True grit

Ceridwen Dovey

In the public imagination, the American astronauts who landed on the moon five decades ago were square-jawed superhumans, not the types to worry about something as banal as housekeeping. But they did, obsessively. Each time they returned to the Apollo Lunar Module after a moonwalk, they were shocked at how much dust they'd tracked in and how hard it was to banish. This was no earthly grime; it was preternaturally sticky and abrasive, scratching the visors on the astronauts' helmets, weakening the seals on their pressure suits, irritating their eyes, and giving some of them sinus trouble. 'It just sort of inhabits every nook and cranny in the spacecraft and every pore in your skin,' said Apollo 17's Gene Cernan.

Over the course of six moon landings, they valiantly battled the dust. They stomped their boots outside, then cinched garbage bags around their legs to stop it from spreading. They attacked it with wet rags, nylon bristle brushes, and a low-suction vacuum cleaner, which Pete Conrad of Apollo 12 called 'a complete farce'. (He ultimately stripped naked and stuffed his blackened suit into a zippered pouch.) No foolproof solution was ever found. Many years after John Young commanded the Apollo 16 mission, he still believed that 'dust is the number one concern in returning to the moon.'

Now, with national space agencies and private corporations poised to do just that, the Apollo dust diaries are relevant once more. In January 2019, China landed its Chang'e-4 probe on the far side of the moon, the latest step toward its stated aim of building a research station. Two months later, the Japanese Aerospace Exploration Agency said it was partnering with Toyota to design a six-wheeled moon rover by 2029. Around the same time, vice president Mike Pence announced plans to put American boots on the moon by 2024. According to NASA administrator Jim Bridenstine, the goal this time around is 'to go sustainably. To stay. With landers and robots and rovers – and humans.' India and Russia have missions planned too. Then there are the private ventures, such as Moon Express, whose Harvest Moon expedition will prospect for water, minerals, and other resources to mine. All of which raises a crucial question: what to do about that troublesome dust? The answer may come from an Australian physicist named Brian O'Brien.

O'Brien became Earth's foremost authority on moondust almost by accident. In 1964, five years before Apollo 11 touched down in the Sea of Tranquillity, he was a skinny, precocious young professor of space science at Rice University in Houston, specialising in the study of radiation. This was during the early phase of Apollo training, when the astronauts were taking crash courses in all manner of subjects – vector calculus, antenna theory, the physiology of the human nose. O'Brien's task was to teach them about the Van Allen belts, two regions of intense radiation that encircle the planet like a pair of inflatable pool tubes. He remembers the Apollo class of 1964, which included Gene Cernan and Buzz Aldrin, as the most 'disciplined and alert' cohort of students he ever had.

In the lead-up to the Apollo 11 launch, O'Brien persuaded NASA to include a little something extra in the payload. It was a small box, about the size of a thick bar of soap, whose main function was to measure the accumulation of moondust. O'Brien describes it as 'a hitch-hiking, delightfully minimalist' device. He sketched it on the back of his drinks coaster on a flight from Los Angeles to Houston, and refined the design on a cocktail napkin. Named the Dust Detector Experiment, or DDE, it was by far the least impressive component of the Apollo 11 science package; NASA didn't even bother to mention it in press releases. But it worked well enough that the agency included modified versions of the original DDE on all subsequent Apollo flights. Four of them are still up there, and to this day they hold the record for longest continually operating experiments on the moon.

For many years, the data that the early DDEs sent back to Earth was thought to be missing, or lost. Since its surprise rediscovery in 2006, those in the inner circle of outer space activities have begun to realise that O'Brien's unassuming detectors have a lot more to tell us about moondust than anyone could have imagined – except, of course, for O'Brien himself. Now 85, still sprightly and living in Perth, he's been waiting half a century for the chance to share with the world what he knows about one of the solar system's most baffling substances.

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O'Brien always had an affinity for extreme environments. He took up spelunking as a teenager, and once got stuck in the depths of Australia's Yarrangobilly Caves for 79 hours. The experience was traumatising – his lamp ran out of fuel, and the only sound, according to a contemporary newspaper account of his rescue, was the 'bats above his head and the feel of their tiny skeletons under his boots' – but it didn't stop him from returning underground. A few years later, while exploring a crystal grotto, he met his future wife, Avril Searle.

By the age of 23, O'Brien had completed a PhD in physics at the University of Sydney and been appointed deputy chief physicist for the Commonwealth Antarctic Division. He was assigned to the icebreaker *Magga Dan* and found himself gazing in wonderment at the aurora australis rippling in reds, purples, and greens across the polar sky. This was in 1958, a year after the Russians launched Sputnik and the same year NASA was founded. O'Brien began to dream of putting a satellite into orbit to study how energised protons and electrons gave rise to the southern lights. He got his chance the following year, when James Van Allen, discoverer of the Van Allen belts, got him a job at the University of Iowa. O'Brien and a few students built a satellite called Injun 1 (named for a villain in Mark Twain's *The Adventures of Tom Sawyer* who, coincidentally, starves to death in a cave). Other satellite launches followed, and in 1963 O'Brien was offered a post in Rice University's new space science department.

Not long after O'Brien and his family moved to Houston, he got a call from NASA. The agency hoped to hire him as an astronaut instructor, but it also invited him to submit a proposal for a science experiment to go to the moon. He suggested a device that would measure the energy spectra of charged particles as they rained down on the lunar surface. From a field of 90 submissions, his was one of seven that got the green light. NASA told him that, as a matter of policy, the experiment should include a dust cover, basically a sophisticated strip of plastic. No one knew at this stage just how pesky moondust would be, but O'Brien figured that if the agency was going to the trouble of installing dust covers, it should also include a dust detector. At first, NASA and its private contractors balked. It would be too difficult, they believed, to construct a detector that was light enough to meet the mission specs and simple enough that it wouldn't take up any of the astronauts' limited time and attention. On the moon, distractions could be deadly.

O'Brien thought this resistance was 'bloody stupid' and quickly persuaded them otherwise. The design he sketched on his cocktail napkin consisted of three tiny solar cells mounted on a box, which was painted white to reflect sun-light. As dust settled on the cells, their power output would drop, providing a clear record of accumulation over time. O'Brien threw in a few bead-sized temperature sensors for good measure. Because the DDE was so small, it could be bolted onto the seismometer that Aldrin and Armstrong were setting up to measure moonquakes. The DDE would feed its data to the seismometer, whose antenna would transmit the readings back to Earth. They'd be stored on reels of magnetic tape for further analysis.

O'Brien made arrangements to have the tapes shipped to him in Sydney, where he and Avril and their three children moved in 1968. He can't quite remember now where he was on the morning in late July 1969 when the Apollo 11 Lunar Module touched down on the moon. He thinks he listened to the radio broadcast between interviews with various Australian news outlets. Yet he does remember, vividly, the moment Aldrin said the module was 'kicking up some dust' as it came in to land, as well as Neil Armstrong's observation, just moments before he stepped off the ladder, that the surface was 'almost like a powder.' With a spike of excitement, O'Brien realised his DDE might very well prove its worth.

As it turned out, the seismometer abruptly overheated shortly after Apollo 11 left the moon. (Before it ceased working, O'Brien says, it registered the footsteps of the astronauts on the ladder and 'the gurgle of the fuel sloshing around'.) But the DDE soldiered on, and soon revealed the mischief that dust could make. Almost as soon as the Lunar Module took off, two of the detector's three solar cells registered a sudden drop in output, one of them by 18 per cent. This was accompanied by a spike in temperature. To O'Brien, there was only one logical explanation: the DDE had been blanketed in dust, which, like blackout blinds, kept light out and heat in. It seemed obvious to him that the seismometer had met the same fate.

If NASA hoped to keep its moon-based instruments working on future Apollo missions, O'Brien concluded, it would need to study the matter of dust-spraying thoroughly. That August, he wrote proudly to an Australian colleague that 'the DDE may really have earned its trip!' But his American counterparts, particularly the technicians at the Manned Spacecraft Center, were not so enthused. Some of them, he believes, were less interested in scientific experimentation than in the chest-thumping goal of landing Americans on the moon. Ultimately, the seismometer stopped accepting commands from mission control, and the whole experiment – DDE included – was shut down.

A couple of months later, NASA released its preliminary science report on Apollo 11. It rejected O'Brien's explanation for the DDE readings. Dusty kickback from the Lunar Module couldn't be to blame, the report said, because otherwise all three solar cells would have been blanketed. (This was in a chapter co-authored by O'Brien, yet he says he 'strongly disagreed' with the findings and never gave permission for his name to be included.) O'Brien tried to argue his case again in the *Journal of Atmospheric Physics*, using one of Australia's first supercomputers, SILLIAC, to crunch and plot the data points on endless ribbons of paper. But the article landed with a thud and was barely cited by other researchers in the decades that followed.

O'Brien was forced to admit defeat in round one of the moondust wars. He changed careers, becoming the first head of the Environmental Protection Authority of Western Australia. The position was based in Perth, and when Avril made the three-day train trip from Sydney, she brought the kids and the 172 reels of DDE data with her. O'Brien asked a colleague at a local university to store the tapes on his behalf. And so, for 40-odd years, he put them out of his mind.

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After the final Apollo landing in 1972, NASA all but lost interest in the moon. There were space stations to assemble, exotic planets to explore, and only so much funding to go around. Then, in 2004, President George W Bush announced what would become known as the Constellation Program. There would be powerful new rockets, redesigned crew capsules, and roomier lunar modules – 'Apollo on steroids,' as one NASA administrator put it. Part of the plan was to establish a permanent 'foothold' on the moon, which meant a renewed focus on the logistics of regular landings and long-term settlement.

This was something that Philip Metzger, a planetary scientist, had been interested in for a while. Metzger was the cofounder of Swamp Works, a kind of tech incubator at NASA's Kennedy Space Center that creates practical solutions to the challenges of working and living in places beyond Earth. As part of his PhD thesis, he'd done research on how to prevent rocket exhaust from stirring up dust and damaging lunar infrastructure, and he had scoured decades' worth of studies on rock and soil samples brought back by the Apollo astronauts. He even had four rare vials of genuine moondust in his laboratory. Over the years, he'd perfected a quick lesson in lunar geology for his team.

It went something like this: the regolith, a blanket of rocky material on top of the primordial lunar bedrock, contains mixed-up dust, gravel and pebbles, and is thought to be about 5 metres thick in the plains and 10 metres thick in the highlands. For all practical purposes, the moon does not have an atmosphere or a magnetic field, so the top-most layer of the regolith is susceptible to space weathering. It's constantly bombarded by cosmic rays and solar wind, which means the dust can become electrostatically charged, like a balloon rubbed on hair. It also receives a steady hail of micrometeoroids.

When the micrometeoroids hit, they create miniature shock waves in the soil, causing some of it to melt and some to vaporise.

The molten soil actually splashes, but then it immediately freezes again, forming tiny pieces of glass. These pieces are 'crazy shaped,' Metzger says, 'jagged, sharp, and very frictional'. Unlike on Earth, where wind and water would smooth them out, they remain this way forever. (When Aldrin and Armstrong planted an American flag near their landing site, they struggled to work the pole into the regolith, stymied by its high glass content. 'It took both of us to set it up and it was almost a public relations disaster,' Aldrin recalled years later.) Thanks to the constant hammering by micro-meteoroids, the soil is also extraordinarily fine, which makes it extraordinarily sticky. Metzger likens it to the 'fine hairs on a gecko's feet that allow it to walk up walls'.

Metzger would end his geology lesson with a sobering summary of health hazards. Our bodies generally cough up or sneeze out most daily irritants. But anything smaller than 10 microns, or about one-seventh the diameter of a human hair, tends to get trapped in our lungs. In the soil sample brought back by Apollo 17, some of the dust is smaller than two microns, as fine as flour. No wonder the astronauts suffered from what Apollo 17's Jack Schmitt called 'lunar hay fever.' (The Australian academic Alice Gorman, in her book *Dr Space Junk vs the Universe*, notes that around the same time as the first moon landing, there was an eye infection epidemic in parts of West Africa. 'People called it Apollo,' she writes. 'The infection was frequently attributed to the arrival on Earth of lunar dust stirred up by the astronauts.')

For all of Metzger's expertise, there was one enigma that kept stumping him. Sitting in his laboratory at the Kennedy Space Center were a few pieces of an old spacecraft called Surveyor 3. Between 1966 and 1968, five Surveyor probes had set down on the moon, providing hard proof that the regolith was firm enough to land on and allaying any fears that the astronauts might sink up to their chins in lunar quicksand. (Later, when Armstrong photographed his own boot print in the soil – one of the most famous images in human history – it was, in fact, to permit the study of 'lunar surface bearing strength.') Surveyor 3's final resting place was within walking distance of the Apollo 12 landing site, and the astronauts had been instructed to bring parts of it home for study. One of them, Alan Bean, noted at the time that the probe's bright-white surface had, after two and a half years on the moon, turned a tan colour.

Previous researchers had assumed this was due to damage from solar radiation, but in 2011 Metzger and his colleagues proved that 'it was actually ultrafine dust embedded all over the microtexture of the paint.' The bigger question, though, was how the dust got there. As Surveyor 3 touched down in the near-vacuum of the moon, the exhaust gas from its engine should have pushed dust away from the spacecraft. Metzger's team couldn't explain it.

By that point, the Constellation Program had been cancelled. The new rockets were over budget and behind schedule, and the Obama administration decided that this particular headache was better left to the private sector; NASA should concern itself with leaner, more science-focused missions. Metzger had already begun hearing from a number of companies aiming for moon shots. Many had entered the Google-sponsored Lunar XPRIZE competition, which promised to award $20 million to the first team that could land a robotic spacecraft on the moon. (Nobody ever managed to pull this off.) The companies were curious how close to the original Apollo sites they were allowed to get. Concerned about the destructive effects of dust spray, Metzger helped draw up a set of official NASA lunar heritage guidelines, recommending a 2-kilometre exclusion zone around Armstrong's boot prints and that intractable American flag. (According to Metzger, this is an arbitrary placeholder figure; because of how moondust behaves, he says, there may indeed be 'no safe distance.')

A few years later, Metzger took early retirement from NASA and joined the planetary science faculty at the University of

Central Florida. His final project at Swamp Works was to come up with moondust mitigation strategies – among them magnets, reusable dust filters, artificial electrostatic charges to repel the dust and make it fall off surfaces, and 'air showers' or 'wands' to blast dust off suits. Even with immediate plans for an American moon base off the table, Metzger says, it had become 'the consensus belief' while he was at NASA that 'the biggest challenge to lunar operation is the dust'.

In 2015, years after he'd given up on solving the mystery of the Surveyor 3 dust deposits, Metzger heard about a series of recently published papers by Brian O'Brien. They contained a truly remarkable theory about moondust. As he read, Metzger realised this was the first acceptable explanation he'd found for the Surveyor 3 conundrum. And it was based, amazingly, on the data from the original DDE tapes.

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O'Brien got back in the moondust game much as he'd entered it – by happenstance. In 2006, when he was in his 70s, a friend mentioned reading something on a NASA website about the sorry state of certain Apollo tape archives. O'Brien decided to track down the reels he'd asked a colleague to store for him all those decades ago. They turned up in a room beneath the tiered seating of a lecture hall in the physics department at Perth's Curtin University. They were covered in (what else?) dust, but they were there, all 172 of them, each one containing about 800 metres of tape. The only problem was that they were in a format so obsolete that the data was out of O'Brien's reach. He sent an email to NASA, offering to repatriate the tapes, but the agency politely declined.

A local radio journalist heard rumours of the discovery and broadcast a story, which made its way to Guy Holmes, an American physicist who had lived in Perth for years and founded

SpectrumData, a company that specialised in digitising large volumes of data from old tape formats. Holmes phoned O'Brien and offered his help, for free. He said he would store the tapes in a special climate-controlled vault until they could find the right machine to decode them. O'Brien gratefully accepted.

Even if Holmes succeeded in his search, O'Brien wasn't sure he'd ever find funding – from NASA or anyone else – to reanalyse the data. But he felt he had one last chance to set the record straight on moondust and finally get some closure on his early career frustrations. So he got to work revisiting his old SILLIAC analyses and paper printouts, determined to publish a peer-reviewed article. It appeared in 2009, almost 40 years after his original moondust paper. This time around, however, his research made a big impression.

O'Brien's story – his dramatic discovery of the tapes at a late stage in his life, his forgotten role in the Apollo program – garnered much media attention. And it was impossible not to fall under the sway of moondust once O'Brien began to explain just how very bizarre it was.

He'd gone back and examined data from the DDE that flew on Apollo 12. That detector differed from its predecessor: it had one horizontal solar cell on top and two vertical ones on the sides. They'd been blanketed in dust as the astronauts loped around on moonwalks, then blasted partly clean when the Lunar Module took off. Curiously, though, one of the vertical cells became completely clean overnight. O'Brien's explanation for this was that the electrostatic charge of the dust – the major source of its stickiness – changes over the course of the month-long lunar day. When the sun is high and UV radiation is at its peak, the dust is extra charged, and thus extra sticky. When the sun goes down, the dust seems to lose some of its adhesive force. In other words, if Pete Conrad had still been on the moon at sunset, he might have had better luck vacuuming off his suit.

Within two months of the article's publication, O'Brien had been made an (unsalaried) adjunct professor at the University of Western Australia. He was invited to speak at the second annual Lunar Science Forum, organised by NASA's Ames Research Center in California. The room was so packed at his presentation that people spilled out into the corridor. There was communal disbelief among the younger moon enthusiasts that they'd never heard of O'Brien or his DDE experiments. 'After that, things started to bubble,' he says.

In early 2010, Holmes had a breakthrough of his own: he'd located an old IBM 729 Mark 5 tape drive in the warehouse of the Australian Computer Museum. It was the size of a two-door refrigerator and in terrible condition, but the museum agreed to lend it to him. A group of SpectrumData employees donated their time to fix it up. The tapes were carefully heated to draw out any moisture, then unravelled at extra-low speed. Holmes says he was very emotional during this salvage process, keenly aware of its historic importance and the trust O'Brien had placed in him. Eventually, the team managed to decode and extract most of the data. O'Brien was – let it be said just once – over the moon. An undergraduate named Monique Hollick, now a space systems engineer for the Australian Department of Defence, signed up to help him analyse the resurrected data. Their years of slow, painstaking work resulted in an even stranger theory about moondust, which they described in 2015.

O'Brien had already explained how the Apollo 12 DDE got clean; what he hadn't explained was how, in the days following the astronauts' departure, it got dusty again. His and Hollick's hypothesis, based on the new data from the tapes, went as follows: after the astronauts picked up stakes, leaving the DDE behind to broadcast its readings, the sun went down for about two Earth weeks. When it rose again, it showered the 'collateral dust' they'd kicked up – more than 2 tonnes in total – with UV radiation. This caused the dust particles to become positively charged. They began to 'mobilise and shuffle around', O'Brien says, like a 'ground mist swirling'. Repelled by one another and by the moon's surface, they levitated. This created a small dust storm high enough above the surface to reach the DDE. The next time the sun rose, the same thing happened, and the next, and the next. Each time, the storm got a little smaller, until finally there was no collateral dust left to feed it.

This is still a somewhat controversial theory. Schmitt, the astronaut-geologist who flew on Apollo 17, is not entirely convinced, because most of the rocks he saw on the moon were free of dust. 'If fine dust were levitating and redepositing with any lateral motion at all,' he wrote to me, 'I would not expect rock surfaces to be clean.' In his own correspondence with Schmitt, O'Brien suggested those rocks had lost their dusty coating as the sun's angles changed and 'cleaned' them.

The debates are ongoing. Other researchers have argued the case for a dust cloud extending tens or even hundreds of kilometres above the moon's surface, although NASA's Lunar Atmosphere and Dust Environment Explorer, launched in 2013, found little evidence of this. Speculations abound, like the idea that moondust, in its undisturbed state, may be arranged in fragile, porous structures called fairy castles. 'We really won't know until we go there,' Metzger says. He feels pretty confident, though, that O'Brien is right and that his theory solves the Surveyor 3 dust-deposit mystery once and for all. Anyone planning a moon mission, he says, should expect levitating dust storms every sunrise around any high-activity outpost and varying dust stickiness during the lunar day.

With countries and companies jostling to set up operations in the moon's most desirable sites – mainly the lunar poles, where water ice is supposedly abundant – life up there could quickly devolve into a dusty and chaotic mess, ripe for human conflict.

The Hague International Space Resources Governance Working Group has already begun drafting recommendations for lunar 'safety zones' and 'priority rights'. Perhaps they ought to include a clause on housekeeping.

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Hanging on the wall of O'Brien's garage office in Perth is a signed photograph of the Apollo astronaut class of 1964. Aldrin and Cernan smile from the bottom row, looking nifty, if a little faded, in suit and tie. Beside the group portrait is a photo of O'Brien with Cernan, during Cernan's visit to Perth in 2016, the year before he died. 'We both look a bit different there to when I lectured to him,' O'Brien said when I stopped by his house one warm afternoon in February. I asked what they'd talked about. 'Moondust,' he replied.

O'Brien was gearing up for a trip to Texas, where he was due to present at a NASA conference called Micro-symposium 60: Forward to the Moon to Stay. He'd be making the journey alone; his beloved wife died in 2017, and Holmes, who accompanied him on a recent visit to Beijing, couldn't make it this time. O'Brien was concerned about how he'd get the compression stockings off on his own after the flight, but he seemed ready to present to a crowd of 200, including representatives from all nine of the US companies recently authorised by NASA to deliver payloads to the moon. He hinted that he's in discussions with several of them and said, somewhat enigmatically, 'I look forward to a lot more dust detectors on the moon.'

On the shelves of O'Brien's office, space memorabilia worthy of a major geek-out was unceremoniously jumbled. I inspected life-size models of his various DDEs, with plaques affixed describing which Apollo mission they flew on. O'Brien was happy to let me play with shiny models of the Chang'e-3 lander and Yutu rover on the coffee table, so long as I first put on white gloves. They were given to him in Beijing by the Chinese Academy of Space Technology, which first got in touch after he suggested that the cause of Yutu's unexplained immobilisation in 2014, after its first lunar sun-rise, was a dust storm – and cheekily recommended that next time they equip the rover with a dust detector. It seems that Chang'e-3 did make some dust measurements, which the Chinese have confidentially shared with O'Brien; all he can say is that he's 'stimulated' by the findings and hopes they'll soon be published.

A few days after O'Brien returned from Texas, I called him to ask how the talk had gone. Moondust is definitely working its way into the zeitgeist, he was happy to report. Back in 2009, he said, when he gave his first talk to the lunar research community, 'I knew nobody and nobody knew me.' This time around, almost everyone knew him.

At times, he admitted, as he wandered down the long, endless corridors of strange airports and conference complexes, he felt every bit his advanced age. 'But when I came out of the Microsymposium, and for several weeks after,' he said, 'I felt young again.'

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