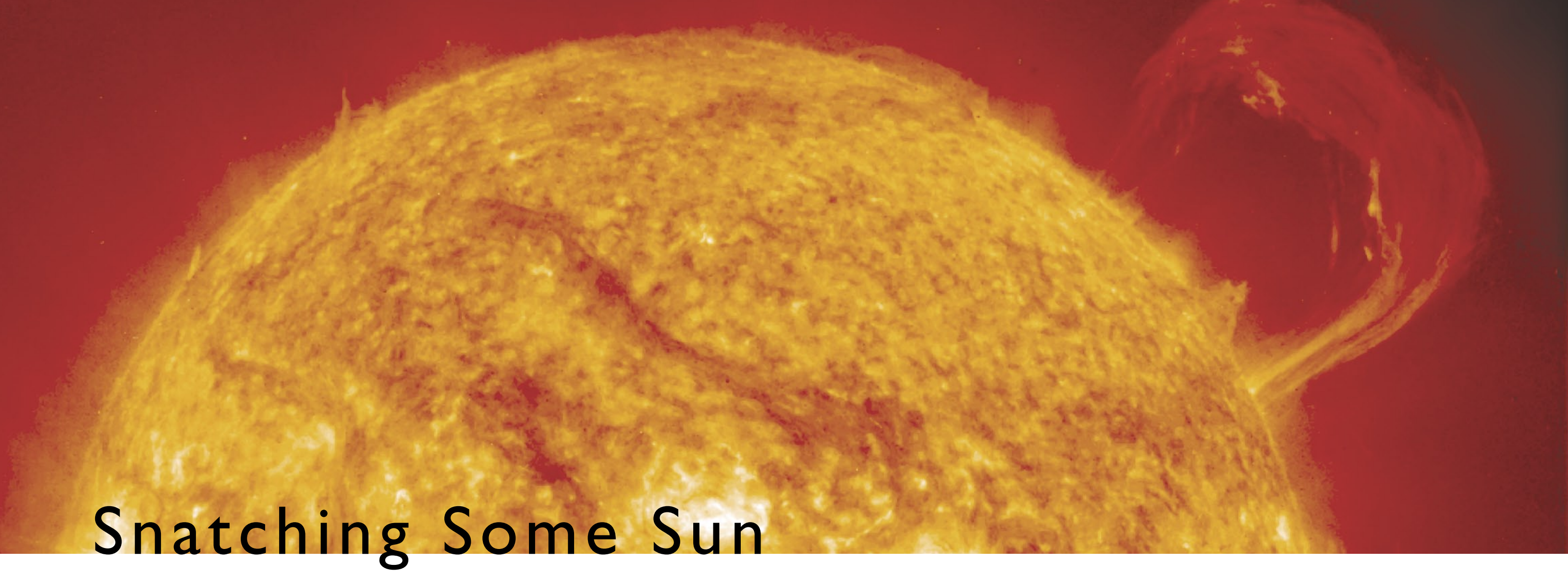


Snatching Some Sun

by Marcus Woo

The Genesis sample-return capsule isn't buried in the ground—it's smashed. The capsule crashed near Granite Peak on a remote portion of the Utah Test and Training Range.

Out of the yawning September sky, pieces of the sun tumbled toward the Utah desert. They were captured solar particles, holding clues to the birth of the solar system, and being returned to Earth in a shiny, 200-kilogram capsule. The plan was for parachutes to slow the pocket-watch-shaped craft, allowing a helicopter to swoop in, snatch it from midair, and gently lower the fragile contents to the ground. But on this bright morning in 2004, the parachutes didn't open, and the helicopter didn't have a chance. The capsule spun and wobbled as it plunged into the ground at more than 300 kilometers per hour.

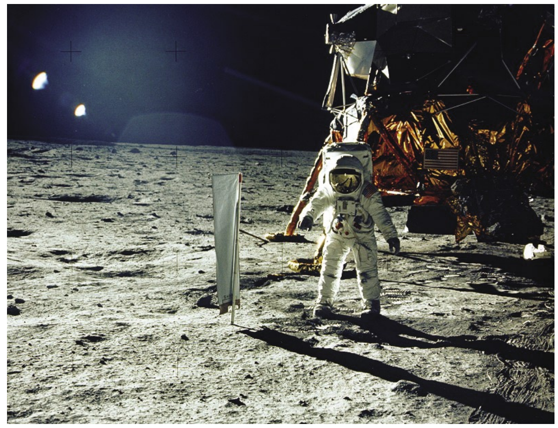
The capsule was a mangled mess. The ground had smashed it open, shattering the delicate wafers that held the tiny solar particles, spilling them onto the desert floor. To some, the three-year, three-million-kilometer trip, costing hundreds of millions of dollars, years of sweat, and decades of thought, looked like it was for naught. On the *NBC Nightly News*, anchor Tom Brokaw called the crash a "sad and bizarre end to this epic journey." For the mission called Genesis, the failed landing seemed like a literal fall from grace.

Mission scientists were more hopeful, however, and hunkered down to see what they could salvage. "We went out and picked up the pieces," says Donald Burnett, professor of nuclear geochemistry, emeritus, and the Genesis principal investigator. The particles scientists were looking for were individual atoms—the elements and isotopes that make up the sun. "You couldn't destroy the atoms in the crash," he says. "The only thing you can do is contaminate them." The atoms were embedded in the wafers, and as long as some surviving pieces were large enough for instruments to analyze, the mission was still alive. After several days of sifting and sorting, they found everything from powder to entire wafers. Cleaning off the Utah dirt and bits of capsule that were mixed into the samples would prove challenging, but the mission was anything but a failure.

Even now, scientists still have lots of cleaning to do, but after more than three years they are slowly arriving at some notable results, including the answer to a decades-long mystery about neon isotopes in the lunar soil. Researchers say they are confident they will complete most—if not all—of the experiments they planned for. All they need is enough time.

In the Beginning, There Was a Big Cloud

Genesis launched on August 8, 2001, but its origins lay more than 30 years earlier on the moon. The Apollo missions had amazed the world, capturing people's imaginations and a space-race victory



Apollo 11 lunar module pilot Buzz Aldrin sets up an aluminum sheet to collect the solar wind. This was the first of the Apollo missions' many solar wind composition experiments.

for the United States. But the astronauts did more than plant flags and take small steps for man and giant leaps for mankind. They also did science experiments, including one designed by researchers at the University of Bern to catch solar-wind particles.

A giant force field called the magnetosphere surrounds Earth, protecting it from the solar wind and other energetic particles from the sun. If researchers want to collect solar wind particles, they have to do it away from Earth—in space or on the moon. During Apollo missions 11 through 16, with the exception of ill-fated number 13, astronauts collected the solar wind with a big sheet of aluminum foil—they used platinum for 16—propped up on a pole. But since they were on the moon for only a few days, the experiment didn't last long, ranging from 77 minutes for Apollo 11 to less than four days for 16. The foil took an inventory of the wind's elements and isotopes, which are atoms of the same element but with a different number of neutrons.

"Isotopic geochemists ooh and aah over a half-percent difference—this was 38 percent!" Burnett explains. "That was just mind-boggling to someone used to thinking of things that were a fraction of a percent."

In particular, researchers looked at the ratio of neon-20 to neon-22 (neon-20 has 10 neutrons while neon-22 has 12). The ratio is about 9.8 to 1 in Earth's atmosphere, but Apollo's lunar foils found a ratio of around 13.7 to 1 for the solar wind—a vast difference that stunned researchers. "Isotopic geochemists ooh and aah over a half-percent difference—this was 38 percent!" Burnett explains. "That was just mind-boggling to someone used to thinking of things that were a fraction of a percent."

But what's the big deal if some isotope ratios are different between Earth and the solar wind? It's that the relative amounts of isotopes and elements are fingerprints left behind by the formation of the solar system. Tracking the isotopic and elemental composition of planets, moons, and asteroids tells scientists how well their models explain the solar system's history. For example, measurements of hydrogen-isotope ratios in Venus's atmosphere suggest that the planet lost a lot of hydrogen in its past. Deuterium is hydrogen with an extra neutron, and deuterium-hydrogen ratios in the outer layers of the Venusian atmosphere are higher than the original amount in the universe as a whole. Since hydrogen is a component of water, the hydrogen loss implies water loss—the isotope measurements imply Venus could have once had bucketfuls of water.

To compare ratios among isotopes, researchers need to know the composition of the cloud from which the sun, planets, moons, comets, asteroids, and assorted rocks and dust specks all formed—the solar nebula. According to standard theory, the solar system used to be a cool cloud of molecular gas, only a few tens of degrees above absolute zero. Then something—possibly a bump from a shock wave made by a distant exploding star—caused it to begin collapsing on itself by its own gravity. As the cloud collapsed, it began to spin, flattening out like pizza dough twirled into the air. The cloud's core grew in density and pressure until it was hot enough for hydrogen atoms to slam into each other, releasing nuclear energy. The sun was born. Meanwhile, the outer regions of the cloud coalesced to form the planets and everything else.

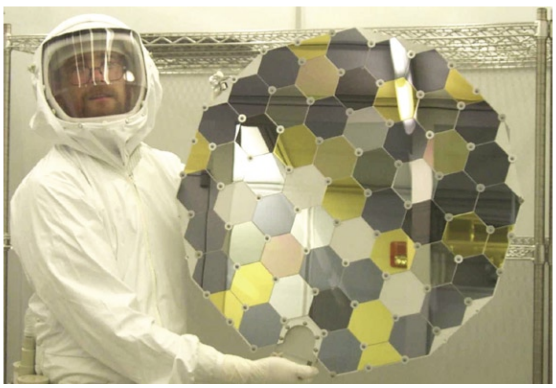
The sun makes up 99 percent of the solar system's mass, so for all intents and purposes it *is* the solar system—and the main product of the solar nebula. Inside the sun, many reactions and processes have changed its composition. But in the sun's outer layers, you should find the same distribution of elements and isotopes that once populated the solar nebula. The sun continuously ejects its outer layers as solar wind, and by capturing the wind, scientists have a piece of history, stretching back to the solar system's birth 4.6 billion years ago.

Comparing the composition of the solar wind—and therefore the solar nebula—with that of other bodies allows researchers to better piece together the story behind the solar system. The Apollo experiments, which first showed the astonishing difference in neon-isotope ratios between Earth and the solar wind, were the inspiration behind Genesis, Burnett says. But not until two decades after Apollo, in 1992, when NASA launched its

Discovery program to push for "faster, better, cheaper" missions to explore the solar system, did Genesis come to fruition. Led by Burnett and Marcia Neugebauer, a distinguished visiting scientist at JPL, the mission would be the first to return samples from outer space since the Soviet Union's Luna 24 brought back moon rocks in 1976.

Here Comes the Sun

Genesis would be a big improvement over the Apollo experiments. Instead of for a couple of days, Genesis collected solar particles for two years, and in place of aluminum foil on a stick, Genesis used 250 hexagonal wafers 10 centimeters wide, made of materials such as silicon, sapphire, diamond, and gold. The wafers were arranged on five collector arrays, three of which rotated in and out to sample the solar wind as experiments dictated, while the other two remained exposed at all times. The materials were chosen to enable researchers to analyze different elements and isotopes. Instead of just the few noble gases the Apollo experiments caught, Genesis cast a wide net to collect as much of the periodic table as it could, stockpiling data for future studies in order to make this the one and only trip ever needed to sample the solar wind. It's the most extensive and best-controlled solar wind collection ever done.



JPL's Andy Stone holds up one of the five collector arrays. Each array holds 50 hexagonal wafers of different materials.

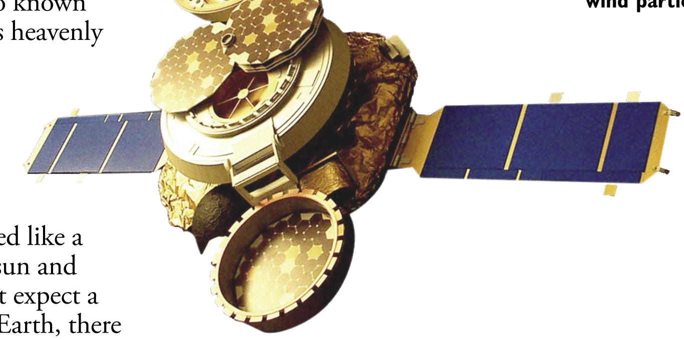
After launch, the spacecraft cruised for three months before arriving at a location between the sun and Earth called L1, or the first Lagrange point. Only 1 percent of the way to the sun, L1 is where gravity from the sun and Earth cancel each other out, resulting in a partially stable place for a spacecraft to occupy with minimal energy—and minimal cost (see *E&S* 2002 no. 4 for a fuller explanation). "It's a great place to park a spacecraft and observe the sun because it's easy to get to," Burnett says. Many other spacecraft, such as the Solar and Heliospheric Observatory, also known as SOHO, have also found a spot in this heavenly parking lot.

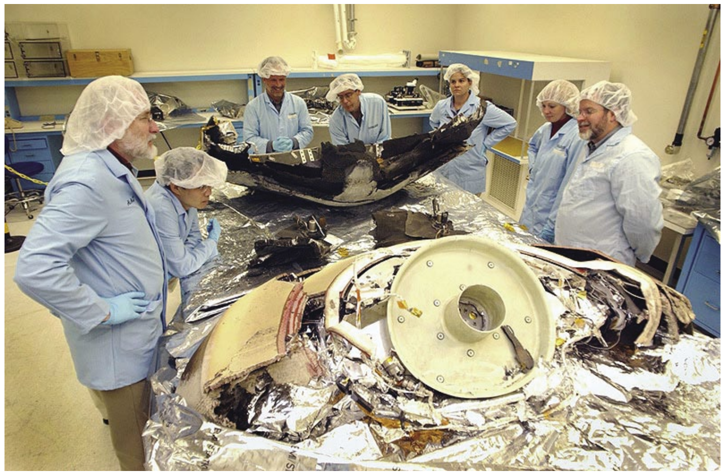
Unlike in a parking lot, however, spacecraft at L1 don't just sit in one place. Genesis, for instance, followed a halo orbit, in which it spent two years looping around an empty point in space. During its orbit, Genesis opened like a pocket watch, exposed its wafers to the sun and began to trap solar wind particles. Don't expect a lot, though. The wind is diffuse—near Earth, there are only five to ten particles per cubic centimeter. Genesis collected a total of 0.4 milligrams of solar wind.

After 27 months of sunshine, Genesis started the five-month journey home on April 22, 2004. Upon arrival at Earth, the spacecraft released the capsule that contained the solar samples. As the spacecraft hurtled away into the depths of space, Earth's atmosphere slowed the capsule's descent. Its final trajectory sent it toward the U.S. Air Force's Utah Testing and Training Range, an arid landscape 130 kilometers southwest of Salt Lake City. There, in a scene worthy of an action movie, Hollywood stuntmen piloting helicopters were to snare the capsule as it drifted down by parachute, and bring the precious cargo to the scientists like a stork delivering a baby.

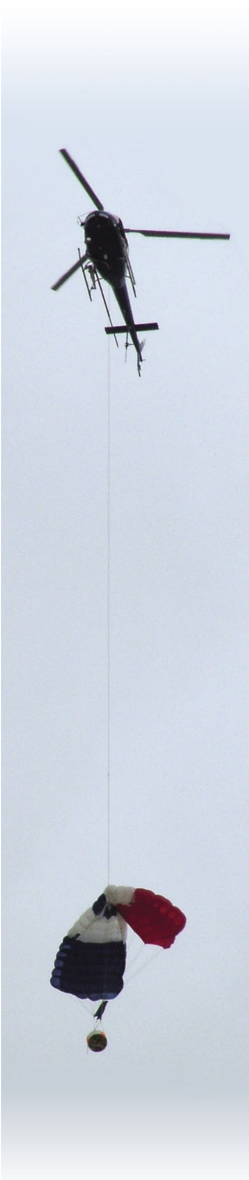
Unfortunately, the team never got to show off its deft maneuver, as the parachutes never opened and the capsule crashed, leaving the helicopters hovering without a package to snag. Had it worked, however, it would've been quite the spectacle—although the scientists weren't in it for the added drama. "We did it for a reason," Burnett says. "We were worried about things breaking." A conventional parachute-assisted landing would have been too risky for the thin and fragile wafers. If gusts of wind blew while Genesis landed, the capsule could hit the ground and tumble, smashing the precious cargo and costing extra time and money to sift through the pieces. That, of course, was exactly what ended up happening. The plan was sound, however, and the only safe option, Burnett says. "We thought it was worth an extra million dollars or so to pick the thing out of the air just to allow us to stay on schedule," he explains. "This was deemed technically feasible, and frankly, it looked like a lot of fun—and it was." During practice, the recovery team was perfect, but on the big day, the landing was anything but fun.

This artist's conception shows the Genesis spacecraft opening up to collect and store samples of solar wind particles.





Large sections of the Genesis sample-return capsule that survived the hard landing were shipped to Lockheed Martin's facilities in Denver, Colorado. Here, engineers begin inspecting the wreckage to figure out why the capsule crashed.



A specially modified helicopter with a boom and winch underneath snags the parafoil chute attached to a model Genesis sample-return capsule. The hook on the end of the boom collapses the chute, allowing the helicopter to retrieve the capsule in midair.

A Smashing Success?

"On September 8, 2004, the Genesis project literally hit bottom," Burnett says. Along with the team, he watched the descent on television monitors at the control center, several kilometers from where the capsule was supposed to land. The cone-shaped drogue chute, which would have provided stability until the main chute deployed, was supposed to have fired at an altitude of 108,000 feet. When the team realized the parachutes had failed, they hardly had enough time to react—the capsule would crash just 20 seconds later, Burnett estimates. But he didn't stick around to watch, he says. By the time the capsule had fallen to 3,000 feet, he had already taken off for the next building, where the recovery team was preparing to be helicoptered to the crash site, roughly 15 kilometers away. Despite the chaos around them, the science team was focused on the task at hand, too busy to worry about what went wrong, according to Burnett. The attitude was, "OK, it's crashed. Let's go out and see what we can get."

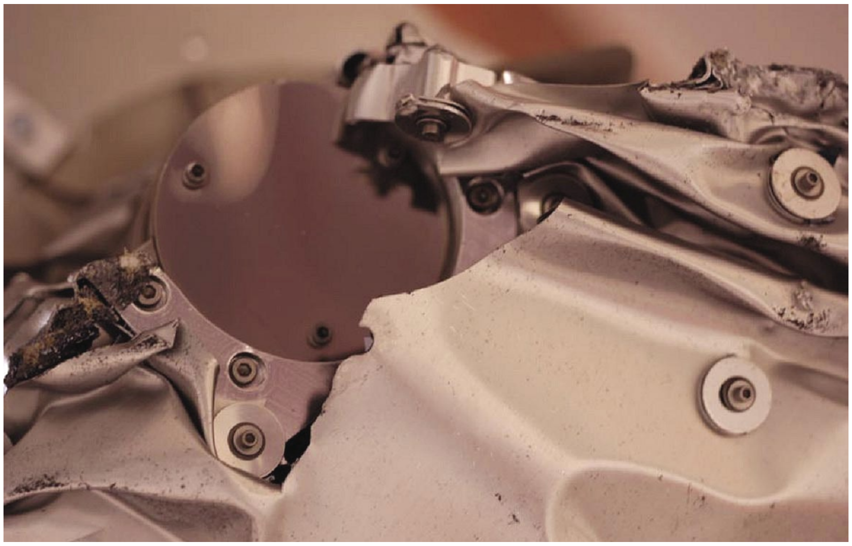
The team was afraid water would seep up from the ground at night and damage the samples, so they wanted to bring back the pieces the same day. The helicopters that were supposed to pick up the capsule from the air were instructed instead to carry the wreckage back to the control center. But by then, they had been flying around all day, and were running out of gas, Burnett recalls. Fortunately, the recovery team, which consisted of people from Lockheed Martin, which had built the craft, and NASA's Johnson Space Center, rescued most of the remains within a few hours—before the gas tanks went dry. They returned the next day to gather the smaller pieces, scooping up the dirt and bringing it back to the hangar where the team had begun digging through the mess of gnarled metal and shattered wafers. Meanwhile, JPL engineers had gone to a hardware store in Salt Lake City and bought every tool in sight, Burnett recalls. "They came back with this big truckload of tools and slowly started systematically crowbarring this thing apart."

With the JPL team prying the wreckage open for the science team to sort the contents, much of the work was finished within two weeks, according to Burnett. Some team members remained in Utah for several more weeks to complete the effort, and the wafer pieces were sent to the distribution center at Johnson Space Center in Houston.

Luckily for science, some macroscopic pieces survived. Had they all been crushed to smaller than three millimeters, instruments wouldn't be able to analyze them. Still, the ongoing process of picking through and analyzing so many bits has proven tedious—instead of 250 wafers, scientists have 15,000 pieces—and most of the pieces are tiny. "There are a lot more three-millimeter pieces than three-centimeter pieces," Burnett says. Meanwhile, the main problem is contamination. With desert dirt and minced scraps of capsule jumbled together, can researchers really clean the wafers?

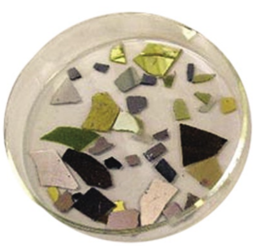
"We can!" Burnett says. "We can because the dirt is really on the surface and our sample is beneath the surface. It's not far, but it's safe—we can prove it's safe." The separation between the dirt and solar wind particles may only be 20 nanometers—20 billionths of a meter—so researchers can't just grind away the top layer. In one cleaning method, they put the material in a water bath. They then fire acoustic waves at microwave frequencies—hundreds of millions to hundreds of billions cycles per second—that jostle the water, dislodging the dirt. "We have to get rid of that dirt while basically taking off no material—not impossible, but a big challenge," he says.

In some experiments, researchers can dodge individual flecks of dirt. In others, dirt isn't even a problem, and for those, researchers already have noteworthy results. For example, contamination is a nonissue when analyzing elements like neon, since those elements aren't in the dirt to begin with.



The metallic glass wafer, designed to collect helium and neon isotopes, survived the crash. The material was the key to solving a decades-long mystery about the lunar soil.

The team also lucked out when special samples survived, such as a wafer made out of a material called metallic glass. "That's amazing," Burnett says. "If you had one material that I thought was too brittle and was going to break during the crash, it was that one." Developed in 1998 by JPL scientist Charles C. Hays while in the lab of William Johnson (PhD '75), Mettler Professor of Engineering and Applied Science, this metallic glass wafer is an alloy of aluminum, copper, nickel, niobium, and zirconium. Unlike regular metals, whose atoms are in a gridlike configuration, atoms in metallic glasses are arranged randomly, as they are in ordinary glass. This configuration makes for a better catcher's mitt for solar wind particles, Hays explains, as high-energy particles such as neon and helium, once embedded, are more easily trapped in the nooks and crannies of the material's random structure. Using metallic glass to catch solar wind particles is a first, and its survival has been crucial in solving a decades-long mystery about neon isotopes in the lunar soil.



The team recovered some relatively large wafer pieces from the crash site. The fact that these fragments survived means most, if not all, experiments can still be done.

Solving a Lunar Puzzle

Apollo's lunar soil samples, which had been exposed to the sun for thousands of years, returned some peculiar data about the solar wind. When researchers measured the neon-20 to neon-22 ratios in the samples, they found ratios clustering around two values, at about 13.8 and 11.2 to 1. The first value was a clear signature of the solar wind, since it agreed with what Apollo's aluminum foil experiments measured. The second value, however, was a mystery. Not only did it not fit with the familiar solar-wind signature, there was a lot of it, so much so that if these neon isotopes came from the sun, the data implied a strange surge of solar activity in the past.

A lower neon-20 to neon-22 ratio implied a higher prevalence of the heavier neon-22 isotope in the solar wind. The wind itself must then have had more oomph, penetrating deeper into the soil grains. To explain the curious data, scientists proposed a new component of the solar wind called solar energetic particles.

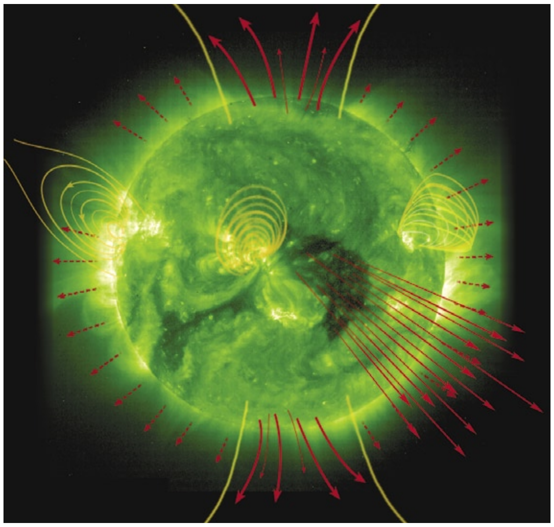
But using data from Genesis, a team from the Swiss Federal Institute of Technology in Zurich reported in 2006 that these solar energetic particles likely didn't exist, and that scientists had been misinterpreting the lunar soil data for 30 years. The key to solving the lunar puzzle was the metallic glass wafer. The researchers were able to release the isotopes layer by layer with a nitric-acid etching technique. The uniform etching revealed how the isotope ratios correlated with depth, which was not the case with the lunar soil. In the metallic glass, the researchers found that neon-20 to neon-22 ratios fell continuously the deeper they went. Deeper levels had the puzzling lower value found in the lunar soil, and the deepest levels had even lower values. In other words, the heavier neon-22 embedded itself deeper into the metallic glass without needing a more energetic source of particles. "It took Genesis samples to see this clearly," Burnett says.

Another advantage of the Genesis data was the lack of cosmic rays. Since the lunar soil was exposed for millennia, cosmic rays had been reacting with it, producing neon that polluted the data. At lower neon-20 to neon-22 ratios, beginning at values near the 11.2 associated with the alleged solar energetic particles, you can't tell whether you're looking at data from the solar wind or cosmic rays. But since Genesis was only up for two years, it avoided cosmic-ray effects, and gave clean data.

Furthermore, when the team compared their results with a computer model of how neon-isotope ratios correlate with depth, the data matched perfectly. The conclusion seemed clear: a simple, single-component solar wind explained the observations. The result might not have been as exciting as discovering a new type of solar wind or some bizarre solar behavior, but at least researchers solved the problem. "There was a mystery of what this stuff was, and we've solved it by doing a clean experiment, without any of the complications of a lunar sample," Burnett says.

Same Differences

In October, a team led by scientists at Washington University in St. Louis reported the second major set of Genesis results. They analyzed the population of neon and argon isotopes in the solar wind and addressed a key question about the crucial assumption upon which Genesis science is based—that the solar wind accurately reflects the solar nebula. The outer layers of the sun preserve the composition of the solar nebula, but the solar wind doesn't necessarily preserve the composition



This ultraviolet image of the sun, taken by SOHO, shows the outer atmosphere of the sun, the corona. The atmosphere is threaded with magnetic fields (yellow lines). Areas with closed magnetic fields give rise to slow, dense solar wind (short, dashed, red arrows), while areas with open magnetic fields—so-called coronal holes—yield fast, less dense solar wind streams (long, solid, red arrows). In addition to the permanent ones at the sun's poles, coronal holes sometimes occur closer to the sun's equator, as shown here just right of center.

of the outer layers. When the sun expels its outer layers as the solar wind, the process could change the chemical makeup. If this happens, then different types of solar wind should also have different compositions.

Genesis sampled the three types of solar wind: high-speed winds that can blow faster than 500 kilometers per second, low-speed winds that blow at less than 500 kilometers per second, and big blasts of solar material called coronal mass ejections. The team found no differences among all three types. Although the implications aren't clear yet, researchers say these high-precision results will be essential for future studies and theories about the solar system's history.

For instance, the study included the most precise measurements yet of argon-36 to argon-38 and neon-20 to neon-22 ratios in the solar wind. In both cases, the ratios are higher than those in Earth's atmosphere. Lower ratios on Earth mean there are less of the lighter argon and neon isotopes in our atmosphere now than in the solar nebula from which our planet formed. Where did the lighter isotopes go? Theory says lighter isotopes have a greater tendency to fly off into space during planet formation, Burnett explains, and so the Genesis data suggests Earth lost some of its atmosphere early in its history. Future analysis of other noble-gas isotopes from Genesis will further refine these models.

It's All Right

Why did Genesis crash in the first place? Investigators concluded a sensor that measured the capsule's deceleration failed to tell the parachutes to open. The G-switch sensor—a silver cylinder no bigger than a pencil's eraser that measures gravitational forces—was installed backward. The investigation report in addition faulted the project's review process for not catching the mistake. Citing the failures of the Mars Climate Orbiter and Mars Polar Lander, the report also criticized NASA's "faster, better, cheaper" philosophy for making missions riskier in the name of saving money.

For Genesis, however, good science is emerging. Burnett has listed 19 main science objectives, and solving the lunar mystery and measuring the argon and neon compositions were two of them. Materials dedicated to the highest-priority experiment, which collected oxygen isotopes, also survived. As they continue to clean the samples, researchers are working hard to check items off Burnett's list. He can't swear all the science will be recovered, but he is optimistic. Still, he regrets the hard landing. "We were ready to go," he laments. "We even cancelled our last practice, we were in such good shape. It was really a shame we didn't get a chance to prove just how good we really were."

Perhaps as a memento of what could have been, Burnett keeps a photo of a helicopter successfully capturing a test capsule beside the door to his office. But the most famous picture, a picture he says he likes to avoid, shows the poor space capsule smashed into the dirt. "It looks like it's buried," he says, describing the semicircular hunk of metal sticking out of the ground. "It's not buried—it's smashed. It was round, now it's D-shaped. The ground was very unyielding at 200 miles per hour."

The landing wasn't pretty, but instead of a sad end, the best description for it may be the words of George Harrison: "Here comes the sun; it's all right, it's all right." □

This silicon carbide target is part of the oxygen isotope collector, Genesis's highest-priority experiment. It survived the crash intact.

PICTURE CREDITS: 29, 30, 32-33—NASA/JPL-Caltech; 30, 35—SOHO (ESA/NASA); 31-35—NASA/JSC