How Airlines (and Crews) Survive in Afghanistan

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Apollo's Boldest Decision

and the man who made it

"Their mission is the most
difficult ever attempted,
and the most dangerous."
— Walter Cronkite

JANUARY 2019

FROM THE DIRECTOR OF THE NATIONAL AIR AND SPACE MUSEUM

The Spirit of Apollo

ON CHRISTMAS MORNING 1968, NASA's Mission Control in Houston waited anxiously for word from the moon. Apollo 8, history's first flight beyond low Earth orbit, had disappeared around the far side more than half an hour before. The astronauts would be out of radio contact during the critical engine burn that would send them back home. Would the explorers return safely to Earth? Confirmation came when Command Module Pilot Jim Lovell radioed, "Roger, please be informed there is a Santa Claus."

Although it is often eclipsed in the popular memory by Apollo 11, which flew just seven months later, many considered the flight of Apollo 8 to be the most challenging, and consequential, mission of the program. None other than Apollo 11 commander—and the first person on the moon—Neil Armstrong called this mission "the spirit of Apollo."

Coverage of the mission, from launch to splashdown, gave an unprecedented level of intimacy to a historic act of exploration. One hundred thousand people saw Charles Lindbergh land in Paris. Lindbergh himself joined the quarter million people who attended the launch of Apollo 8. Millions more watched on television.

Mission Commander Frank Borman recalls preparation for their television transmission from lunar orbit, where the crew read from the Book of Genesis: "We were told that on Christmas Eve we would have the largest audience that had ever listened to a human voice. And the only instructions that we got from NASA was to do something appropriate." From that famous broadcast to the Earthrise photo that sparked the modern environmental movement, Apollo 8 continues to fascinate and inspire 50 years later.

As you'll read in this issue, Apollo 8 was also perhaps the most audacious flight of a historically ambitious program. Six years earlier, President Kennedy had told the nation that to be first in space, "we must be bold." But even NASA, an agency that had defined itself by that very challenge, was shocked by George Low's bold proposition to maintain the U.S. lead in the race for the moon. Only a year before the end-of-decade goal to land an American on the moon, so many critical elements remained untested. And yet, the moonshot succeeded.

The National Air and Space Museum will celebrate the spirit of Apollo 8 at the Washington National Cathedral this month. And over the next year, we'll commemorate all of the Apollo missions and the men and women who made them happen. For more about these planned activities, visit *airandspace.si.edu*. As we examine what the Apollo program has meant for generations born after we returned from the moon, we'll also help define what 21st century moonshots await.

ELLEN STOFAN IS THE JOHN AND ADRIENNE MARS DIRECTOR OF THE NATIONAL AIR AND SPACE MUSEUM.

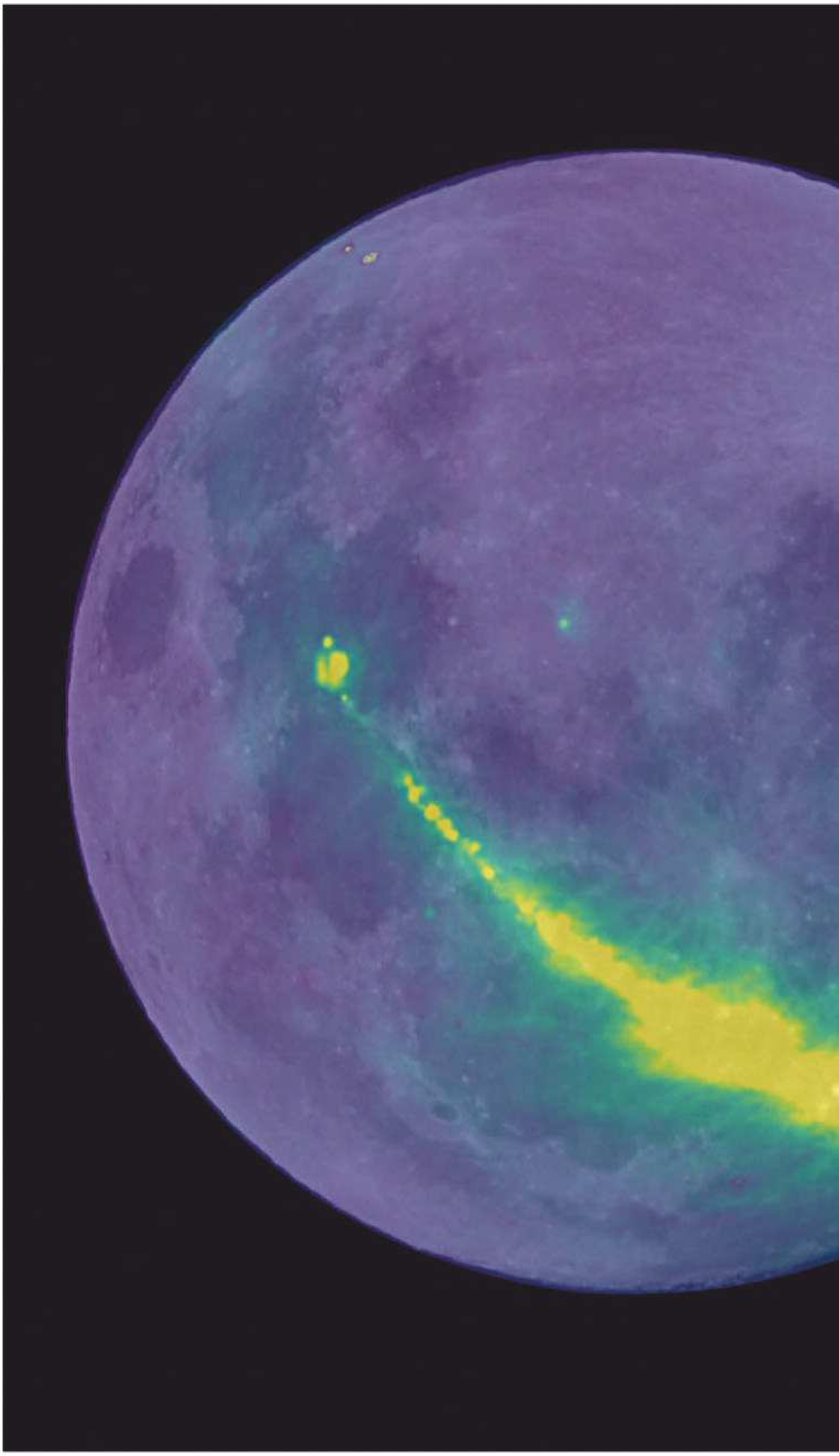
Solar System **Chatter**

A HUNDRED SATELLITES, ALL TALKING AT ONCE. HERE'S THE INTEL. **BY HEATHER GOSS**

UNIVERSE

Milky Way Mirrored on the Moon

WHILE SEARCHING for signals from hydrogen atoms made in the early universe, astronomers created a mesmerizing view of the Milky Way. To find the ancient hydrogen's faint radio waves, scientists using Australia's Murchison Widefield Array first block the glare from other radio sources. They measure earthshine—radio waves from Earth that bounce off the moon and back to their telescope—to subtract it from the sky's overall radio brightness. They also measure radio glare from the Milky Way reflected off the moon. The mirror-image reflection is depicted at right. Calculations complete, the astronomers can now go hydrogen hunting.



MILESTONES

Mars InSight Arrives

If all went well, NASA's Mars InSight lander will have reached its destination at Elysium Planitia on November 26. Its seismometer will study the internal structure of the planet.

China's Moon Mission

The Chang'e 4 mission, carrying a lander and rover, is targeted to launch this month. This will be China's second moon mission, after Chang'e 3 landed successfully in 2013.

New Horizons Flyby

A New Year's flyby is the next mission objective for NASA's New Horizons, which flew by Pluto in 2015. It will pass within 2,200 miles of Kuiper Belt Object 2014 MU69, nicknamed Ultima Thule, at 1:33 a.m. EDT on January 1.

OPPOSITE: NASA/GSFC/ARIZONA STATE UNIVERSITY; TOP: NASA/JPL-CALTECH; CENTER: JAXA; BOTTOM: ROBERTO MOLAR CANDANOSA/SCOTT SHEPPARD/CARNEGIE INSTITUTION FOR SCIENCE

PLANETS

A Gift Before Dying

SIX TEAMS have now published a massive amount of research from data taken during Cassini's final days, before its plunge into Saturn's atmosphere. One exciting discovery is that organic compounds—different from those found on Enceladus and Titan—are raining down on the planet, meaning there is a third unidentified source of those molecules. Read more at *airspacemag.com/cassiniresults*

PLANETS

Rovers on Ryugu

THREE TINY rovers now occupy the asteroid Ryugu. Hayabusa2 (its shadow at left) launched the latest, MASCOT, in October, where it bounced lightly eight times and studied the surface for 17 hours. In January, the spacecraft itself will descend close enough to grab a sample that it will carry back to Earth.

UNIVERSE

Way, Way, Way Out There

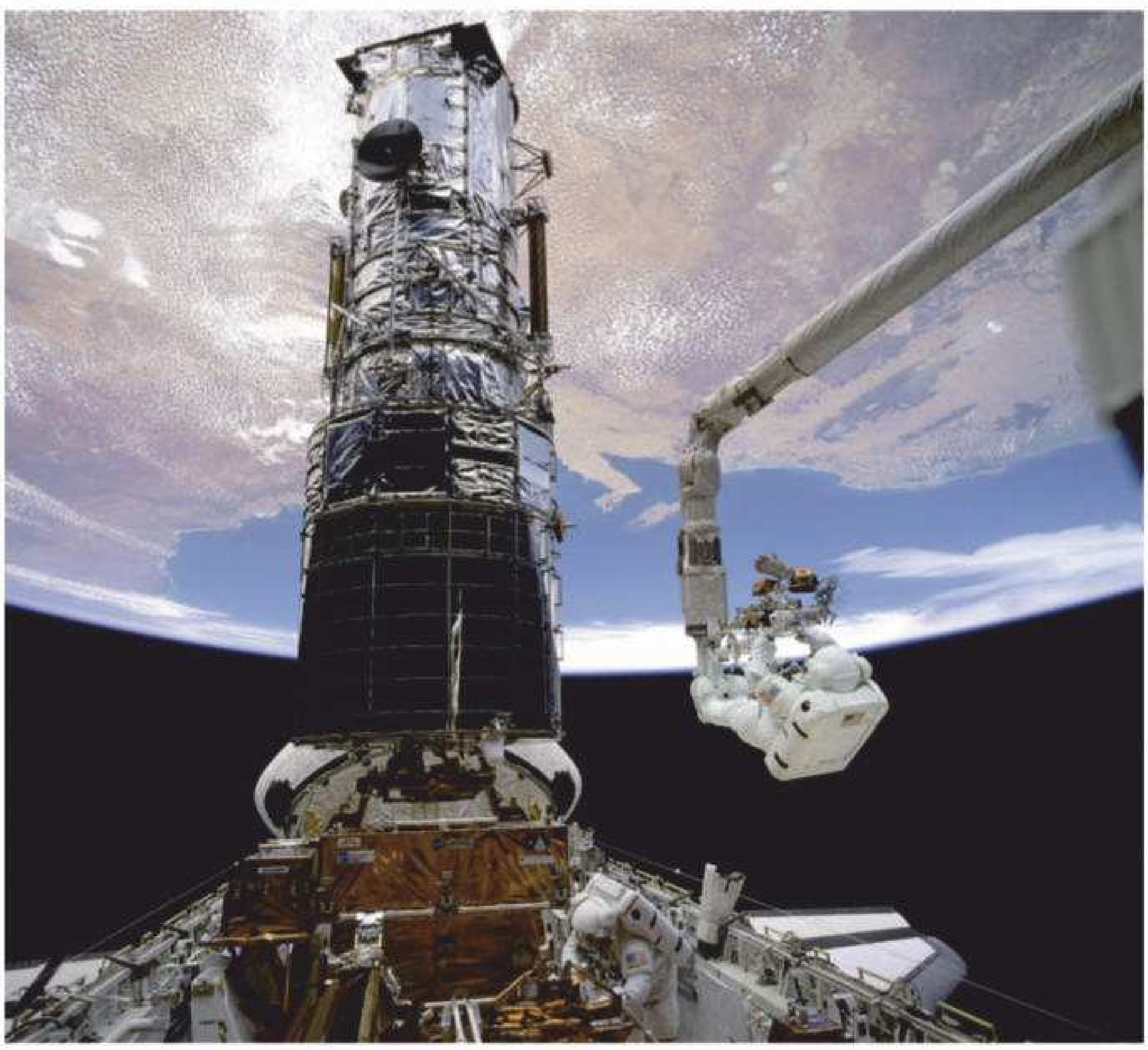
IN THE HUNT for Planet X, the suspected body orbiting outside Neptune, astronomers found a dwarf planet that travels farther from the sun than any known solar system object: 67 times farther than Pluto's orbit. Nicknamed The Goblin, it draws closer to the sun than two other known objects (orbits below), but none gets closer than twice Pluto's orbit. Meanwhile, observers using the Hubble and Kepler space telescopes may have discovered the first moon orbiting an exoplanet.

Long Live Hubble

ON A QUIET FRIDAY AFTERNOON last July, I was giving a tour of the Hubble Space Telescope control center to a group of visitors at Goddard Space Flight Center in Maryland. As Hubble's Deputy Project Manager, giving the occasional tour is one of the "other duties as assigned" in my job, and it's usually a fun one. How often do you get to discuss your work for longer than just a sentence or two to people who actually want to hear about it?

I was deep into my well-rehearsed explanation of how we monitor Hubble when Mike Myslinski, one of our operations managers, walked by. Taking care not to be overheard, he whispered to me that the spacecraft had an anomaly. "Anomaly" doesn't necessarily mean catastrophe. It could be something as mundane as a computer freezing—and as with your laptop or your phone, you do a reboot and you're back in business. It can also mean a piece of hardware has permanently failed. I couldn't find out until I was done with the tour.

I quickly led the group through the rest of the control center, hoping none of the guests would ask why the number of people there was rapidly multiplying. Ten minutes later I said my goodbyes and sped back to join Mike and the team.



Astronauts Story Musgrave (on the robotic arm) and Jeffrey A. Hoffman were part of STS-61, the first of five servicing missions that extended Hubble's life.

NASA

Hubble, he told me, was not pointing where it should, and it didn't know it. Usually, Hubble aligns on its observational targets with a degree of accuracy found in few other spacecraft. It has to be able to see astronomical objects that are billions of light-years away. To do this, it's supposed to be less than 0.000002 degrees off that target.

That Friday, Hubble was almost 40 degrees off. To make matters worse, its solar panels weren't aligned with the sun, so the batteries were not recharging as efficiently as needed. Finally, Hubble's high-gain antennas were not aimed at the communication relay satellite, so the engineering data that would tell us what had gone wrong was stuck on the spacecraft, more than 340 miles above Earth.

We speculated that the anomaly was being caused by a problematic gyroscope. We use the gyro to tell us what direction Hubble is turning and at what speed. When Hubble was launched in 1990, these devices were the most accurate in the world. But one of our current gyros has been acting up for years, giving higher or lower readings than it should—or "noise"—and causing us to miss targets.

The Hubble team has learned to compensate for the faulty gyro. With the space shuttle fleet retired, there's no longer any way to replace a component, so we do all we can to wring out premier science from Hubble while dealing with imperfect parts.

That Friday, the engineers managed to get Hubble back on target within five hours, faster than they could even fully diagnose what had gone wrong. By Monday they had determined the anomaly was triggered when a timer, set to ensure that a sensor would not be overworked, had expired and disrupted software that was installed in 2011 to

To keep capturing images like this one of Westerlund 2, a star cluster 20,000 light-years from Earth in the constellation Carina, the Hubble team uses algorithms to remove noise introduced by particles striking the telescope's aging cameras.

NASA, ESA, THE HUBBLE HERITAGE TEAM (STSCI/AURA), A. NOTA (ESA/STSCI), AND THE WESTERLUND 2 SCIENCE TEAM

help compensate for the noisy gyros. The team devised a modification to ensure the problem would not recur.

Then, on a Friday afternoon in early October, Hubble developed another anomaly, forcing the spacecraft into "safe" mode, from which it cannot perform scientific observations.

This is the reality of operating a 28-year-old spacecraft. Hubble was developed before most American homes had computers, and cell phones were as large as bricks. How long can its aging electronics keep operating in the harsh environment of space? It's a question I'm often asked, and one I cannot answer. We just don't know.

One major concern is the gyros—indeed, it was a failure of that noisy gyro that caused the latest hiccup. Hubble uses three at a time when performing optimally but has a total of six on board, so backups will be available as the gyros wear out. During Hubble's final servicing mission in 2009, astronauts replaced all six. Two have stopped working in the nine years since, and a third gave out on that October Friday this year. Three gyros are currently working, and as this article went to press, we were able to return Hubble to normal operations. We've even determined a way the telescope could continue observing the universe on a single gyro if necessary, using other sensors to compensate. Some objects in the sky would be harder to observe, while others wouldn't be observable as often, but Hubble's utility would be extended further still.

Although the gyros are what keeps me up at night, statistical analysis suggests that fine guidance sensors and their electronics are the elements most likely to shorten Hubble's life. Once the telescope turns toward its target, fine guidance sensors lock onto nearby "guide stars," allowing Hubble to hold steady to get the incredibly high-resolution images that have earned it worldwide fame. Hubble has three fine guidance sensors and uses two at a time. Two of the sensors have been replaced during servicing missions. The third has been in space since Hubble launched and is showing its age. In recent years, we've minimized the use of that original sensor.

Hubble's cameras are a concern, too. As the camera detectors spend time in the radiation environment of space, they deteriorate. When high-energy particles hit the detectors, they can create "holes" that trap electrons. These traps create bright, artificial trails behind every star or bright object in the exposure. The longer a detector is in space, the worse these trails get. An instrument scientist developed an algorithm to remove these trails from the images. This allows astronomers to keep collecting those stunning Hubble pictures we all love.

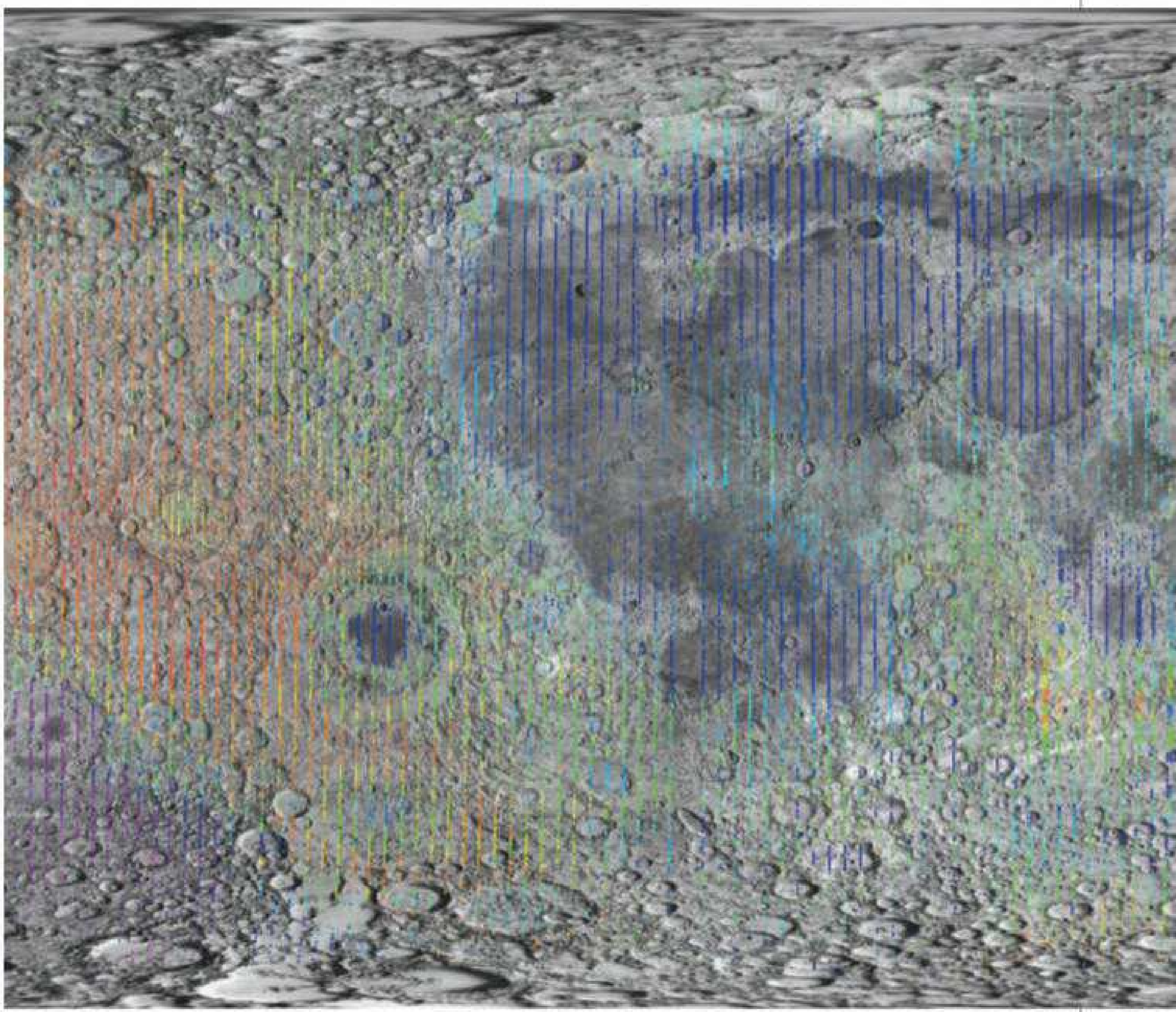
Thanks to the astronauts who replaced and upgraded components on Hubble during the five servicing missions between 1993 and 2009, the telescope has backups for all of its critical systems. The continued pursuit by our engineers and scientists of new ways to work through whatever issues come Hubble's way will prolong its life further. And I can continue to share the excitement of the Hubble mission with our visitors for years to come.

JIM JELETIC

It Found What the Moon's Made Of

MORE THAN 500,000 people watched as Apollo 17, the last crewed mission to the moon, blasted off from Kennedy Space Center on December 7, 1972. When a U.S. probe returned to the moon 20 years later, hardly anyone noticed. The Clementine spacecraft, launched from Vandenberg Air Force Base on January 25, 1994, started as a Department of Defense project. Its miniaturized sensors had been developed for President Ronald Reagan's Strategic Defense Initiative (known as "Star Wars") to detect and track missiles but, with NASA participation, also proved valuable to science.

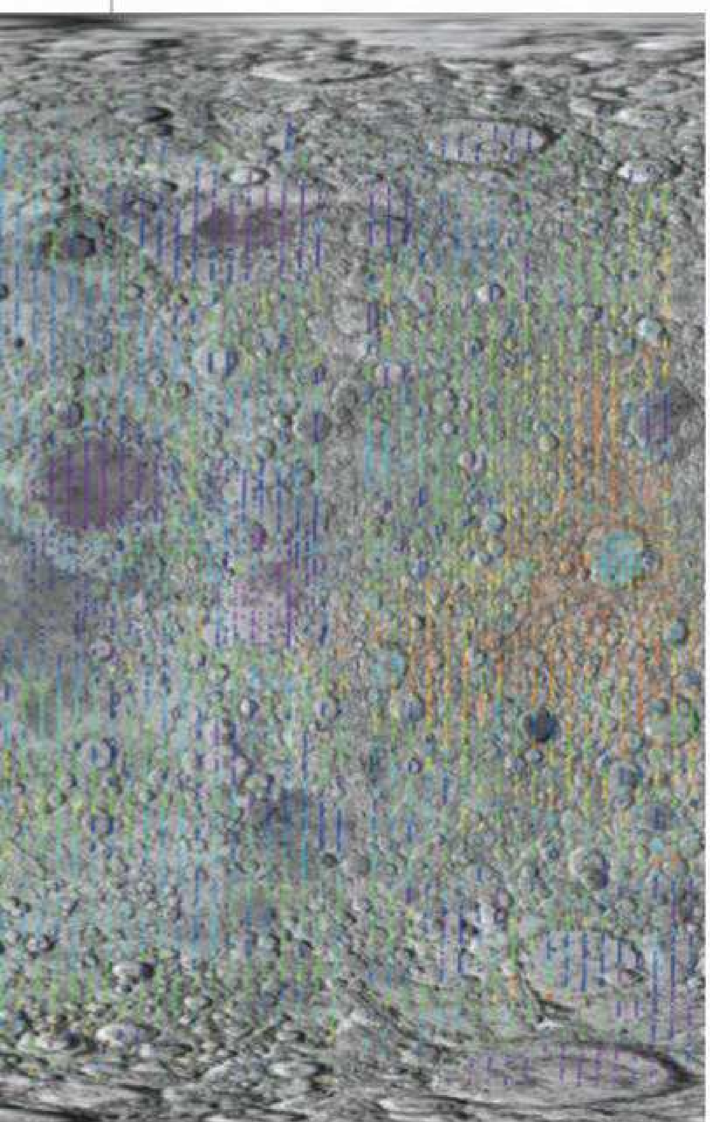
The science objective of the Clementine project (so named because the probe carried just enough fuel to complete its mission before it was "lost and gone forever," like the lyrics of the 1884 folk ballad) was to assess the moon's mineral composition and that of the near-Earth asteroid 1620 Geographos. (An onboard computer glitch prevented the asteroid flyby.)



Above: Lidar measurements of lunar topography from the Clementine mission. Left: The Clementine model; its interstage and solid rocket motor (bottom half) were discarded before insertion into lunar orbit.

LEFT: ERIC LONG/NASM (2006-25314); TOP: MARTIN PAUER

In 2002, the Naval Research Laboratory, Clementine's builder, transferred the spacecraft engineering model to the National Air and Space Museum, where it is on view at the Steven F. Udvar-Hazy Center in northern Virginia awaiting conservation work. The spacecraft created the first global topographic map of the moon and represents a 1990s ethic of "faster, better, cheaper" space exploration. Only two years in development, the probe cost under $80



million, about one-fifth the cost of a traditional space probe mission. Part of Clementine's purpose was to evaluate the performance of commercial, off-the-shelf computers and software in space.

Scientists hoped that the lunar mapping project would show evidence of water ice on the moon, something needed to make an eventual lunar colony feasible. As Paul Spudis—then deputy leader of the Clementine Science Team—wrote in 1996, scientists couldn't find water-bearing minerals in the rocks and soil samples brought back to Earth by the Apollo astronauts. But scientists speculated that water-rich comets and asteroids could have crashed into the moon. While most of the water would be lost into space, some might have stayed in the moon's cold and dark polar regions.

Using seven different types of cameras, a laser altimeter, and a charged particle telescope, the spacecraft spent two months mapping the moon. By the time the project was complete, almost 2 million images were taken—documenting nearly 100 percent of the moon's surface.

During the mapping, images of the South Pole-Aitken basin were taken, revealing that it may be the largest and deepest impact crater in the solar system. But most important of all, Clementine's data indicated the presence of ice in the crater, findings that have been confirmed by subsequent space probes.

"It is probably not too much of an exaggeration to say that Clementine changed the direction of the American space program," Paul Spudis wrote for *Air & Space* in 2014. "Because Clementine had documented its strategic value, the moon once again became an attractive destination for future robotic and human missions."

The original analysis of the Apollo rocks turned out to be incomplete. In 2008, geochemist Erik Hauri, using instruments he developed, did find water in the Apollo 17 samples. Hauri died this past September. His work affirmed the intriguing possibilities found in Clementine's data.

Clementine's template influenced spaceflight for the next 20 years. It led the way for Lunar Prospector, which detected further evidence of ice at the poles, and LCROSS, which discovered water molecules on the moon and, in a dramatic experiment, flew through the ejecta created when its Centaur upper stage crashed into the moon, detecting pure water ice crystals, before itself smashing into the moon.

REBECCA MAKSEL

IN MEMORIAM

PAUL SPUDIS

Moon Man

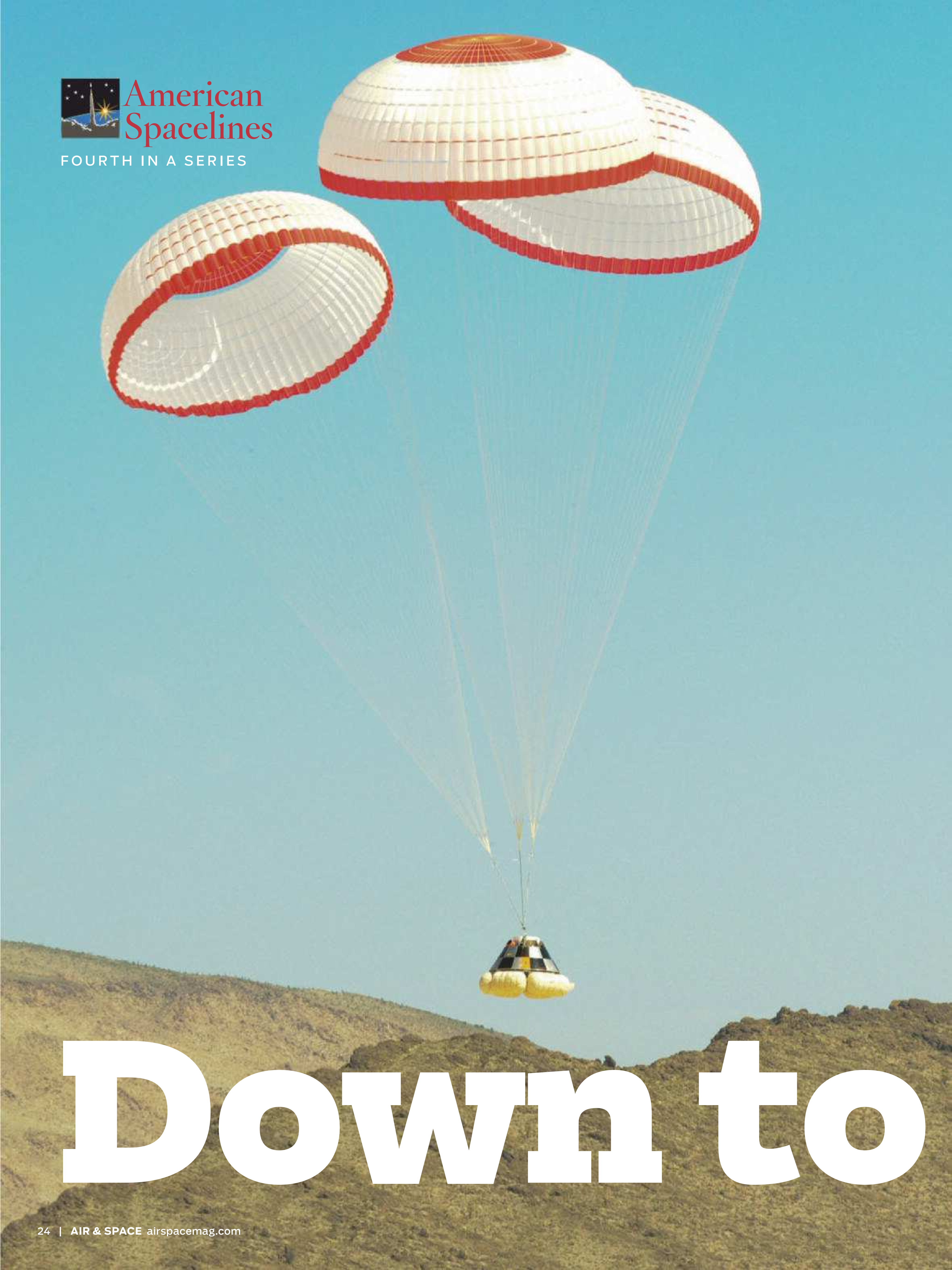
IF THE UNITED STATES returns to the lunar surface in the next year or two—and that's NASA's current plan, using robot landers at first—we can thank Paul Spudis. One of the world's foremost scientific experts on the moon, Spudis, who passed away on August 29 following a battle with lung cancer, spent the last decade lobbying forcefully for a return to the moon, when almost everyone else was focused on Mars.

As a senior staff scientist at the Lunar and Planetary Institute in Houston, he was an investigator on the Clementine and Chandrayaan-1 lunar missions. More recently, he served as chief scientist for Moon Express, one of several companies now spearheading the U.S. return to the lunar surface with small, commercial landers.

But it was Paul's advocacy that may have mattered most. In books, speeches, and hundreds of postings to his "Once and Future Moon" column on our website (*airspacemag.com/spudis*), he laid out the case for a methodical approach to solar system exploration, starting with the moon as a source of water and other natural resources that could be used to help create a true space economy. His fellow scientists, online followers, and moon lovers everywhere owe him a great debt.

TONY REICHHARDT

TOP RIGHT: USRA



American Spacelines

FOURTH IN A SERIES

Down to

Earth

The new U.S. space taxis don't roll to a gentle stop.

NO MATTER WHAT MISSION ASTRONAUTS ARE SENT TO ACCOMPLISH, the engineers who send them must solve two basic problems: how to get the space travelers off the Earth (and into orbit or on their way to the moon or Mars) and how to bring them back again. With decades of experience in shoving payloads into space, the world's space powers have unanimously settled on chemical rockets as the best way to launch astronauts. The question engineers still debate is: What's the best way to land them?

BY CRAIG MELLOW

Boeing and SpaceX, which, through NASA's Commercial Crew Program, are scheduled to send astronauts to the International Space Station next year, have been asked to respond to spaceflight's two basic problems with ingenuity, economy, and gee-whiz technology for the cosmic challenges ahead. Yet one of the most visible elements of their privately designed spacecraft will hearken back deep into last century: They're shaped as capsules, counting on their blunt, high-drag shapes and a brace of parachutes to slow them from an orbital speed of 17,000 mph to a velocity that human occupants can survive when they hit the Earth's surface.

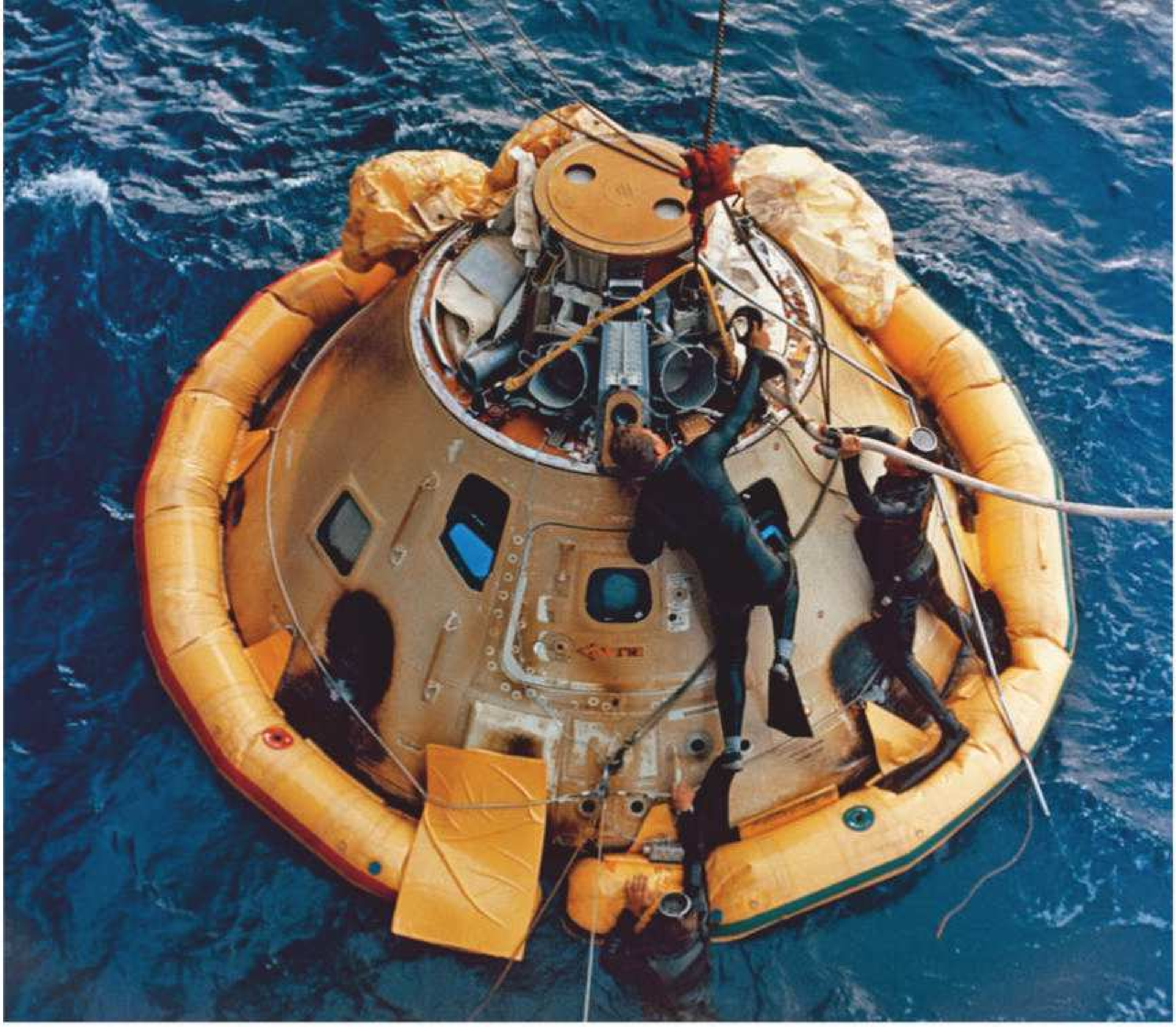
The space shuttle was supposed to end all that when it took its first flight in 1981, providing airliner-like comfort during its gentle runway touchdown. And in creating the next generation of space transportation, SpaceX, at first, really did try to lean into the future. Elon Musk and his team pushed for a new kind of lander, one that relied on thruster rockets, instead of parachutes, to slow the ship and extendable legs to balance it upon touchdown—a so-called propulsive landing. "That is how a 21st-century spaceship should land," Musk boasted in 2014, "anywhere on Earth with the accuracy of a helicopter." SpaceX has largely succeeded with propulsive landing for its payload delivery rockets—the Falcon 9 first stage regularly, and impressively, lands upright on an ocean barge or back at Cape Canaveral. But such leaps forward with live astronauts inside require time and money that NASA was unwilling to commit to a mission whose key selling point was economy. At least that's what space watchers guess from Musk's laconic abandonment of the approach in 2017. So the parachutes came out again.

NASA's astronaut splashdowns have acquired a nostalgic if not mythic tinge at the distance of half a century. But they were hairy affairs in real life. Gus Grissom nearly drowned after the second Mercury flight in 1961—a famous incident made more famous by its inaccurate portrayal in the 1983 film *The Right Stuff.* The next year, Scott Carpenter landed 250 miles off course and spent three hours in a life raft before rescue by the USS *Intrepid*.

Splashdown adventures continued after the moon missions even after more than a decade of fast-paced technological progress. Crews on both the 1974 Skylab 4 mission and the Apollo-Soyuz Test Project a year later ended up face down in the ocean for a while, as heavy seas caught their parachutes and capsized the landing craft. Apollo-Soyuz's problems were compounded by a leak of thruster exhaust into the cabin that required the astronauts to grab oxygen masks, which were harder to reach while they were

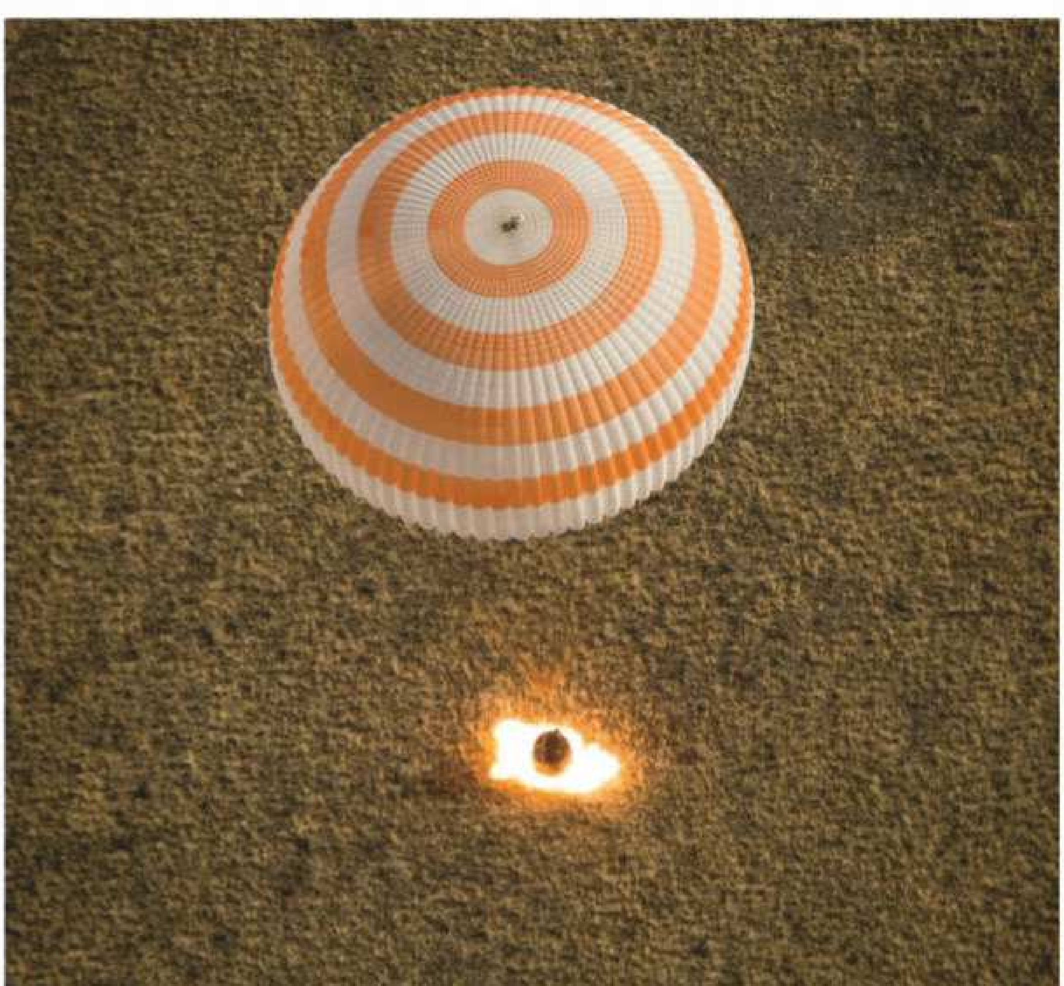
Astronauts may soon drift to the ground in the American West. Opposite: In Nevada, Boeing tests the landing system on its Starliner capsule.

BOEING



Ah, the good ol' days, when U.S. astronauts landed in the ocean (right, an uncrewed Apollo capsule in 1968) and Russian cosmonauts, on land. Below: A Soyuz fires its retrothrusters just before impact. Soon U.S. capsules will do both.

upside down. Crew member Vance Brand passed out during the scramble, and one of his crew had to put his mask on for him. In both cases, inflatable "righting spheres" outside the capsule worked as planned. The ships rotated back to the surface, and the astronauts exited relatively unharmed.



Of course there is an alternative to landing at sea: landing on land, which the Soviet and then Russian space program has been doing since inception. The Soyuz spacecraft, first launched in 1967 and still going strong, thumps back to Earth on the vast, flat steppes of Kazakhstan. It's not the most comfortable experience, ex-passengers report. "It's kind of like a series of explosions followed by a car crash," says Michael Lopez-Alegria, a former NASA astronaut who returned from the International Space Station on a Soyuz in 2007. "After seven months in space, it doesn't feel great."

Soyuz had a near-fatal accident in 1976, when the reentry capsule blew off course and touched down on a partly frozen lake—five miles from shore, at night, in the middle of a blizzard. Rescuers, who reached the partially submerged ship nine hours later, didn't bother opening the hatch for two hours because they assumed the cosmonauts had frozen to death. The hardy Soviets survived, though they never flew again.

Nevertheless, Lopez-Alegria would rather return from space onto terra firma, given the choice. "Landing on water seems like doing a giant belly flop, so I'm not sure the impact is much less," he says. "And afterwards I think I'd be happier on land than bobbing around in the ocean." Ken Bowersox, another Soyuz landing veteran, also thinks land is safer than water. "On land you

TOP: NASA; BOTTOM: NASA/BILL INGALLS

can have a little bit of a rough landing and still crawl out of the vehicle," he notes. "If things don't go well on water, it can get exciting pretty fast." Describing Bowersox's own Soyuz reentry in 2003 as a "little bit of a rough landing" might be an understatement. The capsule veered into a ballistic landing that took it hundreds of miles from target. But "we just waited a few hours," he recalls. "Out on the water, it would have been a lot less comfortable." As for the impact, Bowersox compares it to the aircraft carrier landings he practiced as a Navy pilot. "It gets your attention, but it's not worse than a carnival ride," he says.

NASA did study terrestrial landing at various points in the pre-shuttle age, but rejected it for several reasons. At the time, the agency concluded that the United States lacked a properly vast, empty, flat area in the contiguous states. At least when compared to the open, undifferentiated space of the Kazakh plain, even the Southwest desert couldn't compete, with its canyons, plateaus, and remote towns and reservations. The targeting upon descent just wasn't precise and reliable enough. What the country did have was a vast amount of open water: copious access to two oceans, a coastal launch site, and the existing maritime infrastructure to retrieve astronauts from the water.

Another significant consideration in these terrestrial studies was the weight of the spacecraft. A water landing may end with a smacking plunge, but liquid still has a bit of give; returning on land requires some extra feature to make up for the hard stop, like the retro rockets that Soyuz fires when it's several feet off the ground for a final brake in the seconds before impact. That equipment makes for a heavier vehicle, though, and in the early 1960s, the NASA brain trust, pressed for time, didn't think they

A water landing may end with a smacking plunge, but liquid still has a bit of give; returning on land requires some extra feature to make up for the hard stop, like the retro rockets that Soyuz fires when it's several feet off the ground for a final brake in the seconds before impact.

EASY GLIDER

CONCERNED BY THE PERILS of ocean splashdowns conducted by the Mercury capsules, NASA took a hard look at terrestrial landing for the Gemini program. The agency funded the development and tests of the so-called Rogallo wing, named for designer Francis Rogallo, a kite-flying enthusiast who worked at the Langley Research Center in the late 1950s. His mechanism, which resembled the triangular hang gliders used by hobbyists, was meant to pop out of the returning capsule's fuselage, making the descent mild and maneuverable enough for a runway landing.

Astronauts warmed to the idea, which promised to put them in control and end their "spam-in-a-can" status during Mercury. Moonwalker-to-be Neil Armstrong and a fellow test pilot started building their own Rogallo prototype after hours, persuading skeptical NASA superiors to invest in the technology. But the program was moving too swiftly: "The plan was for Gemini 11 and 12 to come back on land," says Bob Thompson, who oversaw sea rescue for the early space missions. "But we didn't have time for that because Kennedy came out with his audacious commitment to get to the moon by the end of the decade."

In the short time the proponents had to develop the system, the test flights were yielding uneven results, and NASA killed the idea in early 1964, committing the entire Gemini flight cycle to sea landings. The extra weight of the Rogallo wing, Thompson admits, would not have been feasible for the Apollo moon missions in any case.

NASA HISTORY OFFICE

An engineer inspects a Rogallo wing model before a wind tunnel test in 1962. Two years later, the idea was axed.

The futuristic art above won't become real for the commercial crew missions. Time and money constraints led SpaceX to abandon propulsive landing for its Crew Dragon.

SPACEX

could get all that weight to the moon (see sidebar).

But technology improves and objectives change. So Boeing revisited the terrestrial landing question when it started designing its commercial crew vehicle, the Starliner, around 2010. "Returning on land has an advantage over sea in having immediate access to the crew and all the cargo on board," says Michael McCarley, a Boeing career man who worked on the shuttle through its final flight before moving over to the Starliner project as the lead engineer for reentry. But the weight of this kind of capsule is still a problem—or as McCarley calls it, "the mass challenge."

Soyuz may have solved its mass challenge the year the Beatles recorded *Sgt. Pepper*, but the Russian ship can only cram in three astronauts—half of a space station crew. One key to the expanded seven-passenger, terrestrial-landing vehicle was replacing those retro rockets with airbags. The Starliner will rely on six of them (a seventh, in the center, deploys only for an emergency water landing). They're inflated with nitrogen and oxygen like the ones in automobiles but designed like bicycle tires with discrete inner and outer layers. The outer bag has vents that release pressure upon landing, while the inner tube remains firm. Hopefully.

One way or another, a space capsule returning to Earth under parachutes is decelerating through the atmosphere at around 4 Gs before its sudden stop. That compares to a tolerable 1.5 Gs for the glide-to-a-landing space shuttle.

Not only is the airbag system lighter than the Soyuz rockets, it should be easier on bodies already depleted by half a year in space, McCarley says. Ken Bowersox is one enthusiast. "If you look at the stunt people who jump off buildings and land on airbags, that should be a pretty reasonable landing," he comments.

Then there is McCarley's personal pet project: the seat. One way or another, a space capsule returning to Earth under parachutes is decelerating through the atmosphere at around 4 Gs before its sudden stop, says Lopez-Alegria, who still sits on NASA's human exploration advisory council. That compares to a tolerable 1.5 Gs for the glide-to-a-landing space shuttle. But the impact on the astronauts' bodies depends, literally, on where and how they sit. Or lie actually, as a human's spinal column and other vital organs are not designed to absorb 4 Gs in a vertical position. Soyuz passengers already land reclined, with an individually designed seat liner. But McCarley was determined to improve on that with modern ergonomics. He started with a pile of plywood in his garage.

"The overall concept to the seat hasn't changed from the plywood model, but we have added some more advanced materials," McCarley says. The company also added 3D printing technology to shape an entire custom seat for every Starliner passenger. Given the compact space available, this involved intensive study of human body types.

McCarley, who is a stocky 6'1", and Starliner systems engineer Melanie Weber, who stands a bit shy of five feet, modeled themselves for the outer limits of permissible size. Digging deeper into the nuances, the engineers labored to accommodate a range of body types, which they bestowed with pet names like The Orangutan ("long arms that can practically reach across the capsule," McCarley clarifies), or The T-Rex (broad torso with short arms). By designing the range of extremes, the team will be better able to tailor each seat using an astronaut's body scans.

The Boeing team also wanted to improve on the Soyuz-era parachutes. For reasons now lost to the scientific history of the cold war, the Russian ship's series of parachutes—pilot, drogue, and finally the main chute—opens from one side of the capsule, followed by the pyrotechnic release of a rigging system that forces the capsule to hang straight down. Lopez-Alegria describes the result as "pretty violent side-to-side motion, like Mr. Toad's Wild Ride." Boeing promises to smooth the process with two drogue chutes for symmetry, followed by three main chutes for extra stability, not to mention redundancy.

As for where the capsule will set down, the Starliner team is more comfortable with their precision landing than were early NASA engineers. The company has a list of five sites in the West—two at the White Sands Missile Range in New Mexico, the Dugway Proving Ground in Utah, Edwards Air Force Base in California, and Wilcox Playa in Arizona—from which they'll choose primary and backup locations shortly before the end of each mission. Ground crews have been combing for long-forgotten telephone poles and other obstacles, and conducted extensive environmental and cultural surveys to ensure both the safety of the astronauts and the integrity of the land. The Dugway Proving Ground, for example, was established by the Army during World War II to test chemical and biological weapons, and also happens to be an archaeological treasure trove of Native American artifacts dating back 13,000 years.

WHILE BOEING ENGINEERS thought hard about the earthy details of their capsule's descent to hard ground, SpaceX began its work by dreaming about Mars. In January 2011, the company posted a futuristic 15-second video depicting a tidy trapezoidal spacecraft making an unhurried vertical landing sans parachute, buoyed by flames shooting out from the four corners of its base at approximately 30-degree angles. Elon Musk, in the voiceover, describes it as "a propulsive landing with gear, kind of like [how Apollo 11's] Eagle landed on the moon." It looked very cool.

But those flame-shooting SuperDraco thrusters, as Musk subsequently named them, were aimed at more than lowering a 14,000-pound Crew Dragon capsule onto a helicopter pad anywhere on Earth. SpaceX insisted they could bring a ship of similar mass safely to the surface of Mars, where the atmosphere is too thin to land anything of that weight by parachute. The heaviest object dropped there to date was NASA's Curiosity rover, which had about one seventh of that mass and, of course, no fragile human passengers.

SpaceX unveiled a Crew Dragon prototype in 2014 with high hopes for its prospects on two planets. In 2016, it posted video of a test model hovering confidently several yards above a platform in Texas. Then Musk called it off. While the Crew Dragon was

When a capsule misses its mark on land, astronauts aren't left for hours to bob up and down on waves. But they may get cold. Below, a Soyuz retrieval team meets the crew on a blizzardy Kazakh day.

NASA/BILL INGALLS

technically still capable of landing propulsively, he said at a space station research and development conference in July 2017, it would take "a tremendous amount of effort to qualify that for safety." Besides, he had since divined a "far better approach" to landing on Mars, the details of which he's kept under wraps. The capsule still carries SuperDraco engines, but they're to be used only in case of a launch abort. (See "Abort!" Oct./Nov. 2018.) A routine propulsion-landing Crew Dragon seems destined to become a footnote to exploration history, though SpaceX continues to work on the technology for its other vehicles, including the next-generation BFR rocket—an as-yet untested space bus that promises to carry up to 100 passengers to the moon or beyond. The first paying customer for that trip, Japanese billionaire Yusaku Maezawa, was announced in September.

Luckily, the company had a proven Plan B for getting crew to the space station. While SpaceX was fiddling with the futuristic system for a crewed ship, as this magazine went to press its cargo ship has quietly flown 15 successful missions to and from the space station, the capsule splashing down without incident. The company has so far managed to reuse four of the capsules despite the saltwater dunking.

The Crew Dragon is about 50 percent heavier than the cargo model, so SpaceX is compensating for the extra mass with a system of four parachutes that release symmetrically above the vehicle, offering more drag than the classic triangle that unfurled above returning 1960s capsules. More than Boeing's Starliner too, a company statement implies: "Crew Dragon's parachute system is the most efficient system ever designed in terms of packing density and aerodynamic braking capacity."

A still more noticeable difference from days of yore will be the modest flotilla SpaceX deploys to recover Dragon astronauts at sea. Published plans call for a single 164-foot ship, the *GO Searcher*, with support from several inflatable boats that can maneuver closer to the splashed-down capsule. The *GO Searcher* will be equipped with a helipad to ferry astronauts quickly to shore if necessary.

That's a dramatic contrast to the fleet of U.S. Navy vessels that steamed out to meet space travelers of the 1960s and '70s. No fewer than 24 naval vessels awaited John Glenn's splashdown after the first U.S. orbital flight in 1962, with the Air Force in eager reserve. Landings became more accurate quickly, though, and the welcoming party dropped to four vessels by the last Apollo moon flight in 1972. So SpaceX's stripped-down retrieval crew not as minimalist than it might seem. (The company has a more elaborate system, through a partnership with Air Force pararescue teams, for astronaut recovery after a launch abort.)

SpaceX is also predictably eager to expand its reusable technology to the Crew Dragon. The team has gained extensive experience on water sealing and corrosion prevention from reflying four of their

When the Starliner astronauts—Eric Boe (seated left), Chris Ferguson (seated right), and Nicole Mann—come back to Earth after the first crewed mission next year, they'll each be cushioned by seats wholly custom-made from their body scans.

NASA/BILL INGALLS

Instead of the Soyuz's heavy retrothrusters, Boeing designed six lightweight airbags for the Starliner (being tested at Langley Research Center, left) that should put a somewhat more comfortable bounce in its drop back to Earth.

cargo ships. But right now SpaceX is only approved to fly a crew with new spacecraft, creating a somewhat ironic situation where arch-rival Boeing deploys a reusable capsule before SpaceX. Rocket watchers are guessing the hold-up will be temporary.

HUMAN SPACEFLIGHT inevitably involves dwelling on worst-case scenarios. "I'm always thinking, Is there something hidden that we don't know?" says Boeing's Mike McCarley. "Have I looked behind every door and in the back of every closet? It's kind of a personal neurosis, but also a professional neurosis." Since the headlong space race of the 1960s, human spaceflight seems also to involve inevitable delays and frustrating mid-course corrections—from tweaks only the engineers can fathom to shelving whole promising systems like SpaceX's propulsive landing scheme. At the program's inception, commercial crew missions were optimistically targeted for 2015. Currently they're aiming for mid-2019.

None of that should obscure the fact that the private contractors are steadily gaining trust from NASA, and from astronauts past and future, in whatever path they pursue. "To me, I don't care. They're both going to work," Ken Bowersox concludes. "Coming down on land or sea is more of an economic decision."

Nor do program delays reverse a clear direction: The commercial crew flights, retro landing systems and all, point the way toward an exciting new chapter in space exploration, where private companies take on futuristic projects from asteroid mining to Mars colonization. "This is revolutionary in a lot of ways," Lopez-Alegria says. "It's the first time government has loosened the reins on what size washer to use. It will be a renaissance of sorts." That's a door opening that he, and many others, are eager to walk through. Lopez-Alegria's current gig is head of business development for Axiom Space, which wants to build a privately financed successor to the space station at a projected cost of $1.5 billion.

First, though, will come the new commercial vehicles and their dramatic parachute returns—not just to Earth, but for the first time in nearly a decade, to their own country.

NASA

The Man Who Won the Moon Race

Of a thousand tough decisions, this one could have wrecked Apollo, or saved it.

BY RICHARD JUREK

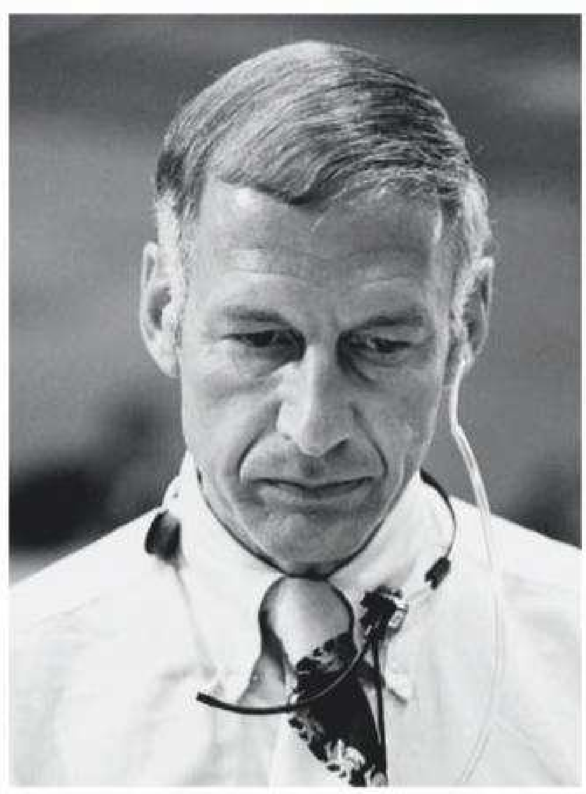
NASA

For its annual "Man of the Year" cover on January 3, 1969, *Time* magazine made the rare choice to honor not just one individual but three: NASA astronauts Frank Borman, James Lovell, and William Anders. Their Christmastime lunar voyage on Apollo 8 had been, in the editors' opinion, a "transcendent legacy" of 1968 and "a journey into man's future."

The magazine's editors also called out for special recognition a single "groundling" from the 400,000 or so people working on Apollo at the time: a 42-year-old, Austrian-born NASA manager named George Low. The name was practically unknown to the public, but had it not been for Low, *Time* proclaimed, "there would have been no Apollo 8 flight to the moon."

The editors could have gone further. Without Low, President John F. Kennedy may never have committed the nation to a lunar landing and once committed, may never have recovered from the Apollo 1 fire that had brought the program to a standstill less than two years before Apollo 8's triumph.

Compared to Apollo-era giants like Wernher von Braun and Neil Armstrong, Low still remains mostly unrecognized. But his reputation has grown with time. "As usual with any great endeavor, it always boils down to a single human being who makes a difference," Apollo 8 commander Frank Borman said during a panel discussion almost 50 years later. "In the case of Apollo, the person in my mind who made the difference was George Low."



George Low during the Apollo-Soyuz mission in 1975. When Apollo 8 launched seven years earlier (opposite), he'd been out to beat, not join, the Soviets.

RENSSELAER POLYTECHNIC INSTITUTE ARCHIVES AND SPECIAL COLLECTIONS

BORN NEAR VIENNA between the world wars, George M. Low was part of an influential family that at one time operated Austria's largest industrial alcohol refinery, fertilizer factory, and export business. In 1938, 12-year-old George, his mother, and two siblings fled the Nazis (his father had died four years earlier) and emigrated to the United States, eventually settling on a farm in upstate New York. In their adopted country, Gertrude Low raised her son not to focus on the past, or on what might have been.

Calm, quiet, and intensely focused on whatever he was doing at the moment, the boy had an affinity for mathematics and mechanical tasks. He remained throughout his life a self-described "dirty-hands engineer." Even in some of his busiest years at NASA, his family could not recall a single time that he called a repairman. Once, when the washing machine broke, Low spent an entire Saturday disassembling it and spreading all the parts across the wet floor, until he found the one damaged piece.

Low attended Rensselaer Polytechnic Institute in Troy, New York, just as the jet age was about to get under way. "Fun is one of the main reasons for doing anything," he believed, and he found plenty in the field of aeronautics. He was drafted into the Army Corps of Engineers while still an undergraduate but eventually returned to Rensselaer to finish his master's degree. In 1949, the same year he got married, Low landed a job working as an aeronautic research scientist for Abe Silverstein at the National Advisory Committee on Aeronautics (NACA) Lewis Research Laboratory outside Cleveland.

Under Silverstein, Low did foundational research on basic aeronautic problems such as boundary-layer flows and high-speed turbulence, at a time when the

Low had the idea to send just the Apollo command and service modules (above, seen during Apollo 11) to orbit the moon, without the lunar lander. The Soviets had planned a similar circumlunar flight, but technical setbacks denied them the triumph they had been promising in space propaganda.

NACA was assisting the Air Force in the classified X-plane program. It was in the course of this work that he first crossed paths with a young test pilot and engineer named Neil Armstrong.

When, in 1958, Silverstein moved to Washington,

D.C., to become director of Space Flight Programs at the newly created National Aeronautics and Space Administration, he took Low with him. Along with pioneering space engineers Bob Gilruth and Max Faget, Low was assigned to the agency's human spaceflight initiative, Project Mercury. While he would have preferred being involved directly with the engineering work, Low was needed to manage the business side of the program, as head of NASA's Office of Manned Space Flight (OMSF).

Right away, Low had an impact. "George was good at everything," Gilruth recalled in a 1987 interview. "He was worth about 10 men." George Abbey, Low's technical assistant during Apollo who would go on to oversee the astronaut corps in the space shuttle era, remembered that his boss "was at work long before most people in the morning and long after they left at night."

Low's attention to detail, and his nearly photographic memory, were legendary. A *Washington Post* reporter marveled, "Low reads every piece of paper that goes through his office. He feels he has to touch everything to assimilate it. But once he does, he never forgets it."

Perhaps because English was his second language, Low developed a mathematician's precision with words. He used a green felt-tip marker to edit and comment on everything he read, so that his notations would stand out and so people would instantly recognize them as his. He even corrected grammar.

TOP: NASA; BOTTOM: COURTESY RUSSIATREK.ORG

The pens were known around the office as his "green stingers" or "green hornets."

A significant part of Low's job was testifying before Congress on everything from budget requests to whether the United States could beat the Russians in space. A licensed pilot, he had a special affinity with NASA's astronauts and would introduce them around to the power players on Capitol Hill. Low had helped come up with the criteria for selecting the Mercury Seven, and he viewed the astronauts' test pilot experience as critical for mission success. "They were the hardest-working bunch of guys I ever knew," Low once said.

When it came to politics, he was a pragmatist rather than an ideologue. Any cold war calculations regarding Apollo he left to the White House and Congress. He was, however, naturally competitive. Low hated to lose, whether it was a game of tennis or a geopolitical race against the Soviets to the moon. "One of the deepest disappointments to me was when I got a phone call, the night of April 12 [1961], at 2:00 a.m., telling me that Gagarin was up," Low recalled later. The Mercury spacecraft had been ready to launch Alan Shepard a few weeks before that. But Wernher von Braun and his rocket team in Alabama, as well as some at NASA headquarters, were concerned about an anomaly that had cropped up on an earlier unpiloted test. "Gilruth and I were ready to go," Low said. "We knew what the problem was, and we were sure we had it solved." After a tense meeting in Washington to make the go/no-go decision, another animal test flight was ordered, just to be safe. Low was disappointed, but he was never one to slam the desk or raise his voice. When he was mad, his colleagues noticed, he went quiet, and his language became more precise and exacting. He accepted the delay to Shepard's flight while always regretting what he called "a political decision."

IN THOSE EARLY DAYS of human spaceflight, Low was one of the principal advocates for a lunar landing as a worthy goal for NASA. In April 1959, as a member of the so-called Goett Committee charged with producing a long-range strategic plan for the agency, Low pushed for the moon. (One writer even went so far as to call him a "Moon Zealot.") Unlike von Braun or some other early NASA figures, he wasn't inspired by childhood dreams of flying rockets into space. Rather, it was the dirty-hands engineer in him that viewed a moon landing as a technically

NASA

Bill Anders (left), Jim Lovell, and Frank Borman during preflight training. Although they had only a few months to prepare for the revised mission, the astronauts were happy to shoot for the moon.

Launch day: December 21, 1968. Borman leads the crew out. Lovell (second) would return to the moon on Apollo 13, but his hopes to land were quashed when an oxygen tank exploded en route, forcing an emergency return. Apollo 8 was Anders' only spaceflight.

challenging—and therefore exciting—target, one that would advance technology the furthest.

When other committee members suggested that a trip around the moon, rather than a landing, would be more prudent, Low, the natural competitor, persisted. He thought that both could figure in a multi-decade program. Circumlunar flight could come first, but it would be followed by a landing sometime in the 1970s.

On July 28, 1960, he presided over NASA's first planning session to solicit feasibility studies for lunar missions. The meeting was attended by more than 1,300 representatives from government, the aerospace industry, and academia. It was here that Low first introduced the program his boss Abe Silverstein had dubbed "Apollo." At a time when NASA rockets were still blowing up on the pad, Low held the crowd rapt as he spelled out Apollo's modular approach to landing humans on the moon.

The press loved the story. The White House, not so much. President Eisenhower viewed human spaceflight as nothing more than a stunt, and Mercury as a one-time program rather than the start of some grand new enterprise. His response was to immediately erase all funding for astronaut flights from NASA's 1961 budget. It took both NASA administrator Keith Glennan and deputy administrator Hugh Dryden to calm the president down. They were able to persuade him to restore funding—but without a lunar landing mission.

Low would not be deterred. In fact, he doubled his efforts to make sure NASA's plans for human spaceflight didn't end with Mercury. "I felt it would be important to have something in the files," he said. "We needed to be prepared to move out with a bigger program, should there be a sudden change of heart within the government and with the administration."

Low wrote Silverstein a memo on October 17, 1960, requesting a small working group—later to be called the Low Committee—to come up with a "proper justification" for the moon program and give it "a firmer foundation" in terms of technical and budgetary requirements. Silverstein approved with a simple "O.K." written on the memo.

Less than four months later, on February 7, Low's committee produced a detailed report on methods for getting to the moon, along with schedules and rough budgets. With proper funding, the report asserted, a lunar landing could be accomplished by the end of the decade.

While the team had been busy working on its study, the country had elected a new president, John F. Kennedy. Within a few weeks of his inauguration, the White House was looking for a PR boost in the aftermath of the Bay of Pigs fiasco. "When President Kennedy's White House called up [NASA administrator] Jim Webb and said, 'Now, what about this moon mission?' NASA already had the answers, primarily through the work of the Low Committee," recalled Max Faget. It was, in fact, George Low's plan that became the foundation for Kennedy's "by the end of the decade" challenge.

NASA (2)

SIX YEARS LATER, when the Apollo 1 fire took the lives of three astronauts and put the moon program's future in doubt, NASA once again turned to Low. In April 1967, Webb tapped him to be the Apollo program manager.

In a BBC interview more than a decade later, Low confessed he had found the accident "appalling." He was convinced it never should have happened. The evening of the fire he had been in his office in Houston, working late and listening over a squawk box to the test under way at Cape Canaveral. It was clear things were not going well. Then, the first muffled sounds of tragedy: "Fire!" Low rushed over to Mission Control, where a call soon came: The astronauts were dead. When Low reached NASA deputy administrator Robert Seamans in Washington on the phone a few minutes later, he was so upset that Seamans couldn't understand him at first. It was a rare show of emotion, something most of Low's colleagues had never seen.

His anger and frustration quickly turned into a steely resolve to fix Apollo's problems. "It was the most challenging time in my life as an engineer," he told the BBC interviewer. Assigned the job of redesigning and rebuilding the Apollo vehicle, he and his team of NASA and contractor personnel set out "to find out what else lurked in that spacecraft and what else could come back to bite us." All the while, he was aware of the clock ticking on Kennedy's challenge. From April 1967 to the end of the decade, the moon would rise and set just 33 more times. "It was a very countable number of times that the moon was going to be in the right position," Low said.

During this period, he typically put in 18 hours a day, seven days a week. "My briefcase was my office; my suitcase, my home, as I moved from Houston to Downey, to Bethpage, to Cape Kennedy, and back to Houston again," he recalled. He tried to reserve Sunday mornings for church and family. A reporter who profiled Low during this period wrote, "He has five children, ranging in age from 4 years old to 15, and they adore the elaborate manner he does everything for them on Sunday, from water-skiing to serving up pancakes for breakfast." By Sunday evening, though, it was back to the telephone conferences and the stacks of paperwork, green pen in hand.

Low's colleagues at the Manned Spacecraft Center had great faith in his leadership. "George Low was a master at getting people to work together," recalled flight director Gene Kranz in a memoir. "The flight directors knew Low well from his middle-of-the-night visits to Mission Control during a flight, where he sat silently in the viewing room."

He often took his lunch to sit with workers at the center and ask how things were going. The trust and respect went both ways. "You would do whatever he asked you to do, regardless of the odds and regardless of the risks," said Kranz. "And you did so because you

After liftoff, mission control shifted from the Launch Control Center in Florida (pictured) to the Manned Spacecraft Center in Houston, where George Low would be watching intently from the back row.

knew he sweated the smallest, most minute detail."

Low knew that one of the fire's overarching causes had been poor coordination of engineering changes to the Apollo spacecraft. Fixing the problem risked making things even worse. "Rebuilding meant changes, and changes meant trouble if they were not kept under perfect control," he said. "Our solution was the CCB, the Configuration Control Board." Its purpose: to keep close track of technical changes that could inadvertently affect some other part of the complex Apollo system.

Low saw to it that the board included "some of the best engineers in the world." He demanded participation from every branch of the Apollo management and supply chain, including contractors like North American and Grumman. He assigned astronauts he trusted to be his eyes and ears at the shops where the spacecraft were being built. At Rockwell, he installed Frank Borman; at Grumman, Jim McDivitt.

Low was named NASA deputy administrator in December 1969, and was a key figure in early planning for the space shuttle. He died in 1984, a few weeks after his son David was chosen as a shuttle astronaut.

"George got us [CCB members] all into a room," recalled NASA's head of flight operations Chris Kraft. "And he said, 'All of you guys, the leaders—you will all attend. No substitutes. I don't want anyone but you. You need to be on board 100 percent, because, together, we are going to run this program."

The CCB met every Friday, promptly at noon, and rotated monthly between Rockwell and Grumman. The meetings often went late into the night, and no one left until all issues were resolved. From the hardware developers to the flight surgeons to the astronauts, Low let all speak their minds. Often the discussions got heated, and Low had to call order with a gavel. But it was not a democracy. "After hearing everybody's opinion for or against, I did not take a vote or delegate. Rather, I made the decisions."

Low kept a table listing any hardware that was experiencing problems: faulty circuit breakers, sticky and malfunctioning valves, poorly wired switches. They were constant, tactile reminders of the importance of paying attention to detail. "Each represented a potential failure in flight," Low said.

Eventually, the board was able to make sense of the chaos. "From June 1967 to July 1969, we met 90 times, considered 1,697 changes, and approved 1,341," Low said. "We tore the command module apart—literally all 2 million parts—and then we put it back together the way we wanted it to be."

"In the astronaut corps, we marveled at the new Apollo spacecraft taking shape," Alan Shepard wrote in 1994. "We were gaining confidence all the while that, yes, they're creating something that will be safe for us to fly." Low always kept that ultimate goal in mind. Later on, he would make it a habit during all the Apollo flights to have breakfast with the astronauts before launch. He wanted to shake their hands, look them in the eye, and let them know he had done everything he could to keep them safe.

BY AUGUST 1968, it was clear to Low that the first flight-ready lunar module would not be built in time for the original December target date for Apollo 8, which was supposed to test both the command/service module and Grumman's lunar landing vehicle in Earth orbit. The lander, Low said, "had what we call 'first ship problems.' It always takes the first ship longer to get through."

The redesigned command module, on the other hand, was looking good, even before its first shakedown flight in Earth orbit, scheduled for Apollo 7 in October. If NASA waited for a similar checkout of the lunar module in Earth orbit, Apollo 8 wouldn't fly until March of 1969. And that would push the first lunar landing well past Kennedy's deadline.

"That was a challenge that meant a great deal to us," said Low. "We didn't want to let the country down." Waiting until March also increased the risk of losing out to the Soviet Union. The Russians were thought to be close to their own human moon shot, and Low hated the prospect of being beaten—again.

The idea of going to the moon before the lander was ready had been planted in his mind more than a year earlier, in his first week as Apollo program manager. During a meeting with Kraft and Deke Slayton, head of the astronaut office, Kraft mentioned several ways the program could make up for delays due to the fire. One was a flight to orbit the moon ahead of the landing, with just the command and service modules. Low made note of it. The idea stuck with him, and he began to focus on it more and more as delays with the lunar lander got worse.

Kraft, though, had mostly put it out of his mind. "We were all taken aback," he recalled, when Low

NASA (2)

proposed the idea for real in August 1968. "It was the boldest decision of the space program," Kraft said.

For Low, it was simply a matter of asking the right question: How can we advance the program with hardware that is ready now? "Navigation to the moon, getting into lunar orbit, the burning of the big engine, the computer programs that were needed for that—we could get all of that out of the way."

The command and service modules, after all, were designed to orbit the moon. "It is a mission that we would have had to face sooner or later anyway," said Low. And it would increase the probability of a successful landing later. "Low's idea to circumnavigate the moon was a stroke of genius," Gilruth said. "It broke the back of the Russian moon-landing effort, and it left the U.S. free to take its time and concentrate on doing the job of landing a man on the moon."

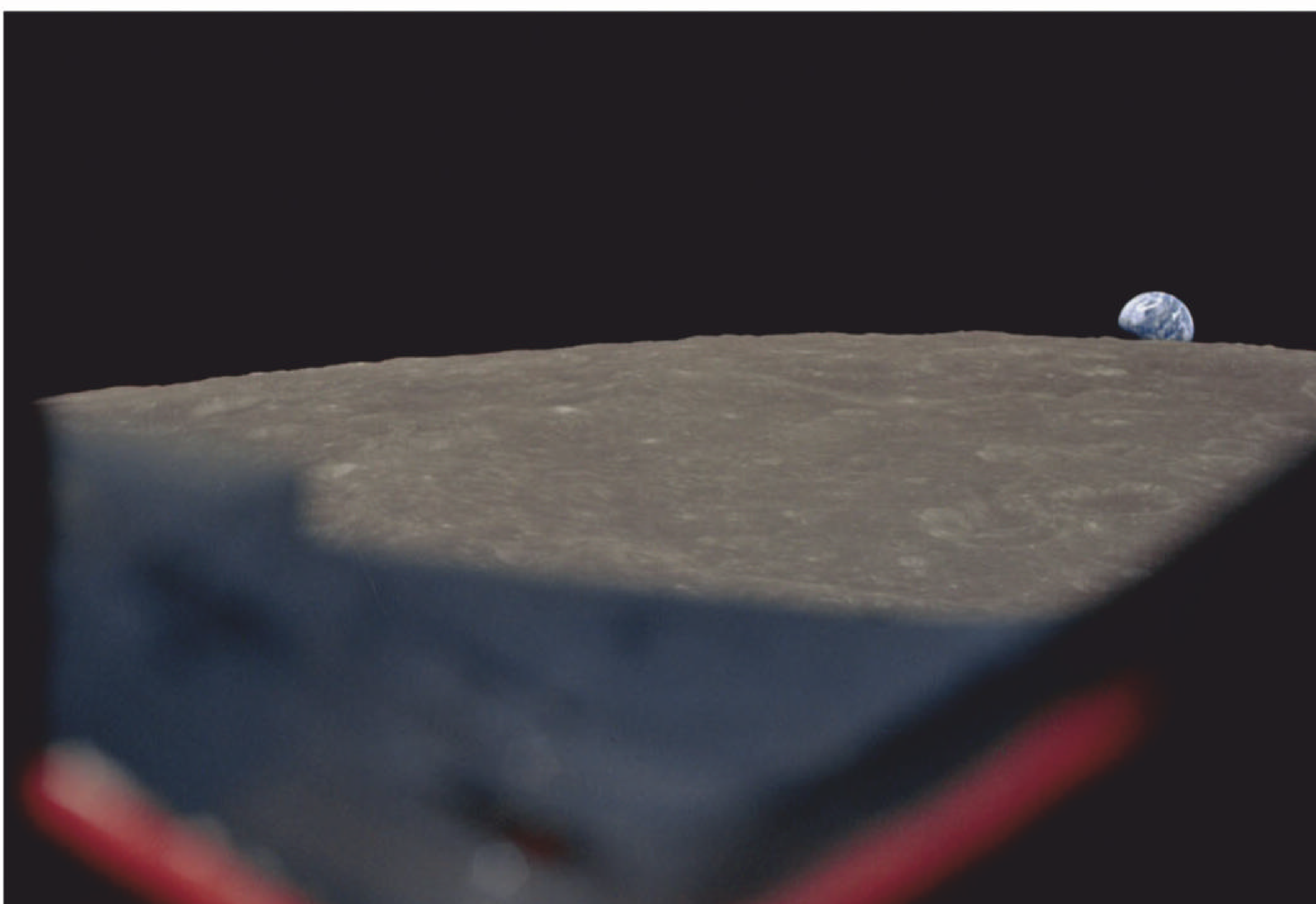
George Mueller, who headed human spaceflight at NASA headquarters, was against the idea at first, claiming it posed an unnecessary risk. Administrator Webb was shocked. "Webb thought we must have lost our minds," Low said. For all his political skill, the administrator couldn't face another fatal accident after the Apollo 1 fire and was already planning to step down before the Apollo 7 flight in October. Fortunately, Tom Paine, his successor, was enthusiastic about sending Apollo 8 to the moon.

Low understood the resistance in Washington, even though he thought the decision was a no-brainer from a purely technical perspective. "Politically, of course, it was a bad decision," he said. "Remember, [the decision on] Apollo 8 came along soon after the Apollo 1 fire." It took multiple private sessions to overcome the skepticism. Finally, after a series of executive meetings in Washington on November 10 and 11, 1968, Apollo 8 was approved for a lunar orbit mission. It was announced to the world the very next day, and less than six weeks later, Borman, Lovell and Anders headed off to the moon.

Following Apollo 8's December 21 launch, the first with astronauts on board the Saturn V, Low monitored the flight from the back row in Mission Control. There were many dramatic and tense moments over the course of that historic week. One came just under 70 hours into the flight, when telemetry confirmed that Apollo 8 had successfully slipped into lunar orbit shortly before 4 a.m. Houston time on Christmas Eve.

As cheers erupted in Mission Control, George Low went outside, filled with relief and satisfaction, and looked up at the waxing crescent moon. He would later recall, "It looked different to me."

The "Earthrise" seen outside the Apollo 8 crew's window was an unexpected prize from their flight. As Anders famously put it, "We came all this way to explore the moon, and the most important thing is that we discovered the Earth."



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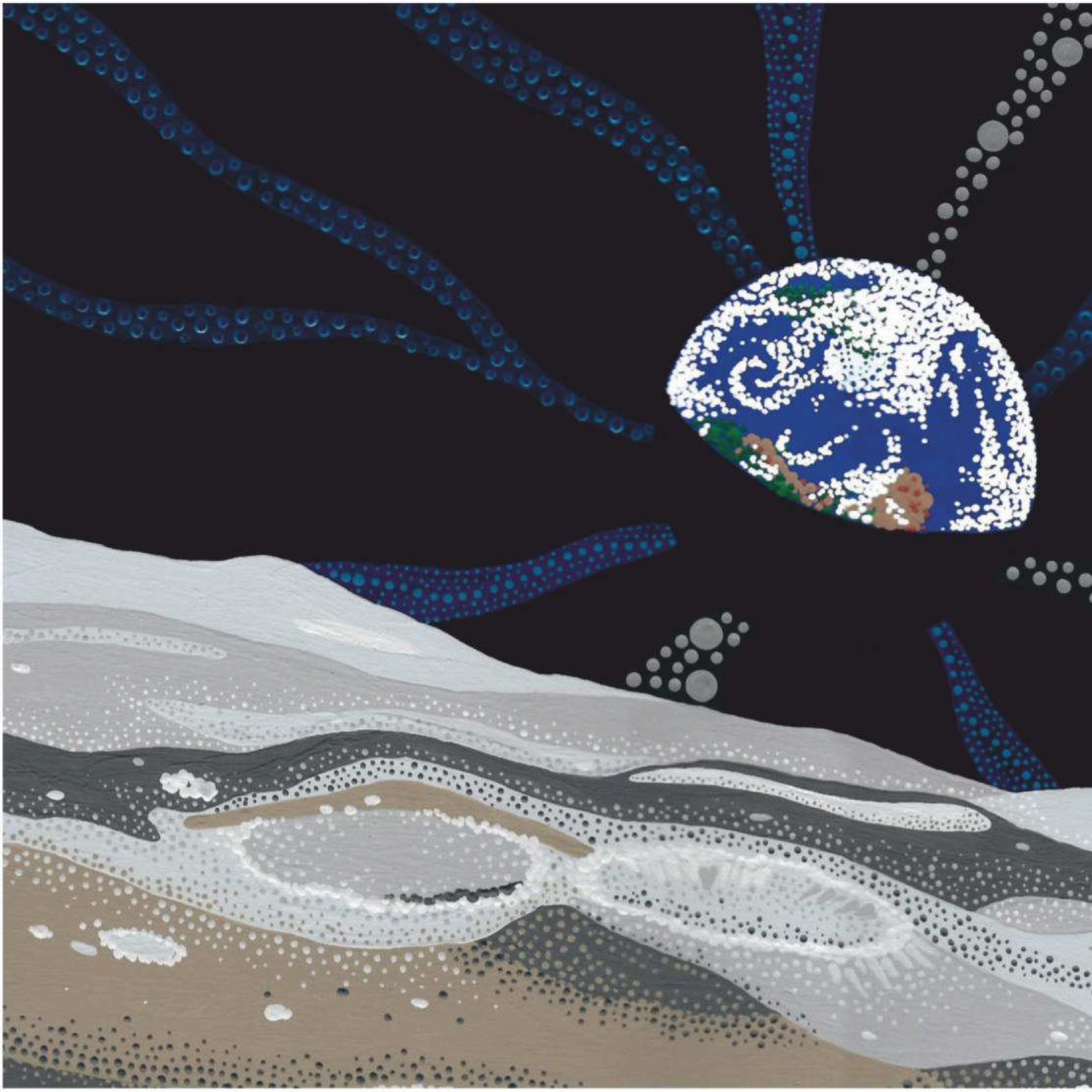

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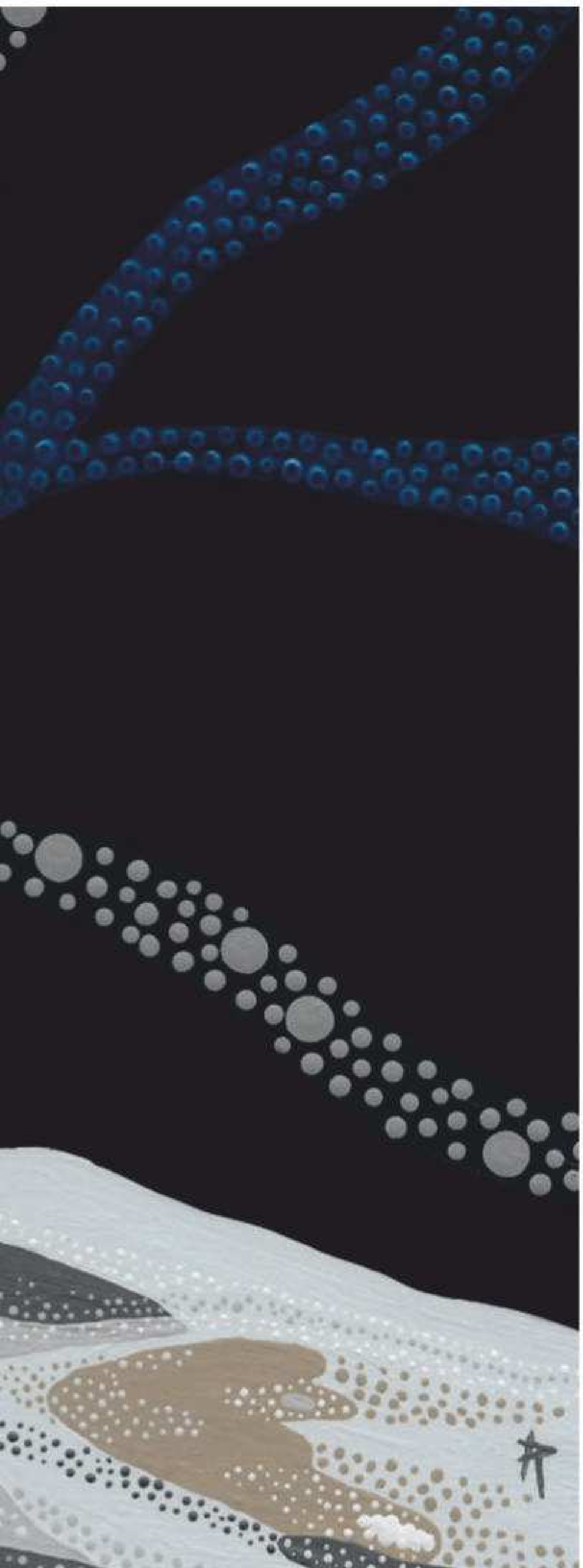

Artists celebrate the 50th anniversary of the planet's most famous portrait.

FORMER ASTRONAUT NICOLE STOTT, who in 2009 became the first to paint a watercolor in space, recently reminded her artist friend Simon Kregar that this month is the 50th anniversary of "Earthrise," the famous photograph of Earth suspended above the moon's horizon, which was taken during the Apollo 8 mission by astronaut Bill Anders. Kregar got an idea. He emailed his fellow artists in the International Association of Astronomical Artists, Earth's only artist's guild devoted to space, suggesting that members commemorate the historic moment. The works you see in this gallery were part of the response. Founded in 1982, the IAAA today has 170 members in 43 countries and is currently participating in an exhibit at Space Center Houston marking NASA's 60th anniversary, "Sixty Years of NASA Art." The show is on view through January 7, 2019.

—*The editors*

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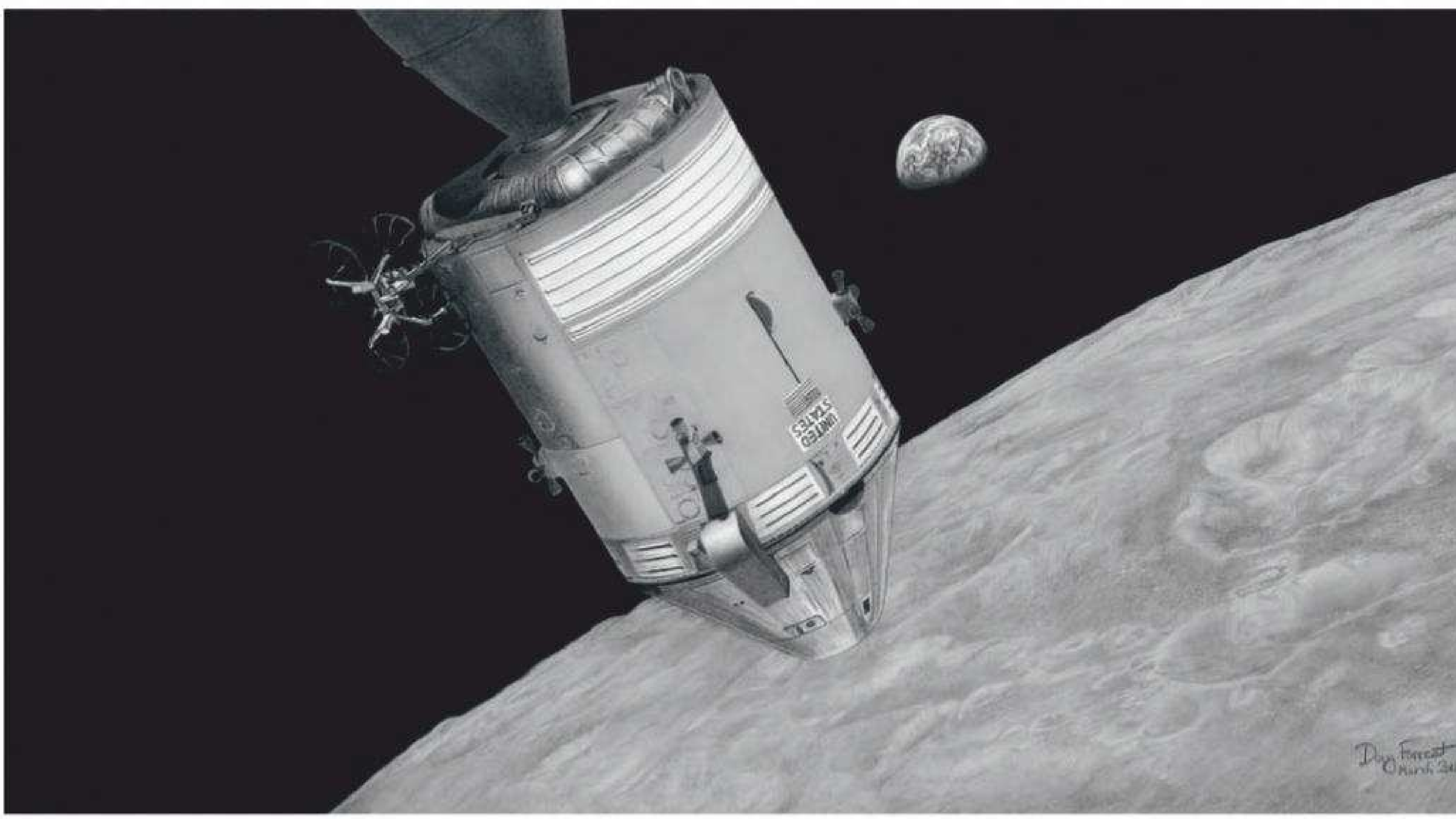
"Earthrise" by Jon Ramer (left) reimagines "Earthrise" by Bill Anders (right). Ramer's "dot art," a style he learned from aboriginal Australians, is acrylic on gessoed masonite.

▶ Notice the cluster of lights on the lunar surface at the lower left of Mark Pestana's "Home II" (24 by 30 inches, oil on canvas). Those intriguing lights are what, at Apollo 8's altitude, astronauts could see of what Pestana imagines: "an ice mining base, near the moon's north pole, producing water, oxygen, and hydrogen for customers preparing for travel through our solar system. The residents of these frontier outposts will regard Earth as their ancestral home."



▲ With "Apollo 8" (graphite on paper), Doug Forrest wanted to capture the exact moment when, as the Apollo 8 capsule rolled on its long axis, the home planet appeared in the spacecraft window. Forrest is amused by the hubbub he heard in the recording of the astronauts during the few moments the Earth was visible. "There was a massive scramble," he says. "Anders was calling for color film, and Lovell was trying to find it."

▶ What if the moon and Earth appeared in the window not of a spacecraft but of an airliner? Does Mark Garlick prophesy an airline that will fly in space, or is this all a dream? "I got the idea spontaneously from just seeing an image of an airplane window. I'm a bit weird like that!" says Garlick, a computer animator with a Ph.D. in astrophysics based in Hove, England. He created "Earth and Moon from Orbit" in 3ds Max and Photoshop.

▲ What fascinated Robin Hart about Apollo missions was "the contrast between the lifeless sphere of the moon and our Earth, which was so full of life." With "Luna Victoria," a 34- by 32-inch triptych painted and airbrushed with gouache and acrylic, she expressed the "human presence" she believed the astronauts carried with them to an alien world.

HOW TO WEIGH A GALAXY

BY HEATHER GOSS

ASTRONOMERS MUST BE CREATIVE when figuring out how much stuff there is in the universe. You can't exactly roll a galaxy onto an industrial scale (even if you could, as Isaac Newton figured out, you'd still have to factor in the influence of Earth's gravity to get its mass). The classical way of determining the amount of matter in an object like a moon, planet, or star is to measure its gravitational interaction with other objects. These early calculations combined Newton's law of gravity with Johannes Kepler's laws of planetary motion—the relationship between the planet's orbital speed and distance from that other object.

When astronomers first began applying these calculations to galaxies by measuring the orbital speeds of their stars, the results were strange. By appearances, most of a galaxy's mass seems to be near the center, so stars closer to the center should orbit faster than those at the edge. (Using our planets for comparison, Mercury has the fastest orbital speed—107,082 mph—and Neptune the slowest—12,146 mph. That's because 99.9 percent of our solar system's mass is in the sun.) In the 1970s, astronomer Vera Rubin and her colleague Kent Ford made observations of the Andromeda Galaxy, the major galaxy nearest to our own, that proved this assumption was way out of whack with what was actually happening. Stars at the edge were traveling nearly as fast as those near the center. The outer stars were orbiting so quickly that the momentum should have torn the galaxy apart. Instead, Rubin proposed that these observations were evidence that there was mass we couldn't see—dark matter—distributed out to the edges that explained

If we could see our own galaxy in its entirety, as we see NGC 6744 (above), a twin galaxy 30 million light years away, measuring the Milky Way's mass would be easy. But we see it from our place in one of its spiral arms and must invent new ways of calculating all the mass we cannot see.

DON GOLDMAN VIA NASA

the stars' movement. Invisible matter posed a bit of a challenge to measuring the mass of galaxies.

Astronomers now need to fine-tune their methods to address the dark matter known to exist in galaxies. In a presentation at the American Astronomical Society meeting last spring, Ekta Patel, a graduate student at the University of Arizona, described what may be a big step in pinning down the accuracy of mass calculations. Her team's goal was to address the difficulty of calculating the mass of dark matter as well as the unique challenge of measuring the mass of the Milky Way. Unlike measuring, for example, the Andromeda Galaxy, which we can see nearly in its entirety and in great detail through powerful telescopes, when it comes to our home galaxy, we're stuck looking out from one of the spiral arms. "Think of trying to take a census of the U.S. population without using the Internet or leaving the city you live in," says Patel. Or inspecting that mole on your back without a mirror. We just can't see it well.

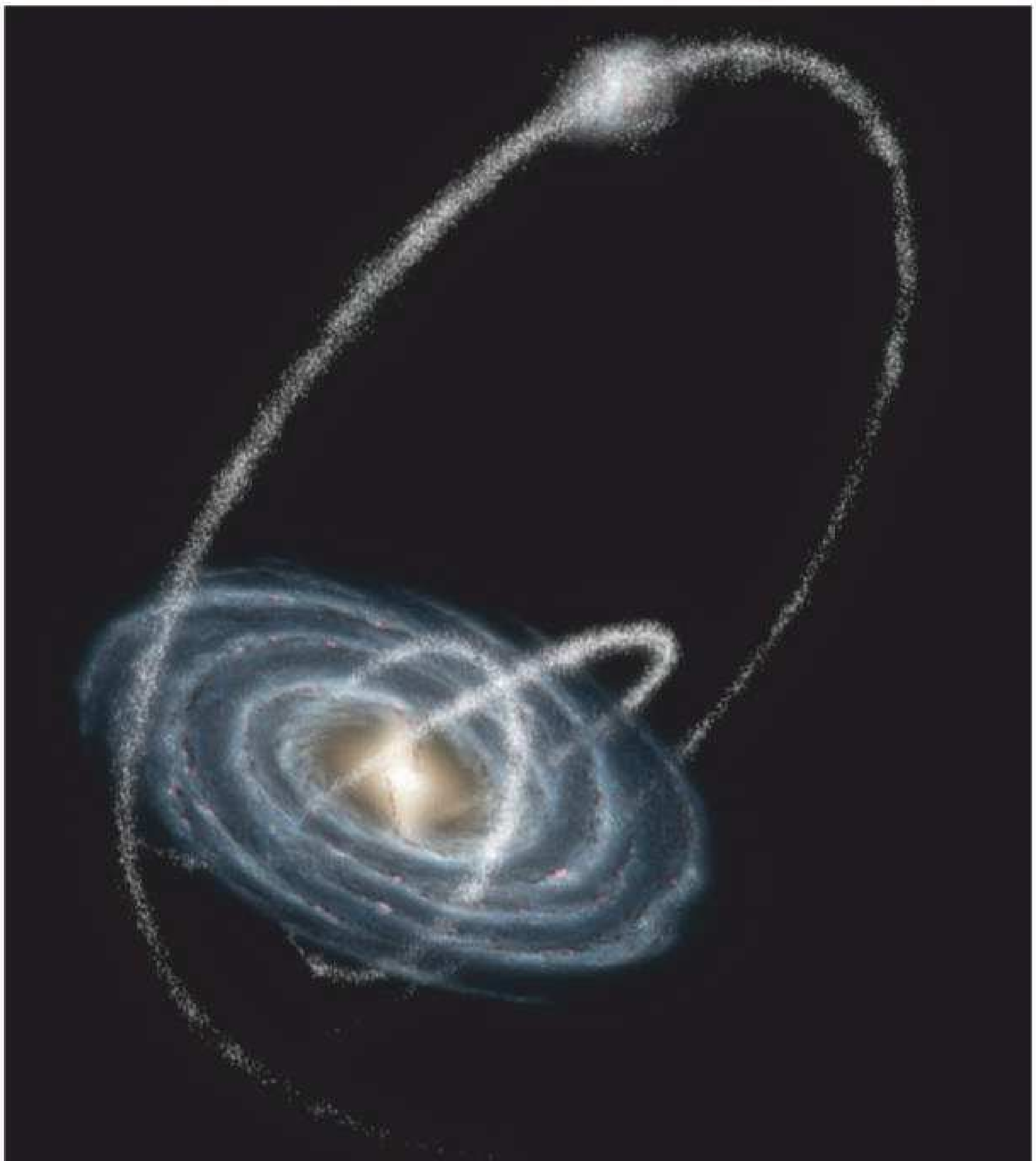
Instead of plotting out stars at various distances in the Milky Way—data that's hard to collect when peering around the galactic core—Patel's team studies the angular momentum of the Milky Way's satellite galaxies, about 50 small ones (that we know of so far) gravitationally bound to ours. Patel calls these "tracer objects," because their movement "traces" the mass distribution of their host galaxy. That movement across the sky, however, is crushingly slow. "These motions are so small it's like measuring the rate of human hair growth at the distance of the moon," says Patel. The only reason these measurements can be made now is that space telescopes—the detail required for this work is beyond the resolution of instruments on the ground today—have been in orbit long enough to see the tracers move measurably.

The Hubble Space Telescope is the best observatory for this data right now. Researchers like Patel rely on a dedicated team at the Space Telescope Science Institute in Baltimore, Maryland, which operates Hubble, to measure those almost incomprehensibly small movements of satellite galaxies across the sky.

Patel's team initially studied the motion of nine tracers for their calculation of the Milky Way's mass, but they plan to refine their estimates by including observations from Europe's Gaia telescope. That mission has been observing for only a little over four years and recently released its second dataset—enough to start measuring movement and allowing Patel to expand the number of Milky Way tracers her team is studying to around 30. "By the end of [Gaia's] mission"—four or five years and several more datasets—"that data will be just as precise as Hubble," says Patel. The James Webb Space Telescope will also contribute significantly to these observations, once its mission starts in the early 2020s.

Patel's team then uses cosmological simulations of the development of Milky Way-like host galaxies along with their satellite galaxies. These simulations provide statistical evidence for which evolutionary pathways would result in the galaxies they're observing. By using this new method, Patel and her team have narrowed the previous estimates of the Milky Way's mass—between 700 billion and two trillion solar masses—to 0.96 trillion solar masses.

The galaxy's prior wide range of potential masses made it impossible for any calculations based on that mass to have precise answers. How much dark matter does the Milky Way have? How did the galaxy evolve and form its current shape? "Not knowing the mass has prevented us from drawing more links between different physical questions regarding how galaxies like our Milky Way evolve," says Patel, because any single question has a variety of solutions. She also acknowledges their conclusion has a margin of error, but they will continue to whittle at the number the longer they're able to observe the tracers.



NASA/JPL-CALTECH/R. HURT/SSC/CALTECH

A tracer galaxy orbits the Milky Way in this artist's impression. Astronomers can use its slow movement to "weigh" the galaxy we live in.

A FRESH LOOK AT CLASSIC AVIATION AND SPACE FILMS

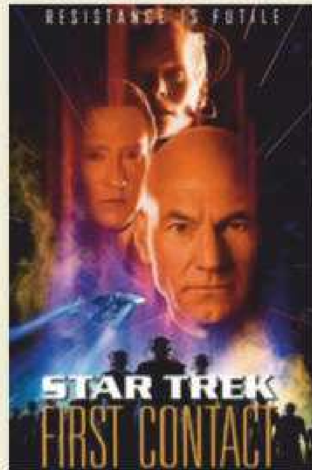
Star Trek: First Contact

Paramount Pictures, 1996. Rated PG-13, 111 minutes.

FINDING YOUR WAY into Star Trek, a 52-year-old property that has spawned multiple television series and more than a dozen feature films adding up to hundreds of hours of filmed storytelling, can be daunting. But *Star Trek: First Contact*, which premiered in 1996, is one of the long-running small-e enterprise's finest and most accessible hours—okay, two hours—and a fine starting point.

The first *Trek* movie to focus exclusively on the Next Generation cast that carried on the franchise for seven syndicated seasons circa 1987–94, *First Contact* is a family affair. It's directed by actor Jonathan Frakes, who played Commander William Riker on the TV show and its big-screen follow-ups, and written by Next Generation veterans Ronald D. Moore and Brannon Braga.

Time travel has been an even more frequent occurrence in the *Trek* films than in its various TV iterations, but *First Contact*'s time-travel plot—wherein the crew of the *Enterprise*-E must travel back from the 24th to the 21st century to prevent their hive-mind enemy The Borg from "assimilating" Earth before ambassadors from the planet Vulcan can reach us—managed to feel urgent and engaging all the same.



Patrick Stewart had always made his Captain Jean-Luc Picard a more intellectual and reserved character than William Shatner's Captain James T. Kirk, but for this movie he asked for and was given a more physical role in the action, wherein Picard must again confront The Borg—an enemy to whom he has lost before, and the defeat haunts him.

Despite the fact Frakes' only directing credits had been episodes of the Next Generation television series before making his big-screen debut, the film looks impressively lavish even now, using its generous-compared-to-TV-but-still-limited budget wisely. *First Contact* also introduces Alice Krige, whose mischievous performance as the Borg Queen made her one of the most memorable of all *Star Trek* villains. For once a movie's poster told the truth: Resistance is futile.

CHRIS KLIMEK IS AN ASSOCIATE EDITOR AT *AIR & SPACE*.

ERIK JACOBS/JACOBS PHOTOGRAPHIC

UNITED STATES MINT

2019
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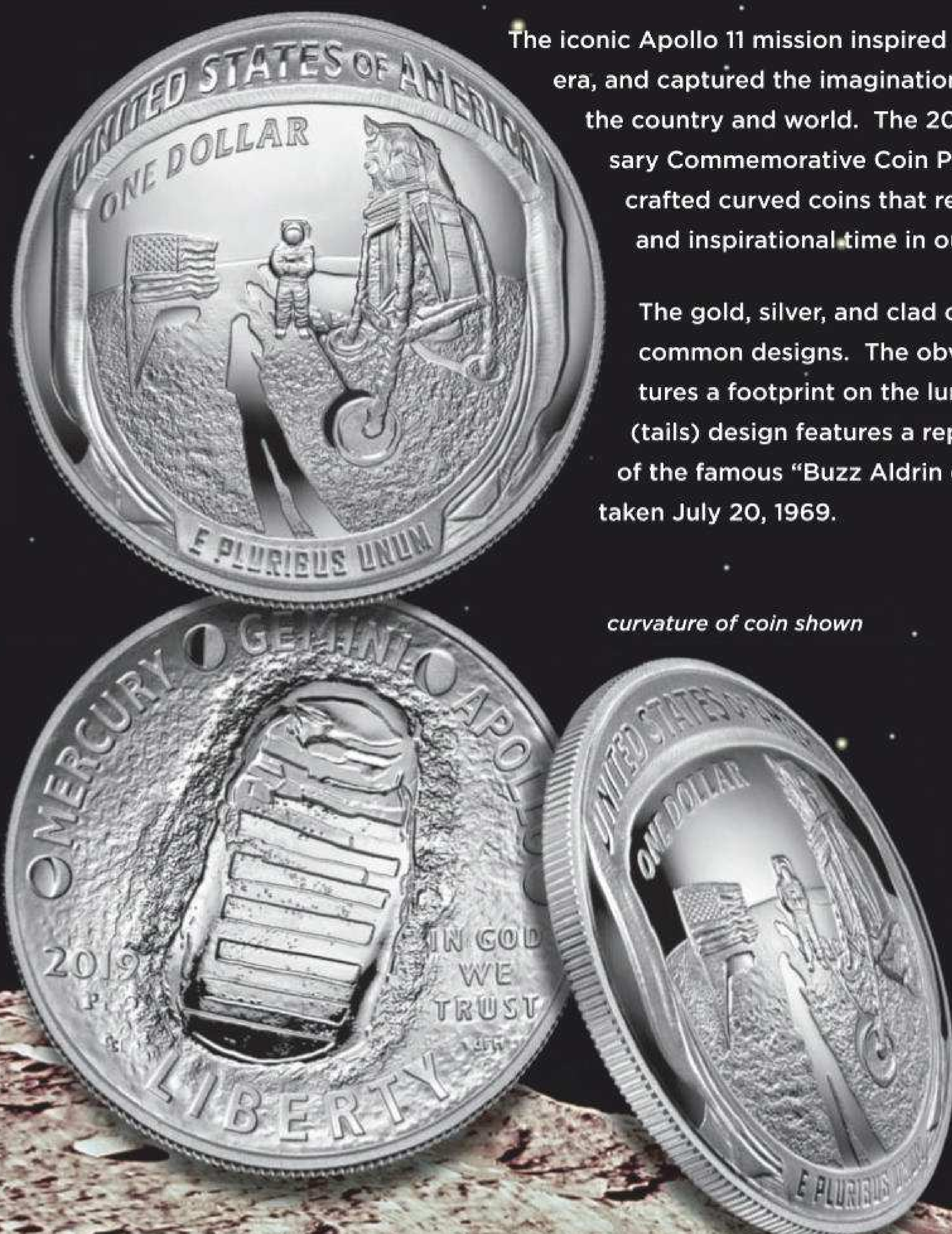

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