmission electron microscopes (TEMs), field-emission gun scanning electron microscopes (FEG-SEMs.) Paradoxically, it takes massive instruments to analyze the tiniest of atomic and material traces if extremely high resolution of data is to be obtained.

Figure #6. Cameca electron microprobe used for geochemical analysis of samples. This instrument has been used to make element concentration maps of Martian meteorites. (Courtesy NASA Johnson Space Center.)

The greater the level of precision and detail called for in a geochemical analysis, the larger and more delicate the instruments that must be used, in ever more stringently climate- and contamination-controlled environments. This is what it takes to tweak apart the stuff other worlds are made of.

Camera technology has lent itself wonderfully well to miniaturization for in situ analysis. Miniaturizing a high-resolution mass spectrometer sufficiently to include it in a Mars lander is not conceivable at the present time. Short of a degree of miniaturization verging on magic (nanotechnology?), doing the best science takes bringing carefully selected extraterrestrial material home.

Some subtleties of Martian material might even be beyond the pale of any analytic instrument on Earth in the year a Mars mission is launched -- but analyzable by the time such a mission returns with a sample, or not long thereafter. Curated, Mars soils, rocks or cores can wait for the next generation of science and scientists.

Another extremely important rationale for sample return is reproducibility of results. When material is curated, researchers can give an experiment another go. Whether it involves a lunar core, a slice of Martian meteorite or a silicon sliver from Genesis, the experiment can be reproduced.

Together with reproducibility goes accessibility. Researchers who propose to study the Moon rocks are carefully screened, but proposals from reputable groups all around the world have been accepted.

In the end, both the return of extraterrestrial samples and non-sample approaches are needed for the best science. We can't use only one avenue at the expense of the other. In situ analysis and remote sensing are important. But sample return is required for the ground truth of the measurements.

The ultimate "ground truth" to be established by sample return missions is the formation of the Solar System.

INTO THE FUTURE, TOWARD THE BEGINNING

The composition of the Sun closely reflects that of the original solar nebula before it differentiated into planets. Analysis of the returned solar wind from Genesis is expected to yield much insight into the primordial solar nebula. The Genesis results will also constitute a base line for findings from upcoming comet and asteroid sample return missions: Stardust and Muses-C.

Stardust, like Genesis, is a Discovery Mission, with mission scope and cost both tightly focused. Launched in 1999, Stardust has as its aim to return a sample of the coma of Comet Wild 2, a primitive comet little changed by recent brief exposure to the inner solar system. The cometary grains will be captured in the brittle, airy, silica-based solid called aerogel. En route to Wild 2 and on its way back, the spacecraft will collect cosmic dust. All samples in the aerogel will be retracted into a sample return capsule scheduled to fall to Earth by parachute in 2006. Stardust should shed light on the early stage of the solar system that was characterized by the formation of primitive iceballs.

Figure #7. Stardust spacecraft. (Courtesy NASA Johnson Space Center.)

Figure #8. Aerogel with particle tracks from a test done aboard the Mir space station. Left, multiple tracks. Right, single track in detail. The particles are at the small end of the tracks. (Courtesy NASA Johnson Space Center.)

Asteroids are the other kind of primordial body highly suitable for sample return missions in the near future. The joint effort of Japan's Institute of Space and Astronautical Sciences (ISAS) and NASA called Muses-C will attempt to sample an asteroid known as 1998 SF36. A portion of the returned sample will come to JSC for curation. Muses-C targets the planetesimal phase of the early solar system. This will complete a sequence of early twenty-first century sample return missions that have been planned with an eye toward establishing a scientific baseline about the early evolution of the solar system.

The value of the Apollo moon rocks notwithstanding, future missions to return materials from the Moon and Mars are not a given. The technical difficulty rises with distance and with gravity. Both of these factors are worse for Mars than for the Moon.

Mars mission plans are in flux due to the failure of recent missions. Despite various proposals to obtain cores and scoops of soils, no sample return missions are currently planned. An international mission may be the only real possibility. Many resources for Mars sample return exist in various nations' space programs. For example, the Italians have a core drill designed for Mars sample return. The French, who are highly interested in Mars sample analysis, have the right size launch vehicle, Ariane 5, and would very much like also to provide an orbiter.

NASA is studying how to construct a planetary sample receiving facility. The Centers for Disease Control has been consulted, as has the American Biological Safety Association. Mars samples must be quarantined well enough to prevent contamination by Earthly micro-organisms as well as the release of Mars organisms, if any, into Earth's ecosphere. Building a suitable facility takes time and money.

The rocks and soils of Earth, Moon and Mars date from a time when the solar system was a finished product. Of these, the Moon has been least altered by geological and biological processes. But the results of the analysis of the Apollo samples show that even the Moon is an evolving body. For the material of the truly early solar system, we must turn to the solar wind, comets and asteroids. Then we can take the findings from samples returned from the Moon and Mars to continue the weaving of the very long and intricate tapestry which is the history of our solar system.

Prometheus brought fire back from the gods to human kind, a myth for the foundation of technology. Our space-faring robots will bring back the Moon and Mars, the Sun, asteroids and comets. The result will be scientific insight into the evolution of the solar system, and with that we will better understand the fabric of the universe.

SUGGESTED READING

CAPTEM, the Curation and Analysis Planning Team for Extraterrestrial Materials, is a high-level panel sponsored by NASA and consisting of independent scientists. This group has done a summation of lunar science from combined remotely sensed and lunar sample data sets. Much information can be found on their Web Site: http://cass.jsc.nasa.gov/captem/

Johnson Space Center Astromaterials Web Site: http://sn-io.jsc.nasa.gov/

NASA Headquarters' Space Science Web Site with context and links to all space science missions past, present, future and proposed: http://spacescience.nasa.gov/

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LIST OF FIGURES

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