 by Shannon Hall

SOFIA's End

NASA's SOFIA observatory came to an abrupt end last September, leaving many scientists despondent and a number of projects unfinished.

The Boeing 747 lifted toward the sky, taking off at a hefty pitch and shoving Jim De Buizer back in his seat. The goal was to reach 35,000 feet — and fast.

At that altitude, the pilots would ease up on the throttle and open a 4-meter-wide door in the side of the fuselage. It wasn't a death wish: They were exposing a 19-ton, 2.5-meter telescope to the starry sky.

It was May 26, 2010, the first night observing with the world's largest airborne telescope — otherwise known as the Stratospheric Observatory for Infrared Astronomy, or SOFIA — and De Buizer had goosebumps. "You're taking off to get the first photons for an observatory ever," De Buizer says. "And that's just pure adrenaline that whole entire time."

From the ground, water vapor in our atmosphere blocks most infrared light. But at its maximum altitude of 45,000 feet, SOFIA flies above 99% of that water vapor, giving it unique access to the far-infrared part of the electromagnetic spectrum. Since the project became fully operational in 2014, it has been the only telescope that could study celestial objects at these wavelengths.

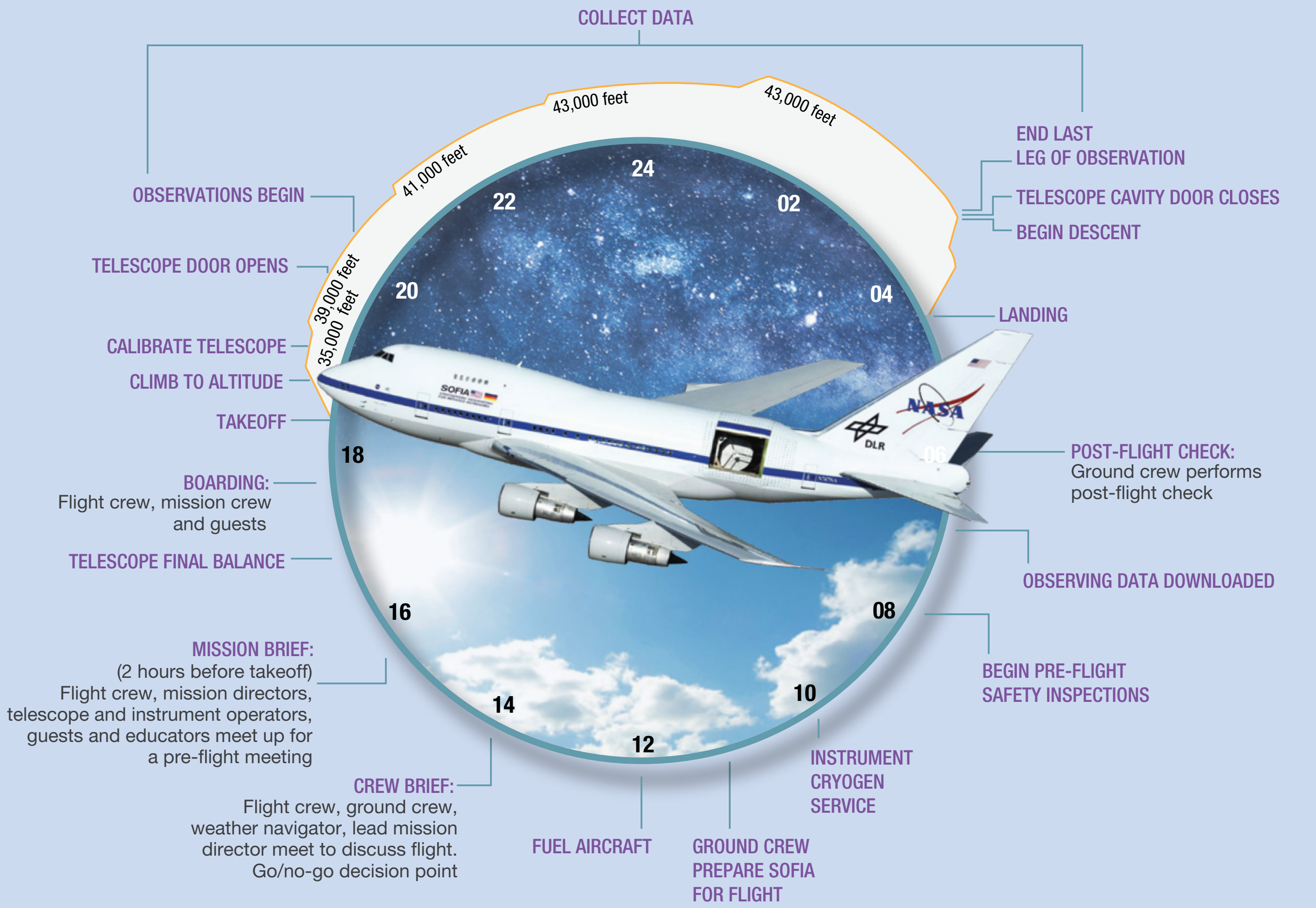
"It's a one-of-a-kind observatory," says Alfred Krabbe (University of Stuttgart, Germany), the director of the German SOFIA Institute. (SOFIA is a joint mission between NASA and the German Aerospace Center, or DLR.)

So when De Buizer and his colleagues pointed the telescope toward Jupiter on that first night, they probed depths of the planet that had never been seen before. The composite image (obtained by De Buizer on the ground after only an hour's sleep) revealed heat that had been trapped since the planet's formation and was now pouring out through holes in the clouds.

The image exceeded his expectations. And by the time SOFIA completed its development phase in 2014, he and many other scientists were looking forward to what they thought would be a 20-year run, giving an unprecedented view of the infrared sky — a part of the spectrum rich with information about planets, newborn stars, and galaxies.

◀ **THE KEYHOLE** This composite image shows magnetic fields (swirling lines) detected by SOFIA in the Keyhole Nebula, part of the larger Carina Nebula, or NGC 3372. The magnetic fields have the same orientation to those in the larger cloud complex except in the big loop structure at center, where the field aligns with the direction of Eta Car's powerful winds. The alignment confirms that stellar feedback can disturb magnetic fields in star-forming clouds, and that Eta Car likely made the loop structure. The background image is from the European Southern Observatory's 3.6-meter telescope on La Silla. The inset by astrophotographer Steve Mazlin gives a clearer sense of the nebula, taken using hydrogen-alpha (red) and O III (blue) filters, with a green channel synthesized from the other two.

SOFIA: NASA / SOFIA SCIENCE TEAM / Y. SEO / ESO; INSET: STEVE MAZLIN / SSRO / PROMPT / CTIO



▲ **A DAY IN THE LIFE OF SOFIA** The daily operations timeline crammed everything necessary for a safe and successful observing run into a single 24-hour period. SOFIA flew up to four days each week.

But merely eight years later, on April 28, 2022, NASA and DLR announced that they would shut SOFIA down.

In its short lifetime, the observatory discovered water on sunlit portions of the Moon. It measured magnetic fields in stellar nurseries and distant galaxies. It followed up and vastly improved on many discoveries made by the Herschel Space Observatory, which operated at far-infrared wavelengths from 2009 to 2013. And it even measured atomic oxygen in Earth's atmosphere, helping climate scientists refine their models of climate change.

But SOFIA still fell short of expectations. Over its first five years in operation, the observatory did not generate large numbers of high-profile results (measured by the number of citations in scientific journals). That, along with the observatory's high operating price tag of $85 million per year — second only to the Hubble Space Telescope — forced NASA to decommission it.

So at the end of September 2022, the Boeing 747 lifted into the air and the telescope captured its last images.

Many scientists were left heartbroken and downright angry, frustrated by a swift decision they felt was based on outdated information. The shutdown also left many projects unfinished, without any alternative instruments to continue them: There is no longer an operating far-infrared observatory.

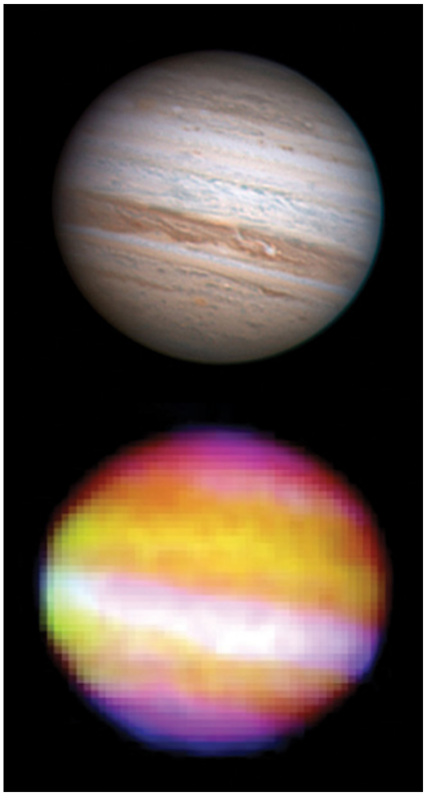
"To rip this gigantic hole into the coverage of the electromagnetic spectrum is — in my eyes — not defendable," says Bernhard Schulz (also University of Stuttgart), the top German representative on the SOFIA science team. "It is rather a scientific crime than anything else."

"A Crazy Idea"

SOFIA came from a long line of airborne astronomy. As early as the 1920s, astronomers used biplanes to chase solar eclipses. In 1968, NASA started using a Learjet equipped with a 30-centimeter telescope to study Jupiter and nebulae.

The next year, the agency began planning the Kuiper Airborne Observatory (KAO), which featured a 36-inch telescope that stared through a hole in the roof of a military transport

SOFIA STATUS AND FUTURE PROSPECTS 2022 / NASA / SOFIA / MONIKA ROSE aircraft. KAO flew for 20 years and made several major discoveries at infrared wavelengths, including the first sightings of the rings of Uranus and a definitive identification of an atmosphere on Pluto. KAO retired in 1995 to make room for its successor, SOFIA.



◀ **A NEW VIEW OF JUPITER** Bands appear on Jupiter at both visible *(top)* and infrared *(bottom)* wavelengths, but this composite infrared image from SOFIA's first-light flight in 2010 includes wavelengths either difficult or impossible for ground-based instruments to observe. The white strip is a relatively transparent cloud band through which Jupiter's interior heat shines.

INFRARED: NASA / SOFIA / USRA / FORCAST TEAM / JAMES DE BUIZER; VISIBLE: ANTHONY WESLEY

In many ways, these airborne observatories have an edge over both their space- and ground-based counterparts.

Unlike space-based observatories, they can land. That means instrumentation can be repaired or updated with improving technology. Satellites, on the other hand, carry outdated equipment designed long before launch and can't be fixed should something go wrong. And unlike ground-based counterparts, plane-based telescopes can fly above most of the atmosphere and to any location on Earth, enabling them to observe objects in both hemispheres and seek the best paths across the globe for occultations. In 2015, for example, SOFIA watched Pluto slide across the face of a distant star — a rare celestial alignment that allowed scientists to collect crucial data on the dwarf planet's atmosphere.

But for all the upsides, stabilizing a telescope on such a bumpy platform is a tough problem. "It's a crazy idea," Schulz says. "There's nothing less stable than an airplane."

For SOFIA, engineers spent years finding ways to direct airflow around the hole in the fuselage to prevent the telescope from shaking uncontrollably. They also sat the telescope on 24 air springs and three dampers, to absorb most of the plane's vibrations. The bearing floats on a very thin film of oil to offer soft support. And the telescope utilizes gyros to measure its own movement, counteract that movement, and steady itself. It's no wonder the original completion date (which was supposed to be 2001) was pushed back to 2014. The budget also ballooned from $265 million in 1997 to $1.1 billion by the time SOFIA finally became fully operational.

Fields at Play

SOFIA filled the gap left by Herschel's decommissioning in 2013, covering a range that subsequent high-profile observatories like the James Webb Space Telescope and the Atacama Large Millimeter/submillimeter Array (ALMA) in Chile don't. And that gap is crucial.

When astronomers observe the energy output of star-forming galaxies, they find that roughly half is in the form of mid- to far-infrared radiation. "So if you didn't study the universe in the far-infrared, you would only get half the picture," says Naseem Rangwala (NASA Ames Research Center), SOFIA's project scientist. "There's so much at this wavelength range that's waiting to be discovered."

Take the question of star formation. To build a star, the universe needs two major ingredients (gas and dust) plus a blend of things like gravity and turbulence. Astronomers know the basics of how a star is born, but according to most computer models, star formation should occur at a much faster clip than the one we observe. So what's slowing it down? Researchers have long wondered if magnetic fields — which are so mysterious they were ignored in early computer models — could be the culprit.

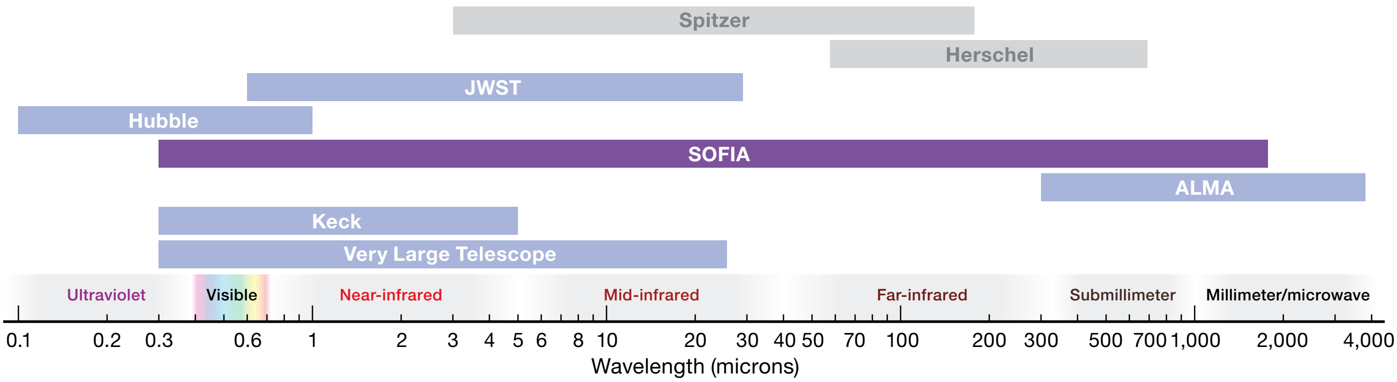
To find out, scientists built an instrument for SOFIA called HAWC+, which maps the alignment of incoming light waves and can reveal crucial information about magnetic fields. When Thushara Pillai (Boston University) used HAWC+ to observe a nearby cluster of roughly 50 young stars, she was able to pinpoint the zone where gravity becomes the dominant player. Here, magnetic fields suddenly change orientation: Instead of supporting gas filaments against collapse, they succumb as gravity takes over and drags the gas (and the magnetic fields trapped inside) to become channels flowing into a central, star-forming hub. It's gravity's conquest of magnetic fields that allows stars to form.

The finding suggests that magnetic fields are a key player in star formation. But one cloud alone cannot explain why star formation is so slow. So Pillai started a SOFIA survey to repeat this experiment on a much larger sample.

Meanwhile, her colleagues used the same instrument to

Airborne Telescopes

Planes aren't the only way instruments take to the skies: Scientific balloons also have a long, successful history (*S&T:* Feb. 2018, p. 16). These balloons typically fly between 96,000 and 127,000 feet above sea level, can carry the equivalent of three cars' weight in gear, and stay aloft for anywhere from 2 hours to 2 months. But they don't have their own propulsion; they must follow the winds. This is not as prohibitive as it sounds: Campaigns over Antarctica, for instance, utilize the predictable patterns of seasonal stratospheric winds to plan observing targets in advance.



▲ **INFRARED GAZE** SOFIA spanned wavelengths that other major facilities don't currently observe (the Spitzer and Herschel space telescopes have shut down). Balloons are often used for far-infrared studies as well, but they don't have a set wavelength range — it depends on the instruments flying — and so don't appear here.

map magnetic fields beyond the Milky Way. Consider M82, a so-called *starburst galaxy* undergoing an exceptionally high rate of star formation, akin to the universe's earliest galaxies. There, scientists discovered that the galactic wind blowing from the center of M82 is so intense that it drags the galaxy's magnetic field along with it — potentially explaining how the intergalactic medium in the early universe was initially seeded with a magnetic field (*S&T:* Sept. 2021, p. 22).

▼ **STAR FORMATION** This composite image of the Serpens South Cluster shows magnetic fields (streamlines) superposed on an infrared image. In the dense gas filament (center left), gravity has overcome the resistance of magnetic fields, dragging the gas and fields into an inward flow that fuels star formation.

"When I was a grad student, magnetic fields were something that we always put under the rug," Rangwala says. "Now we are producing textbook-changing results."

But the largest splash of all was perhaps water on the Moon. In 2020, SOFIA detected water in one of the largest craters visible from Earth. Scientists determined the concentration was 100 to 400 parts per million — roughly the equivalent of a 12-ounce bottle trapped in a cubic meter of lunar soil. While scarce, the water raises intriguing questions about how it persists and potentially migrates across the Moon.

Paul Lucey (University of Hawai'i, Manoa), one of the planetary scientists responsible for the detection, began a much larger SOFIA survey to map the Moon entirely. He wanted to better understand whether water can migrate and eventually supply the poles. That work is crucial for future missions to the Moon — including NASA's upcoming Artemis 3 mission, which will land near the lunar south pole.

If astronauts could recover water on the Moon, then it could be used for drinking water and converted into fuel, reducing the load future spacefarers must take in their ventures beyond Earth. "It changes the economics of space resources pretty substantially," Lucey says.

But Lucey's map won't be completed. Neither will Pillai's survey that might have pinpointed how star formation occurs. Both are victims of SOFIA's abrupt end.

Grounded

SOFIA's scientific output has long been questioned. In 2019, NASA commissioned a flagship review, which detailed the observatory's low productivity. Over its first five years of operations, for example, SOFIA produced roughly two dozen scientific papers per year. That is far too low for a project that costs NASA more than $80 million per year. Compare it to ALMA, which publishes about 500 scientific papers each year and cost the National Science Foundation $51 million in 2022. (Mind you, ALMA can work both day and night and typically observes half of the total hours in a year.)

In response to the flagship review, SOFIA brought in a

WAVELENGTH DIAGRAM: GREGG DINDERMAN / *S&T*; SERPENS SOUTH CLUSTER: NASA / SOFIA / T. PILLAI; NASA / JPL-CALTECH / L. ALLEN new director, Margaret Meixner (then of the Space Telescope Science Institute), who ramped up scientific productivity. She hired postdoctoral researchers, ran multiple virtual conferences, and increased the total number of flights per week to four. (SOFIA couldn't fly every night of the week because of scheduled maintenance and the higher cost of additional crew.) Meixner even bolstered the amount of SOFIA data in archives to entice astronomers to dig through past observations and publish fresh papers on them.

In all, the observatory doubled its annual publication rate from 2019 to 2022. Its scientific output during that time was even on par with what the Herschel Space Observatory had achieved during its operations. "We hit all records in 2022: total number of annual publications, research hours achieved in flight, flight cadence — everything," Meixner says. "All the metrics were very high, which just demonstrates that SOFIA had really hit stride."

Meixner and her colleagues planned to document these changes in a second review that would take place in 2022, called the senior review. The team finished the draft early, certain that NASA would see a clear improvement. But NASA never looked at it.

In January 2022, NASA pulled SOFIA from the review, and in April, the agency announced they would shut down the observatory. That decision cited the 2020 decadal survey, which echoed the flagship review's argument that SOFIA is expensive to operate and does a limited amount of high-priority science.

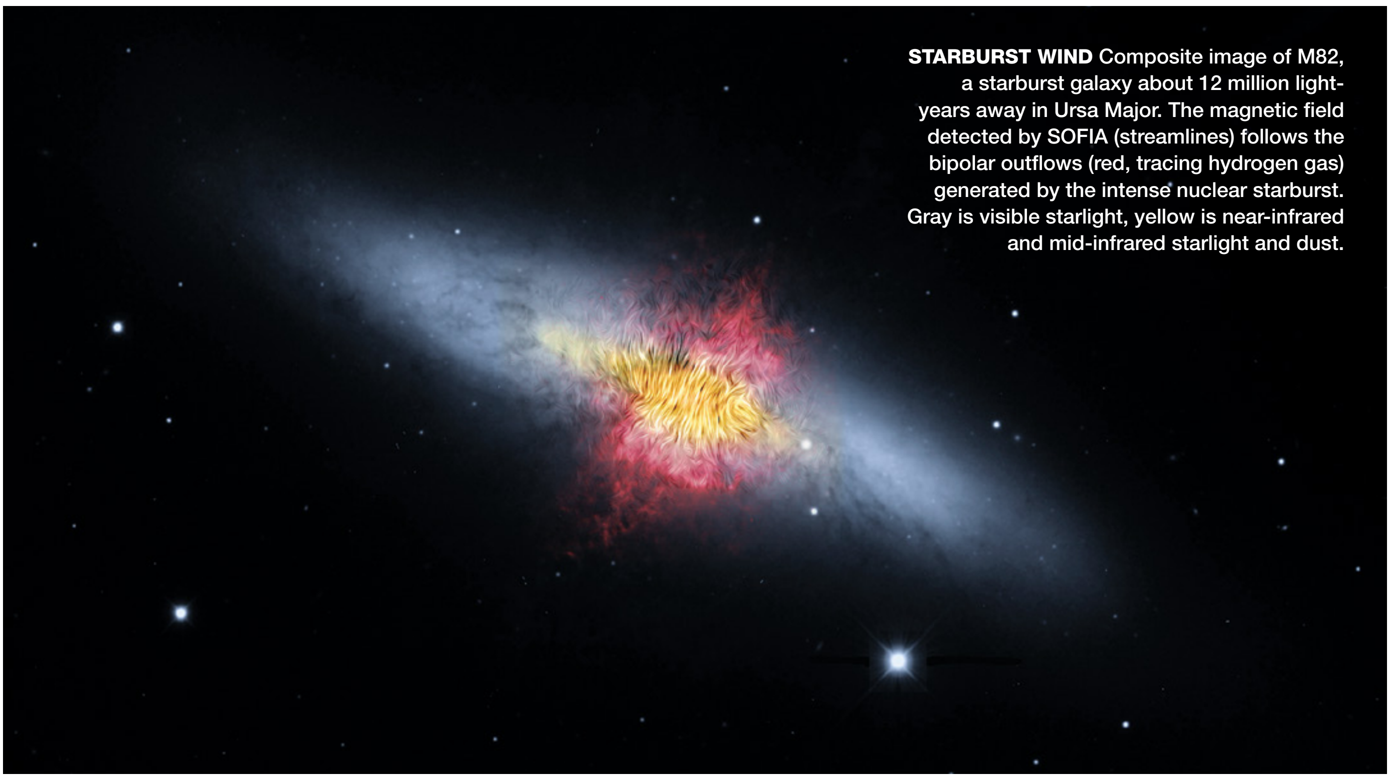
But the decadal survey did not include Meixner's directorship, the ramp-up in productivity over the last three years, or exciting results like Pillai's early magnetic-field work and Lucey's detection of lunar water. NASA's decision was therefore based on outdated data, critics say. One dissident even accused NASA of wanting to shut SOFIA down and trying to prevent the project from making its case.

But Paul Hertz (NASA), who was the Astrophysics Division Director when the decision occurred, says the decadal survey "found no evidence that SOFIA could, in fact, transition to a significantly more productive future." Nor is NASA ending SOFIA "early," as many SOFIA scientists assert, he adds.

Although SOFIA was capable of operating for 20 years, no prime mission lifetime was officially set early on, he argues. "It was assumed by NASA that the prime mission would match that of Hubble and Chandra (and subsequently Webb), which is five years," he says. The agency and project later formally recognized this five-year prime mission in the SOFIA Program Commitment Agreement that was signed in 2015.

That means that SOFIA's prime mission technically ended in 2019, five years after the observatory became fully operational. Following the flagship review at that time, NASA extended the mission for three years until 2022.

The limited prime mission, however, was not effectively communicated to the SOFIA team. Harold Yorke, who was SOFIA's Science Mission Operations Director from 2016 to 2020, says that NASA headquarters informed the project as late as 2018. (Yorke forfeited all documents when he retired from the project and is hesitant to assign a specific date, but he's certain the news came much later than the start of SOFIA.) There is even a Congressional record from 2018, which quotes a "prime mission lifetime of 20 years."



STARBURST WIND Composite image of M82, a starburst galaxy about 12 million light-years away in Ursa Major. The magnetic field detected by SOFIA (streamlines) follows the bipolar outflows (red, tracing hydrogen gas) generated by the intense nuclear starburst. Gray is visible starlight, yellow is near-infrared and mid-infrared starlight and dust.

NASA / SOFIA / E. LOPEZ-RODRIGUEZ; NASA / SPITZER / J. MOUSTAKAS ET AL.

The German Aerospace Center also appears to have been left out of the loop. Krabbe and his colleagues were shocked to learn the same news. "It was a one-sided decision," Krabbe says. "As far as I know, the German Aerospace Center never agreed to that."

The change was a major blow to the SOFIA project. "That was a death sentence," Schulz says.

Money Matters

The sad reality is that NASA doesn't have the money to fund every worthy project. "There has never been a budget where we could cover everything we would like to do," says Thomas Zurbuchen, who served as NASA's associate administrator for science until the end of 2022.

And SOFIA is far from cheap. Jet fuel, maintenance, and overhead for safe flight operations all cost money. In 2021, SOFIA accounted for 6% of the overall astrophysics budget, a larger share than any other program except for the Hubble Space Telescope. (Development of the James Webb Space Telescope is not included in the astrophysics program; it's a separate line item in the budget.) And NASA covers 80% of SOFIA's budget; DLR only supplies 20%.

"It just comes down to a numbers game," Lucey says. "So the astrophysics program, every dollar it spends on SOFIA is a dollar they can't spend on something else. And the amount of science per dollar is kind of low. It does great science, but just not enough of it for every dollar spent."

NASA runs a careful calculation of operating costs relative to scientific output, and the result has changed dramatically over the last three decades, Zurbuchen explains.

When SOFIA was first conceived in the 1990 decadal survey, it was a lot more complicated and expensive to send an observatory to space. So the solution seemed simple: Use an airplane to capture infrared science faster. But SOFIA wasn't fast enough. Space-based technology evolved at a rate that outpaced SOFIA's delays, allowing observatories like Herschel and Spitzer to launch in the interim.

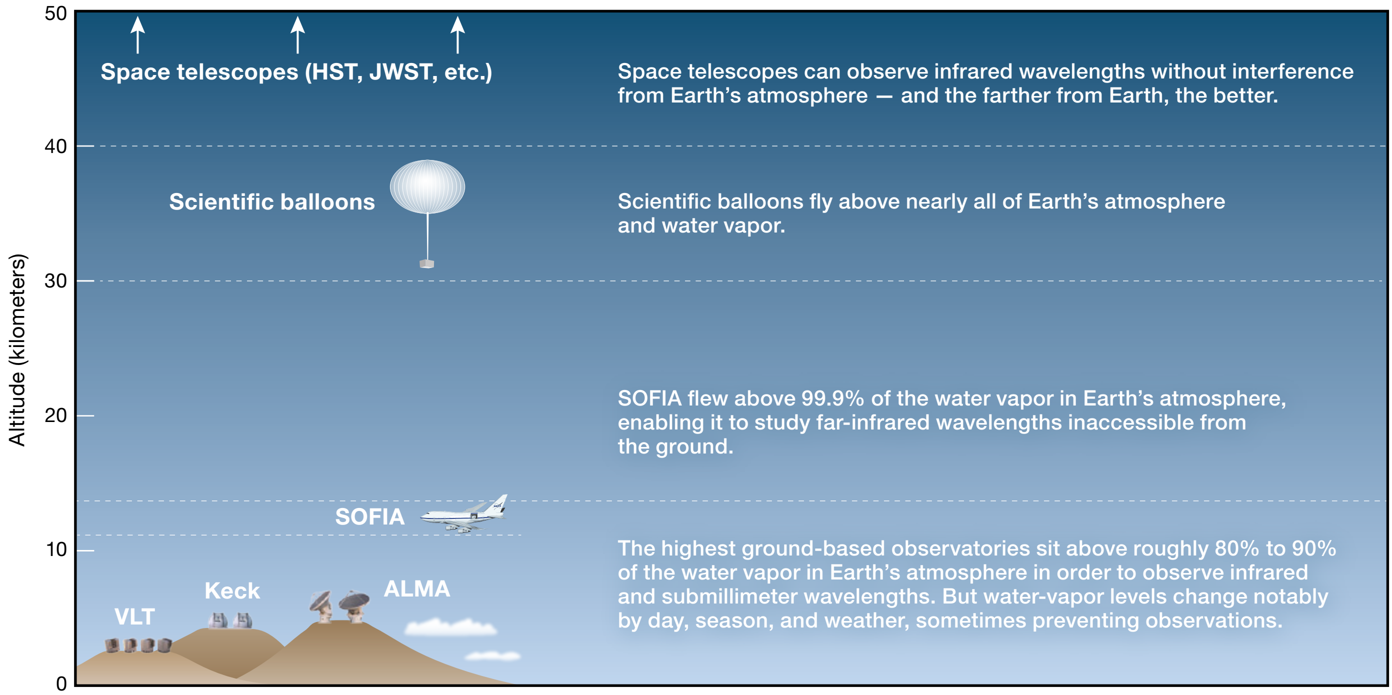
"There are science opportunities that have a window of opportunity, and if you miss it, it's going to get harder," Zurbuchen says. "And the case that was at the heart of SOFIA became less important."

That explains why SOFIA has often been on the cutting block. In 2006, NASA tried to cancel the project, but Congress and Germany forced the agency to restore it. In 2014, NASA again threatened SOFIA's funding — just 11 days after the observatory became fully operational. And NASA continued to try to nix SOFIA in 2020, 2021, and 2022, until it finally succeeded.

Many argue, however, that you can't look at the yearly budget alone. Yes, SOFIA is more expensive to operate on a year-to-year basis than a satellite, but its overall expenses are much lower. The Hubble Space Telescope, for example, cost roughly $4 billion to build, launch, and operate for the first 8 years of its lifetime. SOFIA has only cost $1.8 billion. Other space-based observatories, on the other hand, have cost much less: The Kepler Space Telescope, which ran for 9 years, was only $704 million.

Although Meixner respects NASA's right to make this decision, she thinks that the numbers argument is flawed. "If they had let it go on for three more years, we would have

Observatories by Altitude



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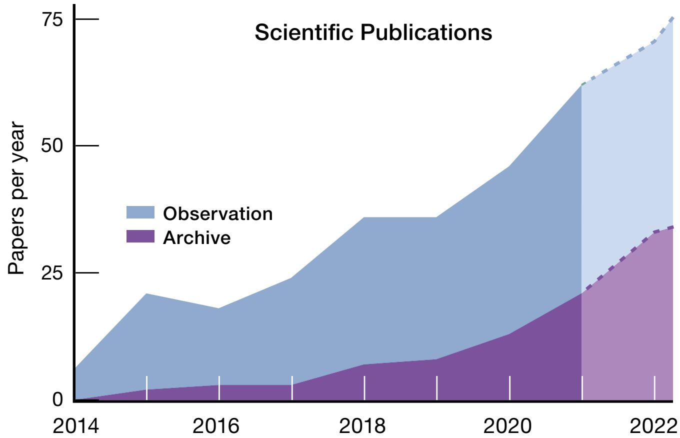
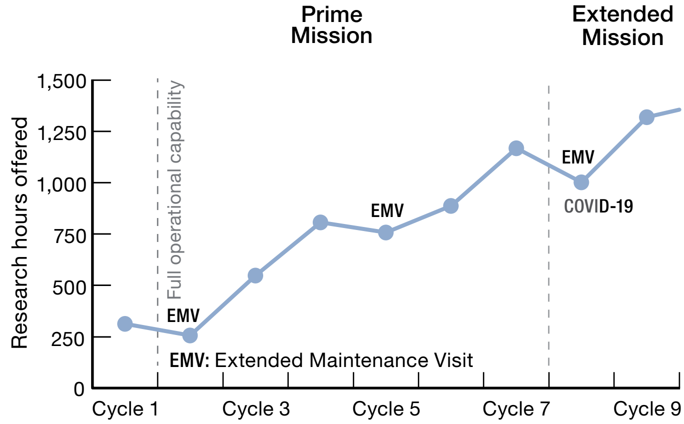


▲ **PERFORMANCE** Annual publications, including those based on mining SOFIA's data archive (purple), grew since full operations began in 2014. The lighter-shaded regions are projections based on the team's planned improvements, prior to the decision to shutter the program.



▲ **OBSERVING TIME** SOFIA's available observing time increased over the years, with impacts from maintenance and the pandemic. Cycle 1 began in mid-2013; after that, most observing cycles lasted about one year, beginning in the early part of the calendar year (except for 2020–22).

collected so much more data to increase the archive and also to increase publications," she says. "And, you know, it would have been a minor increase in total costs for the mission, but it would have been at a higher science return."

A Gap in the Spectrum

For many, the shutdown is heartbreaking. But this is natural, Zurbuchen notes. When the team that flew Cassini ended the mission by slamming the probe into Saturn, many cried. When the team that controlled Spitzer sent the last command to the probe, there were also tears. And when Opportunity died, people were literally sobbing. "The fact that there's an emotional component is what we expect," Zurbuchen says. "Our people really care for their missions. And SOFIA is not different."

But in this case, SOFIA's finale ended a 54-year-marathon of similar observatories and left a gap in the electromagnetic spectrum. "They just took the axe and just cut it," Schulz says.

Luckily, Lucey's lunar survey had already imaged several crucial locations, including the upcoming landing sites for the Artemis mission. The researchers will have enough data to nail down the behavior of water, but they won't have a measurement of every single point on the Moon at a number of times a day — the original goal.

"With a comprehensive data set, you'll make unanticipated discoveries," Lucey says. "We've learned from other wavelength regions that the places on the Moon that are sometimes the most interesting are very small and rare. So they're easy to miss."

The gap is more than an absence of infrared discoveries, though. It's also an absence of infrared astronomers.

Already, many young scientists are fleeing the field of far-infrared astronomy. That could be a major problem in the future. "Science in a way is still done a little bit like a medieval guild," Schulz says. In a guild, you have a master and an apprentice; in science, you have a professor and a student. The professor passes down expertise, including a lot of information that is not published in textbooks or scientific papers.

"When we are at the point where we have money again for a new infrared space mission, then we will have nobody who really knows how to work with the data or even how to build the instrumentation," Schulz says. Astronomers will have to re-invent the wheel.

But Hertz argues that it has never been a requirement or even an expectation that every wavelength has a mission operating at any given time. That's just not possible. "Missions come and go," he says. "And they always have over the history of NASA. And there's always gaps somewhere in the electromagnetic spectrum."

In many ways, that makes the archival data from SOFIA even more important. Pillai takes this optimistic tone, arguing that it will be the best available dataset until the next far-infrared observatory — even if it's incomplete.

And De Buizer (who was on the first-light flight and became SOFIA's planning and scheduling manager) agrees: "Astronomers are going to have our data to really sift through and mine and make new discoveries," he says. "So in that way, the legacy of SOFIA is exciting."

There is no question that SOFIA was unique. And because of that, scientists like De Buizer advanced the field of infrared astronomy. "Whatever next mission comes is going to be better because of SOFIA," De Buizer says. "In the sadness, I can take pride in that."

■ Contributing Editor **SHANNON HALL** is an award-winning freelance science journalist who lives 1 mile above sea level — and above approximately 18% of Earth's atmosphere.

FURTHER READING: Read up on milestones in airborne astronomy from the 1920s to 1990s: **https://is.gd/aeroastrohist**.

SOFIA STATUS AND FUTURE PROSPECTS 2022 / NASA / SOFIA / MONIKA ROSE (2)