"True Grit"–Unearthly Dust

by **Trudy E. Bell**

"**Dust is going to be <u>the</u> environmental problem for future missions, both inside and outside habitats.**"
– Harrison H. "Jack" Schmitt, geologist and Apollo 17 astronaut

Sand and dust. On Earth, you tread them underfoot without a thought.

Yet on the Moon and Mars, the sand and dust have such bizarre and lethal properties that in June 2005 NASA officially ranked them among the top hazards to be mitigated if any human astronauts or robotic machinery are to establish permanent outposts on either planet—and survive.

We're not talking house dust. Most dust that collects on furniture in your home is actually organic material: dead human skin cells, pet dander, pollen grains, textile fibers, human and animal hairs, parts of plants and insects, and the like. For the most part, it's soft—wipe it off with a cotton cloth and it won't scratch polished wood. And it's usually not thick—even an attic corner that hasn't been swept in years may have less than an eighth of an inch.

On the Moon and Mars, though, the dust is razor-sharp grit: shards of inorganic rock and powdered glass. Wipe your spacesuit's sun visor, and you've scratched the protective layer of gold. Get it into your spacesuit's joints, and you've fouled the bayonet attachments and air seals. Work with tools, and the abrasive dirt clogs bolt holes, dulls tools, and chews up your gloves. Try to brush it off your spacesuit before re-entering your habitat, and its barbed edges dig the particles further into the fabric. Track it inside the habitat, and it becomes airborne. Breathe it in, and if you're lucky you'll sneeze it out—but the finest motes may lodge deep in your lungs where your immune system can't reject them, putting you at risk of silicosis, the "stone-cutter's disease" that killed hundreds of unprotected miners in the 1930s.

And that's just the Moon.

On Mars, there's all that, plus there's strong evidence suggesting Martian dust may be such a strong oxidizer (think of powdered bleach or lye) laced with heavy metals such as hexavalent chromium (think of the carcinogen in the movie *Erin Brockovich*) that it may be corrosive and chemically poisonous. This pernicious grit gets whipped through the thin air at hurricane speeds in planet-wide dust storms or in the scores of towering daily dust devils that bedevil Martian summers, scouring surfaces and filtering into the tiniest openings.

And on both planets, the dust is highly magnetic (for different reasons), so it sticks to anything with an electromagnet, including motors and electronics.

Welcome to the gritty reality of establishing permanent outposts on the Moon in preparation for sending humans on to Mars, the ambitious mission toward which NASA has reorganized its priorities since President George W. Bush announced his Vision for Space Exploration in January 2004.

Lunar dust is full of tiny holes and is jagged like little burrs, making it uniquely abrasive and giving it a large surface area for its mass—characteristics that also give it bizarre properties that must be reckoned with by any astronauts returning to the Moon.

So what are scientists and engineers doing to ensure that it won't, well, grind human planetary exploration to a halt?

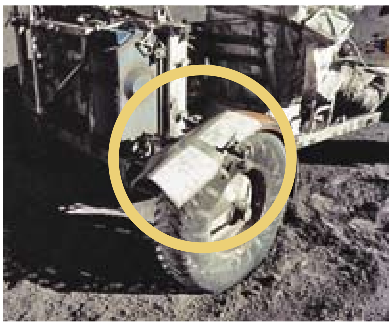
Dirty dozen

Only 12 humans have ever set foot on another planet—the astronauts of Apollo missions 11, 12, 14, 15, 16, and 17 who landed on the daytime side of the Moon between 1969 and 1972. Their stays ranged from 21 hours for Neil Armstrong and Buzz Aldrin, *MA B '62*, of Apollo 11, to 75 hours for Harrison H. "Jack" Schmitt and Eugene A. Cernan, *IN A '56*, of Apollo 17. The last three missions included an open dune-buggy-like Lunar Rover, which allowed astronauts to roam afield.

As revealed by the *Apollo Lunar Surface Journal* (the transcript of the radio transmissions between Houston and the Moon for all six surface missions), after Apollo 14, landing parties were equipped with a house-paintbrush-sized dust brush six inches across and an inch thick. Every few minutes, they had to stop just to "dust and dust and dust some more" so they could connect batteries, see dials or camera settings, assemble experiments, operate tools, or even identify different geological samples. Each of three Lunar Rovers broke a fender, so the exposed wheel shot up a thick rooster tail of lunar dust that showered their occupants and equipment with inches of clogging filth.

"It was just an unacceptable situation" with "the potential of compromising the rest of our mission," Cernan exclaimed later—which was why Mission Control concentrated on ways the astronauts could cobble together makeshift fenders (a map, a clamp, and some duct tape). "There's got to be a point where the dust just overtakes you, and everything mechanical quits moving."

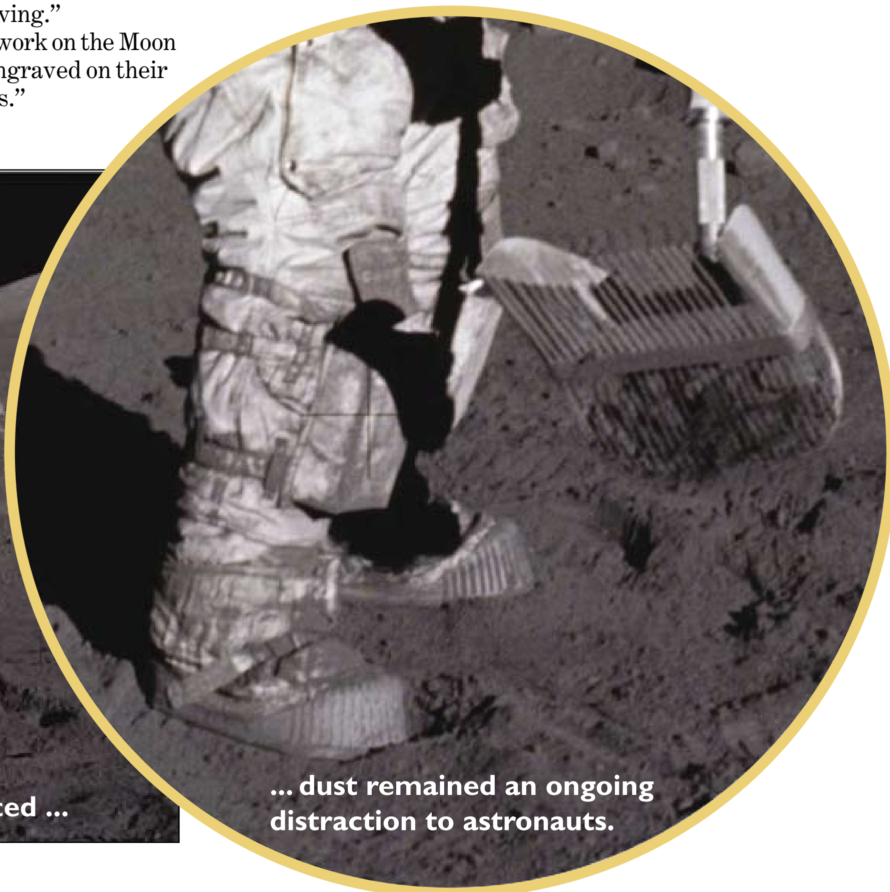
Schmitt affirmed, "Anyone planning to work on the Moon or Mars ought to have Gene's statement engraved on their forehead and on the inside of their glasses."



Lunar rover wheels stirred up so much dust (above) that makeshift dust fenders had to be added (left).

Photos on this page courtesy of NASA

While few at home likely noticed ...



... dust remained an ongoing distraction to astronauts.

Lunar "rays" and glows

While orbiting the Moon, the astronauts routinely photographed the solar corona (the sun's outer atmosphere) just before lunar "sunrise" each orbit and just after lunar "sunset," for an experiment to determine the corona's full spatial extent *sans* total solar eclipse. But they serendipitously saw something else intriguing: "bands," "streamers," or "twilight rays" that persisted for about 10 seconds before lunar sunrise or lunar sunset. Such rays were also reported by Apollo 8, 10, and 15.

Sketches by the Apollo 17 astronauts in 1972 reveal that lunar twilight rays closely resemble beams of sunlight and shadow seen radiating upward from the horizon on Earth if the sun is setting behind low clouds or mountains, observed astronomers Aden and Marjorie Meinel in their book on meteorological optics: *Sunsets, Twilights, and Evening Skies*. Technically known as "crepuscular rays," on Earth such beams arise because sunlight is scattered (reflected in all directions) from tiny water droplets or motes of dust high in the atmosphere.

Equally suggestive, early Surveyor spacecraft that soft-landed on the Moon before Apollo returned photographs showing an unmistakable twilight glow low over the lunar horizon that persisted after the sun had set. Also, the horizon did not look razor-sharp, as would have been expected in a vacuum where there was no atmospheric haze.

In the 1970s, several planetary scientists wrote papers speculating that all these phenomena were caused by sunlight being reflected from dust somehow suspended above the Moon. At the time, the observations and speculations gained little traction, because few scientists could understand how—absent an atmosphere—lunar dust could hover above the Moon's surface. After all, even if temporarily kicked up by, say, a meteorite impact, wouldn't dust particles rapidly settle back onto the ground?

Well, no—at least not according to the "dynamic fountain model" for lunar dust proposed last year by Timothy J. Stubbs, Richard R. Vondrak, and William M. Farrell of the laboratory for extraterrestrial physics at NASA Goddard Space Flight Center. "We use the word 'fountain' to evoke the idea of a drinking fountain: the arc of water coming out of the spout looks static, but we know the water molecules are constantly in motion," Stubbs explained. Their model hypothesizes that individual microscopic grains of lunar dust may be constantly leaping up from and falling back to the Moon's surface, giving rise to a rarefied "dust atmosphere" composed of dust particles in constant motion.

What could cause dust particles to jump off the Moon? Two words: *electrostatic lofting*.

Extraterrestrial electrostatics

According to Stubbs, lunar dust is electrostatically charged by the Sun in two different ways: sunlight itself by day, and the solar wind (charged particles flowing out from the Sun) by night.

On the day-lit side of the Moon, solar ultraviolet and X-ray radiation is so energetic that it ionizes atoms and molecules on the surfaces of dust grains in the regolith (the powdery lunar "soil"). Minus outer electrons, positive charges build up on the lunar surface until the tiniest particles of lunar dust—those one micrometer and smaller—are repelled and lofted from meters to kilometers high. Although they do fall back, the process is repeated endlessly.

On the night-dark side of the Moon, though, "data from the Lunar Prospector mission suggests that the [electrical] potential might be hundreds of volts negative," Stubbs continued. So he and his colleagues think dust is repelled from the surface on the Moon's dark side—but it would have a negative charge due to electrons coming from the solar wind, which flows around the Moon onto the night side.

Where things get really interesting, then, is at the Moon's terminator—the moving line of sunrise or sunset between lunar day and night. With a net positive charge by day and a net negative charge by night, there could be "significant horizontal electric fields forming between the day and night areas, so there might be horizontal dust transport," Stubbs speculated. "Dust would get sucked across the terminator sideways." Because the biggest flows would involve microscopic particles invisible to the naked eye, no astronaut would see dust speeding past. Still, if on the Moon's dark side and alert for lunar sunrise, Stubbs said an astronaut "might see a weird, shifting glow extending along the horizon, almost like a dancing curtain of light."

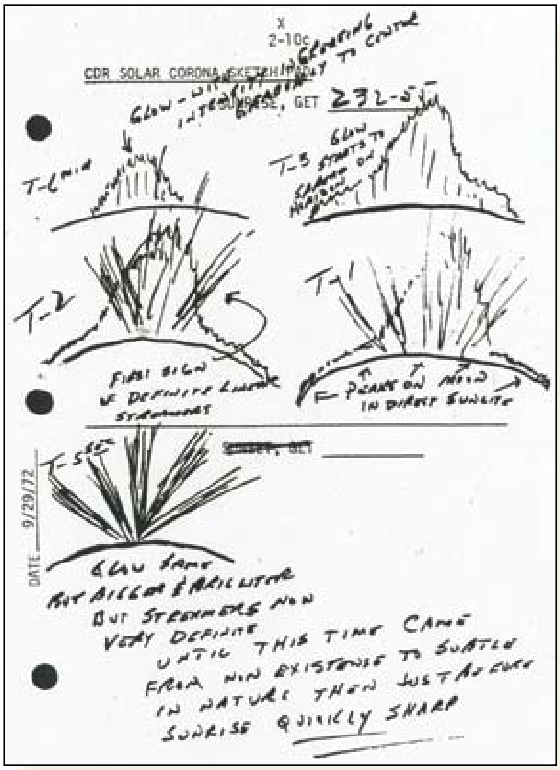


Fig. 1. These sketches by Apollo astronauts of high-altitude "bands," "streamers," or "twilight rays" at lunar sunrise or sunset set several planetary scientists wondering whether lunar dust might be suspended high above the Moon's surface.

Ground truth

Possibly giving credence to the exotic dynamic-fountain hypothesis are two sets of experimental data.

First, in 1972 one of the experiments Apollo 17 left on the Moon was Lunar Ejecta and Meteorites (LEAM), designed to look for dust grains ejected when meteorites struck the lunar surface or for grains hitting the moon from comets or from interstellar space. LEAM had three sensors that could record the speed, energy, and direction of tiny particles: one each pointing up, east, and west.

Surprisingly, "LEAM saw a high number of particles every sunrise, mostly coming from east or west rather than from above and mostly far slower than the energies expected for lunar ejecta or for interplanetary or interstellar grains," explained Gary Olhoeft, professor of geophysics at the Colorado School of Mines in Golden. The high counts of low-energy particles lasted about 40 hours before and 30 hours after sunrise. Olhoeft and others now suspect LEAM was recording evidence of a long and skinny sunrise dust storm—yes, a dust storm on the airless Moon!—sweeping along with the terminator and stretching all the way from its north pole to its south.

Additional indirect evidence comes from the fact that a few hours after every lunar sunrise, LEAM's internal temperature rocketed up so high that each day "LEAM had to be turned off because it was overheating," Olhoeft said. Although puzzled at the time, scientists today wonder whether the observations meant that "lunar dust was acquiring an electrostatic charge and was being kicked up to cover LEAM, darkening its surface so the experiment package absorbed rather than reflected sunlight," Olhoeft added.

Meantime, in a Zen-like experiment, Mian Abbas, a senior space scientist in the dusty plasma laboratory in the national space science technology center at Marshall Space Flight Center in Huntsville, AL, and colleagues Paul Craven and Dragana Tankosic spend days at a time examining—a single grain of lunar dust. Using lunar dust provided by Lawrence A. Taylor of the University of Tennessee, Abbas and company are investigating how individual grains lose electrons and become positively charged when illuminated with intense ultraviolet light.

"Experiments on single grains are helping us to understand how lunar dust on the Moon can be given an electric charge and then levitated to high altitudes," Abbas said. A single particle of lunar dust is injected into a basketball-sized vacuum chamber, which is pumped to simulate the near-perfect vacuum on the Moon. Then he shines a UV laser onto the particle and painstakingly controls the strength of electric fields in the chamber until the particle levitates and is suspended. At that point, Abbas can measure its electrical charge, the rate at which it charges, and other important characteristics.

Already, Abbas has found that lunar dust grains larger than one to two micrometers across charge at a rate of 10 to 30 times more than the current estimates and that bigger grains charge up more than smaller grains (0.5 micrometer) —just the opposite of what some theories predict. (Stay tuned. Abbas now wants to bombard dust grains with a beam of electrons from an electron gun, mimicking the solar wind during the long lunar night.)

If Stubbs, Olhoeft, and Abbas are right, then engineers have some planning to do. "Charged, levitating dust particles moving across the lunar surface could lower visibility when the terminator passes," said Olhoeft, "and could stick to astronauts' faceplates, cameras, and spacesuits."

Dusty magnetism

Meantime, Taylor and his colleagues were studying lunar dust to calibrate data recorded by the Clementine orbiter launched in 1994 to map the Moon. "Remote-sensing instruments on satellites don't see rocks. They see soil particles reflecting sunlight," Taylor explained. So he and his colleagues characterized the chemical composition of minerals in lunar regolith at the old Apollo landing sites so as to correlate it with what Clementine recorded there and elsewhere. While studying the powdery dirt, however, Taylor noticed two things.

First, the regolith was full of glass beads that were themselves full of particles of metallic elemental iron—so-called "nanophase" iron—which made the glass magnetic. Best estimate is that such glass forms when micrometeorites strike the Moon at cosmic velocities—tens of kilometers per second (more than 25,000 miles per hour)—heating the regolith more than 2,000°C, literally the surface temperature of red stars, vaporizing molecules that then separate into their elemental forms.

A CHANCE ENCOUNTER

◀ BEFORE
Reddish dust on Mars deposits itself thickly on every surface as shown in this photograph taken during an experiment on the Spirit rover in Gusev Crater on March 23, 2005.

AFTER ▶
Later, a passing dust devil apparently removed much of the accumulated dust.

Photos courtesy of NASA

Second, every regolith particle, regardless of size or composition, seemed to have a thin external coating less than a micrometer thick of the same nanophase iron. Such a thin iron coating on relatively massive sand- or gravel-sized particles isn't enough to make them magnetic. But on the smallest dust particles (less than 20 micrometers across) it is, and the finest dust can be picked up with a magnet.

When Taylor mentioned this in 2002 to Apollo 17 geologist-astronaut Schmitt, "Jack exclaimed, 'Heck, if only we'd had a brush with a little magnet attached!' " Taylor recalled, because it was the finest dust that was most troublesome. "That's when I realized our basic scientific research could help solve lunar dust problems," Taylor said.

Since then, Taylor has designed a prototype air filter that uses electromagnets. "When the filter gets dirty, you pull the plug on the electromagnet, tap it, and the dust falls into a disposal container." He's even thinking radically. "I'm one of those weird people who like to stick things in ordinary kitchen microwave ovens to see what happens," he confessed to several hundred scientists at the Space Resources Roundtable/Lunar Exploration Advisory Group conference in October 2005. When he put a small pile of lunar soil into a microwave oven, he found it melted at 1,353°C, faster than his tea water boiled at 100°C—moreover, it happened "lickety-split," he said, within 30 seconds at only 250 watts. The nanophase iron beads so efficiently concentrated the microwave energy that they sintered or fused the loose soils into large clumps.

That observation has inspired Taylor to imagine machinery to abate dust by fusing it into useful products. "Picture a 'microwave Zamboni' outfitted with an array of magnetrons," the gizmo that's the guts of a microwave oven, Taylor suggested. "With the right power and microwave frequency, an astronaut can drive along, sintering continuous brick down half a meter deep—and have a few other magnetrons set at different frequencies and power that would melt the top inch or two to make a glass road," he continued. "Or say that you want a Moon-based radio telescope. Find a round crater, dig it out to a parabolic shape, run a lunar-dust microwave 'lawnmower' up and down the crater's sides to sinter a smooth surface, and hang an antenna from the middle—*voila*, instant Arecibo!" he exclaimed, referring to the 305-meter-diameter radio telescope in Puerto Rico formed from a natural circular valley.

Devil-chasers

According to the 2004 Vision of Space Exploration, the Moon is to serve as a testbed for evaluating the effectiveness of equipment and techniques for astronauts who might live and work on Mars. But the two bodies have less in common than meet the eye. Aside from Mars's gravity being twice that of the Moon (and a third that of Earth), Mars also has an atmosphere—far thinner than that atop Mount Everest to be sure, but enough to make significant differences in the behavior of Martian dust and its engineering challenges.

For example, every Martian summer, when daytime high temperatures soar all the way up to a balmy 20°C (68°F) from the summer nighttime low of -90°C (-130°F), the devils of Mars come alive.

Dust devils, that is.

Each Martian spring or summer day, they begin appearing about 10 a.m. as the ground heats and start abating about 3 p.m. as the ground cools (Mars's solar day of 24 hours 39 minutes is 39 minutes longer than Earth's). At the peak of Martian summer, "if you looked around in the middle of the day, you'd see half a dozen," said Mark T. Lemmon, associate research scientist in the department of atmospheric sciences at Texas A&M University.

These are no little Arizona desert whirlwinds, only a few tens of meters high and a few meters across and past in seconds. Martian dust devils are monster columns one to two km across and towering eight to 10 km high, 10 times larger than any tornado on Earth—so big, they've been photographed from the orbiting Mars Global Surveyor.

What looks like hair lying across a ring (left) are actually tracks from hundreds of dust devils traveling around and through a crater on Mars, scouring away lighter material to reveal darker soil underneath, as photographed by Mars Global Surveyor on December 5, 2003. Although the tracks generally trend in one direction by prevailing winds, some curve or even spiral due to variations in local terrain. Mars Global Surveyor has even photographed dust devils themselves in the very act (below), whose long shadows reveal they can tower up to eight to 10 km high.

Photos on this page courtesy of NASA

Photo courtesy of NASA

Three Martian dust devils were captured on video (one frame shown above) on August 19, 2005, by the Spirit Rover in Gusev Crater. This and other movies plus various still photos can be accessed and viewed at *photojournal.jpl.nasa.gov/PIADetQuery.html* by typing "dust devils" under "Search by feature name."

Because red-brown sand and dust whip around faster than 30 meters per second (110 kilometers per hour), "the sand in the lower part of a Martian dust devil would be the biggest hazard," Lemmon went on. "The atmospheric pressure on Mars is only one percent of that at sea level, so astronauts wouldn't feel much wind. But they'd still be pinged by high-speed material."

Moreover, as grains of sand and dust keep banging into one another, Martian dust devils may become electrified through triboelectric charging (the prefix "tribo" meaning "rubbing"). In both terrestrial and Martian dust devils, "you cannot assume that the dust—which can blow in from anywhere—is the same composition as the local sand," cautioned Lemmon. Smaller dust particles tend to charge negative, taking away electrons from the larger sand grains.

Moreover, because dust devils are powered by a rising central column of hot air, the negative-charged dust is carried upward, leaving the heavier positive-charged sand swirling near the base. The charges get separated, creating an electric field. "In Arizona dust devils, we've measured electric fields on the order of 20 kilovolts per meter," said William M. Farrell, staff scientist in the solar system exploration division at NASA Goddard Space Flight Center, Greenbelt, MD. That's peanuts compared to the electric fields in terrestrial thunderstorms, where lightning doesn't flash until electric fields get 100 times greater—enough to ionize air molecules. But a mere 20 kV/m "is very close to the breakdown of the very thin Martian atmosphere," Farrell pointed out.

More significantly, Martian dust devils are so tall that their stored electrical energy may be quite high. "How would those fields discharge?" Farrell asked. Even if lightning wouldn't ordinarily occur naturally on Mars, the presence of an astronaut might induce filamentary discharges, or local arcing. "You'd have to watch out for corners, where electric fields can get very strong," he added. "You might want to make your vehicle or habitat rounded."

Another consideration would be "radio static as charged grains hit bare-wire antennas," Farrell warned. And after the dust devil was gone, a lasting souvenir of its passage would be an increased adhesion of dust to space suits, vehicles, and habitats via electrostatic cling.

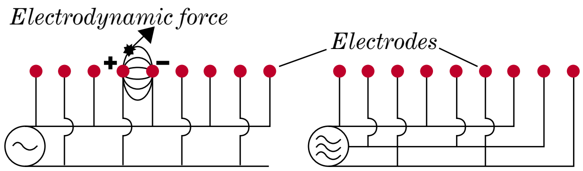
Planetary meteorologists now think dust devils may be responsible for throwing so much dust high into the Martian atmosphere, possibly triggering planet-wide dust storms. More importantly for potential astronauts, that dust may carry negative charges high into the atmosphere as well. Such a high-altitude charge build-up could pose a hazard to a rocket taking off from Mars, as happened in November 1969 when Apollo 12 lifted off during a thunderstorm; the rocket exhaust ionized the air, leaving a trail of charged molecules all the way down to the ground, triggering a lightning bolt that struck the spacecraft.

Dust busting

"One of the best ideas is to keep space suits external to habitats," said Schmitt in a recent interview: design suits so they dock to the outside of a habitat as if they were a separate vehicle for astronauts to enter and exit.

Meanwhile, a team led by Carlos I. Calle (lead scientist at NASA's electrostatics and surface physics laboratory at Kennedy Space Center) has used a bit of intellectual judo to figure out how to use dust's electrostatic charge to repel it, adapting a technique devised by electrostatics pioneer Senichi Masuda of the University of Tokyo during his work in the 1970s on air-pollution filters. Because smog particles are often charged, Masuda developed a prototype of what he called the "electric curtain:" a series of parallel electrodes—thin copper wires—spaced roughly a centimeter apart in a circuit board, to which Masuda applied alternating current. But instead of providing the same alternating current to all the parallel electrodes at once, Masuda slightly delayed the onset of the current to each successive electrode. That slight delay made the electromagnetic field of each electrode to be out of phase with its neighbors, creating an electromagnetic wave that rapidly traveled horizontally across the surface on which the electrodes lay. Any charged particles lying on the surface were lifted and swept along by that traveling electromagnetic wave, like surfers before an ocean wave.

In 2003, after seeing how Martian dust collecting on the solar panels of Mars Pathfinder deprived it of electric power, Calle and his collaborators wondered if the electric



(a) Single-phase electric curtain. (b) Three-phase electric curtain.

curtain could free solar panels of dust. After all, Calle reasoned, "human and robot astronauts can't always be cleaning windows."

To let sunlight through, the device would need transparent electrodes. So Calle and his colleagues made electrodes out of indium tin oxide, transparent semiconducting oxides used in the touch screens of personal digital assistants, and moved the electrodes just a few millimeters apart. The result was a transparent film, flexible as a sheet of vinyl, that they call an electrodynamic dust shield.

When the shield was put in a vacuum chamber that was then pumped down to the rarefied atmospheric pressure of Mars or the Moon and covered with simulated lunar or Martian dust (ground-up volcanic ash and cinders from terrestrial volcanoes), most of the dust is thrown off to the side in seconds. "I'm hoping to try the experiment with actual lunar dust with its nanophase iron," Calle said. He also wants to make the concept work around sharp angles, such as folds of a space suit.

Minimizing 'Murphy's Law'

What would engineers designing any spacecraft to carry the first humans to Mars need to know to maximize the odds of a safe return to Earth? That's the focus of a June 2005 report "An Analysis of the Precursor Measurements of Mars Needed to Reduce the Risk of the First Human Mission to Mars" by NASA's Mars exploration program analysis group.

The heart of this report is a full-page table on page 11 that lists 20 risks, "any one of which could take out a mission," said the report's lead author David Beaty, Mars program science manager at the Jet Propulsion Laboratory. Top risks include Martian dust's corrosiveness, grittiness, and effects on electrical systems, as well as dynamics of the Martian atmosphere (including dust storms) that would affect landing and takeoff. "Then we asked, 'what would we need to learn by sending robotic missions to Mars to reduce each risk?'" Beaty continued.

Added James R. Garvin, NASA chief scientist at Goddard Space Flight Center: "We need to understand the dust in designing power systems, space suits, and filtration systems. We need to mitigate it, keep it out, figure out how to live with it."

Returning samples of Martian dirt to Earth is deemed crucial. Despite the pounds of lunar regolith Apollo returned to Earth, "lunar dust does not equal Martian dust," Garvin cautioned. "Scientists and engineers simply need to get their hands on real Martian dirt." The significance of a sample even as small as 1 kilogram "should not be underestimated" for both its scientific and engineering value, Beaty added.

Given the tall challenges, would Schmitt personally want to return to the Moon or go to Mars? "I'd love to!" he exclaimed instantly. "Don't get so deeply immersed in this [dust problem] that you scare yourself off! Dust is a number-one engineering design challenge for long-term habitats and settlement, but it's not a problem that should keep us from going!"

References

• One of several papers from the 1970s hypothesizing that the twilight glows photographed by the Surveyor landers and the "lunar rays" seen by the Apollo 17 astronauts were caused by suspended lunar dust is at *adsbit.harvard.edu/cgi-bin/nph-iarticle_query?db_key=AST&bibcode=1974LPI.....5..475M&letter=.&classic=YES&defaultprint=YES&whole_paper=YES&page=475&epage=475&send=Send+PDF&filetype=.pdf* . Another is at *adsbit.harvard.edu/cgi-bin/nph-iarticle_query?db_key=AST&bibcode=1974Moon...10..121R&letter=.&classic=YES&defaultprint=YES&whole_paper=YES&page=121&epage=121&send=Send+PDF&filetype=.pdf* .

• Abstracts of two papers about the dynamic-fountain model of lunar dust appear at *weboflife.nasa.gov/0506.doc* and *www.lpi.usra.edu/meetings/lpsc2005/pdf/1899.pdf* .

• More about LEAM appears at *ares.jsc.nasa.gov/humanexplore/exploration/exlibrary/docs/apollocat/part1/LEAM.htm* .

• A 1996 paper about Pathfinder electrostatic discharge is at *powerweb.grc.nasa.gov/pvsee/publications/marslight.html* .

• The 77-page MEPA report is at *mepag.jpl.nasa.gov/reports/mhp_ssg_(06-02-05).pdf* .

• Larry Taylor's 2005 paper on sintering lunar dust is at *www1.jsc.nasa.gov/toxicology/Taylor.pdf* .

• One paper by Carlos Calle on the electrostatic repeller is at *empl.ksc.nasa.gov/publications/development%20of%20self%20cleaning%20dust%20shield%20-%20RA%20Sims.pdf* .

• Comparison of terrestrial crepuscular rays "lunar rays" sketched by Apollo astronauts appears in *Sunsets, Twilights, and Evening Skies* by Aden and Marjorie Meinel (Cambridge University Press, 1983), pp. 123–126.

• Levitation of lunar dust was voted one of the 10 weirdest things in the universe; see *www.space.com/scienceastronomy/top_10_weird_list-7.html* .

As a 19-year-old physics major at the University of California, Santa Cruz, with a summer job at Lick Observatory, **Trudy E. Bell** vividly remembers hearing "the Eagle has landed" when Apollo 11 touched down at Tranquillity Base. Here she's photographing Masami Nakagawa, associate professor of mining engineering at the Colorado School of Mines (Golden), and Otis Walton, CEO of Grainflow Dynamics Inc. (Livermore, CA), observing the behavior of a prototype Mars rover in the sand and dust of the Great Sand Dunes National Park in southern Colorado in October 2005. Bell (t.e.bell@ieee.org and home.att.net/~trudy.bell), managing editor for the *Journal of the Antique Telescope Society* and contributing editor to THE BENT, has an M.A. in the history of science and American intellectual history from New York University (1978). A former editor for *Scientific American* (1971-78) and *IEEE Spectrum* (1983-97), she has written or edited a dozen books and nearly 400 articles on the physical sciences, technology, bicycling, and history of exploration.