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The space issue

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Where to?

50 years after Apollo 11, space technologies have radically changed life on Earth—and we're still just at the beginning.

One message of this special issue is how, well, *normal* space exploration has become since Neil Armstrong and Buzz Aldrin landed on the moon almost exactly 50 years ago.

The number of satellites launched each year is shooting up as rockets get cheaper and satellites get smaller (see the charts on pages 14 and 30). Though only a few hundred people have been to space, billions depend on it: much of modern life would grind to a halt without GPS, satellite communications, and imagery from space. Apollo's most important legacy, we argue (page 8), wasn't that it put a person on the moon, but that it taught people to manage the kinds of gigantic engineering projects that have made those once miraculous technologies thoroughly mundane. Even a return visit to the moon, which could happen in the next few years, would now be a lot easier (page 48).

If once the biggest problems in space were how to get stuff up there, make it work, and bring it back, today's problems arise because humanity has gotten all too good at doing so. There could soon be enough imaging satellites to subject everyone on Earth to constant real-time surveillance (page 32); there are fights over an increasingly crowded radio frequency spectrum (page 40); and it can only be a matter of time before someone acquires both the means and the motive to attack someone else's satellite, potentially launching the first full-on space war (page 36).

But if some activities in space have become mundane, far more remain out of reach. Hence, the bulk of the stories here are about the miracles people are still trying to make happen. What makes space glamorous, after all, is not the mere act of getting to where no one has gone before, but the imagination, ingenuity, and hubris required to do it.

An aura of the mad genius who strives for what others would call impossible or foolish clings to many of the people you'll meet on these pages. There's Dave Masten and his crew, winning a NASA competition with a spacecraft cobbled together from, among other things, a discarded trash can lid (page 52). The people at Relativity Space, who've vowed to 3D-print virtually an entire rocket in 60 days (page 16). (Their CEO, Tim Ellis, is also one of our remarkable 35 Innovators under 35, whose profiles you can read if you flip the magazine around.) Breakthrough Starshot's Philip Lubin, with his plan to use lasers to power a tiny probe to the nearest star at one-fifth the speed of light (page 66). Helen Hwang and her NASA team, who had to develop a heat shield to withstand energies no spacecraft had ever encountered (page 76). Valentin Glushko, the dean of Soviet rocketry, who doggedly insisted on designing an engine of a kind nobody else had built, which then powered US rockets after the Soviet Union collapsed (page 22). The visionaries—or, some would say, delusionaries—who saw a future in mining asteroids for profit (page 62).

Gideon Lichfield is editor in chief of MIT Technology Review.

IAN ALLEN

Technology also leaves its mark on culture, so we've included brief excerpts of the best astronaut memoirs (page 74), a history of how the space age shaped rock music (page 80), and a science fiction story about a secret rebellion in a satellite cleanup crew (page 84).

The overall lesson, though, is a simple one: however routine some uses of space become, the things we can't yet do there remain a source of wonder and inspiration. And those things can quite literally fill a universe.

THE SPACE ISSUE

Cover photo by Bob O'Connor: A time-lapse shot of a SpaceX Falcon 9 launch in 2018. At left, the rising arc shows the rocket taking off; at right, the reusable boosters return to Earth.

Back cover photo by Christie Hemm Klok.

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The shadow of Apollo

Space technology has changed the world—but not in the way the dreamers of the 1960s imagined.

by **Konstantin Kakaes**

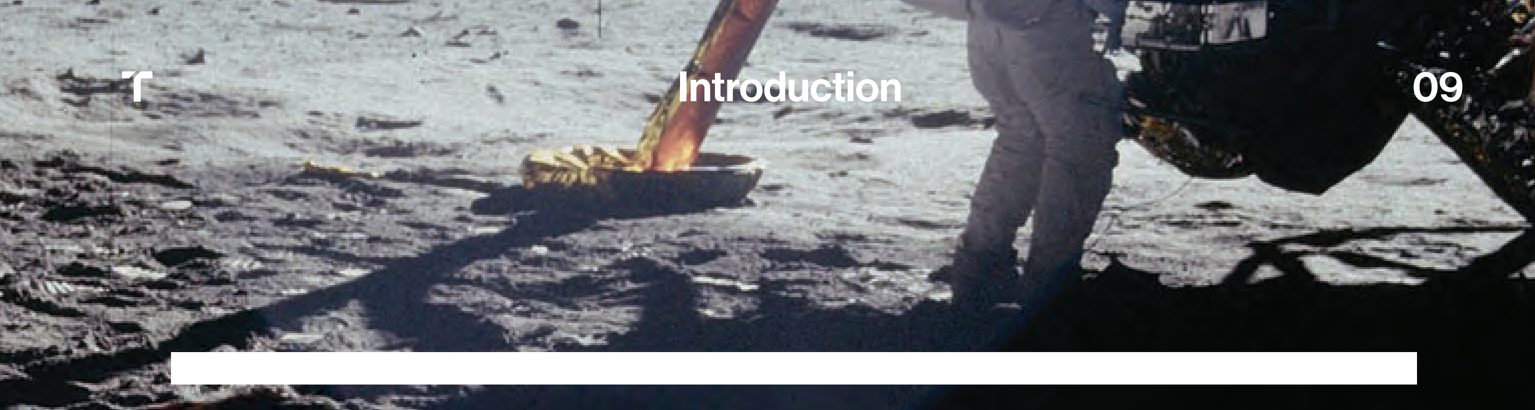
Fifty years after Neil Armstrong stepped onto the moon, it's hard not to conclude that he got things backwards. The moon landing was a giant leap for a man—Armstrong's life was forever changed—but, in hindsight, only a small step for mankind.

It's not that putting people on the moon wasn't a difficult collective achievement—it was. But getting to the moon has done little in the long run to change human society.

As Roger Launius, an eminent space historian, writes in his new book *Apollo's Legacy*, "At a basic level, the president's Apollo decision was to the United States what the pharaohs' determination to build the pyramids was to Egypt." Its most resonant impact is not a particular technology, but simply the metaphor: *If we can put a man on the moon, why can't we do X*?

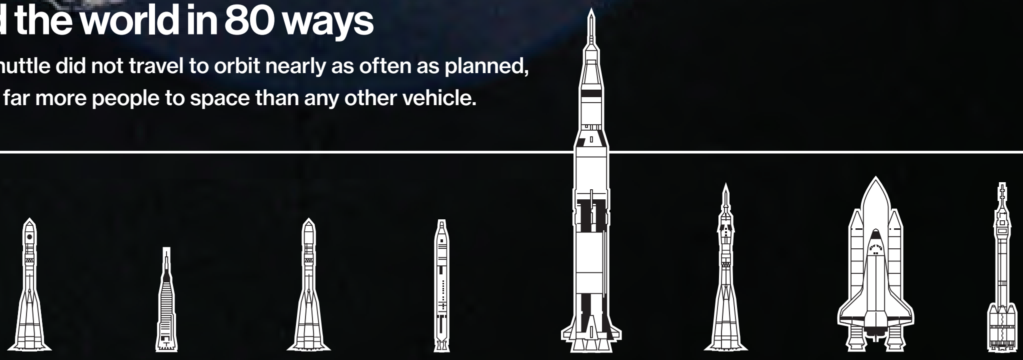
The "X's" that usually come up in these discussions, such as figuring out how to solve climate change or poverty, "all have some potential for the application of technical solutions," Launius notes. "But they are largely political and social problems." And Apollo did not solve *any* political or social problems. Other "X's"—say, curing cancer—depend on developing whole new forms of scientific knowledge.

By contrast, the success of the Apollo program, which at its peak employed 400,000 people, rested on good engineering management of myriad interdependent technical innovations, not on scientific revolutions. The Manhattan Project—which employed 125,000 and cost about a quarter as much as Apollo in inflation-adjusted dollars—changed the world far more by introducing



Around the world in 80 ways

The space shuttle did not travel to orbit nearly as often as planned, yet it carried far more people to space than any other vehicle.



Vessel	Vostok	Mercury	Voskhod	Gemini	Apollo	Soyuz	Space shuttle	Shenzhou
Time line	1961–1964	1962–1963	1964–1965	1965–1966	1968–1972, 1973, 1975	1967–present	1981–2011	2003–present
Country operating	USSR	USA	USSR	USA	USA	USSR/ Russia	USA	China
Total launches	6	4	2	10	15	142	135	6
Occupants launched to orbit	6	4	5	20	45	376	852	14

Space stations	Crewed missions	Total visitors
International Space Station	**94**	**236**
Skylab [US]	**3**	**9**
Mir [USSR/Russia]	**39**	**137**
Salyut (4) and Almaz (2) [USSR]	**18**	**39**
Tiangong (2) [China]	**3**	**8**

Total crewed orbital launches

319

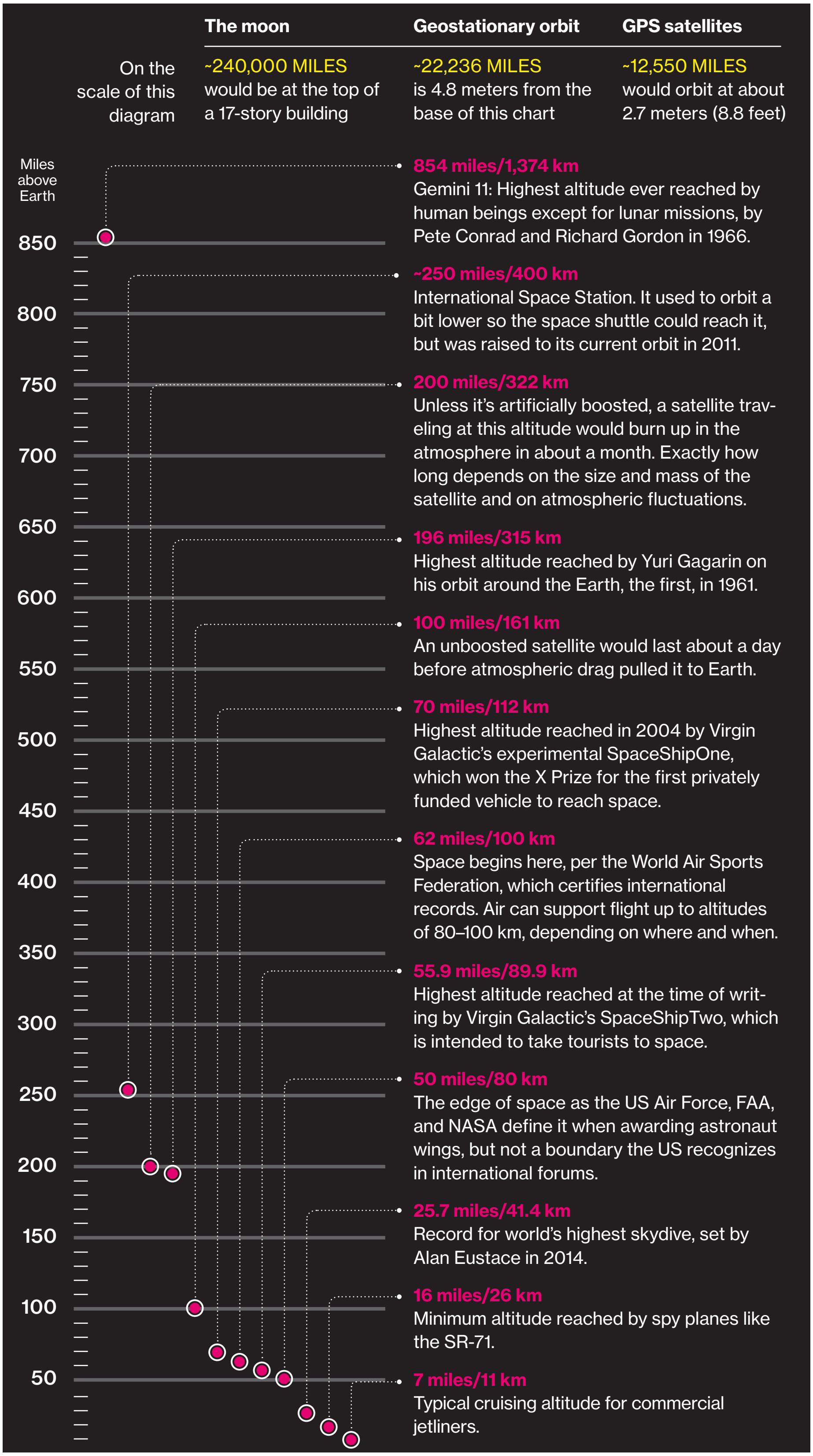
Occupants launched into orbit

1,322

SOURCE: BRYCE, HUMAN ORBITAL SPACEFLIGHT STATISTICS. || MULTIPLE TRIPS TO SPACE FOR A GIVEN INDIVIDUAL ARE COUNTED MULTIPLE TIMES. TOTALS ARE AS OF MAY 31, 2019

Where does space begin?

Ever since Sputnik first overflew the United States and did not get shot down, it's been widely accepted that national sovereignty does not extend into space. Exactly where, though, does sovereignty end? Despite numerous UN meetings, no consensus exists. Physically, too, the line between heaven and Earth is indistinct. What's space in one context is still atmosphere in another, depending on whether you're a satellite, an astronaut, or a would-be space tourist.



the atomic bomb. *That* was a giant leap, though maybe not in such a good direction.

What can be said for Apollo's impact on humanity is that the management of complex technical systems it required is something we have indeed grown very, very good at. Modern airplanes and computers are incomprehensibly complex. And yet they work—not because of Apollo, but for the same reasons.

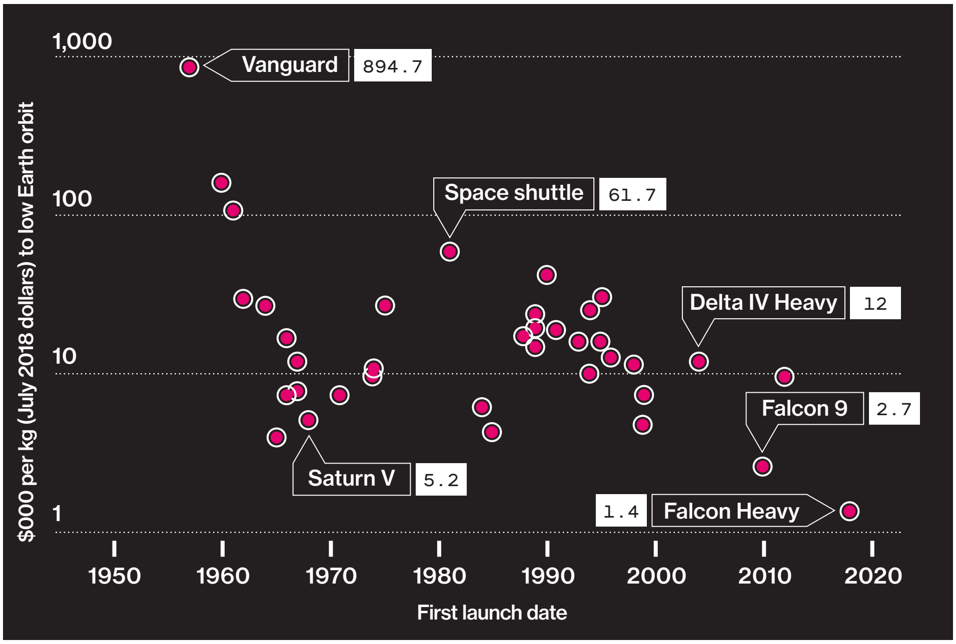
It is thanks to these sorts of systems that even though humanity hasn't returned to the moon since 1972, there has been slow and steady progress in human spaceflight, remarkable robotic exploration of the solar system, and—perhaps most important—a profound reordering of life on Earth by satellites orbiting it.

To get a sense of how pervasive space activity has become, it helps to look at some statistics. Since 2000, the US, Russia, China, India, and Europe have launched large rockets successfully 1,125 times, and unsuccessfully only 39 times. That's a failure rate of about 3.5%. Many, if not most, of these failures have come in the first few launches of a new model, which means that the failure rate for tried-and-tested rockets is even lower. By contrast, from Sputnik's 1957 launch to July 1969, 20% of launches failed.

When Armstrong and Buzz Aldrin landed on the moon, 37 men and one woman, from the US and the USSR, had orbited the Earth. Today 495 men and 63 women have, from 40 or so countries. The space shuttle was inarguably a disaster: each flight was supposed to cost $10 million but ended up costing $1.6 billion. Fourteen people died when *Columbia* and *Challenger* were lost. And yet the shuttle carried far more people to space than any other vehicle. The International Space Station (ISS), too, is laughably over the originally promised budget, for negligible scientific return—but if human spaceflight

Weight, weight, don't tell me

It's tough to say exactly how much it costs to launch a kilogram into Earth orbit, and why. Small rockets offer flexibility, and big ones can have economies of scale. However, take the Delta IV Heavy, built by Boeing and Lockheed Martin. How much of its $350 million cost should be ascribed to the $17 million paid to Lockheed's CEO in 2018 or to the $30 million paid to Boeing's? On the other hand, SpaceX has attained far lower launch costs with its Falcon rockets.



SOURCES: THE RECENT LARGE REDUCTION IN SPACE LAUNCH COST; HARRY JONES, 48TH INTERNATIONAL CONFERENCE ON ENVIRONMENTAL SYSTEMS, 2018. COST OF DELTA 4 HEAVY LAUNCHES IS DOWN BUT THE REAL PRICE IS A SECRET; SANDRA ERWIN, SPACENEWS, MAY 14, 2019.

eventually becomes common, the ISS data on how to keep people alive and healthy in space for long periods will begin to look valuable.

Prior to July 20, 1969, the United States had sent two space probes flying by Venus on brief visits, and one by Mars. The Soviet Union had successfully received data from three Venusian probes. Nobody had sent spacecraft through the asteroid belt into the outer solar system, and the data from Mars and Venus offered just fragmentary glimpses.

Today, every planet in the solar system has been visited by space probes: Mars and Venus many times; Jupiter by a pair of orbiters; Mercury and Saturn by an orbiter each; Uranus, Neptune, and Pluto on brief visits. There have also been an assortment of missions to comets and asteroids.

In 1969, a single space telescope had been successfully launched; today dozens of such instruments have surveyed the skies. Notably, the Kepler space telescope discovered 2,343 planets outside the solar system—over half of the 3,972 such exoplanets found to date. In 1969, nobody knew if there were any exoplanets; today we know they outnumber stars, and also roughly what proportion of them are likely to be at the right size and distance from a star to potentially harbor life.

On July 20, 1969, 116 satellites were orbiting the Earth, not counting the moon or *Apollo 11*. At the time of writing, over 2,100 are. But their importance has grown much more than their sheer numbers: no aspect of 21st-century life is imaginable without them.

Communications satellites already cover the entire globe. For those with even modest resources, being out of reach is now more a deliberate choice than a logistical necessity. Satellite communication remains relatively expensive, but if Elon Musk and other entrepreneurs have their way, this will soon change. GPS, on the other hand, is free, courtesy of the US Air Force, which consequently has played the unlikely role of driving taxi companies around the world out of business and acting as a matchmaker for the millions who use apps like Tinder, Grindr, and Bumble. Military actions—from drone strikes to aircraft-carrier battle groups wandering the oceans—are so fundamentally mediated by communications and reconnaissance satellites that it's impossible to imagine the last few decades of world history without them.

Cubesats and other small satellites have begun to change the economics of low Earth orbit in important ways. Because they are capable and lightweight, and hence on the way to becoming ubiquitous, one could say that we're in the process of raising the surface of the Earth by a few hundred or a few thousand kilometers. Just as air travel was once the stuff of fable and has become mundane, the same has become true for machines in Earth orbit.

But unlike satellites, people cannot be shrunk. So as long as launch costs remain high, human travel to space will remain rare. Those costs have been stuck for a while, in part because of the ways in which rocket technology, governments, and the military got tangled together. Musk and Jeff Bezos, with their billions, are in the midst of sawing through that Gordian knot. But it remains to be seen if their efforts will lead to a flash in the pan of space tourism for elites or a durable giant leap into space, the first steps toward colonies on Mars or in giant cylinders orbiting the sun.

The Apollo program failed to make such a leap. Its success was in taking the technology of the time as far as it could go, just as the pharaohs built the absolute biggest pyramids they could. It was a monument to ingenuity and to determination. But monuments are, by design and by definition, ends and not beginnings. ■

The US Air Force acts as a matchmaker for the millions who use apps like Tinder, Grindr, and Bumble.

Konstantin Kakaes is a commissioning editor at MIT Technology Review and the editor of the space issue.


1

LAUNCH

HOW DO WE GET THERE?

The race to cheaper launches

By
Konstantin Kakaes

Illustrations
by John MacNeill

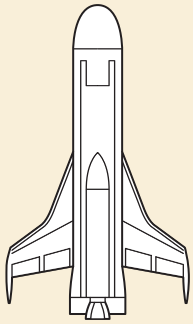
In the closing decades of the last century and the first decades of this one, the average cost of launching a kilogram into Earth orbit simply would not change. The price stubbornly hovered above $10,000, and new idea after new idea failed to break the impasse.

This stymied innovation—after all, if it's expensive to launch something, it becomes tricky to take other kinds of risks. But opinion was split: Had things stagnated because there was never enough money to see ideas through? Or was it because other improvements—in, say, materials science or autonomous navigation—were insufficiently mature?

All that has changed in the last few years as new craft broke the deadlock, most notably SpaceX's Falcon Heavy, which is about a tenth as costly, per kilogram, as its closest competitor.

Now the central question is whether this is the start of a new plateau or whether, as Elon Musk hopes, it signals ever cheaper launches and ever more space innovation. The success or failure of these systems will help find an answer.

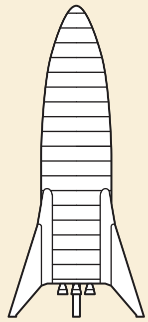
5 NEW PLANS



XS-1

1

Ever since the 1960s, engineers have dreamed of a spaceplane that can be reused frequently in a way that makes space travel more like air travel. Nobody has yet come close. The XS-1, being built by Boeing for the Pentagon research agency DARPA, is supposed to be able to make 10 flights in 10 days, taking up to 5,000 pounds (2,268 kilograms) to orbit for under $5 million. Test flights are planned for 2020.

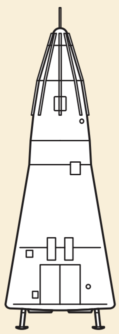


Starhopper

2

Starhopper is a prototype of the first stage of SpaceX's planned Big Falcon Rocket, or BFR. The company plans to use it to send people to Mars, as well as to run half-hour shuttle services on Earth between cities like New York and Shanghai. BFR's payload capacity is about three times that of the Falcon Heavy, though Elon Musk has said he believes it will cost less to build. An early version of Starhopper successfully completed a tethered test flight in Texas in April.

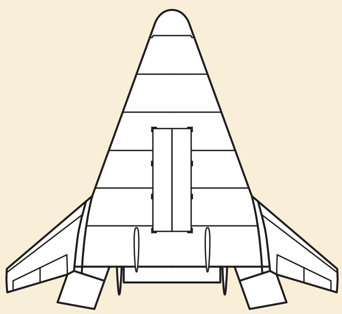
5 FAILURES



Delta Clipper (DC-X)

1

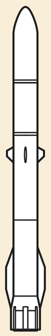
Single-stage-to-orbit has long been a goal of rocket designers, since avoiding multistage rockets would make things cheaper, faster, and more reusable. The small-scale DC-X from McDonnell Douglas flew several suborbital flights, but the program was canceled before a full-scale, orbit-capable version could be built. It was a victim, depending on whom you ask, of immature technology or of shortsighted bureaucrats. Several Delta Clipper engineers now work for Blue Origin, whose New Shepard rocket is said to be inspired by the DC-X.



Venture Star/X-33

2

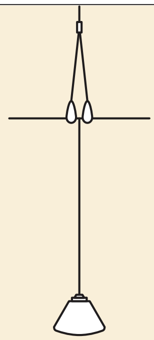
NASA spent over a billion dollars on the X-33, a half-scale suborbital version of what would have been the Venture Star. The full-size craft would have been comparable in size to the space shuttle, and the agency even built a dedicated $32 million "spaceport" for it at Edwards Air Force Base in California. But NASA and Lockheed Martin, the company that built the X-33, had many design disagreements, and the program was canceled before the rocket ever flew.



New Glenn

3

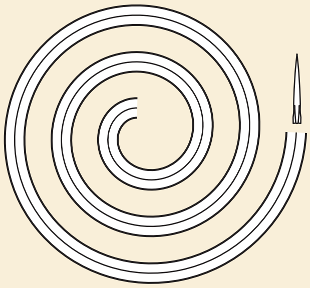
This rocket has a payload capacity by weight similar to that of the Falcon Heavy, but it is far wider at seven meters in diameter. That means it has twice the usable volume. Its first stage will fly back to be reused, much like the failed Baikal booster (below). Blue Origin, which is building the rocket, is tight-lipped on test flight dates but is competing for an Air Force contract that would require launches as soon as 2022.



Tethers

4

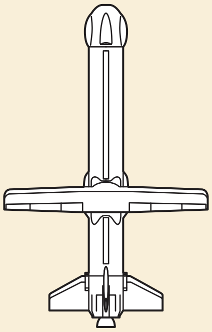
Even if rockets can be reused and achieve economies of scale, fuel is still a major cost. Tethers seek to change this in two different ways. One approach works like swinging a rope, transferring momentum from one end to the other. Tethers Unlimited, a startup, hopes to use this technique to "catch" satellites that don't have enough energy to get to orbit, and give them an extra boost. Another type of tether would use Earth's magnetic field to boost the orbit of satellites attached to either end of it. Some test flights have already taken place, and the next is scheduled for June.



Spinlaunch

5

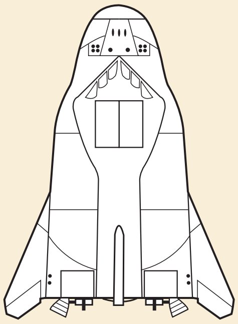
Tethers can transfer momentum between objects already in space—but what can you do while you still have the ground to push against? That's the plan for Spinlaunch, a startup that raised $40 million in venture funding in 2018. The company broke ground on a launch facility in New Mexico in May and plans to launch its first satellites in 2022. It wants to fling as many as five satellites a day to the edge of space using powerful turbines and small onboard rockets—sort of the opposite of a tether elevator.



Baikal

3

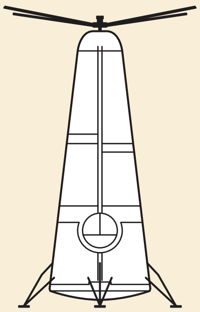
The Baikal booster, designed in the 1990s as a reusable first stage for the Russian Angara rocket, was an idea before its time. Like the first stage of SpaceX's Falcon rocket, the Baikal was supposed to fly back to be used again. But unlike the Falcon first stage, which uses the same rocket to land that it used to take off, the Baikal had an additional jet engine for landing, which added weight and complexity.



HL-20/HL-42

4

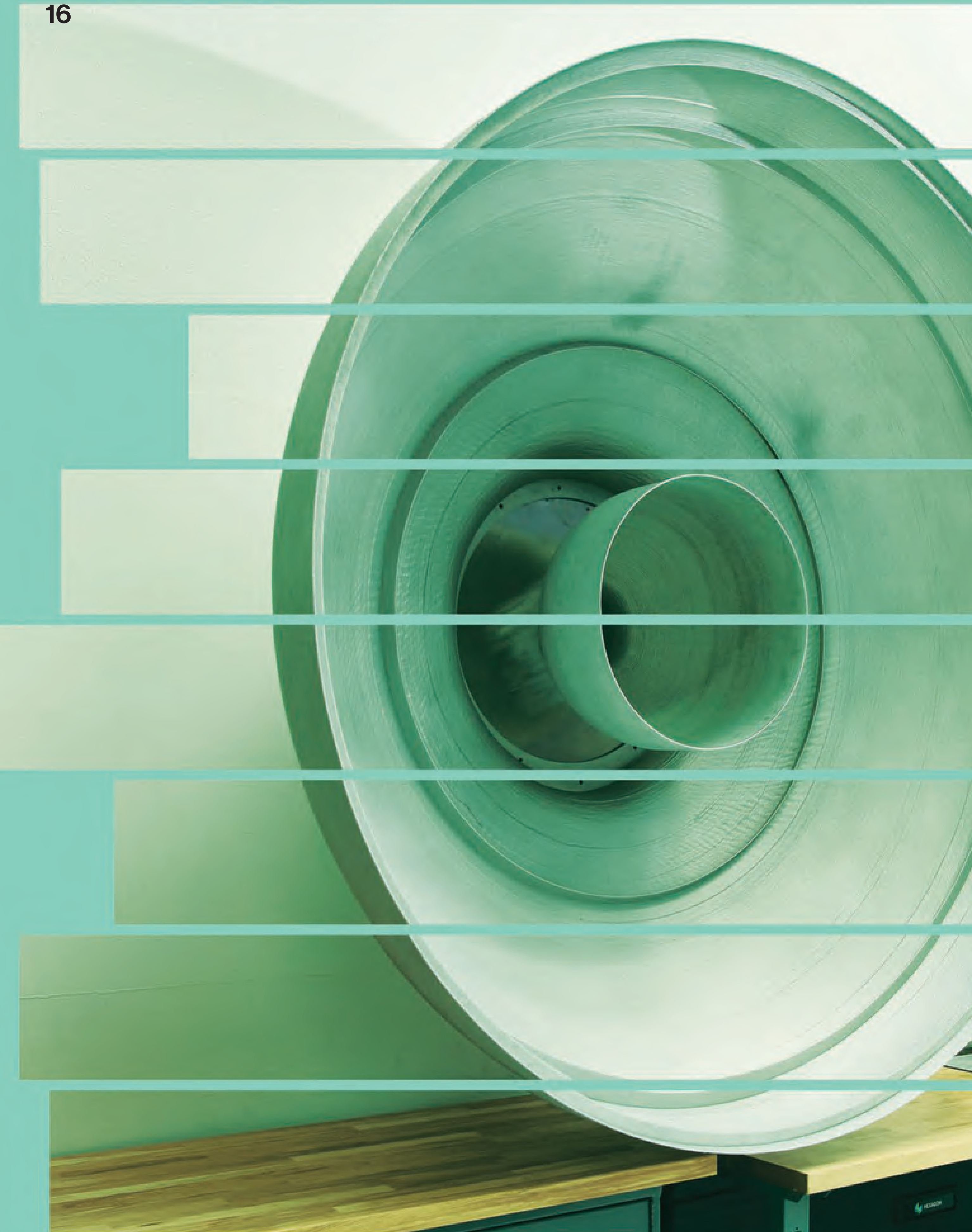
In the wake of the 1986 explosion of the space shuttle *Challenger*, the HL-20 was designed to safely and cheaply carry passengers to the space station Freedom. Neither it nor the HL-42, a scaled-up successor, ever made it to space. However, Sierra Nevada's Dream Chaser spacecraft, which is based on the HL-20 design, is slated to deliver cargo to and from the International Space Station starting in late 2020.



Roton

5

Another failed single-stage-to-orbit idea, the Roton, made by Rotary Rocket, stands in the Mojave spaceport as a warning and inspiration to would-be space pioneers. By making the rocket spin rapidly, engineers hoped to eliminate the need for costly and complicated pumps. A prototype made three test flights in 1999, but it was difficult to control. The company ran out of money before the kinks could be worked out.



Printed rocket pieces like this propellant tank cap are office decor at Relativity.

BUILDING FROM THE GROUND UP

Relativity Space plans to launch an almost entirely 3D-printed rocket next year. But does the world really need one?

By Erin Winick

Photos by Damon Cesarez

The once pristine white floors featured in Relativity Space's PR photos are now scuffed and coated with the residue of a typical machine shop. Inside its warehouse on the outskirts of Los Angeles, three robot arms hang imposingly next to a container filled with a coil of metal wire. The container's lid has a jagged hole as if someone punched through it on a bad day; duct tape has been slapped on to cover the sharp edges. This is a machine that's been pushed to its limits, in service of a lofty goal. Led by its founders, Tim Ellis and Jordan Noone, Relativity is attempting to create 95% of its rocket, Terran 1, using 3D printing, in just 60 days.

You read that right: the plan is to go from raw material to a launch-ready rocket in two months. If it sounds audacious, that's because it is. Hugely. 3D printing is having a moment in the spaceflight industry—everyone from SpaceX to Blue Origin to lesser-known startups and old-guard rocket shops are tinkering with the technology, and some have gone so far as to print their own engines from scratch. But even engineers on the cutting edge of 3D-printed rocketry don't know what to make of Ellis and Noone's upstart firm. And more than one think they're just crazy.

Traditionally the aerospace industry hasn't been quick to change, and for good reason: rockets are controlled explosions that put huge sums of money and, sometimes, human lives on the line. Relativity is aiming to win over skeptics and holdouts with a test launch in 2020. Thing is, they haven't even printed a whole rocket yet.

At their core, rockets consist of four main systems: payloads, guidance, propulsion, and structures. The payload is whatever the rocket is carrying. The guidance consists of sensors that keep the craft on target, and propulsion is made up of the fuel and engine that make it go. The structures are the rest of the frame, cone, and fins of the rocket—parts that are typically fabricated using ultra-precise CNC milling machines and hand welding.

That's all a way of saying that behind every successful launch is a tremendous amount of labor and a vast network of suppliers working in concert to assemble each vehicle. By streamlining the supply chain, Relativity hopes to sharply cut production time.

But this goal of printing Terran 1's more than 100-foot-tall (30-meter) exterior and fuel tank comes with an additional challenge: creating printers that can accomplish the task. "Building a rocket company is hard, building a 3D-printing company is hard, and building both together at the same time is borderline nuts," says Ellis, Relativity's CEO. "But while it's the hardest part of the job, it is also the secret sauce that will make Relativity a world-changing company."

There's still a way to go before doing any world changing, though. "We're not going to fly a rocket unless we get these metal 3D-printing technologies developed," Ellis admits. "So that provides quite a bit of existential kick in the butt to figure it out, because this is the only way we're going to actually make it to our goal."

Children of the Stargate

Relativity's solitary 20-foot-tall printer, Stargate, has been serving the company since it exited stealth mode in 2017, but it's finally about to get a break. In a nearby building are four updated, fresh-out-of-the-box models.

Humans are still in the loop with Relativity's Stargate printers—for now, anyway.

Each one is shielded by long black flaps that run from the warehouse ceiling to the floor and betray their newness with a pungent plastic smell. One has a small toy basketball hoop hanging on it—as if, so far, it's more often served as a backboard than a rocket printer.

A giant image splashed across the wall depicts a hoped-for vision of the company's future: a warehouse filled with nothing but Stargates, smaller printers, and robot arms. An engineer's paradise, and a machinist's nightmare. It's the "robots are taking our jobs" headlines in mural form.

The hulking machines seem to smirk at decades of rocket assembly. During the Apollo program, engineers faced extreme difficulty achieving perfect welds on the Saturn series of rockets. Even experienced welders had to be given specialized training to complete the long, precise welding passes required. Now a robot is welding the entire thing.

Stargate and its offspring use a variant of what's known as directed energy deposition. Traditional manufacturing methods involve carving a finished product from a block of material. 3D printing builds up an object layer by layer instead, enabling the creation of lightweight objects with intricate internal structures that are impossible to make any other way. The most prevalent form of 3D printing is called fused deposition modeling—a material, often plastic, is melted and squeezed out of a nozzle in precise patterns to build an object. Combine that with welding and you have directed energy deposition.

The basics of welding involve supplying a steady stream of metal wire with one hand and heat with the other. Stargate does this automatically, feeding wire out of an extruder on the end of a tall robotic arm. The metal is heated using electric plasma (and sometimes a laser) and then laid down according to a computer's instructions. A combination of electronic controls, thermal imaging cameras, and sensors mounted near where the material is deposited adapt the print as it's created. "Our vision of 3D printing is software-defined automation for aerospace," says Ellis. "That's getting toward the long-term vision of 3D-printing rockets on Mars. These are exactly the tools we're going to need to actually build stuff on other planets."

"Building a rocket company is hard, building a 3D-printing company is hard, and building both together at the same time is borderline nuts."

The way Ellis talks about his company brings to mind Elon Musk's exultations about SpaceX and Tesla, only Ellis says he is completing a piece of the Mars puzzle Musk isn't yet tackling. "The thought is having two products. One is the rocket launch vehicle. The other is the factory," he says. "Over time, the factory we see being able to shrink down smaller and smaller and smaller until it's eventually something that we can actually just launch on a big rocket." You build the machine that makes the machine. And then launch it to Mars. Simple.

Even fellow rocket companies aggressively pursuing 3D printing (a.k.a. additive manufacturing) aren't entirely convinced this is how the future looks. Rocket Lab, one of only a few small satellite launchers that fly commercial flights, has relied on additive manufacturing to create engines, valves, manifolds, and a number of other complex components; its CEO, Peter Beck, says, “There’s no way that we can produce the volume and the performance of the engines that we’re producing now without 3D-printing technology.” But an entire rocket? “To go and print an avionics box or tank or something like that doesn’t make any sense, because there’s much more efficient processes for doing that,” says Beck. “I don’t want to rain on Tim’s parade. I wish him the absolute best, but from an engineering perspective, it makes absolutely no sense to us.”

In the end, customers are the ones who will need proof of the wisdom of Relativity’s method. Like most rocket companies before their first launch, Relativity is selling its customers on test data and the team that’s been assembled. “Ultimately, it’s a belief and a leap of faith that we’re going to go execute,” says Ellis. “But yeah, it’s a pretty big one. And definitely, it’s a process to get to it.”

Evidently some customers are willing to take that leap. Relativity has already publicly announced three clients with launches booked for 2021 and 2022: the Canadian communications company Telesat, Washington-based Spaceflight (which helps coordinate satellite ride shares on larger launches), and Thailand’s mu Space. Noone says that once Relativity shows it can launch successfully in 2020, it plans to increase the number of flights it launches each year to 12 to 24.

These kinds of aggressive time lines are baked into the company’s lore. Three years ago, shortly after Ellis and Noone each left their first jobs out of college at Blue Origin and SpaceX, respectively, they pitched investor Mark Cuban via email to ask for seed funding. The message had the subject line “Space is sexy: 3D printing an entire rocket.” Cuban, who conducts the majority of his business through email, replied five minutes later saying he wanted to invest $500,000. Two months later he did. According to Cuban, it wasn’t just the additive-manufacturing element that caught his eye. “The idea was unique. I wish I had thought of it,” he says. “They were qualified, and they were local.” (Ellis is from Texas, where Cuban lives.)

Since the infusion, Relativity has put its foot on the gas. In the past year it’s grown from 14 people to more than 80. The team now includes Tim Buzza, one of the first SpaceX employees and former VP of launch for both SpaceX and Virgin Orbit, and David Giger, a 12-year SpaceX employee who served as the senior director of engineering for the company’s Dragon capsule.

Ellis, the front man for hiring and raising capital, doesn’t seem to have trouble winning people over at all levels. He’s got a spot on the White House’s National Space Council Users Advisory Group, and contracts and cash are flowing into the company. Relativity has closed a $35 million series B funding round, scored a deal with NASA to test its engines at the Stennis Space Center in Mississippi, and received permission to launch at one of the most competitive launch sites in the world: Florida’s Cape Canaveral.

This last coup, announced in January, lines the Terran 1 up to launch from the hallowed Launch Complex 16, which once played host to Titan missile launches, the Apollo program, and the Gemini program. High-profile moves like that have forced Relativity’s name into conversations about companies like SpaceX, Blue Origin, and United Launch Alliance, previously the only three outfits with permits to lift off from Cape Canaveral.

If Terran I is going to get to space, its 11-foot-tall fuel tank needs to work like a dream.

“I don’t want to rain on Tim’s parade. I wish him the absolute best, but from an engineering perspective, it makes absolutely no sense to us.”

Printing takes off

Relativity is far from alone in hoping that 3D printing will propel it into the elite of spaceflight. Startups including Virgin Orbit, Firefly, and Electron are all vying to prove that they, like Rocket Lab, have what it takes to launch small satellites to space. Even established companies like Aerojet Rocketdyne are trying to prove 3D printing is on par with—or even more reliable than—traditional manufacturing techniques.

But no one is going for it as hard and fast as Relativity. Aerojet builds engines for government contracts and human-rated rockets like NASA's Space Launch System, which have to be extra consistent and reliable. The company says that more than 60% of its research and development for 3D printing has been nothing more than establishing a database of the chemical and structural properties of different materials. "Others may kind of skip over that, and that's their right to do that as a risk-accepting posture," says Jeff Haynes, Aerojet's senior manager of advanced programs.

By contrast, at Relativity, "if we put a fully printed engine on the test stand, successfully fire it, and then fly it, that for us is success," says Noone. "You could write hundreds of pages of specifications telling you how to get there, and how to manufacture it, but we have our ways that we do it. I wouldn't want to be hung up on creating the specification rather than just trying something and demonstrating that it works."

Printing a rocket means making test sections, cutting them to pieces, and testing some more. Did we mention testing?

That "move fast and break things" mentality would lead to a lot of sleepless nights for most rocket designers. Virgin Orbit, a competitor of Relativity's, has additive-manufactured parts on its first LauncherOne rocket, but the company is happy to go easy on trendy tech. "The LauncherOne vehicle engine right now uses very reliable manufacturing methods that NASA has proved out since the '50s and '60s, because [priority] number one for first-launch vehicles is reliability," says Virgin Orbit's advanced-manufacturing manager, Kevin Zagorski.

The other companies giving additive manufacturing a chance run the gamut from Jeff Bezos's Blue Origin—where Ellis had a hand in purchasing the company's first metal 3D printer during one of his three internships there—to Launcher, a small startup that claimed to have made the world's largest 3D-printed rocket engine. Heavy hitters like SpaceX, NASA, Rocket Lab, United Launch Alliance, and ArianeGroup have entered the 3D-printing ring as well.

The reasons most of these organizations give for using the technique are twofold: you can build something with fewer parts and tweak designs more quickly. Initially, Rocket Lab's Beck saw additive manufacturing getting a bad reputation because it wasn't being used effectively. "Someone would take a subtractively manufactured [i.e., machined] component and attempt to 3D-print it. It would turn out more expensive and more time consuming," he says. "But like any new technology, it's all about designing for the process. Where 3D-printed parts really excel is where you have really high complexity and you merge a lot of parts into one."

For its part, Relativity boasts that Terran 1 will have just a hundredth as many parts as a standard rocket. Its engine, Aeon 1, is made from only three parts pieced together.

How much of this is a PR stunt, though, is hard to sort out. Announcing you've made the first whatever is tempting, especially for small startups. Relativity, for example, claims to have built the largest metal 3D printer—as do Sciaky and Titomic, two industrial hardware companies that aren't in the space business. "Everybody's looking to try and have a point of differentiation and trying to grab some headlines," says Beck. "If someone wants to talk about 3D-printing something, then fine, but it's somewhat amusing."

Even if 3D-printing an entire rocket isn't practical, "I'm really confident that in any case it will result in useful spin-offs," says Dan Erwin, head of astronautical engineering at the University of Southern California. Erwin ran USC's rocket lab when Ellis and Noone studied there but hasn't worked with them since. "I have the intuition that this is one of those 'If you build it, they will come' kind of things," he says. Regardless of whether Relativity launches a rocket by next year, it is forcing a slow-moving industry to take a closer look at, and perhaps advance, a technology that has uses outside spaceflight. The end result might be nothing more than a new breed of printer. Or it might be the Mars-bound rocket we've all been promised. "Life is too short to just wait for the future to happen faster," says Ellis. "We should create it."

Erin Winick was MIT Technology Review's space reporter at the time of writing. She is now a science communications specialist for the International Space Station.

THE ENGINE THAT CAME IN FROM THE C

An Atlas V rocket launches from Cape Canaveral in Florida in 2013, carrying a NASA space probe toward Mars. The rocket's first-stage engine was built just outside Moscow.

CAN **SPACEX** AND **BLUE ORIGIN** BEST A DECADES-OLD **RUSSIAN** ROCKET ENGINE DESIGN?

D

BY **MATTHEW BODNER**

An hour before sunset

on May 24, 2000, an unusual rocket took off from Launch Complex 36 at Cape Canaveral Air Force Station. Like most rockets, the Atlas 3 had inherited its design from an intercontinental ballistic missile—in this case, from America's first such missile, designed to threaten the Soviet Union with nuclear annihilation. This was not unusual. But the rocket had a new first stage, one that was considerably more powerful than those it replaced. The RD-180, as the engine is called, was built by NPO Energomash in a factory outside Moscow. In a marriage that would have been unimaginable at the height of the space race, a Russian engine was powering an American rocket.

In the two decades since, 83 more such rockets have taken off from Florida.

On the Atlas 3 and its successor, the Atlas 5, the RD-180 carried at least 16 American spy satellites to orbit, along with 13 military communications satellites, a half-dozen GPS satellites, two military weather satellites, and three missile warning satellites, designed to detect rocket launches from, among other countries, the one where it was built. It launched four American Mars missions. NASA's launch of New Horizons to Pluto in 2006 and Juno to Jupiter in 2011 were both made on the back of the RD-180.

The RD-180 is remarkable not only for the geopolitical peculiarities of its rise to prominence, but because it was in many ways simply *better* than any other rocket engine of its time. When, in February 2019, Elon Musk announced a successful test of SpaceX's Raptor engine, which is intended to power the company's next-generation rocket Starship, he bragged of the high pressures reached in the Raptor's thrust chamber: over 265 times atmospheric pressure at sea level. Raptor, he said on Twitter, had exceeded the record held for several decades by the "awesome Russian RD-180."

After Russia annexed the Crimea in 2014, the RD-180's days as a staple of American rocketry were numbered. Defense hawks had long been uncomfortable with the arrangement, but the engine was both very good and, given its capability, cheap—and so it stayed. But as relations with Russia frayed, congressional opponents of the engine, led by Senator John McCain, succeeded in passing a prohibition against the engine's use in American rockets after the end of 2022. This has forced the Air Force to find a new rocket to succeed the RD-180-powered Atlas 5.

All of which raises a question: How did a decades-old Russian engine become the bar against which America's best rocket scientists measure themselves?

If you want to understand what made the RD-180 such a good engine, it helps to understand that there is a great deal of craft involved. Though hundreds of people collaborate on rocket engines, having someone with an instinct for good design in charge is vital: the trade-offs are too complex to be figured out by brute force or by committee. In the case of the RD-180, that someone was named Valentin Glushko.

After the USSR lost to America in the race to the moon, designing the best possible rocket engine became "a national priority," according to Vadim Lukashevich, an aerospace engineer and Russian space historian. Soviet leaders wanted to build the world's most powerful rocket, the Energia, to sustain their space stations in Earth orbit and to lift the Buran, a would-be Russian space shuttle. Glushko was given resources to build the best engine he could, and he was good at building engines. The result was the RD-170, the RD-180's older brother.

The RD-170 was among the first rocket engines to use a technique called staged combustion. The US space shuttle main engine, also developed in the 1970s, was another. By contrast, the F-1 engines in the first stage of the Saturn V rocket, which launched Apollo to the moon, were of an older, simpler design called the gas-generator engine. The key difference: staged-combustion engines can be more efficient, but they're at greater risk of exploding. As William Anderson, who studies liquid-fueled rocket engines at Purdue University, explains, "The rates of energy release are just extreme." It takes someone with a really astute imagination, Anderson says, to understand the crazy stuff that's going on inside rocket engines'

CRAIG F. WALKER/GETTY IMAGES; PREVIOUS SPREAD: BILL INGALLS/NASA combustion chambers. In Russia, that astute person was Glushko.

To understand why Glushko's engines were such an engineering achievement, we need to get a little bit technical.

The Russian RD-180 engine has powered dozens of Atlas V launches, some carrying satellites designed to spy on, among other countries, the one where it was built.

There are two key measures of a rocket's performance: thrust, or the amount of force a rocket exerts, and specific impulse, a measure of how efficiently it uses its propellants. A rocket with high thrust but low specific impulse won't reach orbit—it would have to carry so much fuel that the weight of the fuel would necessitate more fuel, and so on. Conversely, a rocket with high specific impulse but low thrust would never leave the ground. (Such rockets work well in space, though, where a steady push suffices.)

A rocket engine, much like an aircraft jet engine, burns fuel together with an oxidizer—often oxygen—to create hot gas that expands down and out of the engine nozzle, accelerating the engine the other way. Unlike jet engines, which get oxygen from the air around them, rockets need to carry their own oxygen (or other oxidizer), since in space, of course, there isn't any. Like jets, rockets need a way to force the fuel and oxygen into the combustion chamber at high pressure; all else being equal, higher pressure means better performance. To do that, rockets use turbopumps that spin at hundreds of rotations per second. The turbopumps are driven by turbines, and they, in turn, are powered by pre-burners, which likewise burn some fuel and oxygen.

The crucial difference between staged-combustion engines like the RD-180 and gas-generator engines like the Saturn's F-1 lies in what happens to the exhaust from those pre-burners. While gas-generator engines dump it overboard, staged-combustion engines reinject it into the main combustion chamber. One reason for doing this is that the exhaust contains unused fuel and oxygen—the pre-burners can't burn it all. Throwing it away is a waste, which matters in a rocket that also has to lift every pound of fuel and oxygen it's going to use. But reinjecting the exhaust entails delicately balancing the relevant pressures and flow rates so that engines don't blow up. It requires a whole series of turbopumps to make it work. Teams of experts typically need a decade or more of simulation and testing to figure out how to get it right.

The RD-170 and RD-180 have another advantage. They are oxygen-rich, which means exactly what it sounds like: they inject extra oxygen into the system. (The space shuttle main engine, by contrast, is a fuel-rich engine.) Oxygen-rich engines tend to burn cleaner and to ignite more easily. They also make possible higher combustion-chamber pressures, and thus better performance—but they are more prone to explode, so for decades there weren't any major

> **"There was so much invested in the shuttle that no one at NASA wanted to talk about developing an oxygen-rich staged-combustion engine ... Oxygen will burn most things if you provide a spark."**

efforts to make them work in the US. "There was so much invested in the shuttle that no one at NASA wanted to talk about developing an oxygen-rich staged-combustion engine," says Anderson. "Oxygen will burn most things if you provide a spark." This requires great care in the materials used to build the engine, and even greater care in making sure no foreign materials—such as specks of metal debris—ever make their way into it. "The more we learn about the physics of what goes on inside a combustion chamber, the more we realize how unsteady it really is," says Anderson.

If the RD-170 was arguably the best rocket engine of its generation, the space shuttle main engine was arguably second best (and was substantially more expensive to make). Neither lived up to its potential. The space shuttle engine was stuck with a lemon of a vehicle, which was much more cumbersome than its designers had hoped it would be. The RD-170, on the other hand, flew only twice: once in 1987 and once in 1988. Though developing it had been a national priority, by the time Glushko proved that it worked, the Soviet Union was about to fall apart.

The 1990s were a turbulent time in Russia, especially for the space program. To survive without government financing, newly privatized aerospace firms turned to the commercial market.

That's when Jim Sackett, an engineer who'd been working for Lockheed at NASA's Johnson Space Center in Houston, moved to Moscow. Lockheed became interested in using oxygen-rich staged combustion to power the next generation of Atlas rockets, with which it planned to compete for Air Force and NASA contracts.

Sackett, who was put in charge of Lockheed's Moscow office, was tapped to approach Energomash, a post-Soviet space industry firm that came to own the RD-170 and related engine technology. Energomash enthusiastically welcomed Lockheed's interest. But the RD-170 was too powerful: the Atlas rockets Lockheed was looking to send into space were considerably smaller than the Energia, for which the RD-170 had been designed. So Energomash essentially cut the engine in half—the firm drew up a proposal for a two-chamber derivative of the four-chamber RD-170 that could be used in the Atlas. This was the birth of the RD-180.

The relationship required remarkable integration between Russian and American military-industrial contractors. Lockheed set up an office at Energomash, in a Moscow suburb. It was a huge operation, Sackett remembers. "They've got a metallurgy plant there, so they forge their own metals," he says. "They have all their own machine shops, all of their own test facilities. It is a lot of stuff, all of it under one roof. And eventually, all of it turns into a rocket engine."

It took about a year of daily, in-depth technical meetings between Sackett's team and Energomash executives and engineers to understand whether or not the proposed purchases of RD-180 engines would work. Lockheed wanted a small, no-commitment deal. Energomash held out for a long-term arrangement. The contract was signed at the end of a marathon six-hour session in 1996, Sackett says. The result: a 101-engine, billion-dollar deal.

The US Air Force, Lockheed's main customer, demanded access to 10 key technologies needed to produce the RD-180, in case relations with Russia ever foundered and America had to make the engines itself. It was a big ask. The US was after a crown jewel of Soviet space technology, and the Russian government was not thrilled. "But they saw no alternative," Sackett

COURTESY IMAGES

says, "because the country did not just have a change of heart, they went broke. They just went flat broke. This is how they saved the company."

Though more attention has been paid to American-Russian cooperation on the International Space Station, in many respects the RD-180 collaboration went deeper. After all, the space station is not crucial to the national security of either country, while reconnaissance and communications satellites are.

Now that relations between the two countries have frayed, Sackett argues, the US could just manufacture the RD-180 domestically. The engine's critics say it would be astronomically expensive to do so. But the cost "shouldn't be astronomical!" Sackett says. "We have smart people here, and we have the recipe! This is exactly why we identified and negotiated for those 10 key manufacturing technologies, so that we could take the drawings and the notes and then go build them."

The design of the RD-180 informs both Blue Origin's BE-4 (left) and SpaceX's Raptor (right), two contenders to replace it.

That's not likely to happen, in part because after decades of stagnation, American companies are finally working on engines that just might be better than the RD-180.

An engine's performance has profound influence over the design of the rocket above it. So when Congress mandated that the Air Force stop using the RD-180, this provoked a competition not just for a new engine, but for a whole new rocket. Such a competition was inevitable—after all, designs don't last forever. But because designing new engines and rockets is expensive and time consuming, the timing for making a switch is always politically contentious. The congressionally mandated RD-180 ban forced the issue.

There are four serious contenders to build that new rocket: SpaceX, Blue Origin, the United Launch Alliance (a Boeing–Lockheed Martin joint venture known by its initials, ULA), and Northrop Grumman. Two of them will be chosen, on the theory that having two winners creates ongoing competition, while naming one would result in a monopoly that could then turn around and gouge the Air Force. Thousands of jobs are at stake: if ULA loses, it may go out of business.

The New Glenn, Blue Origin's entry in the competition, uses the BE-4, Blue Origin's newest and most powerful engine. (As does ULA's rocket—the two firms are simultaneously competitors and business partners.) The designs of both the BE-4 and SpaceX's Raptor are informed in crucial ways by the RD-180. The BE-4 is an oxygen-rich staged-combustion engine, like the RD-170 and RD-180. The Raptor, meanwhile, resembles the RD-180 in that it feeds the pre-burner exhaust into the combustion chamber—ensuring that almost all the fuel and oxidizer stored in the rocket's tanks are used to generate thrust. However, the Raptor relies on a tweak to Glushko's approach: both fuel-rich and oxidizer-rich flows power its turbopumps—theoretically resulting in maximal efficiency.

In a way, the BE-4 and Raptor are like an attempt to build a better violin than Stradivarius did, using modern methods. Blue Origin and SpaceX have access to better diagnostics and more sophisticated simulation techniques than Glushko did. They also have another design feature important to the American Air Force: they're made in the US.

Possibly the greatest technical advantage these new engines have over the RD-180 is that they use methane as fuel rather than kerosene, as the RD-180 does. Kerosene can gunk up the works of an engine after repeated use. Methane has higher specific impulse, and burns cleaner. It is also much easier (in principle) to synthesize on Mars, which Musk aims to do.

Neither new engine has yet reached orbit. SpaceX is planning test flights of its Starhopper rocket, which will eventually be powered by three Raptors, for this summer. These flights will be short hops, a few thousand feet in the air above SpaceX's test site in Texas. Blue Origin is also testing the BE-4 in Texas, and has started building a factory in Alabama where it will manufacture the engines. It has rented Launch Complex 36, where the RD-180 first took flight, from the Air Force and plans to launch the New Glenn there in 2021.

Energomash, meanwhile, is desperately hoping that the Russian space program will again start using its engines. Some 90% of its production has gone to the US in recent years, says Pavel Luzin, a Russian space industry analyst. Like its American counterparts, Energomash now risks being made obsolete by Musk and Bezos—who, with their freedom from legacy design constraints and willingness to spend money and take risks, have finally jolted rocket engine design out of decades of stasis. ■

Matthew Bodner is a journalist in Moscow who writes about aerospace and the military.

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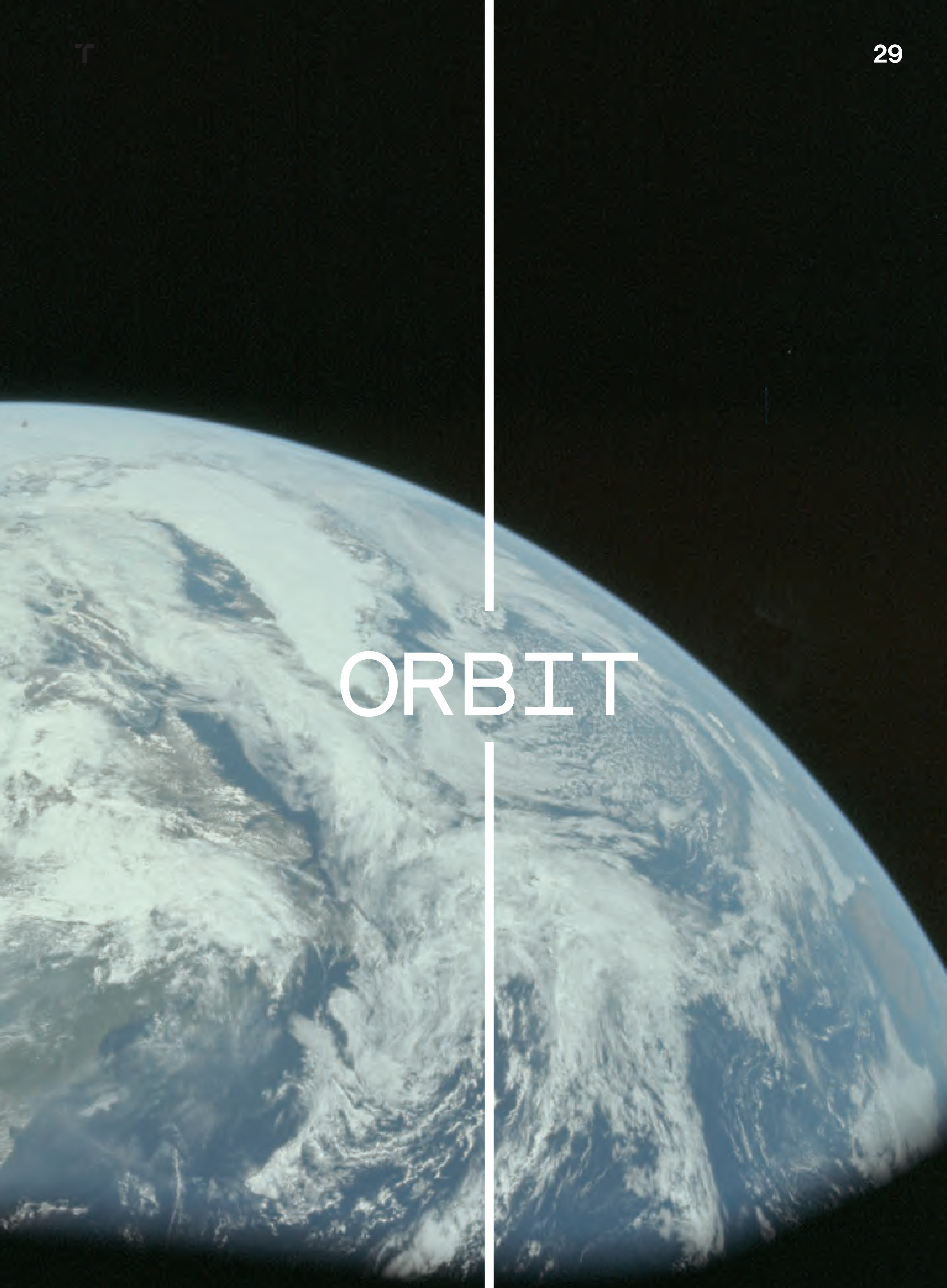

ORBIT

A more crowded heaven

By
Tate Ryan-Mosley,
Erin Winick, and
Konstantin Kakaes

As you read this there are about 2,000 satellites orbiting above our heads, and apart from an occasional glimpse in the night sky, they're pretty much invisible. But they have become a huge part of everyday life on Earth. Want to find your way around? Tap a button and your phone talks to a constellation of GPS satellites. Those stunning images of Arctic sea ice and animations of ocean-churning hurricanes? Satellite-based, of course. These days, the view from orbit is so ubiquitous that most of us have probably forgotten a time when it wasn't part of our perspective.

Over the next few years, there's going to be even more hustle and bustle in orbit. By 2025 as many as 1,100 satellites could be launching each year—up from 365 in 2018. Just one project, SpaceX's ambitious Starlink, aims to fly 12,000 small satellites by 2027. It and similar projects aren't just crowding the skies—they're delivering a host of technological upgrades meant to improve life planetside.

Bird's-eye views

From mapping the planet in minute detail to simply making sure a smartphone user doesn't get lost, satellites do a little bit of everything. And they work better in groups. These four satellite constellations each perform a synchronized function without which your life wouldn't be—or soon won't be—the same.

Internet access

Starlink

Number of satellites: 60 launched; ~12,000 planned
Manufacturer: SpaceX
Launch dates: 2019–2027

Starlink is one of several projects aiming to create low-cost, high-speed global satellite internet that can compete with terrestrial networks while connecting far-flung rural communities. The satellites will be deployed at three different altitudes within low Earth orbit. At a little over 200 kilograms apiece, they're relatively small as satellites go, but each batch of 60 offers up to 1 terabit per second of bandwidth, enough to stream 4K video to about 40,000 people simultaneously.

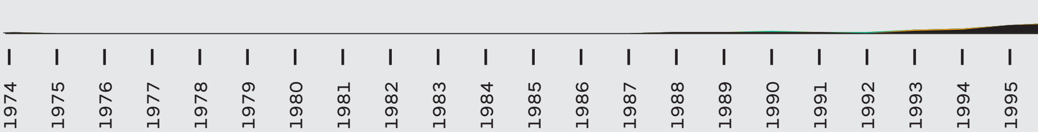
Weather monitoring

GOES-R

Number of satellites: 2 launched; 4 planned
Manufacturer: Lockheed Martin and Harris
Launch dates: 2016–2024

Weather forecasting isn't just an addendum to the evening news: better predictions of severe weather can save thousands of lives. New machines sitting over the equator in geostationary orbit are pushing forecasts to the next level. In 2016, the GOES-R satellite program started monitoring clouds and water vapor using reflected solar radiation. This is different from ground-based radar methods, which send signals into the sky and analyze the returns. Two GOES (for "geostationary operational environmental satellite") satellites have launched so far. Using onboard instruments like the Geostationary Lightning Mapper and the Advanced Baseline Imager, which collects images in 16 channels of visible, near-infrared, and infrared light, the satellites have already improved forecast lead times. The next satellite in the series, GOES-T, has had some setbacks, but all four GOES satellites are expected to be up and running by 2024.

Key
- Multipurpose/other
- Space science
- Technology development
- Navigation
- Earth observation
- Communications



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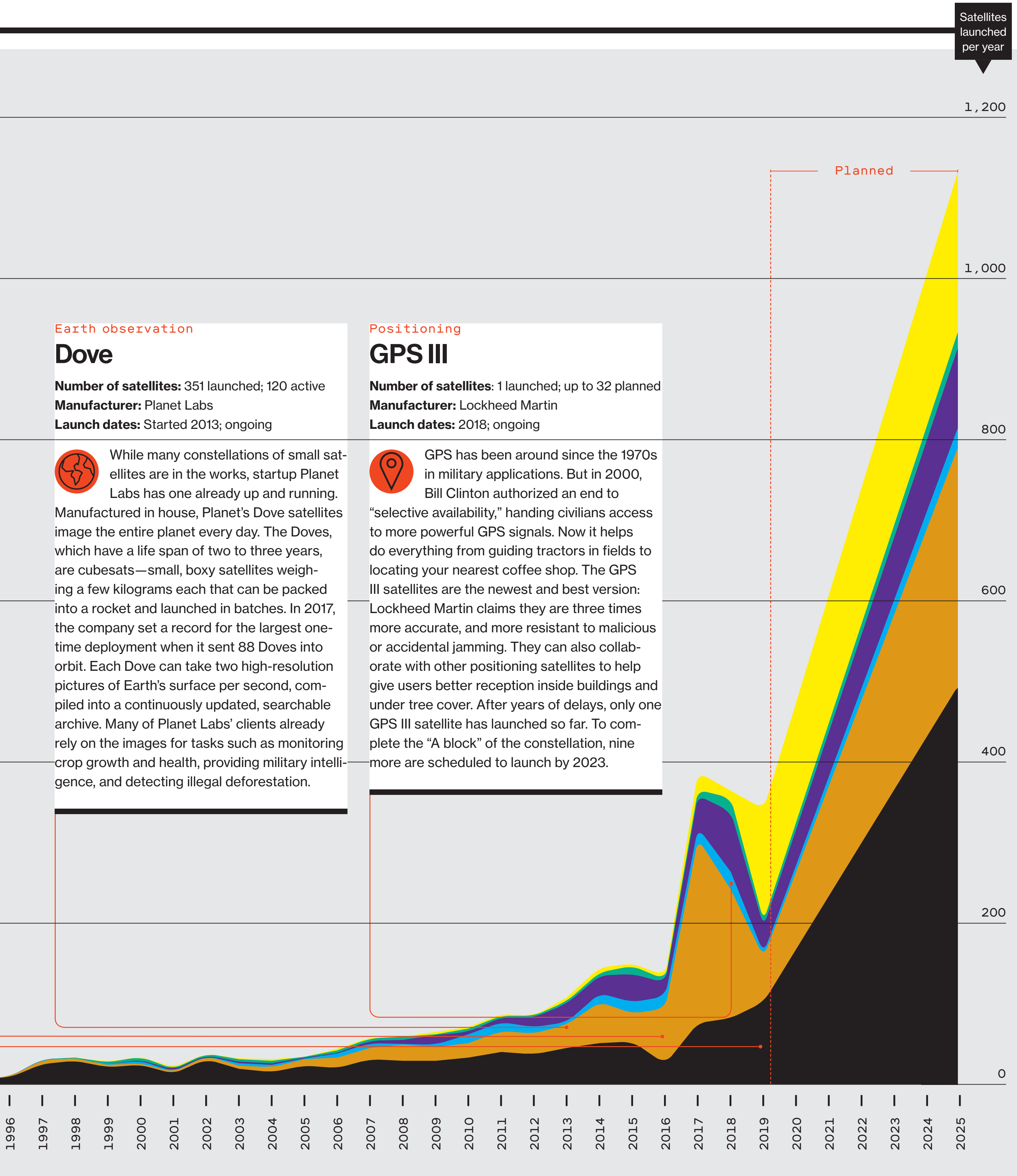


Earth observation

Dove

Number of satellites: 351 launched; 120 active
Manufacturer: Planet Labs
Launch dates: Started 2013; ongoing

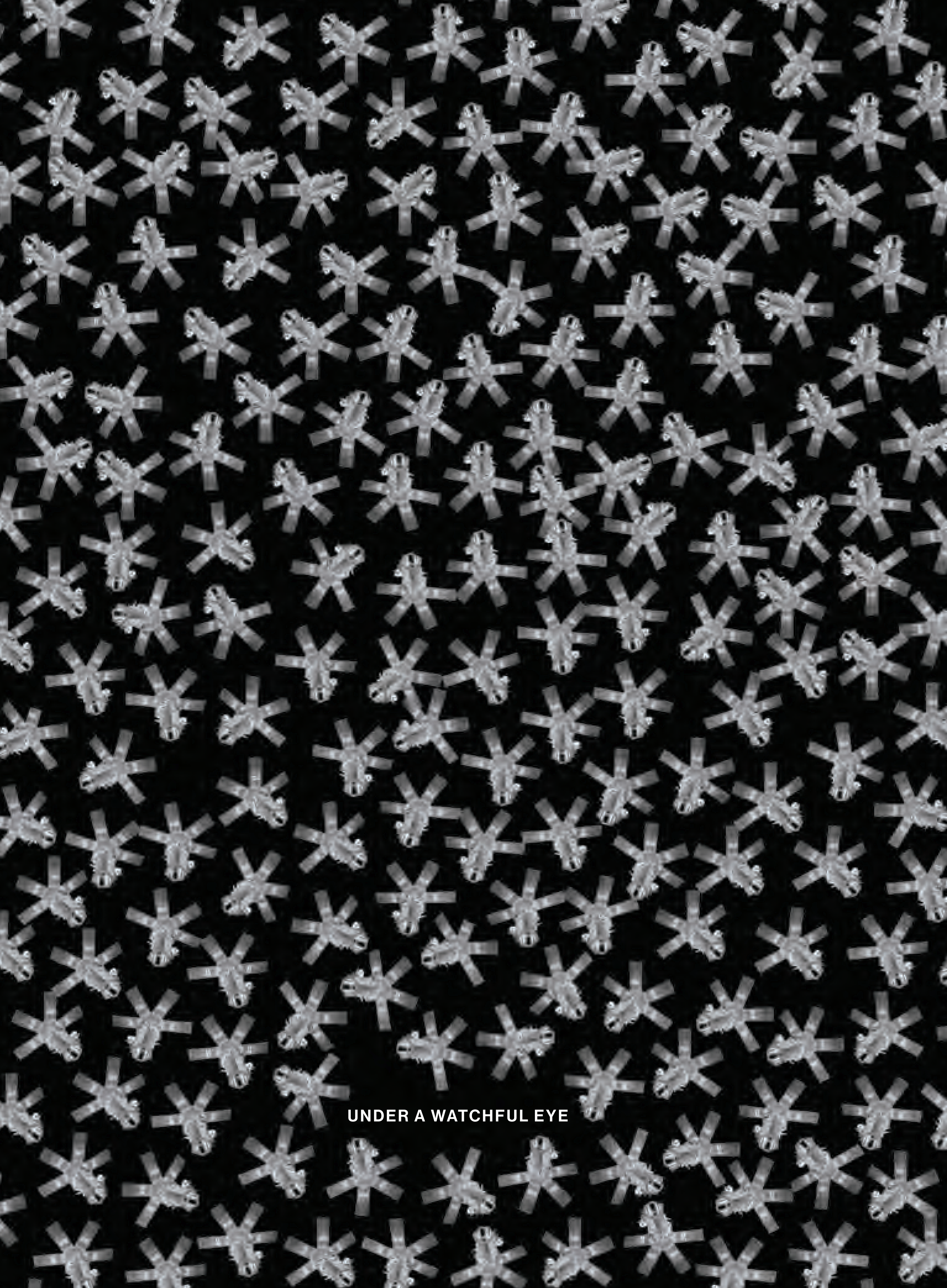
While many constellations of small satellites are in the works, startup Planet Labs has one already up and running. Manufactured in house, Planet's Dove satellites image the entire planet every day. The Doves, which have a life span of two to three years, are cubesats—small, boxy satellites weighing a few kilograms each that can be packed into a rocket and launched in batches. In 2017, the company set a record for the largest one-time deployment when it sent 88 Doves into orbit. Each Dove can take two high-resolution pictures of Earth's surface per second, compiled into a continuously updated, searchable archive. Many of Planet Labs' clients already rely on the images for tasks such as monitoring crop growth and health, providing military intelligence, and detecting illegal deforestation.

Positioning

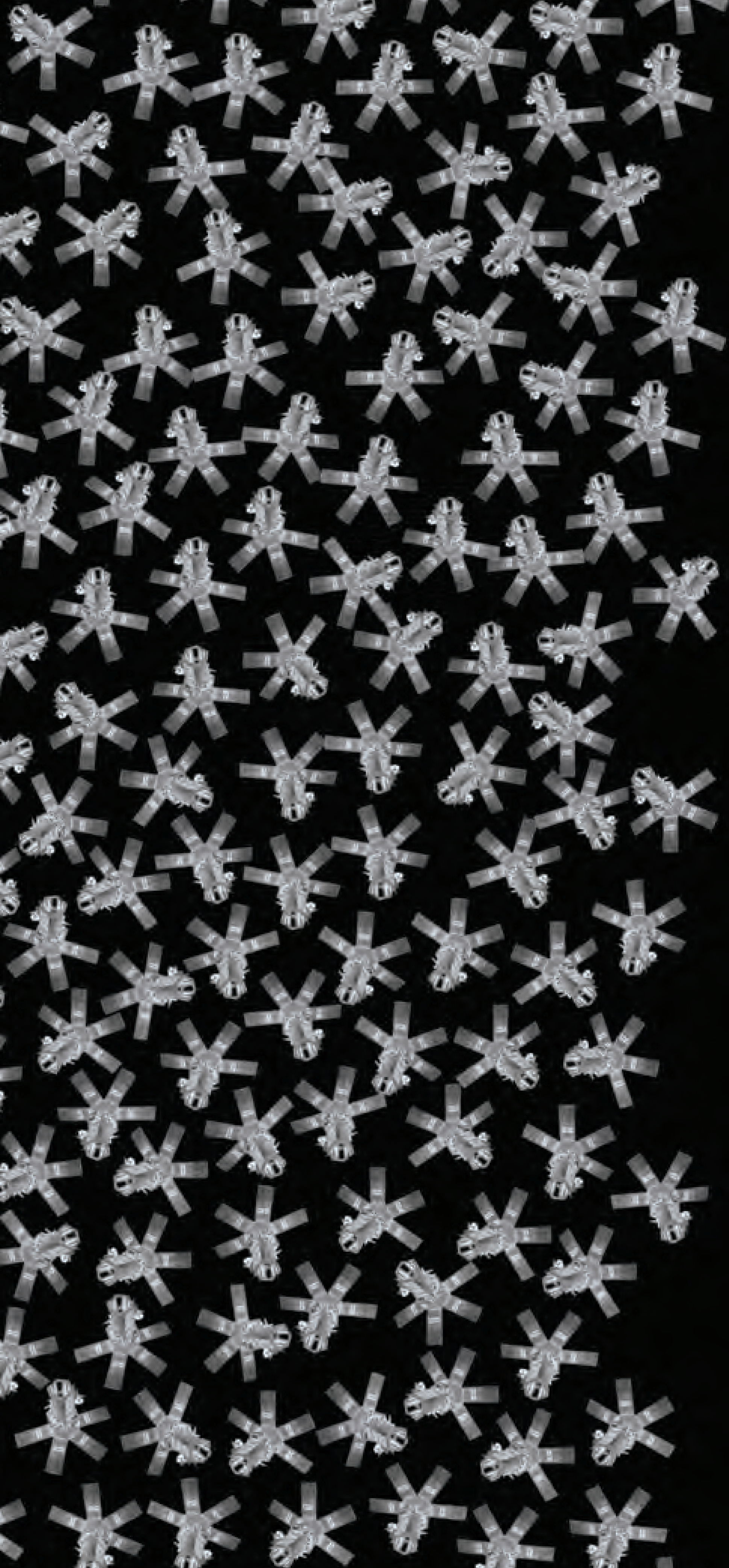
GPS III

Number of satellites: 1 launched; up to 32 planned
Manufacturer: Lockheed Martin
Launch dates: 2018; ongoing

GPS has been around since the 1970s in military applications. But in 2000, Bill Clinton authorized an end to "selective availability," handing civilians access to more powerful GPS signals. Now it helps do everything from guiding tractors in fields to locating your nearest coffee shop. The GPS III satellites are the newest and best version: Lockheed Martin claims they are three times more accurate, and more resistant to malicious or accidental jamming. They can also collaborate with other positioning satellites to help give users better reception inside buildings and under tree cover. After years of delays, only one GPS III satellite has launched so far. To complete the "A block" of the constellation, nine more are scheduled to launch by 2023.



UNDER A WATCHFUL EYE



SATELLITES CAN ALREADY SEE YOU. SOON THEY'LL SEE YOU MORE CLEARLY AND MORE OFTEN. IS THIS THE END OF PRIVACY?

By Christopher Beam

In 2013, police in Grants Pass, Oregon, got a tip that a man named Curtis W. Croft had been illegally growing marijuana in his backyard. So they checked Google Earth. Indeed, the four-month-old satellite image showed neat rows of plants growing on Croft's property. The cops raided his place and seized 94 plants.

In 2018, Brazilian police in the state of Amapá used real-time satellite imagery to detect a spot where trees had been ripped out of the ground. When they showed up, they discovered that the site was being used to illegally produce charcoal, and arrested eight people in connection with the scheme.

Chinese government officials have denied or downplayed the existence of Uighur reeducation camps in Xinjiang province, portraying them as "vocational schools." But human rights activists have used satellite imagery to show that many of the "schools" are surrounded by watchtowers and razor wire.

Every year, commercially available satellite images are becoming sharper and taken more frequently. In 2008, there were 150 Earth observation satellites in orbit; by now there are 768. Satellite companies don't offer 24-hour real-time surveillance, but if the hype is to be believed, they're getting close. Privacy advocates warn that innovation in satellite imagery is outpacing the US government's (to say nothing of the rest of the world's) ability to regulate the technology. Unless we impose stricter limits now, they say, one day everyone from ad companies to suspicious spouses to terrorist organizations will have access to tools previously reserved for government spy agencies. Which would mean that at any given moment, anyone could be watching anyone else.

The images keep getting clearer

Commercial satellite imagery is currently in a sweet spot: powerful enough to see a car, but not enough to tell the make and model; collected frequently enough for a farmer to keep tabs on crops' health, but not so often that people could track the comings and goings of a neighbor. This anonymity is deliberate. US federal regulations limit images taken by commercial satellites to a resolution of 25 centimeters, or about the length of a man's shoe. (Military spy satellites can capture images far more granular, although just how much more is classified.)

Ever since 2014, when the National Oceanic and Atmospheric Administration (NOAA) relaxed the limit from 50 to 25 cm, that resolution has been fine enough to satisfy most customers. Investors can predict oil supply from the shadows cast inside oil storage tanks. Farmers can monitor flooding to protect their crops. Human rights organizations have tracked the flows of refugees from Myanmar and Syria.

But satellite imagery is improving in a way that investors and businesses will inevitably want to exploit. The imaging company Planet Labs currently maintains 140 satellites, enough to pass over every place on Earth once a day. Maxar, formerly DigitalGlobe, which launched the first commercial Earth observation satellite in 1997, is building a constellation that will be able to revisit spots 15 times a day. BlackSky Global promises to revisit most major cities up to 70 times a day. That might not be enough to track an individual's every move, but it would show what times of day someone's car is typically in the driveway, for instance.

Some companies are even offering live video from space. As early as 2014, a Silicon Valley startup called SkyBox (later renamed Terra Bella and purchased by Google and then Planet) began touting HD video clips up to 90 seconds long. And a company called EarthNow says it will offer "continuous real-time" monitoring "with a delay as short as about one second," though some think it is overstating its abilities. Everyone is trying to get closer to a "living map," says Charlie Loyd of Mapbox, which creates custom maps for companies like Snapchat and the Weather Channel. But it won't arrive tomorrow, or the next day: "We're an extremely long way from high-res, full-time video of the Earth."

Some of the most radical developments in Earth observation involve not traditional photography but rather radar sensing and hyperspectral images, which capture electromagnetic wavelengths outside the visible spectrum. Clouds can hide the ground in visible light, but satellites can penetrate them using synthetic aperture radar, which emits a signal that bounces off the sensed object and back to the satellite. It can determine the height of an object down to a millimeter. NASA has used synthetic aperture radar since the 1970s, but the fact that the US approved it for commercial use only last year is testament to its power—and political sensitivity. (In 1978, military officials supposedly blocked the release of radar satellite images that revealed the location of American nuclear submarines.)

Meanwhile, farmers can use hyperspectral sensing to tell where a crop is in its growth cycle, and geologists can use it to detect the texture of rock that might be favorable to excavation. But it could also be used, whether by military agencies or terrorists, to identify underground bunkers or nuclear materials.

The resolution of commercially available imagery, too, is likely to improve further. NOAA's 25-centimeter cap will come under pressure as competition from international satellite companies increases. And even if it doesn't, there's nothing to stop, say, a Chinese company from capturing and selling 10 cm images to American customers. "Other companies internationally are going to start providing higher-resolution imagery than we legally allow," says Therese Jones, senior director of policy for the Satellite Industry Association. "Our companies would want to push the limit down as far as they possibly could."

What will make the imagery even more powerful is the ability to process it in large quantities. Analytics companies like Orbital Insight and SpaceKnow feed visual data into algorithms designed to let anyone with an internet connection understand the pictures en masse. Investors use this analysis to, for example, estimate the true GDP of China's Guangdong province on the basis of the light it emits at night. But burglars could also scan a city to determine which families are out of town most often and for how long.

Satellite and analytics companies say they're careful to anonymize their data, scrubbing it of identifying characteristics.

While GPS data from cell phones is a legitimate privacy threat, you can at least decide to leave your phone at home. It's harder to hide from a satellite camera.

But even if satellites aren't recognizing faces, those images combined with other data streams—GPS, security cameras, social-media posts—could pose a threat to privacy. "People's movements, what kinds of shops do you go to, where do your kids go to school, what kind of religious institutions do you visit, what are your social patterns," says Peter Martinez, of the Secure World Foundation. "All of these kinds of questions could in principle be interrogated, should someone be interested."

Like all tools, satellite imagery is subject to misuse. Its apparent objectivity can lead to false conclusions, as when the George W. Bush administration used it to make the case that Saddam Hussein was stockpiling chemical weapons in Iraq. Attempts to protect privacy can also backfire: in 2018, a Russian mapping firm blurred out the sites of sensitive military operations in Turkey and Israel—inadvertently revealing their existence, and prompting web users to locate the sites on other open-source maps.

Capturing satellite imagery with good intentions can have unintended consequences too. In 2012, as conflict raged on the border between Sudan and South Sudan, the Harvard-based Satellite Sentinel Project released an image that showed a construction crew building a tank-capable road leading toward an area occupied by the Sudanese People's Liberation Army. The idea was to warn citizens about the approaching tanks so they could evacuate. But the SPLA saw the images too, and within 36 hours it attacked the road crew (which turned out to consist of Chinese civilians hired by the Sudanese government), killed some of them, and kidnapped the rest. As an activist, one's instinct is often to release more information, says Nathaniel Raymond, a human rights expert who led the Sentinel project. But he's learned that you have to take into account who else might be watching.

It's expensive to watch you all the time

One thing that might save us from celestial scrutiny is the price. Some satellite entrepreneurs argue that there isn't enough demand to pay for a constellation of satellites capable of round-the-clock monitoring at resolutions below 25 cm. "It becomes a question of economics," says Walter Scott, founder of DigitalGlobe, now Maxar. While some companies are launching relatively cheap "nanosatellites" the size of toasters—the 120 Dove satellites launched by Planet, for example, are "orders of magnitude" cheaper than traditional satellites, according to a spokesperson—there's a limit to how small they can get and still capture hyper-detailed images. "It is a fundamental fact of physics that aperture size determines the limit on the resolution you can get," says Scott. "At a given altitude, you need a certain size telescope." That is, in Maxar's case, an aperture of about a meter across, mounted on a satellite the size of a small school bus. (While there are ways around this limit—interferometry, for example, uses multiple mirrors to simulate a much larger mirror—they're complex and pricey.) Bigger satellites mean costlier launches, so companies would need a financial incentive to collect such granular data.

That said, there's already demand for imagery with sub–25 cm resolution—and a supply of it. For example, some insurance underwriters need that level of detail to spot trees overhanging a roof, or to distinguish a skylight from a solar panel, and they can get it from airplanes and drones. But if the cost of satellite images came down far enough, insurance companies would presumably switch over.

Of course, drones can already collect better images than satellites ever will. But drones are limited in where they can go. In the US, the Federal Aviation Administration forbids flying commercial drones over groups of people, and you have to register a drone that weighs more than half a pound (227 grams) or so. There are no such restrictions in space. The Outer Space Treaty, signed in 1967 by the US, the Soviet Union, and dozens of UN member states, gives all states free access to space, and subsequent agreements on remote sensing have enshrined the principle of "open skies." During the Cold War this made sense, as it allowed superpowers to monitor other countries to verify that they were sticking to arms agreements. But the treaty didn't anticipate that it would one day be possible for anyone to get detailed images of almost any location.

And then there are the tracking devices we carry around in our pockets, a.k.a. smartphones. But while the GPS data from cell phones is a legitimate privacy threat, you can at least decide to leave your phone at home. It's harder to hide from a satellite camera. "There's some element of ground truth—no pun intended—that satellites have that maybe your cell phone or digital record or what happens on Twitter [doesn't]," says Abraham Thomas, chief data officer at the analytics company Quandl. "The data itself tends to be innately more accurate."

The future of human freedom

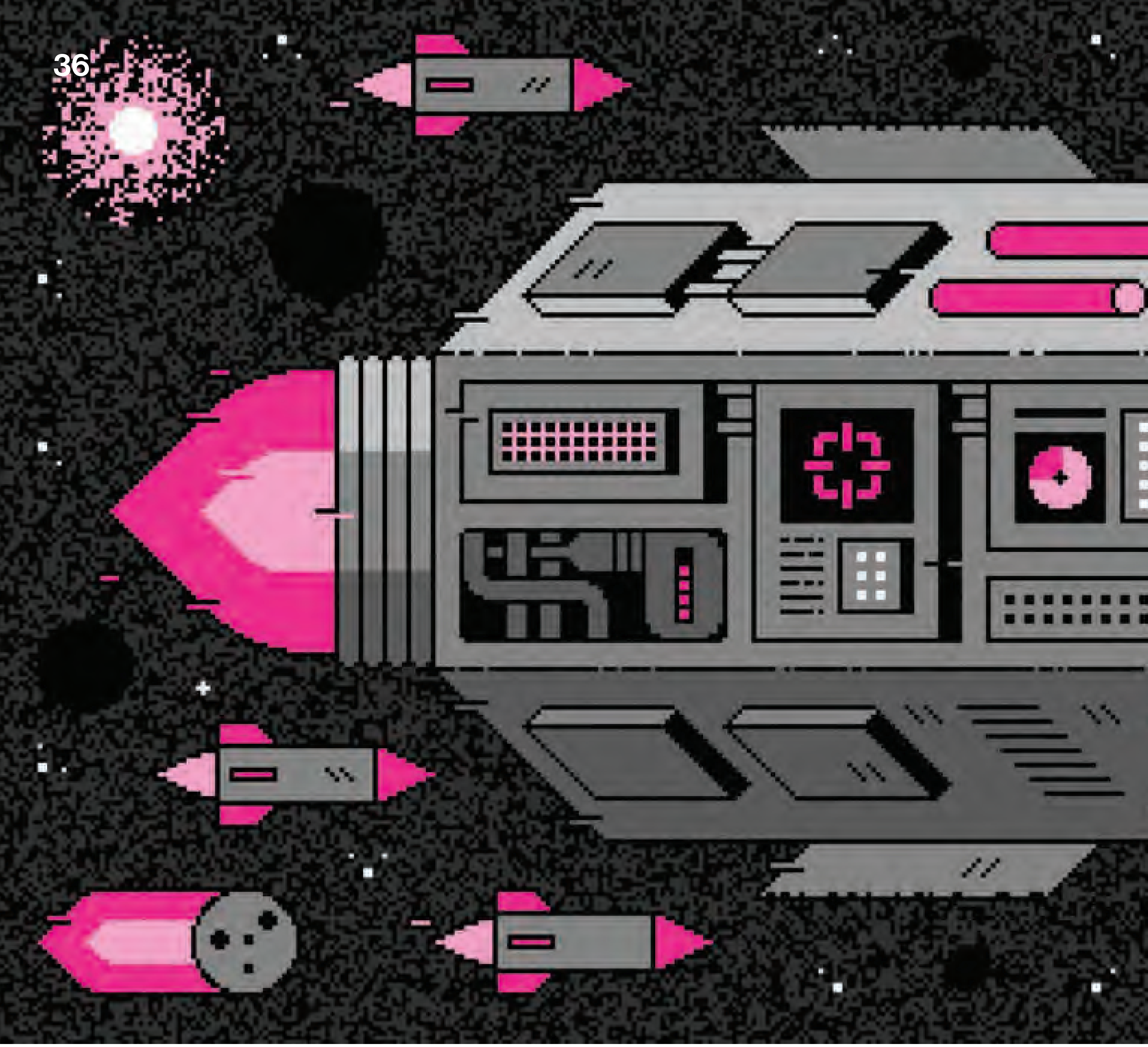
American privacy laws are vague when it comes to satellites. Courts have generally allowed aerial surveillance, though in 2015 the New Mexico Supreme Court ruled that an "aerial search" by police without a warrant was unconstitutional. Cases often come down to whether an act of surveillance violates someone's "reasonable expectation of privacy." A picture taken on a public sidewalk: fair game. A photo shot by a drone through someone's bedroom window: probably not. A satellite orbiting hundreds of miles up, capturing video of a car pulling into the driveway? Unclear.

That doesn't mean the US government is powerless. It has no jurisdiction over Chinese or Russian satellites, but it can regulate how American customers use foreign imagery. If US companies are profiting from it in a way that violates the privacy of US citizens, the government could step in.

Raymond argues that protecting ourselves will mean rethinking privacy itself. Current privacy laws, he says, focus on threats to the rights of individuals. But those protections "are anachronistic in the face of AI, geospatial technologies, and mobile technologies, which not only use group data, they run on group data as gas in the tank," Raymond says. Regulating these technologies will mean conceiving of privacy as applying not just to individuals, but to groups as well. "You can be entirely ethical about personally identifiable information and still kill people," he says.

Until we can all agree on data privacy norms, Raymond says, it will be hard to create lasting rules around satellite imagery. "We're all trying to figure this out," he says. "It's not like anything's riding on it except the future of human freedom."

Christopher Beam is a writer based in Los Angeles.

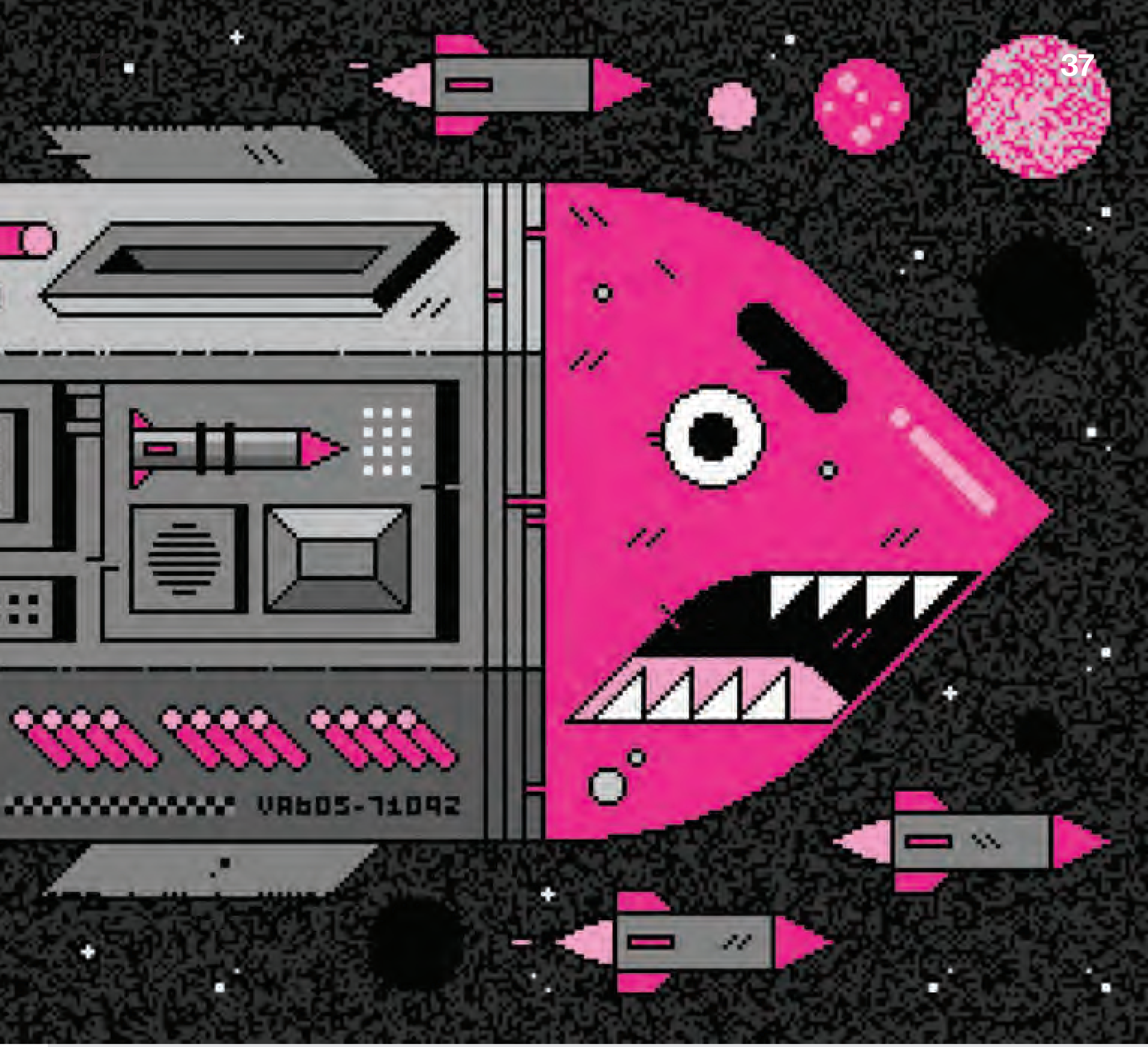


How to fight a war in space

SATELLITES ARE SO CRUCIAL THAT ATTACKING THEM COULD BE SEEN AS AN ACT OF WAR. THE BAD NEWS IS, IT MAY HAVE ALREADY HAPPENED.

Last March, India became only the fourth country in the world—after Russia, the US, and China—to successfully destroy a satellite in orbit. Mission Shakti, as it was called, was a demonstration of a direct-ascent anti-satellite weapon (ASAT)—or in plain English, a missile launched from the ground. Typically this type of ASAT has a "kill vehicle," essentially a chunk of metal with its own guidance system, mounted on top of a ballistic missile. Shortly after the missile leaves the atmosphere, the kill vehicle detaches from it and makes small course corrections as it approaches the target. No explosives are needed; at orbital speeds, kinetic energy does the damage.

The idea of shooting down satellites has been around as long as satellites have. The first (failed) ASAT test, by the US, was back in 1958, just two years after the launch of *Sputnik*. During the Cold War, the US and the Soviets both developed sophisticated anti-satellite weaponry. The US had missiles that could be launched from fighter jets (successfully tested in 1985) as well as



(and get away with it)

By Niall Firth

Illustrations by Nick Little

nuclear-tipped missiles capable of obliterating enemy satellites. China's own first successful ASAT test was in 2007.

Despite the posturing, no nation has yet destroyed another's satellite—mainly because most of the countries that can do it are also nuclear powers. But as satellites become more intertwined with every aspect of civilian life and military operations, the chances are increasing that someone, somewhere will decide that attacking a satellite is worth the risk—and just possibly trigger the world's first full-blown space war.

In at least some sense, the superpowers have been conducting space war almost since the days of *Sputnik*, using satellites to spy on enemy movements and to coordinate their own forces. During the Cold War, the US and the Soviets used space to watch for incoming nuclear attacks and to marshal nuclear weapons. It was an era when the first move in space could only be the prelude to a nuclear attack.

Today, much more civilian infrastructure relies on GPS and satellite communications, so attacks on them could lead to chaos. The military leans more heavily on satellites too: data and video feeds for armed UAVs, such as the Reaper drones that the US military has flying over Afghanistan and Iraq, are sent via satellite to their human operators. Intelligence and images are also collected by satellites and beamed to operations centers around the world. In the assessment of Chinese analysts, space is used for up to 90% of the US military's intelligence. "When people look at war in space, they think about it happening in the future and [think] it will be cataclysmic. But it's happening now," says Victoria Samson, Washington office director at the Secure World Foundation.

Space is so intrinsic to how advanced militaries fight on the ground that an attack on a satellite need no longer signal the opening shot in a nuclear apocalypse. As a result, "deterrence in space is less certain than it was during the Cold War," says Todd Harrison, who heads the Aerospace Security Project at CSIS, a think tank in Washington, DC. Non-state actors, as well as more minor powers like North Korea and Iran, are also gaining access to weapons that can bloody the noses of much larger nations in space.

That doesn't necessarily mean blowing up satellites. Less aggressive methods typically involve cyberattacks to interfere with the data flows between satellites and the ground stations. Some hackers are thought to have done this already.

For example, in 2008, a cyberattack on a ground station in Norway let someone cause 12 minutes of interference with NASA's Landsat satellites. Later that year, hackers gained access to NASA's Terra Earth observation satellite and did everything but issue commands. It's not clear if they could have done so but chose not to. Nor is it clear who was behind the attack, although some commentators at the time pointed the finger at China. Experts warn that hackers could shut off a satellite's communications, rendering it useless. Or they could permanently damage it by burning off all its propellant or pointing its imaging sensor at the sun to burn it out.

Another common mode of attack is to jam or spoof satellite signals. There is nothing fancy about this: it's easier than hacking, and all the gear required is commercially available.

Jammers, often mounted on the back of trucks, operate at the same frequency as GPS or other satellite communication systems to block their signals. "They basically throw a bubble around the jammer where the satellite signals don't work," says Brian Weeden, a space policy expert also at the Secure World Foundation. Jamming can interfere with the command signal going from the base station to the satellite, or it can mess with the signal before it reaches the end users.

There are strong suspicions that Russia has been jamming GPS signals during NATO exercises in Norway and Finland, and using similar tactics in other conflicts. "Russia is absolutely attacking space systems using jammers throughout the Ukraine," says Weeden. Jamming is hard to distinguish from unintentional interference, making attribution difficult (the US military regularly jams its own communications satellites by accident). A recent report from the US Defense Intelligence Agency (DIA) claims that China is now developing jammers that can target a wide range of frequencies, including military communication bands. North Korea is believed to have bought jammers from Russia, and insurgent groups in Iraq and Afghanistan have been known to use them too.

Spoofing, meanwhile, puts out a fake signal that tricks GPS or other satellite receivers on the ground. Again, it's surprisingly easy. In the summer of 2013, some students at the University of Texas used a briefcase-sized device to spoof a GPS signal and cause an $80 million private yacht to veer hundreds of meters off course in the Mediterranean. Their exploit wasn't detected (they later announced it themselves). Russia also seems to use spoofing as a way of protecting critical infrastructure—or maybe even President Vladimir Putin himself as he moves around, keeping him safe from potential drone assassinations by hiding his location.

As well as being hard to pin on anyone, jamming and spoofing can sow doubt in an enemy's mind about whether they can trust their own equipment when needed. The processes can also be switched off at any time, which makes attribution even harder.

But sometimes, someone might want to cripple a satellite. That's where lasers come in.

No nation can yet put lasers in space that literally shoot down satellites. Generating enough power for such lasers is hard, whether one uses electricity or chemicals.

However, high-powered lasers could in theory be fired from ground stations or mounted on aircraft. All the major space powers have put research funding into such weapons. There's no evidence that anyone has yet used lasers to destroy targets in space, though aircraft-borne lasers have been tested against missiles within the atmosphere. The DIA report suggests that China will have a ground-based laser that can destroy a satellite's optical sensors in low Earth orbit as early as next year (and that will, by the mid-2020s, be capable of damaging the structure of the satellite). Generally, the intention with lasers is not to blast a satellite out of the sky but to overwhelm its image sensor so it can't photograph sensitive locations. The damage can be temporary, unless the laser is powerful enough to make it permanent.

Lasers need to be aimed very precisely, and to work well they require complex adaptive optics to make up for atmospheric disturbances, much as some large ground-based telescopes do. Yet there is some evidence, all unconfirmed and eminently deniable, that they are already being used. In 2006, US officials claimed that China was aiming lasers at US imaging satellites passing over Chinese territory.

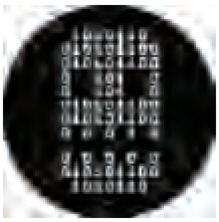
"It's happening all the time at this low level," says Harrison. "It's more gray-zone aggression. Countries are pushing the limits of accepted behavior and challenging norms. They're staying below the threshold of conflict."

In November 2016, the Commercial Spaceflight Center at AGI, an aerospace firm, noticed something strange. Shortly after it was launched, a Chinese satellite, supposedly designed to test high-performance solar cells and new propellants, began approaching a number of other Chinese communications satellites, staying in orbit near them before moving on. It got within a few miles of one—dangerously close in space terms. It paid visits to others in 2017 and 2018.

A space arsenal

Satellites are vulnerable because of both what they are and where they are. Space weapons don't have to be showy to be effective. These techniques particularly worry military planners.

Cyberattacks
Satellites are computers that happen to be in space, so they are vulnerable to attacks that disable or hijack them, just like their terrestrial peers.



Jammers
Many satellites were built without special concern for jamming, so their signals can easily be overwhelmed by malicious broadcasts.

Spoofing
Impersonating adversaries' satellites is usually trickier than jamming a signal, but easier than taking over the satellites—with similar effects.

Lasers
Blowing up a satellite with a laser is hard, but temporarily blinding its sensors is a lot easier. This may already be happening.

Co-orbital attack
Refueling and fixing satellites sound like good ideas. But if you can loiter close to a satellite, you can threaten it with a surprise attack.

Another Chinese satellite, launched last December, released a second object once it reached geostationary orbit that seemed to be under independent control.

The suspicion is that China is practicing for something known as a co-orbital attack, in which an object is sent into orbit near a target satellite, maneuvers itself into position, and then waits for an order. Such exercises could have less aggressive purposes—inspecting other satellites or repairing or disposing of them, perhaps. But co-orbiting might also be used to jam or snoop on enemy satellites' data, or even to attack them physically.

Russia, too, has been playing about in geostationary orbit. One of its satellites, Olymp-K, began moving about regularly, at one point getting in between two Intelsat commercial satellites. Another time, it got so close to a French-Italian military satellite that the French government called it an act of "espionage." The US, similarly, has tested a number of small satellites that can maneuver around in space.

As the dominant player in space for decades, the US now has the most to lose. The DIA report points out that both China and Russia reorganized their militaries to give space warfare a far more central role. (President Donald Trump's revival of the idea of a Space Force, while much ridiculed, may boost its importance in military thinking.) And there are fears among the US military that the US has lost its edge. "Russia and China are making advances in developing counterspace systems faster than we are protecting our satellites, which makes us increasingly vulnerable to attacks in space," Harrison says.

In response, the US military is starting to make satellites tougher to find and attack. For instance, the NTS-3, a new experimental GPS satellite scheduled for launch in 2022, will have programmable, steerable antennas that can broadcast at higher power to counter jamming. It's designed to remain accurate even if it loses its connection with ground controllers, and to detect efforts to jam its signal.

Another solution is not just to make single satellites more resilient, but to use constellations in which any one satellite is not that important. That's the thinking behind Blackjack, a new DARPA program to create a cheap network of military communications satellites in low Earth orbit.

Such constellations could also be used to control nuclear weapons, said General John Hyten, the head of US Strategic Command, at the National Space Symposium in April. Instead of relying on hardened communications links, he said, nuclear command and control needs to have "a near infinite number of pathways that go through every element of space: hardened military space, commercial space, different kinds of links … so that the adversary can never figure out how the message is getting through."

The 1967 Outer Space Treaty prohibits weapons of mass destruction in space or on "celestial bodies" like the moon. It also forbids "military bases, installations and fortifications" on celestial bodies, though not in Earth orbit. The major spacefaring nations ratified the treaty long ago, but the ambitions of the treaty to codify peaceful uses of space seem increasingly distant, as hawkish rhetoric and actions grow more common.

The UN has tried for decades to get nations to agree not to "weaponize" space. Representatives from more than 25 countries met at a closed meeting in Geneva in March to discuss a new treaty. "The underlying difficulty in breaking the impasse is the continued distrust between major powers," says Hitoshi Nasu, a space lawyer based at the University of Exeter in the UK, who is working with colleagues to write a guide on how international law applies to space.

But much as in the days of the Cold War, the only way to stop a conflict in space is to signal strongly that you are willing and able to carry one out, says Harrison: "Today, we are not adequately prepared for such a conflict, and our lack of preparation undermines deterrence and makes conflict in space more likely."

Niall Firth is MIT Technology Review's news editor.


PLEASE
Take A
Number

FULL SPECTRUM DOMINANCE

By MARK HARRIS
Illustrations by NICOLÁS ORTEGA

Squabbles in orbit as rival constellations fight over frequencies.

It's getting crowded up there. Flocks of cubesats, fleets of orbiting cameras, and the first broadband internet mega-constellations from the likes of SpaceX, Amazon, and OneWeb are quickly filling low Earth orbit. If all the services launch as planned, there could soon be 10 times as many satellites operating in orbit as there are today.

The rise in dangerous space junk is a concern. But there's a more immediate headache for satellite operators: a tightening squeeze on the radio frequency spectrum required to operate from orbit. Could space startups squabbling over getting their fair share actually hold back this nascent industry?

Electromagnetic radiation spans a wide range of frequencies and energies, but only specific bands are useful for communication to and from space. High-frequency x-rays would be dangerous; microwave signals are absorbed by the atmosphere; low-frequency radio waves are less effective at transmitting information and require large, ungainly antennas.

Like people shouting at a party, competing signals at the same radio frequency can interfere and make communication difficult, so the spectrum needs to be parceled out in bite-size chunks for different uses. Multiplexing systems allow operators to share spectrum by finely slicing time slots and frequency channels as well as by encoding signals so that many different messages can be transmitted simultaneously. But bands of frequency still need to be assigned to particular users, to avoid interference that would make radio spectrum unusable. Many of the most desirable frequencies for orbital links were allocated to traditional radio and

TV broadcasts long before the first satellites were launched. Now, as the heavens fill with more satellites, the scramble for radio frequency slots is growing ever more fractious. Regulators are being asked to deal with more companies, more spacecraft, and more disputes than ever before. Paperwork can stretch out for years, even as enthusiastic startups attempt to disrupt a conservative industry.

Swarm Technologies is no stranger to regulatory tussles. When this small Silicon Valley startup launched four tiny experimental satellites in 2018, it neglected to obtain the necessary authorization from the US Federal Communications Commission, one of the agencies whose approval needs to be granted before launch can take place. The FCC found out and slapped the company with a $900,000 penalty.

The company now wants to launch a 150-strong constellation to communicate with the growing number of internet-connected devices on Earth. Because its satellites are so small, and thus cheap to launch, Swarm reckons its messaging services will cost an order of magnitude less than existing satellite systems. All it needs is a few slivers of VHF radio spectrum.

However, longtime satellite operator Orbcomm has laid claim to those frequencies for decades, and it operates one of the very messaging systems that Swarm aims to disrupt. In a petition to the FCC to dismiss Swarm's constellation application, Orbcomm wrote that the startup "attempts to simply ignore Orbcomm's clearly vested … spectrum rights."

"There really are scarcity concerns in orbit," says Thomas Hazlett, an economics professor at Clemson University and author of *The Political Spectrum*. "If you want to put up a satellite for communications, you may have potential conflicts with other users. There is a real need for rules to help coordinate this use."

The International Telecommunications Union (ITU) is the body tasked with unpicking these competing claims. Formed in the mid-19th century to standardize telegraph technologies, it has helped regulate who gets to place satellites in orbit since the dawn of the space age. The agency, which also makes it possible to make telephone calls from one country to another, among myriad other regulatory responsibilities, is now part of the United Nations. But individual countries also want some say about spacecraft flying overhead. That means operators like Swarm also have to work with national agencies in the countries in which they intend to operate (in particular, the FCC controls access to the all-important American market).

Unsurprisingly, newcomers see these regulations as barriers intended to keep them on the ground. In a lengthy response to the FCC, Swarm claimed that Orbcomm has no rights to the spectrum it wants to use and that the company's "frivolous" petition "represents nothing more than the attempt of a longtime monopolist to use the licensing process to maintain its privileges."

Stable circular orbits around Earth are associated with particular velocities, which vary with altitude. (Satellites in elliptical orbits speed up when closer to Earth and slow down as they reach the farthest point in their orbit.) At 35,786 kilometers (22,236 miles), the orbital speed matches Earth's rotation. Spacecraft flying directly above the equator at that altitude will appear frozen in the sky to an observer on the surface. Such geostationary slots enable a single large satellite to serve a wide geographic area, whether in relaying communications or, say, monitoring the weather.

Allowing for some elbow room between neighboring satellites, there are perhaps 1,800 useful geostationary spots on this great circle, around 400 of which have become occupied over the years. As might be expected, there is more interest in spots above rich regions like North America and Europe than above sparsely populated Pacific islands. Countries were allocated slots above their longitude, and then individual satellites were allowed to take up residence on a first-come, first-served basis.

At first, spectrum seemed to be a solvable problem. Not only did frequencies have to be sliced up between just a small number of operators in one area, but the same frequencies could be reused over and over again around the globe. Everyone understood the rules, says Tim Farrar of satellite consulting firm TMF Associates.

The rules of the game are changing, however. Operators want to pack small, cheap satellites onto ride-sharing rockets and send them into low Earth orbit, or LEO. From just a few hundred or thousand kilometers up, satellites with cameras have a much better view of the planet; for communications systems, the shorter distance to the surface can save power and reduce latency. With a multitude of altitudes and orbits to choose from, there should be room for all.

Spectrum is now becoming the limiting factor in who gets to deploy new communications constellations. Satellites in LEO whiz around the planet in a matter of hours, potentially causing interference not only to one another but to every geostationary satellite they pass beneath. At first, the ITU's solution was to do the same thing it had done for geostationary orbit: the first operator to apply to use a slice of spectrum was given priority. Everyone following would have to agree not to interfere.

Spectrum is now becoming the limiting factor in who gets to deploy new communications constellations.

But interference is a slippery concept. "Geostationary coordination is relatively straightforward," says Diederik Kelder, chief strategy officer at LeoSat, which is planning a constellation of at least 84 internet satellites in LEO. "Whereas in [LEO] it's a very complex thing. You need very sophisticated modeling tools to grasp the impact."

Foreseeing a coming spectrum crunch, the FCC decided to push forward with spectrum-sharing policies where everyone planning to use similar frequencies would be considered at the same time—so-called "processing rounds" that would theoretically create a fairer playing field.

But there have been unintended consequences. More disputes have erupted as new entrants try to find regulatory loopholes or technical fixes while established operators attempt to protect their frequencies from interference, whether real or imagined. The incentive for companies to apply for frequencies as soon as possible also means that they have to file requests at the ITU and FCC long before their satellites have been built or, sometimes, even fully designed.

SpaceX is the most ambitious of the new LEO generation. In 2015, Elon Musk unveiled a plan to use a mega-constellation of satellites called Starlink to deliver global broadband internet that would reach many developing and underserved regions. SpaceX originally asked permission to launch 4,425 satellites, but it upped that to nearly 12,000 in 2017—a constellation that the FCC finally licensed in late 2018.

In the run-up to the launch of its first commercial satellites, SpaceX tinkered with its plan yet again, asking to move some of its satellites closer to Earth and change the frequencies they would use. Its own analyses supposedly showed no new interference, but other satellite companies were not happy. Kepler, another satellite communications startup, called its claims "fundamentally misleading." OneWeb, which plans its own mega-constellation of more than 2,500 internet satellites, similarly said SpaceX's interference calculations "[included] misleading operational assumptions, an incomplete analysis parameter set, and highly misleading conclusions."

The FCC approved SpaceX's plan, and the company launched its first 60 Starlink satellites in May. Its rivals will now have to launch their satellites hoping that their interference concerns were unfounded.

At least this spat was quickly settled. The nightmare for newcomers is that disputes can lead to interminable regulatory delays.

In 2001, for example, a company called Mobile Satellite Ventures applied to the FCC to repurpose some of its satellite frequencies for a hybrid satellite/terrestrial communications service. Ten years later the company, now called LightSquared, received a conditional waiver to proceed that was swiftly suspended over concerns that it might interfere with GPS navigation signals. LightSquared almost immediately filed for bankruptcy, but with the passing of nearly another decade, and yet another name change, Ligado Networks continues LightSquared's fight. It has promised to reduce the power of its transmissions by over 99% yet still faces sustained pushback from nervous, and possibly jealous, aerospace competitors.

"Ligado's decision to waste 40 MHz of satellite spectrum should not be rewarded with a windfall," rival satellite operator Iridium wrote to the FCC in July 2018. In April, Ligado noted in a meeting with the FCC that the agency had been considering its latest application for over 1,000 days. As this issue went to press, the FCC had yet to rule on it.

Nevertheless, Ligado's approach shows how technology could help quell squabbles. The firm was able to dramatically reduce its power requirements thanks to increasingly sensitive receivers. Multiplexing systems also continue to improve, because of both improved computing power and increasingly intricate, clever techniques for encoding and decoding signals.

High-gain antennas allow satellites to create focused spot beams targeting specific areas below them. The tighter that focus, the more often those frequencies can be reused. Other new systems plan to use even more tightly focused lasers for one satellite to communicate with another, reducing the demand for radio frequencies. New phased array technologies mean satellite signals can now be received by small and cheap electronically steered flat-panel antennas rather than the unwieldy parabolic dishes of old. GPS-equipped satellites and user terminals alike can be programmed to avoid transmitting toward rival LEO or geostationary satellites.

Some experts believe that the best way to unleash technological innovation is for regulation to take a back seat to market-based solutions, like the existing auctions for terrestrial wireless spectrum. But there is no clear mechanism for such a global spectrum auction.

In any case, though converting free allocations of satellite frequencies into tradeable rights might offer incentives for cooperation over obstruction, it would be a fraught process at a global scale. The orbital economy is already dominated by a handful of the world's most powerful nations. Giving preferential access to those companies with the deepest pockets seems likely to perpetuate historical inequities, and to exclude developing countries with the most to gain from reaching the next technological frontier.

Not everyone sees the need for a revolution in orbit. Farrar believes that satellites and ground stations will be regularly forced to pause operation until the risk of interference subsides, thus dramatically reducing their capacity and threatening already shaky business plans. "It would be a disaster from an economic point of view if everyone gets to operate," he says. "But it's inconceivable that [all these companies] will do what they've announced they plan to do."

In which case a tortuous bureaucracy that defers, delays, and disrupts business plans might be just what space needs.

Mark Harris is a writer in Seattle and a frequent contributor.


3

ESCAPE

HOW FAR WILL WE GO?

Mars invasion 2020

By
Tate Ryan-Mosley

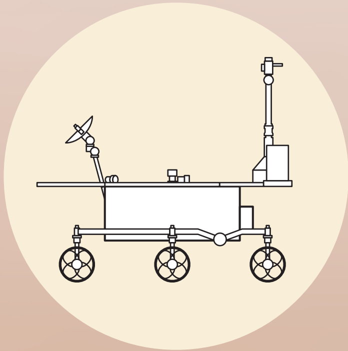
Illustrations by
John MacNeill

Every two years or so, Earth and Mars snuggle close in their orbits. As they near one another, a prime window opens for launching missions to our rusty neighbor, and the next opportunity is near at hand. In the summer of 2020, four space agencies around the world plan to launch pioneering missions. NASA's Mars 2020 aims to land a rover that will release a small autonomous helicopter. The EU and Russia are sending a joint mission—complete with tiny ovens that will bake small batches of soil in search of signs of life. China and the UAE, meanwhile, are busy preparing what would be their first trips.

If successful, the newcomers will add to the ranks of explorers and scientists chipping away at the planet's mysteries.

Among those mysteries are the questions on everyone's mind when they think of the Red Planet. Is there life there? Was there ever? And perhaps most alluring: Could we one day live there?

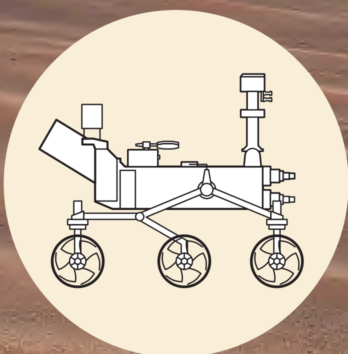
China Mars Probe



China has a lot on the docket for what it hopes will be its first successful mission to Mars. It's attempting to orbit the planet, complete a landing, and deploy a rover on the surface. The mission is an escalation of China's space ambitions after the country landed on the dark side of the moon in early 2019 and invested in a "Mars simulation" camp on the country's remote Qinghai-Tibet plateau. If the mission is a success, the orbiter will study the Martian atmosphere and take magnetic field readings, while the HX-1 rover will explore the Martian surface for 90 days. So yeah—a huge chunk of everything NASA has done in nearly five decades of visiting the planet, all rolled into one mission.

Owner:	China National Space Administration
Cost:	Unknown
Type:	Orbiter and rover
The first:	Chinese mission to Mars

Mars 2020

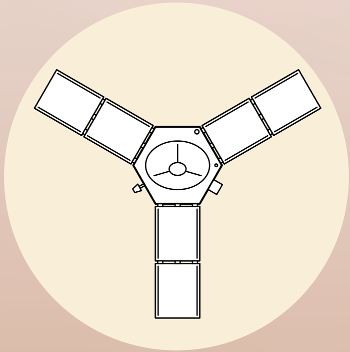


NASA's shiny new rover is going to be the Martian equivalent of a billionaire's yacht—complete with a private chopper. Building on the missions that gave us the Spirit, Opportunity, and Curiosity rovers, Mars 2020 will feature better autonomous navigation capacity and will come loaded with instruments. That includes imaging tools, atmospheric sensors, experimental oxygen-producing engines, and a drill that can bore a few inches into interesting rocks or soil (some of the samples it digs up may one day be returned to Earth). And the four-pound helicopter? If it lifts off as planned, it will be the first heavier-than-air object to fly on another planet.

Owner:	NASA
Cost:	$2.46 billion
Type:	Rover and helicopter
The first:	Heavier-than-air flight on another planet

NASA/JPL-CALTECH/MSSS

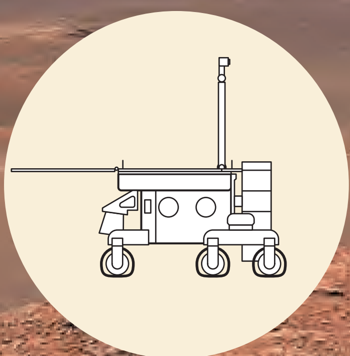
Hope Mars Mission



In its first mission beyond Earth orbit, the United Arab Emirates is going big and going to Mars. The aim of the Hope probe is to produce the first “truly global picture of the Martian atmosphere.” The planet’s ancient climate probably could have sustained liquid water on the surface, but its atmosphere was decimated long ago and most, if not all, remaining water is either vapor or locked up as ice underground. An ultraviolet spectrometer aboard Hope will track traces of oxygen, hydrogen, and other gases as they escape into outer space. What it finds would tell us a lot about why Mars’s atmosphere has dwindled—and whether or not it could one day be replenished.

Owner:	UAE Space Agency
Cost:	Not released, but the UAE has spent $5.4 billion so far on its space program.
Type:	Orbiter
The first:	Space exploration mission by the UAE

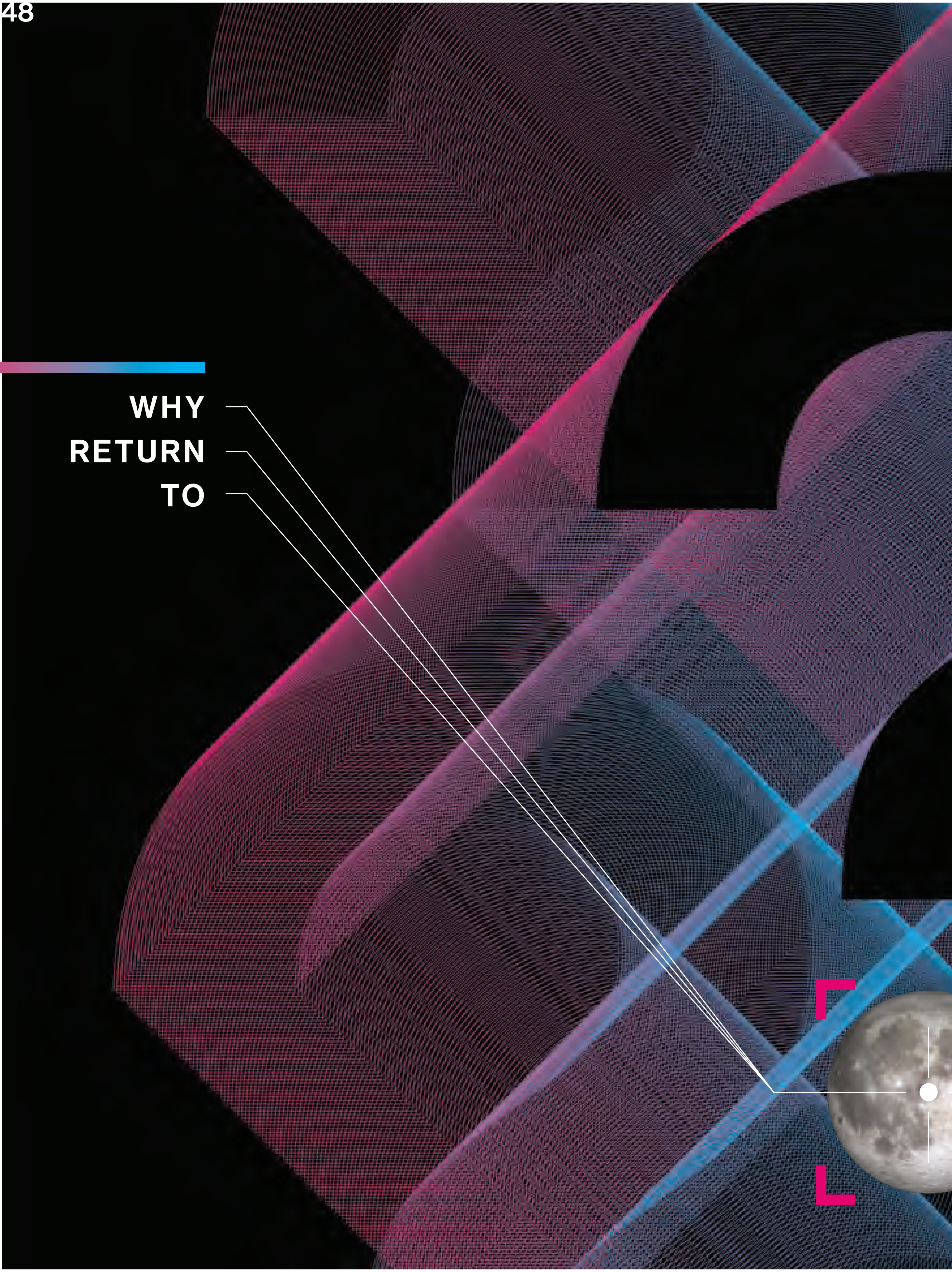
ExoMars



This mission is part of a program that started with a 2016 launch of an orbiter and a prototype lander (which sadly crashed). The 2020 version will send a Russian lander and a European rover to one of two Martian locations rich in ancient organic material (either Mawrth Vallis or Oxia Planum, near the equator). There it will drill into the planet’s surface, analyzing the local chemistry in search of signs of life. And by “analyzing,” we mean baking samples at up to 900 ˚C in 30 single-use ovens and then running the resultant vapors through a gas chromatograph. If any tiny critters get cooked in the process, the aroma they give off will get a lot of attention.

Owner:	ESA and Roscosmos
Cost:	$1.45 billion
Type:	Rover
The first:	Two-meter drill into the surface

WHY RETURN TO



A return to the moon is hard to justify in practical terms, but it nonetheless seems almost inevitable—and that may be purpose enough.

THE MOON?

By_**OLIVER MORTON**

JEFF BEZOS, who created a company that has delivered more purchases than any other in the history of the world, stands in front of a craft designed to deliver things beyond it. It is called Blue Moon, and its blocky form, dominated by a spherical hydrogen tank, sits under stage lighting of an appropriately muted but still ethereal hue.

With a payload capacity of 4,500 kilograms (9,900 pounds), Blue Moon is the biggest lunar lander designed since Grumman built the Apollo lunar module in the 1960s. It could fly—if that is the word for something so wingless—in the next few years, Bezos tells his audience in Washington, DC. Odds are it will take a bit longer. But there's a fair chance that Blue Moon will, in some form or other, reach the moon, and that one of its extended forms will carry a human crew.

NASA will need considerable assistance from private aerospace companies like Bezos's Blue Origin to meet Vice President Mike Pence's goal, announced a few weeks before Blue Moon's unveiling on May 9, of putting an American back on the moon by 2024. On May 16, NASA announced contracts for studies and prototypes with 11 companies interested in providing it with lunar landers and other spacecraft; Blue Moon got funding, as did an unnamed, even larger moon lander from Elon Musk's SpaceX. (Another of the 11 companies is the much smaller and scrappier Masten Space Systems, profiled on page 52.)

The Pence acceleration had no compelling rationale beyond an unwillingness to let China seize the "strategic lunar high ground." It is true that once China builds the very large new rocket its engineers are now planning, the Long March 9, and gains experience with space operations using its proposed space station, a moon mission seems the logical next move. But given that the Chinese space program is characterized by slow, measured steps, that seems a much more likely proposition for the 2030s than the 2020s. Pence's urgency might simply have more to do with the fact that, were Donald Trump to win a second presidential term, a 2024 moon landing could take place during Pence's own campaign to become president.

The uncomfortable truth about any trip to the moon is that it is not really about the moon, and never has been. For Pence it is about some mixture of politics and China; for China it is about China, too. For Musk it's a distraction on the way to Mars, but one he will tolerate if others pay or the publicity is good. For Bezos, it's a stepping-stone to a greater vision of space and human destiny. He subscribes to the dreams of Gerard K. O'Neill, a Princeton professor who in the 1970s proposed building vast industrial concerns in orbit, their workers and managers housed in spinning, city-size habitats. The moon, in this vision, is at best a handy source of raw materials until the asteroid-mining boom kicks in (which, as explained on page 62, will take a while if it happens at all).

Apollo was not really about the moon either. It was driven by a desire to show the world, and America's own citizens, that the United States' capitalist system could achieve greater things than the Soviet Union's socialist one. The fact that going to the moon would be very difficult and supremely costly—"We choose to go to the moon in this decade, and do the other things, not because they are easy, but because they are hard," as President Kennedy said in 1961—was of the essence. Doing something cheap or easy could not, by definition, show the effort America was willing to put into a remarkable project. The moon itself was not of the essence: Kennedy initially resisted the idea, suggesting that desalination plants providing limitless fresh water for all might be a better show of America's technological supremacy.

But the world was entranced by space, all the more so after Yuri Gagarin's flight in April 1961. And America clearly lagged the Soviet Union. In 1957 it had been surprised by *Sputnik*; at the time of Kennedy's famous speech it had yet to launch an astronaut into orbit. Part of the moon program's appeal was that it leapfrogged over that shortcoming. Though the Soviet Union had better rockets—basically, big ICBMs—for putting people into orbit, it was no closer to the considerably larger rockets needed for moon missions than the US was. By deploying $120 billion (in today's dollars), the US beat its rivals to the goal. A supreme symbol of national achievement was created, and that was enough; the moon could go on its way without further interference from the neighbors.

As an honest contemporary Kennedy might put it:

I guess it might even be

Jeff Bezos unveils the module he'd use to bring humans back to the moon.

The current geopolitical rivalry with China that Pence pointed to is not like that of the Cold War. China may think putting people on the moon would be a nice symbol, pleasing at home and impressive abroad. But it would not make the world look on in wonder in the way Apollo did, and Chinese footprints there would not cement a Chinese reputation for technological primacy. That is the job of the industrial policy until recently known as

MARK WILSON/GETTY IMAGES; PREVIOUS SPREAD: NASA GODDARD (MOON)

"Made in China 2025," which seeks to have Chinese companies lead the world in 10 technology areas that are all firmly terrestrial and profit driven. It is true that "aerospace equipment" is one of those areas—but it is only one, and "Made in China" is mostly about what Chinese consumers can use in their millions and Chinese companies can export. Moon rockets are doubly disqualified.

For all this, symbolism still matters. If China got serious about going to the moon, an America with no such plans would have but two options. It could either pooh-pooh the whole venture—darling, the moon's *so* last century—or it could make plans of its own. The first option might sound unconvincing, and the second would look like playing catch-up. Getting out in front, as Pence is doing, is thus a plausible strategy. Look at it as a maintenance payment on the great symbol of Apollo. If China gets to the moon and America is not there, then Apollo, which signified America's greatness in 1969, will come to signify lost greatness instead.

And the moon makes sense in other ways. America has a human spaceflight program and no appetite to scrap it; the International Space Station is a finished project; and going to Mars is a much harder undertaking. If you really want to do something with people in space (a condition not all US administrations meet), the moon is the obvious next objective. And today's technologies should make it much less of an effort than it was in the 1960s. So why dilly-dally and let some later administration take the credit? As an honest contemporary Kennedy might put it: "We don't really choose to go to the moon, but we sort of feel we have to, and though it may not be exactly easy, it doesn't look all that hard. I guess it might even be kind of cool."

"We don't really choose to go to the moon, but we sort of feel we have to, and though it may not be exactly easy, it doesn't look all that hard. kind of cool."

But two things make the possibly imminent return interesting beyond sublime technological oomph, geopolitical signaling, and nifty science. One lies in the fact that, indeed, it doesn't look all that hard; the other in the new quasi-practical allure that the moon has taken on over its fallow decades.

Ever since the Apollo program was canceled, people keen to return to the moon have talked, often somewhat fantastically, about the resources it might offer. In the past couple of decades, this speculation has focused on the moon's poles. Because the moon sits up very straight in its orbit, there are craters at its poles into which the sun never shines. Some astronomers have long suspected that, over the billennia, comet impacts have left tenuous and transitory atmospheres frozen into these cold traps. An increasing body of evidence strongly suggests that they have.

Those cometary residues are probably composed of some mix of water, ammonia, carbon monoxide, and more besides. If so, they could be a source of light elements—hydrogen, carbon, nitrogen—in which the moon is sorely lacking. If food can be fabricated from these instead of shipping it from Earth, a moon base becomes more plausible. What is more, light molecules such as hydrogen and methane make good rocket fuels. Being able to refine fuel from lunar ice would make both getting from point to point on the lunar surface and getting back to Earth easier and cheaper.

Even better, some entrepreneurs believe that because of the moon's weak gravity, it could be cheaper to fly rocket fuel from there than from the Earth's surface to spacecraft in Earth orbit. They thus imagine the moon becoming both a source of wealth and a vital component of the space-based industrialization favored by Bezos and his ilk.

But this leads us to the lunar-resource paradox: a market for orbital fuels big enough for a moon base to earn its keep providing them suggests a large orbital economy. A large orbital economy suggests that the cost of launching things to space from Earth has become a great deal cheaper. But if launching from Earth is a great deal cheaper, why pay the high capital costs of setting up a moon-based supply? There will only be enough orbital demand for light elements to justify the expense of a moon base if the cost of launching from Earth to orbit is so low as to undercut the market for such lunar supplies.

Skepticism about this particular proposal might yet be proved wrong, however. Economic history often works out strangely, producing niches almost no one foresaw. More broadly, the fact that people want to go to the moon for possibly dubious reasons is a by-product of the more cheerful fact that they may soon be able to go to the moon for many reasons, because going to the moon will not be so hard. Yusaku Maezawa, a wealthy Japanese fashion entrepreneur, has signed a contract for a trip around the moon—not to its surface—with SpaceX simply because he wants to go, and to take a team of artists along with him to see what they make of it.

The one thing the moon has been proved to offer beyond prestige and science is perspective. For more people to see the harsh glories of the moon, both for themselves and as a context for the beautiful blue-green world fixed above them in the sky, and for those people to be a more diverse sample of humankind than the stalwart white, male American astronauts of Apollo, might come close to justifying a return in and of itself. Since the logic of space programs needing something to do makes that return highly likely, it will be a welcome dividend. It may, in the future, come to be seen as having been the main point.

Oliver Morton's latest book is The Moon: A History for the Future. He is on staff at the Economist.

By **HALEY COHEN GILLILAND** Photographs by **SPENCER LOWELL**

The
big
stuff

Can a tiny startup lead America back to the moon — this time to stay?

Dave Masten stared at his computer monitor over a jumble of screwdrivers, tea packets, and dog-eared physics textbooks that cluttered his desk. “Anybody want to watch this?” he called out to no reply. It was about noon on Thursday, April 11. He scanned his office, a scrubby quadruple-wide trailer at the Mojave Air and Space Port in Southern California’s high desert, but found he was alone.

That isn’t uncommon. The entire team at Masten Space Systems, the rocket company that Masten founded in 2004, numbers 15 people. The seven based in Mojave—mostly young men who wear T-shirts emblazoned with sayings like “I need my space”—spend some time at their desks, working through equations or crafting proposals for clients like NASA. But they are more often found in the converted military garage across the dusty parking lot, tinkering with rocketry.

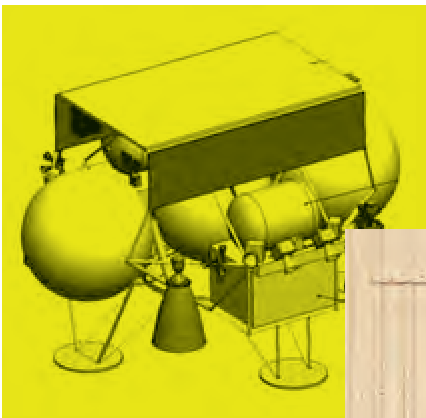
Masten turned back to his monitor, which was showing the live-stream broadcast of Beresheet, a lunar lander developed by SpaceIL, a privately funded Israeli nonprofit. Beresheet had been launched by a SpaceX Falcon 9 rocket a few months earlier, and had spent the previous week orbiting the moon in preparation for its landing attempt. If it touched down without issue, it would become the first private vehicle ever to land on the moon.

As Beresheet descended, Masten strained to make out the chatter in the background of the SpaceIL broadcast. A few minutes before the targeted landing time, he heard someone say the team had lost contact with the inertial measurement unit, which measures the spacecraft’s acceleration and rotation.

“Shit,” he thought. “They lost the mission.”

Masten’s interest in Beresheet’s flight was personal. His firm is hard at work on its own moon lander.

That lander, the XL-1, is just under three and a half meters (11.5 feet) long and just over three meters wide. With technical input (though not funding) from NASA through its Lunar Catalyst program, the Masten team designed the lander to carry a 100-kilogram (220-pound) scientific payload to the moon’s surface and survive there for 12 days. Three spherical propellant tanks balanced on spindly legs huddle beneath a rectangular solar panel, giving the probe the appearance of a giant ant carrying a matchbox on its back. The tanks hold a proprietary combination of nontoxic liquids that spontaneously ignite when combined, powering four main engines and 16 maneuvering thrusters, all of which hang off the contraption’s sides. The whole thing weighs 675 kg (1,488 lb) without fuel, and 2,675 kg, as much as a Toyota Tacoma pickup, when “wet.” It is simple and cheap, and was promising enough for NASA to select Masten in late 2018 as one of nine companies to take part in the Commercial Lunar Payload Services program (CLPS, pronounced “clips”).



Getting to space has always been expensive; getting to the moon, even more so. Astrobotic, one of the CLPS participants, quotes a price of $1.2 million per kilogram to reach the lunar surface. (Other companies generally refrain from putting a number on it.) As NASA sets out to return humans to the moon by 2024—a surprise deadline recently imposed by the Trump administration—CLPS is an attempt to figure out if private companies can get there quickly and on the cheap. NASA will pay for cargo to be delivered to the moon, but not to design or build the spacecraft that get it there. The aspiration is for CLPS to function like a lunar delivery service.

Masten is the smallest of the nine CLPS companies. Lockheed Martin, with 100,000 employees and a market value of $96 billion, is the biggest. NASA’s latest budget

Masten's Xodiac rocket (previous spread).

Masten's design for its XL-1 lunar lander (above) and the entrance to its aviary (right), where its rockets are stored.

Dave Masten (above right), founder and CTO of Masten Space Systems.

allocates $80 million per year to CLPS, and if the program goes well, this could increase to a total of $2.6 billion over the next decade. Being part of CLPS gives companies the right to compete for contracts through a series of "task orders"—if they aren't chosen, they aren't paid. If they are, they get a fixed fee and have to figure out how to use it to get to the moon.

On May 31, the first task order (totaling over $250 million) was awarded to three firms: Orbit Beyond, which will launch in September 2020, and Astrobotic and Intuitive Machines, which plan July 2021 launches. Steven Clarke, NASA's deputy associate administrator for exploration, says subsequent task orders will create a "good cadence of missions"—initially about two a year, increasing to three or four missions per year by around 2023. None of the CLPS entrants are building a new launch vehicle; they will buy rides to orbit from commercial providers. For instance, Orbit Beyond and Intuitive Machines plan to ride to Earth orbit on a SpaceX Falcon 9.

NASA has not landed a vehicle—let alone a person—on the moon since 1972. Going back just for bragging rights no longer makes much sense. Dave Murrow, a senior manager working on CLPS at Lockheed Martin, says, "Flags and footprints were great in the 1960s—it was very important for us as a nation at that point. But now we need something sustainable."

It is unclear if there will ever be enough demand for lunar travel to support a healthy industry (see "Why return to the moon?" page 48). The answer will hinge partly on what the landers find on the moon. Marshall Smith, director of human lunar exploration programs at NASA headquarters, believes there is an abundance of water at the moon's south pole that could be converted to rocket fuel and drinking water for astronauts.

Dean Eppler, a NASA veteran (and economic geologist) who is now chief lunar scientist at the Aerospace Corporation, is less certain. Lunar orbiters, he said at a recent forum his firm organized in Colorado Springs, have gathered about as much information as they can. To figure out if mining the moon for water is viable, "we really have to get down on the ground," he said. "That's what the CLPS program is going to be important for. And thank God it's here, because it would be a hard road without it."

Ever since the end of the Apollo program, NASA has struggled to reinvent itself as an efficient enterprise. The "Faster, Better, Cheaper" initiative of Daniel Goldin, who ran the agency from 1992

The Masten offices, in a quadruple-wide trailer an hour and a half from LA.

to 2001, is now widely derided; critics accused it of contributing to two failed Mars missions and the 2003 disintegration of the space shuttle *Columbia*, in which seven astronauts died. "We as an industry got to a spot where, wow, those failures were really painful. We're not going to do that again," Murrow says.

Eager to stretch money further without repeating the same mistakes, NASA increasingly relies on private partnerships. Beginning in 2006, it used a concept similar to CLPS to bid on cargo shipments to the International Space Station, recalls Lori Garver, a former deputy administrator of NASA.

The program spurred SpaceX to create the Falcon 9 launch vehicle, which cost about $390 million to develop. NASA estimates that had it developed the vehicle, the cost would have ballooned to between $1.7 billion and $4 billion. But outsourcing is no guarantee of success: a more recent effort to use commercial providers to send human crews into Earth orbit is meeting with the same sorts of delays that NASA's own programs confront. And Garver questions if the lunar market is big enough to be viable.

CLPS takes a particularly streamlined approach. The CLPS request for proposals was about a dozen pages, compared with the hundreds of documents with endless compliance requirements that normally accompany NASA collaborations. The contracting structure is designed to make protest lawsuits difficult—a wonky but important detail if NASA is to move quickly, since procedural hang-ups are a frequent source of delays. And NASA appears to have gone out of its way to give smaller firms a chance. Though not as small as Masten, the three firms chosen for the first task order are all modest by the standards of aerospace. Apart from Lockheed Martin, only one of the other participants is a large aerospace firm: Draper, a nonprofit corporation that was founded in 1932 as part of MIT.

Chris Culbert, the chief technologist at NASA's Johnson Space Center (JSC), who manages CLPS, told the Aerospace Corporation forum, "This might be the best chance in many of our careers to actually tell NASA how to do things differently." Trent Martin of Intuitive Machines, who previously spent a decade each at Lockheed Martin and NASA, is even more effusive: "I've been around the agency a really long time, and I've never seen anything like it." If CLPS works as designed, even bigger firms like Lockheed and Draper must prove they can compete on cost and speed with much leaner companies.

For Lockheed, a CLPS contract would be nice. But for the smaller companies, the stakes are higher. Steve Bailey, who runs Deep Space Systems, says he's "betting the company" on CLPS. Murrow of Lockheed Martin muses, "Sustainable economic activity isn't going to happen from just one company dominating or monopolizing—it's going to happen from a diverse set of participants with different strengths and weaknesses, different risk postures, and, frankly, different probabilities of success."

For NASA, CLPS represents an ideal sort of lean agility. Officials from the administrator, Jim Bridenstine, on down have taken to saying the agency is more interested in taking swift "shots on goal" than in certain but plodding progress.

The first CLPS task order was assigned before NASA had figured out what, exactly, it wants delivered where: "Within the next couple of months we'll have sorted out which payloads will go on which landers," Culbert said when the orders were announced. His team at JSC numbers fewer than seven people—a sign, he says, of the trust NASA is putting in commercial providers.

Of the CLPS competitors, Masten Space Systems has an ethos that seems particularly well aligned with this focus on speedy experimentalism. Dave Masten thrives on rapid movement, an inclination that surfaces in his personal life—he marked his recent 50th birthday by attempting a 50-mile trail run—and his professional one. As a rocket engineer, he has long advocated for relentlessly testing and tweaking reusable machines rather than trying to nail designs on the first try. This means that even though Masten is tiny, it can lay claim to forms of experience that larger companies lack. Xombie, Masten's first operational rocket, has flown 227 times—which the firm claims is a record for any rocket-powered airframe.

For Masten, the CLPS program presents a path to a more stable future, after years of scraping by. But "not to get stinking rich, because this is aerospace, and you don't actually get rich in aerospace," Dave Masten says. Masten chose to be chief technology officer of the firm that bears his name so that he can spend more time building rockets, and less worrying about money. Sean Mahoney, a jovial 45-year-old with a rugby player's build who serves as Masten's CEO, has a habit of leading new hires to the Roton ATV, a failed rocket displayed in the center of the Mojave spaceport, and telling them: "We're not guaranteed success. We're not trying to minimize risk or downside. We're working for some big stuff."

As a child growing up outside Cleveland in the 1970s, Dave Masten so loved rockets that his normally education-focused parents let him miss school to watch NASA launches on television.

Eager to experiment with his own designs, Masten would decamp to an open field next to the local elementary school with his younger brother to fly Estes model rockets they assembled from cardboard tubes and balsa wood fins. Inspired by his father, a software engineer who had a penchant for radio-controlled airplanes, Masten wondered: if he fastened wings to one of the rockets and outfitted it with radio control, could he land it like a shuttle?

Eventually he would return to rocketry, but Masten began his career in more earthbound fields. Though he ultimately left college a semester short of graduating, he paid for his mechanical engineering studies by welding for a General Motors supplier before briefly enlisting in the Army, where he learned to drive fuel tankers and despise large bureaucracies.

"We're not trying to minimize risk or downside. We're working for some big stuff."

After moving to Silicon Valley, Masten got involved with various tech firms, including Andiamo Systems, a network hardware company, which Cisco bought in 2002 for approximately $750 million. This didn't make him Jeff Bezos wealthy, or even Elon Musk rich. But it did give him enough money to dedicate himself to rocketry full time. Along with three others he had met at space conferences and through the Experimental Rocket Propulsion Society (ERPS), an amateur group obsessed with high-power rocketry, he founded Masten Space Systems in 2004.

From its first days in the cramped Santa Clara workshop it shared with ERPS and another company, Masten Space Systems has focused on creating reusable rockets that take off and land vertically. The partners fervently believed this approach would reduce the cost of rocket missions, making space more accessible. "We had half a million bucks," recalls Jonathan Goff, an amiable propulsion engineer who was one of Masten's cofounders. "We figured we'd build a flight demonstrator to convince people we knew what we were doing, raise the last of the money to go suborbital—that would take a year, maybe two at the most. And then we'll either have enough money to go orbital, or raise money to go orbital."

It did not work out that way. Both Masten and Goff categorize the first vehicle the company built as an abject failure. Flaws in the code meant that when the team eventually tested the craft, tethering it to a crane to keep it from crashing onto the landing pad below, it would take off and spin on the tether like a dizzy puppet.

Meanwhile, Masten and his partners soured on Santa Clara. Their workspace was cramped, and the neighbors often complained about the noise from Masten fiddling with rocket igniters in the back room. Plus, to test their rocket engines away from people, the Masten team had to drive their test trailer—a clunky steel thing they nicknamed the "hot dog stand"—two hours into the Diablo mountain range.

Encouraged by colleagues at another small rocket company, XCOR, Masten Space Systems packed up its gear and drove south. The destination was Mojave, a tiny town in Southern California's high desert, whose long coexistence with aerospace meant the residents were "more likely to cheer than call the cops" when they heard the roar of rocket boosters, Masten remembers.

By the time Masten Space Systems moved into an old Marine motor pool maintenance building at the Mojave airport (the Marine Corps had taken it over during World War II), the complex was already well known among aerospace buffs. It was in a warehouse in Mojave that Jeana Yeager, Burt Rutan, and Dick Rutan built the *Voyager*, which in 1986 became the first plane to circumnavigate the world without refueling. In 2004, the Federal Aviation Administration designated the Mojave complex a "commercial spaceport." A few days later, Burt Rutan's SpaceShipOne took off from Mojave to become the first private vehicle to enter space with people on board.

Still, Masten's early relationship with Mojave was ambivalent. He enjoyed the fact that—an hour and a half from Los Angeles, the closest large city—the sky was so inky black he could stand amidst the hangars and gaze up at the Milky Way. The small, dust-beaten town was less appealing. Just a mile or two from where billionaires like Richard Branson and Microsoft cofounder Paul Allen would land in their private jets to check on their rockets, many of Masten's neighbors suffered from startling poverty and drug addiction.

Not that he saw them much. During his first months as a Mojave resident, Masten spent more nights on a cot set up in the company's spartan office than in his nearby apartment.

He had plenty to worry about. As the team struggled to fix their unruly rocket, a team from the Discovery Channel visited Mojave to film a program on new space companies. Soon after the crew clicked on their cameras, Masten's rocket spun out of control during a tethered test flight. The team cut its engine, but by that point it was high enough that when it dropped, the force with which the rocket pulled on the tether tipped the crane forward. The foot of the rocket caught on the launch pad and the machine ripped in two. On tape. "I was pretty sure we were done," Goff recalls.

The foot of the rocket caught on the launch pad and the machine ripped in two. On tape.

By that point Goff had just $50 left to his name; Masten had not taken a salary for years. They were about to close the business and go their separate ways when they received a call from Joel Scotkin, a New York–based investor, who had sold his financial technology consulting firm to Accenture. Scotkin had always been excited by the potential for private companies to transform spaceflight; despite the challenges, he was impressed by Masten's proprietary engine designs that ran on oxygen and rubbing alcohol. In 2007 he wrote Masten Space Systems a check that, though not huge, allowed the company to push forward. "It was one of those moments where you pull the airplane up but still have grass stains on the fuselage," Goff recalls.

Things began turning around for Masten in 2009.

In the fall of that year, the company had qualified for a NASA "Centennial Challenge" that judged teams on their ability to simulate accurate moon takeoffs and landings. The first phase of the competition required landing on a well-marked, flat circle 10 meters in diameter. Masten Space Systems entered its Xombie rocket, which won $150,000 for second place behind Armadillo Aerospace, a small Texas rocket startup.

The second part of the challenge a few weeks later carried a million-dollar prize and involved landing on a rocky, cratered surface meant to resemble the moon. Masten decided to use a larger, more powerful aluminum-frame rocket named Xoie. Difficulties with their initial design meant that they were "starting from a pile of parts" a month before the rocket had to be competition ready. They worked 80-hour weeks and tested it about 20 times over the course of several days. The night before their scheduled competition flight, Xoie managed to hover for the required three minutes despite gusts of up to 40 miles (64 km) per hour. Goff recalls thinking: "Holy crap, we're ready!"

The next morning, though, as an eager audience looked on, Xoie refused to start. Goff slid his finger along the rocket's engine and felt moisture: it was leaking alcohol, the liquid the vehicle used as fuel.

The company was nearly out of money again. If they lost the challenge, they would likely have to shutter. "We thought, okay, it's a $300,000 vehicle, but it's a million-dollar prize, and we're going to go out of business if we fail anyway. Might as well roll the dice," Goff recalls.

Finally, they got the engine to light and Xoie roared into the sky. Goff recalls the power of the rocket reverberating in his ribs. He watched, mesmerized, as Xoie hovered high above the Joshua trees and sagebrush of the Mojave Desert, and rejoiced when he saw it touch down in the designated landing area.

But his celebration quickly gave way to panic: no sooner did Xoie land than its oxygen tank burst into flames.

The judges decided to grant the company one more flight attempt the following day—but they would need to be ready at 5 a.m. That gave the team a little less than 12 hours to determine the cause of the fuel leak and fix their charred rocket. "Even when we got the word that we would be allowed to try again if we could repair the vehicle … we were almost ready to give up," Scotkin wrote at the time in an email recapping the challenge. "Almost all of the MSS personnel looked like walking dead."

Goff hurriedly drove to a FedEx facility to pick up a replacement tank. When he returned an hour later, he found that members from other challenge teams had gathered at Masten's workshop to help. Masten and Scotkin sent him and the rest of the weary team home to rest, and with the support of the volunteers, they got to work.

If they couldn't get the rocket to stop leaking, mused Keith Stormo of High Expectations Rocketry, a small group from

The in-flight control box Masten's pilots use to fly its rockets.

Idaho, perhaps they should build a sump to collect drips and a catheter to divert them from critical parts? Masten's team found a Rubbermaid trash can lid, glued it on, and used baling wire to hold it tight. Overnight, Masten and a few others patched the tank insulation, repaired the faulty wires, and re-ran the damaged plumbing.

They finished everything mere minutes before their designated launch time. After the team rapidly filled Xoie's fuel tank with isopropyl alcohol, Masten's launch director, Ben Brockert, ordered his colleagues to run.

"We were engineers who were fat and out of shape," Goff recalls, so he and his coworkers were still about 75 feet shy of what would be considered a safe distance from the fully fueled rocket when Brockert began counting down to blastoff.

Xoie completed two flights that lasted the requisite three minutes, and went on to win the challenge with an average landing accuracy of 7.5 inches (19 cm) from the target. The vehicle built by Armadillo Aerospace, which had previously held the lead, came in at 34 inches.

Suddenly, Masten Space Systems had earned $1 million and a reputation for punching above its weight.

A figurine from the video game Kerbal Space Program sits Velcroed onto Xombie, Masten's record-holding rocket.

Wrenches and other rocket-building tools.

In May 2010, Elon Musk sent an email to SpaceX's propulsion, avionics, and structures teams with a link to a video hosted on a hobbyist website. You could watch Xombie take off vertically, ascend, and then pause in midair as its engine (deliberately) flickered out. As the rocket hurtled downward, the pilot re-lit the engine and the rocket gently descended to the ground. It was the first time a vertical takeoff, vertical landing rocket had ever done so. NASA called the in-air relight "a major step towards flying payloads to suborbital altitude." In writing to his team, Musk was succinct: "Pretty cool!" Masten says with a chuckle: "I was doing it before it was cool, and now it's cool and everyone talks about [Musk] doing it and it's like: uh, okay. He wasn't the first to do these things."

Over the past five years, Masten has come close to getting several significant contracts. In 2014, the Defense Advanced Research Projects Agency (DARPA) invited it to compete against industry giants Boeing and Northrop Grumman to build a reusable experimental spaceplane called XS-1. The contract would have paid up to $140 million. "I think they went out of their way to make sure that there was a small company involved to have a chance to prove or not prove itself," Masten reflects. But he could not hire talent or raise capital rapidly enough. DARPA chose Boeing.

While it hasn't yet scored a giant contract, though, Masten's ability to fly and land precisely has proved useful to NASA. Precision is one of the main challenges facing the next generation of landers for both the moon and Mars. Touching down might look easy, Mahoney says, but it's like "balancing a broom on the tip of your finger that's spitting fire and getting lighter at the same time." And that's on smooth surfaces.

As Lockheed's Murrow explains, "The interesting places on a planetary body—we know this from going to Mars—are not always the safe, flat places." Water, he says, is likely to be in the permanently

shadowed side of a crater—so you'd want to land near enough to the crater's edge to explore it, but not so close you fall in.

The 2020 Mars Lander, which is managed by NASA's Jet Propulsion Laboratory (JPL), uses new precision guidance systems to avoid boulders and find smooth areas for landing. In a series of flights in 2013 and 2014, JPL tested a prototype of the lander's vision system on Masten's Xombie rocket. It climbed over 1,000 feet in the air before autonomously landing, guided by comparing images from a digital camera with a known map. In 2017 a newer NASA system, called Cobalt, flew on Xodiac, another Masten rocket. The precise lidar on Cobalt allows a lander to find a flat spot with even greater precision.

Last year Masten tested a sample-return device built by Honeybee Robotics, a firm located not far from JPL in Pasadena, through a NASA-run matchmaking program that pairs experimental payloads with commercial launch vehicles. The "PlanetVac" is essentially a little vacuum that replaces one foot pad of a planetary lander; it's a simple, lightweight instrument that, if successful, might offer a cheaper and more reliable way of gathering samples.

These collaborations have burnished Masten's reputation and provided enough cash for it to chug along as, in Masten's words, "a small company that does a couple of basic services with NASA and the Department of Defense."

Winning one of the coming CLPS task orders would set it on a different trajectory altogether. But CLPS is no longer the only large competition Masten is in contention for. In late May, NASA announced that six companies had been chosen to develop prototype human moon landers. Of the CLPS nine, there are two firms on the list: Lockheed Martin and Masten.

A few days after Beresheet's crash, several Masten engineers stood around a whiteboard puzzling over an equation. On a wood laminate table by the trailer's front door, Mahoney, who commutes to Mojave from Georgia, had deposited a stack of yellowing Atlanta newspapers from July 1969. "Astronauts Test Landing Module; Apollo Moves into Moon Gravity," announced the Atlanta Constitution on July 19. "Men Walk on the Moon; Eagle Ready to Return," read the Atlanta Journal.

The day was gusty, even for Mojave, where the wind has been known to topple tractor-trailers. As Dave Masten walked across the parking lot from the office to the aviary where his rockets are stowed, he had to clutch his black wire sunglasses to his head to keep them from flying off.

He poked at the electronic lock on the aviary door and stepped inside the drafty, largely empty warehouse. Walking past walls hung with tools, he affectionately patted Xombie, a 10-foot (three-meter) tangle of steel tubes, aluminum propellant tanks, and carbon-fiber-wrapped pressure tanks, as he might a well-behaved pet. The rocket had been named by several Masten interns after they devoured "every zombie movie Netflix had to offer." (Nightlife around Mojave, a town of 6,104, is limited.) It was, in the end, well named. After all, it has flown more times than any other rocket, with plenty of bumps and dents to prove it.

In a week and a half's time, Masten's team would have to submit its bid for the first CLPS task order—a detailed plan for how it would get the first bundle of cargo safely to the surface of the moon. Masten's engineers were beginning to work longer days and gear up for the crunch that inevitably precedes a deadline. "Second-to-last week you start thinking about working 12- to 16-hour days," Masten says. "Then the last week you get some guys thinking: 'I'll sleep when I'm dead.'"

The proposal was not the only thing on Masten's mind. Another company had recently hired away his only remote pilot, and Masten would have to train a replacement. Money was a constant frustration. Since Masten Space Systems is a small company with relatively few customers, it is particularly painful when those customers—like NASA—don't pay on time. During the government shutdown earlier this year, Masten and Mahoney had to forgo their salaries to make sure they could pay the rest of their team. Masten sighs. "I mean, that's happened to me so many times. We've got lots of money," he says, and pauses for effect. "We've got no cash."

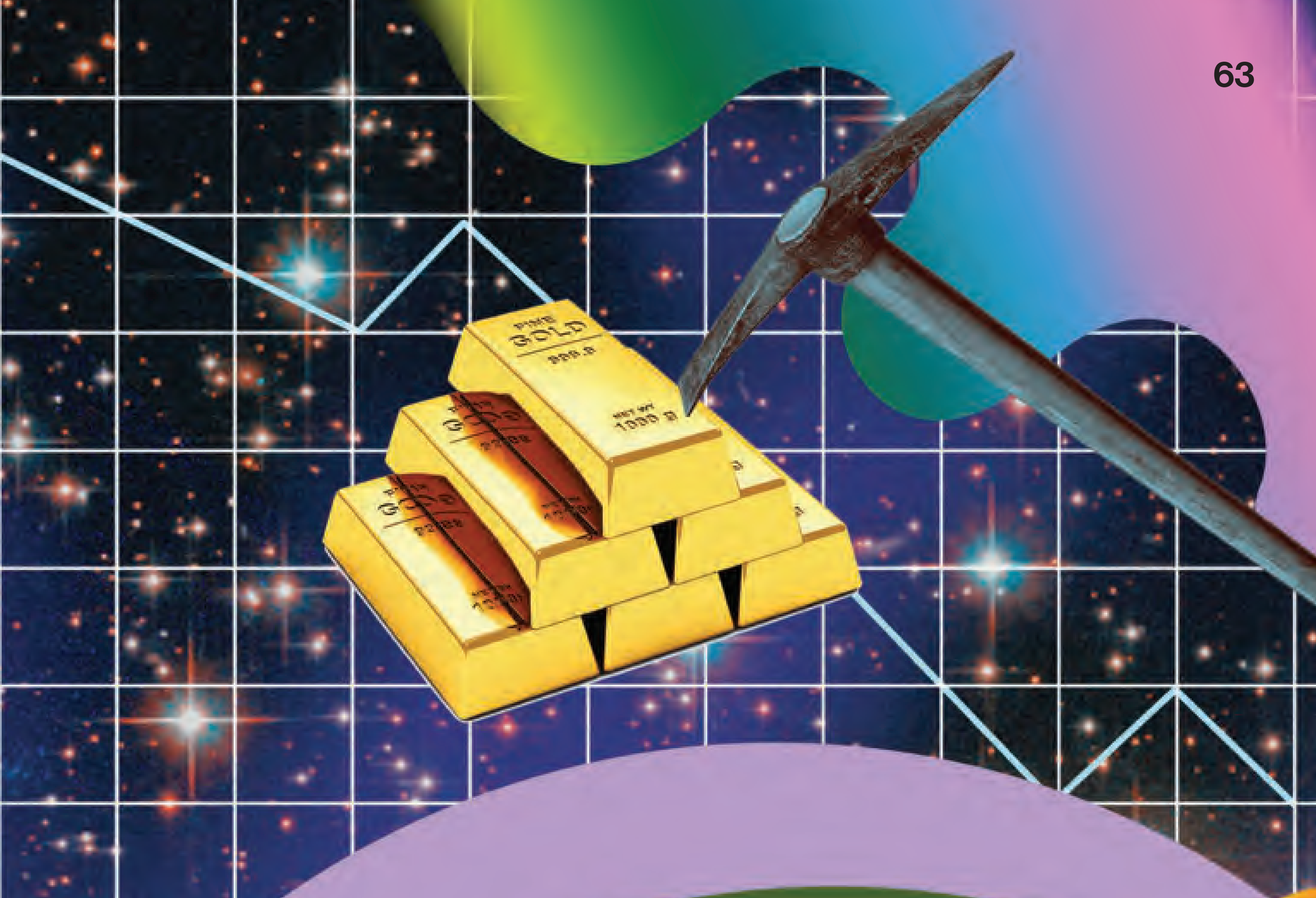
Two days after Beresheet crashed into the moon, Morris Kahn, an Israeli entrepreneur who is chairman of SpaceIL's board, announced that his team was already planning a new mission. If shots on goal really are more important than scoring, the American government will have to respond to failures with comparable enthusiasm. Masten might gamely take risks, but will NASA?

I asked Dave Masten how he felt about the Beresheet crash; after all, it meant he still stood a chance of being at the helm of the first privately funded lunar mission.

"I felt the pain of losing a vehicle," he replied. "Being first is not much of a motivator for me." When I asked him to clarify what was, he responded earnestly: "Landing on it, period. You know, the whole purpose of this company was for me to step on the moon." T

Haley Cohen Gilliland is a writer based in Los Angeles.

THE ASTEROID BUBBLE

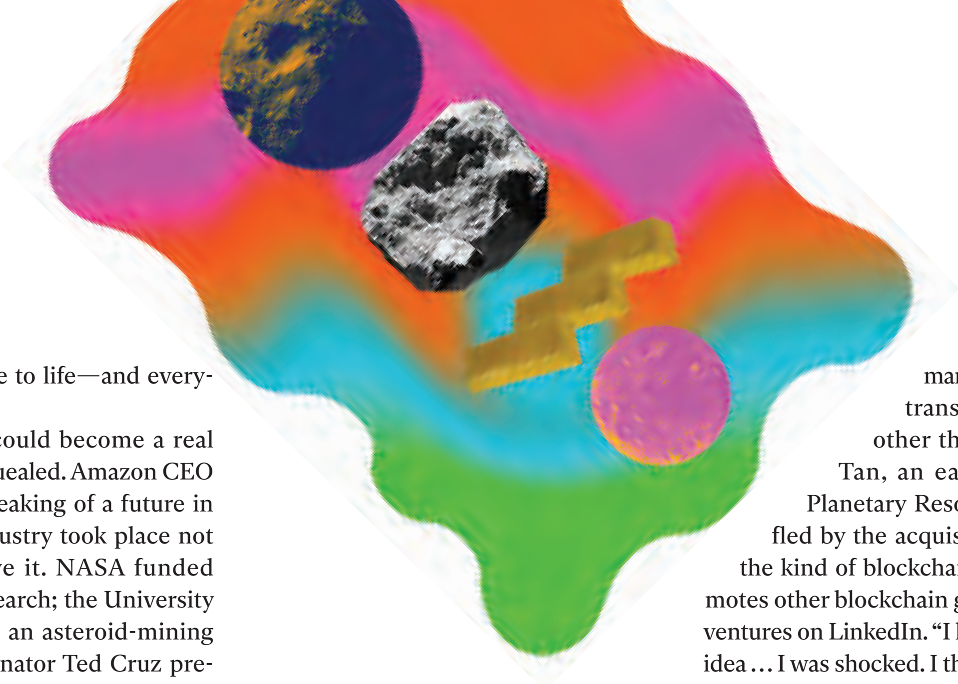


A SHORT HISTORY OF THE SPACE INDUSTRY'S FAILED FIRST GOLD RUSH

BY **ATOSSA ARAXIA ABRAHAMIAN**
ILLUSTRATIONS BY **CHRISSIE ABBOTT**

In the best of worlds, Chris Lewicki and Peter Diamandis might have changed the course of human civilization. Their startup, Planetary Resources, was launched in 2012 with the modest dream of mining asteroids for minerals, metals, water, and other valuables. The founders' résumés and connections gave the zany idea institutional legitimacy: Lewicki had worked on major NASA missions such as the Mars Spirit and Opportunity rovers, and Diamandis was a well-known space-tourism booster. Together with a third partner, Eric Anderson, Planetary Resources had raised $50 million by 2016, of which $21 million came from big-name investors including Google's Eric Schmidt and filmmaker James Cameron.

Before long, a competitor called Deep Space Industries (DSI) appeared on the scene. It raised much less cash: just $3.5 million, supplemented by some government contracts. But it had its own high-profile backers, pie-in-the-sky goals, and a particularly evangelical board member named Rick Tumlinson, who made the rounds at conferences pitching the company's vision. "Crazy ideas: that's what moves culture forward," he said at a 2017 event in New York. "Nothing says this is impossible except our own belief systems."



It was sci-fi come to life—and everybody loved it.

"Space mining could become a real thing!" headlines squealed. Amazon CEO Jeff Bezos began speaking of a future in which all heavy industry took place not on Earth, but above it. NASA funded asteroid-mining research; the University of Colorado offered an asteroid-mining degree program; Senator Ted Cruz predicted that Earth's first trillionaire would be made in space.

"There was a lot of excitement and tangible feeling around all of these things that we've been dreaming about," says Chad Anderson (no relation to Eric), the CEO of Space Angels, a venture capital fund that invests in space-related companies.

Also crucial to the money-making opportunities was the burgeoning commercial space sector's lobbying, which shepherded the SPACE Act through Congress in 2015. This not-uncontroversial bill included a "finders, keepers" rule whereby private American companies would have all rights to the bounty they extracted from celestial bodies, no questions asked. (Before that, property rights and mining concessions in space, which belongs to no country, were not a given.)

That, in turn, would make it possible to work toward a goal that Eric Anderson predicted could be reached by the mid-2020s: extracting ice from asteroids near Earth and selling it in space as a propellant for other missions. Water can be broken into hydrogen and oxygen to make combustible fuel, or—as in DSI's technology—just heated up and expelled as a jet of steam.

"Both companies believed one of the early products would be propellant itself—that is, water," says Grant Bonin, the former chief technology officer of Deep Space Industries. "What DSI had been doing is developing propulsion systems to run on water. And everyone who buys one is creating an ecosystem of users now that can be fueled by resources of the future."

By the spring of 2017, Planetary Resources was operating a lab in a warehouse in Redmond, Washington, decorated with NASA paraphernalia and vintage pinball machines. Engineers tinkered with small cube satellites behind thick glass walls, crafting plans to launch prospecting machines. Luxembourg had given the company a multimillion-dollar grant to open a European office. Japan, Scotland, and the United Arab Emirates announced their own asteroid-mining laws or investments.

The stars had burned through their red tape. The heavens were ready for Silicon Valley.

Then things started going south. Last summer, Planetary failed to raise the money it was counting on. Key staffers, including Peter Marquez, the firm's policy guy in Washington, had already jumped ship. "We were all frustrated about the revenue prospects, and the business model wasn't working out the way we'd hoped," recalls Marquez, who now works for a Washington, DC, advisory shop called Andart Global.

"There was more of a focus on the religion of space than the business of space," Marquez adds. "There's the religious [segment] of space people who believe that almost like manifest destiny, we're supposed to be exploring the solar system—and if we believe hard enough, it'll happen. But the pragmatists were saying there's no customer base for asteroid mining in the next 12 to 15 years."

Amid rumors that it was auctioning off its gear, Planetary Resources was acquired last year by ConsenSys, a blockchain software company based in Brooklyn that develops decentralized platforms for signing documents, selling electricity, and managing real estate transactions, among other things. Anderson Tan, an early investor in Planetary Resources, was baffled by the acquisition—and he's the kind of blockchain guy who promotes other blockchain guys' blockchain ventures on LinkedIn. "I honestly have no idea … I was shocked. I think they wanted to acquire the equipment and assets," he says. "For what? I'm not so sure."

DSI, in turn, was acquired by an aeronautics company named Bradford Space. These acquisitions aren't taking the companies anywhere. "They're gone; they're done. They don't exist," says Chad Anderson.

The lack-of-vision thing

What went wrong? Predictably, ex-employees and investors tell slightly different stories.

Bonin blames DSI's demise on investors' unwillingness to take long-term risks. "We had a plan that would take off after a certain point, and we didn't get to that point," he explains. "And we were only $10 million away from hitting that point, but our planning was decades long, and a VC fund's life cycle is one decade long. They're incompatible." Meagan Crawford, who worked with Bonin and is now starting her own venture capital fund for commercial space startups, concurs: "A traditional VC time line is 10 years, when they have to give money back to investors, so in seven years they want to exit. A 15-year business plan isn't going to fit in."

On the money side, the story is a little less forgiving. "They did not deliver on their promises to investors," says Chad Anderson, whose Space Angels invested in PR. "Both companies were really good at storytelling and marketing and facilitating this momentum around a vision that their technology never really substantiated." He adds, "I think that these weren't the right teams to do it."

There were also bigger structural obstacles—such as, in former employees' telling, the lack of any infrastructure for an asteroid-mining industry. That put investors off, too: "If you mine an asteroid, mostly likely you'll [have to] send it to the moon to process it. It wouldn't be processed on Earth, because the cost would be tremendous," says Anderson Tan. "So then it's like a chicken-and-egg problem: do we mine first and then develop a moon base, or invest in building up the moon and then go to asteroid mining?"

Finally, asteroid miners had to compete for funding with a proliferating number of other space-related ventures. Between 2009—"the dawn of the entrepreneurial space age"—and today, "we've gone from a world with maybe a dozen privately funded space companies serving one client, the government, to one with more than 400 companies worth millions of bucks," Chad Anderson says. So if commercial space startups seemed like an out-there proposition in 2012, by 2018 VCs who wanted space in their portfolios could have their pick of companies with better short-term prospects: telecom startups selling internet access, for instance, or firms analyzing the much-more-accessible moon.

"The bottom line is that space is hard," says Henry Hertzfeld, the director of the Space Policy Institute at George Washington University. (Hertzfeld advised Planetary Resources on legal matters; the space world, on Earth, is still very small.) "It's risky, it's expensive; lots of high up-front costs. And you need money. You can get just so much money for so long."

To succeed, says Hertzfeld, the companies would have needed to make a profit from other uses of their technology—such as DSI's water propulsion system, which could be used in satellites, and PR's hyperspectral sensors, which it built to analyze the composition of asteroids but can also be put to work surveying the Earth. "But they didn't generate the revenues," he says, "and there's a limited amount of time for a company to exist without a profit."

According to Space Angels, $1.7 billion in equity capital poured into space companies in the first quarter of 2019, nearly twice as much as in the last quarter of last year. Of that, 79% went toward satellite businesses and 14% to logistical operations, like rocket launches. The fund's own interests mirror these trends.

"The commercial space industry is maturing to the point where it's more serious now," says Peter Ward, the author of *The Consequential Frontier*, a forthcoming book about the privatization of space. "Some of the people I talked to now see asteroid mining as a bit of a joke."

Building a new frontier

In spite of these failures, former asteroid miners sound remarkably chipper about their prospects—and humanity's interstellar future. Asteroid mining was a gateway drug for high hopes and big dreams.

ON THE MONEY SIDE, THE STORY IS A LITTLE LESS FORGIVING.

Tamara Alvarez, a doctoral student at the New School in New York who has attended space conferences around the world, says that the rhetoric around space mining maps perfectly onto older frontier tropes. "The mining thing resonated with a lot of people because of the gold rush narrative. There's something unconscious there that they tapped into," she says.

Similarly, though neither asteroids nor 19th-century California actually created many overnight billionaires, they did create frameworks for how an economy based on a particular resource would function. "There wasn't all the gold in California, but it brought an infrastructure that people made money off of," says Alvarez. "Services, fishing—all this grew out of ambitions for gold. With asteroids, it's the same thing: when you get the idea that there's all the gold or whatever you need waiting for you, the infrastructure gets built too."

The asteroid miners seem to have thought of it that way. "I think when DSI and PR got started, the headlines all said asteroid-mining [companies] were like [traditional] mining companies," says Grant Bonin. "But internally we'd joke: We're not miners yet. We're the pickax and shovel or Levi's jeans of space. We're the creators of tools that were brought into existence that would support the vision, but also help a lot of other people to do a lot more."

Equally significant is that the prospect of asteroid mining pushed governments to think about property rights in space. "The horizon for asteroid mining is still a couple of decades off, but I do think we're going to do Mars missions, and we'll need resources in space," says Marquez. "And thanks to asteroid mining, the policy framework's been established."

For now, DSI and PR face uncertain futures. None of the space workers interviewed for this article had a clue what a blockchain company like ConsenSys was doing with asteroid prospecting tools. In November the company told journalist Jeff Foust of SpaceNews that PR's "deep space capabilities" would "help humanity craft new societal rule systems through automated trust and guaranteed execution," whatever that means. A spokeswoman has since said the company "is taking a new form and is less focused on asteroid mining."

But Bonin says many of his DSI colleagues quickly found work elsewhere. And engineers laid off from PR have banded together to start a company called First Mode, which builds hardware that can operate in harsh environments both on Earth and above it; the company, according to its founders, is already profitable.

So the asteroid-mining industry may have collapsed for now, but its players are still hard at work. "When we reflect back [to] 2012 when these two companies came into existence, and think about how they were trying to crack that nut for seven years, one of the really cool things from my standpoint is these have gone into different companies," says Bonin. "Part of me is sad when these things break up, but we've seeded the industry with true believers who care about a human future in space to benefit of all humankind."

Atossa Araxa Abrahamian is a journalist based in New York.

Next stop: Alpha Centauri

Shooting tiny spacecraft to other stars requires audacious thinking and technological progress—but Breakthrough Starshot's backers say it is just a matter of time.

By Kate Greene

Photographs by Michelle Groskopf

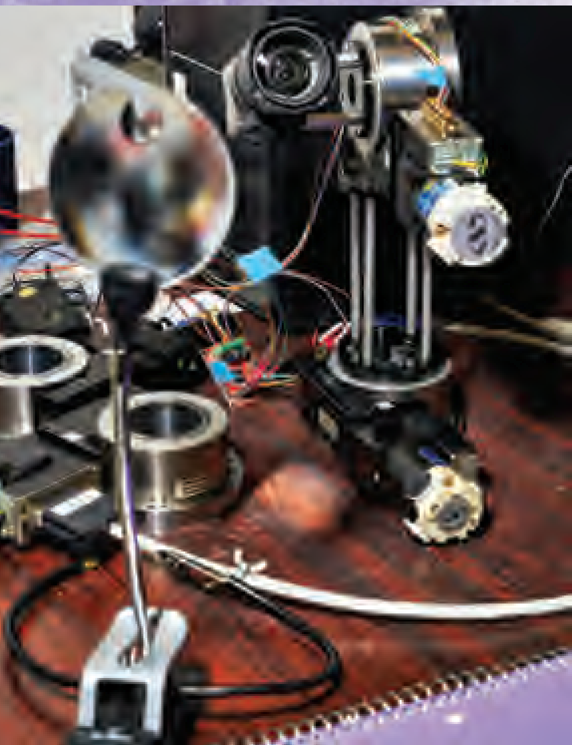
Starship conferences attract a hopeful crowd: researchers, inventors, and hobbyists enthused by the idea of building spacecraft that can fly between star systems. The excitement at these gatherings can make it feel as if anything is possible—but also as if nothing is. Many of the schemes put forward are too vague, and they almost always have too many technological gaps to fill.

In 2015, Philip Lubin, a cosmologist from the University of California, Santa Barbara, took the stage at the 100-Year Starship Symposium in Santa Clara. He outlined his plan to build a laser so powerful that it could accelerate tiny spacecraft to 20% of the speed of light, getting them to Alpha Centauri in just 20 years. We could become interstellar explorers within a single generation. It was quite the hook.

Because Lubin is an excellent public speaker, and because the underlying technologies already existed, and because the science was sound, he was mobbed after the talk. He also met Pete Worden, a former research director of NASA's Ames Research Center, for the first time. Worden had recently taken over as head of the Breakthrough Initiatives, a nonprofit program funded by Russian technology billionaire Yuri Milner. Six months later, Lubin's project had $100 million in funding from Breakthrough and the endorsement of Stephen Hawking, who called it the "next great leap into the cosmos."

Starshot is straightforward, at least in theory. First, build an enormous array of moderately powerful lasers. Yoke them together—what's called "phase lock"—to create a single beam with up to 100 gigawatts of power. Direct the beam onto highly reflective light sails attached to spacecraft weighing less than a gram and already in orbit. Turn the beam on for a few minutes, and the photon pressure blasts the spacecraft to relativistic speeds.

Not only could such a technology be used to send



At Lubin's UC Santa Barbara lab, the experimental cosmology group studies the early universe.

Combining Lubin's research in directed energy with other passions such as propulsion has helped Starshot unfold.

Prashant Srinivasan is among those working on laser-propelled wafer-scale spacecraft that the group hopes could reach Alpha Centauri in a generation.

sensors to another star system; it could dispatch larger craft to Earth's neighboring planets and moons. Imagine a package to Mars in a few days, or a crewed mission to Mars in a month. Starshot effectively shrinks the solar system, and ultimately the galaxy.

It's fantastic. And also a dream. Or a sales pitch. Or a long-term, far-out project that can't be sustained long enough for the nonexistent technologies it requires to be built.

Lubin is a young 66. He walks fast, and his thick hair and full beard are dark. When I went to meet him in Santa Barbara this April, he told me that he had been a serious kid, disturbed by the realities of the world. He sought solace in math and science because he found them beautiful. "I loved school," he explains. "I used to study all the time. It was like a retreat for me: ride my bike to the library and devour books."

Even so, he didn't expect he'd follow an academic path—it didn't seem possible. His family valued education, but his Lithuanian father, who worked as a mail carrier, never even graduated from high school. His Russian-born mother was a secretary. "I grew up with an internalization that college was for other people," he says. After encouragement from a school counselor in Los Angeles, though, he attended community college; teachers there prodded him to transfer to UC Berkeley. And there, his professors nudged him to apply to graduate school. Eventually he landed at Harvard. "When I look back on it," he says, "I was a total knucklehead."

Today Lubin is a cosmologist. For much of his career, he's built equipment to measure the background radiation of the universe, but his scientific and technical interests are varied. It was at a defense technologies conference, talking about using lasers to defend Earth against incoming asteroids and comets, that he first came up with the idea for Starshot.

He also tells me about another obsession: propulsion. Most rockets today run on liquid fuel, much as they did when Germany invented the V2 during the Second World War. The last 75 years in computing, by comparison, have produced a trillion-fold increase in speed. "Wouldn't it be neat if propulsion could advance like that?" says Lubin. "The SLS"—NASA's super-heavy rocket, which has already cost $12 billion and still isn't ready—"could cost less than a penny."

Lubin's labs at UC Santa Barbara feature a cluttered warehouse that feels typical of experimental physics setups: giant spools of optical fiber, racks of oscilloscopes, tool boxes, circuit boards. One cabinet for solvents, another for snacks.

As we walk through the labs, he is quick to acknowledge that Starshot still faces a lot of challenges. There is, for example, no laser yet powerful enough to do this kind of blasting. There are no light sails that could take such a beam without being obliterated. There are no less-than-gram-size spacecraft to make the journey, and questions about laser supply and laser location remain. And then there are the ethical and geopolitical implications of building such a powerful directed energy source. After all, it could also be a weapon.

At the whiteboard, postdoctoral researcher Peter Krogan begins walking me through the solutions to these issues. First up: building the laser array.

The challenge here is figuring out how to fix the frequency of billions of lasers, each 10 centimeters in diameter, and stabilize them so they can be combined into a single large beam. Locking more beams together allows the strength of the laser to be scaled up to the levels proposed. The team's current working plan is for an array located on the ground, which keeps costs lower than if it were placed in orbit but adds other complications—such as overcoming atmospheric interference. This requires a beacon attached to the spacecraft that sends a signal back through the atmosphere, letting the ground-based lasers fix on their target. To couple the array, Krogan is working on "nested phase locking," where a smaller array synchronizes before seeding the next layer in the array, and so on. If this can work for two layers of lasers—their immediate research goal—then it might just be possible to do it for the five layers that simulations say is best for a 100-gigawatt beam.

The second big challenge is the solar sail. While the concept has been around for decades, it wasn't successfully deployed until 2010, when Japan's Ikaros spacecraft tested a sail 14 meters (46 feet) square during its mission around the sun. But a sail that can take the gentle pressure of solar photons is drastically different from one that can withstand the most powerful laser ever built—the difference between letting an April mist hit your face and getting pummeled by a firehose.

To manage this, the Starshot sail needs to be extremely robust, though it must also be extremely lightweight. The key, Krogan explains, is to let some of that power leak through: the sail's material must be transparent and reflective simultaneously. Glass is one of the more promising candidates, though it would need to have its properties adjusted to achieve the perfect mix of reflectivity and transparency. The ideal material still needs to be invented, but there are some promising advances, Krogan says.

The third major challenge is building the tiny spacecraft. The smallest objects orbiting Earth right now are cubesats, which are 10 centimeters on each side and weigh about a kilogram. Lubin's team wants to shrink the entire craft to the size of a microchip—what they call "wafer-scale." They've miniaturized prototypes to the size of a matchbook and even a quarter. But their best working models currently weigh about 100 grams, still 100 times too heavy for the Alpha Centauri mission. Obstacles include integrating the electronics and photonics, making it able to withstand the radiation in deep space, shrinking the power supply, developing an ultra-small onboard thruster … the list goes on.

But while the technical challenges are real, the major difference between Starshot and many other interstellar projects is that it doesn't require new physics or even fundamentally new technologies. When Lubin was developing the idea, he sent the details to colleagues for feedback. They were “people who would rip it to shreds,” he says. “The people who take no prisoners and have no mercy and are completely comfortable saying, ‘You idiot!’… I said, ‘Please destroy this, because I’m tired of working on it.’ In the end, everyone I spoke with said, ‘Well, it should work.’”

By the time Breakthrough’s technical experts vetted the concept, the outline was solid. Worden was excited. “We were all convinced that this was the first really plausible interstellar technology that we could do in our lifetime and would be affordable,” he says.

And even if not all the problems will be solved, it’s worthwhile to solve some of them, he says. For example, developing a fully capable spacecraft that weighs less than a gram would be a major revolution. Cubesats were dismissed by many until just a few years ago; now there are constellations of them. Chipsats, he says, will mature soon and revolutionize science and communications. Low-cost, efficient laser arrays could be useful for jobs like pushing space junk out of the way. And advances in light sails would allow microscale spacecraft within our own solar system to reach other planets in months, not years. “That’s going to change our understanding of objects in our solar system, and the search for life,” says Worden. “And commercially, it’s going to be hugely valuable when looking for space resources.”

Lubin isn’t afraid of a little complexity.

There is one issue that cannot be solved by technology, though: geopolitics. Lasers would help propel solar sails, says Joan Johnson-Freese, a professor of national security affairs at the US Naval War College who also sits on the Breakthrough board. “But when you start talking about firing lasers, people get very nervous.”

She suggests that international agreements would likely ensure the broadest, most beneficial use of such a powerful laser. And the military potential of space is not new: today anything China does in space is considered dual-use. “The same is true for the US,” she says. “China could interpret anything we do as threatening.”

One way forward could be to democratize exploration. Historically, the US and other superpowers have dominated space, but Starshot could open it for countries that don’t have access. A nation that launched a fleet of chipsats could access communications, exploration, and commercial reconnaissance that were previously unaffordable. It’s a rare project that has such big technological, scientific, commercial, and geopolitical implications.

“It requires some careful thinking, and also transparency, and possibly international collaboration and conversations in the long run,” Lubin says. “Luckily, we have some time, because we’re not deploying anytime soon.”

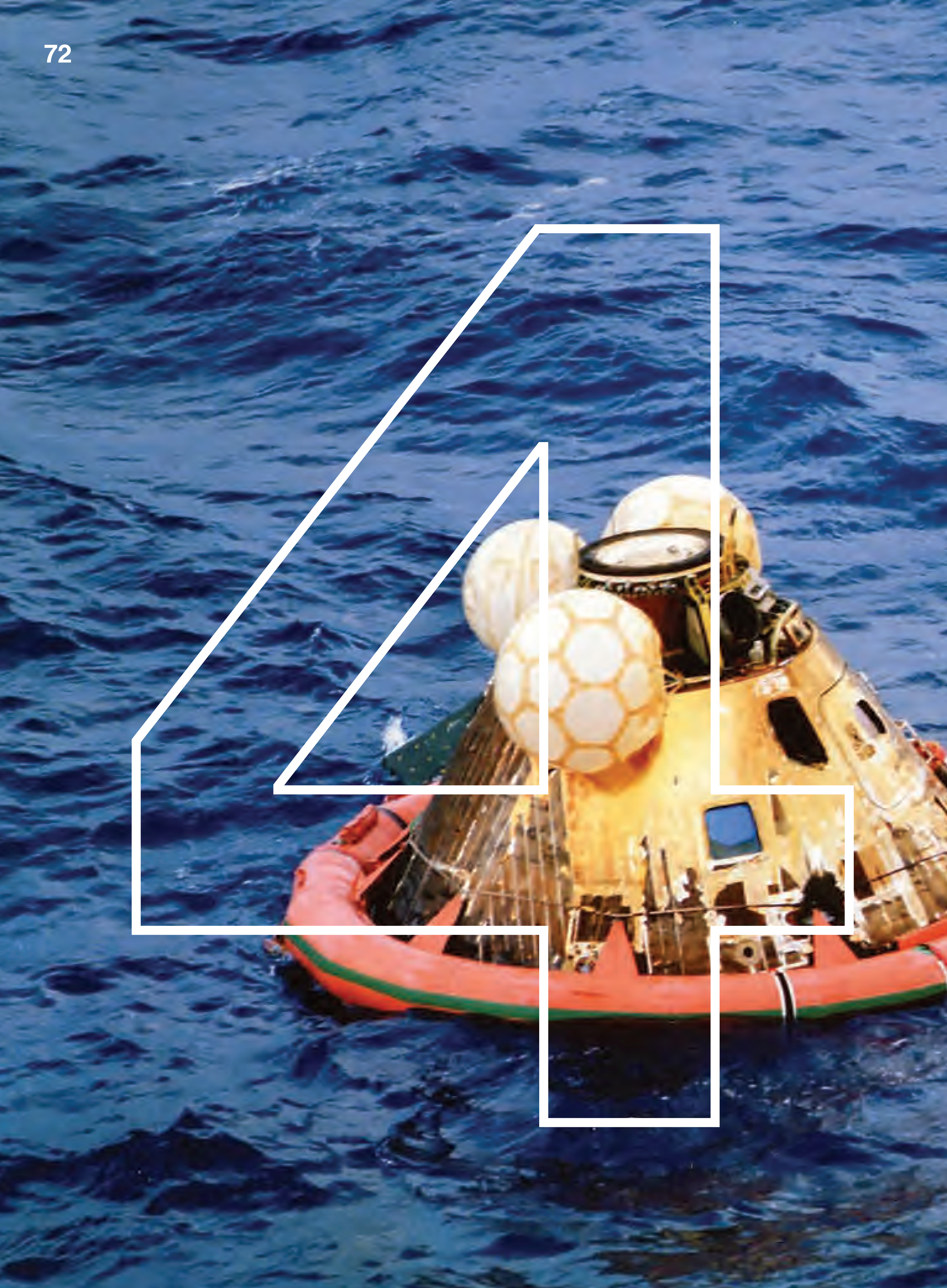
So when will Starshot be realized? One goal is to get probes to Alpha Centauri by 2061, the 100th anniversary of Yuri Gagarin’s pioneering orbital flight. That’s a long way off, almost certainly beyond Lubin’s lifetime. He says the project will have a chance only if people realize that it is “milestone based,” a road trip with many points along the way.

But that long horizon means it’s going to need money. NASA’s contributions expired this year. Other cash has come from an anonymous philanthropist. And so far, Breakthrough’s funding has yet to arrive.

“We’re a new organization, and we’re still in the startup phase,” says Worden, promising that the cash will come once negotiations between universities, contractors, and regulators have been completed.

It’s a puzzle, but Lubin isn’t afraid of a little complexity. That’s exactly what this whole endeavor is about. “This isn’t just a single-use technology,” he says. “It’s not just wafers to the stars. It’s cubesats to Europa, or humans to Mars quickly, or the ability to keep a spacecraft in orbit longer at low altitudes, or to protect the planet from external threats like asteroids. If you don’t understand the whole breadth of this technology, then you’re missing the beauty of the transformation it makes possible.”

Kate Greene is an essayist, poet, and former laser physicist.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RETURN

SO WHAT WAS IT LIKE?

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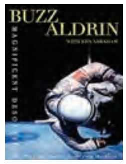

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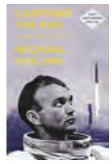

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The write stuff: 10 astronaut memoirs

At the time of writing, 558 people have orbited the Earth. Approximately 10% of them have written books about the experience. Most of these books are not very good. The achievement does not redeem the writing, which is as formulaic as the checklists necessary for safe space travel. Awe is inspired, fears conquered, and dreams realized. But the best of these books explain with unmatched immediacy what it is to go to space and to safely return.

—*Konstantin Kakaes*

Space shuttles Discovery, Columbia (2)

Rhea Seddon

On improvising repairs in space:

“This entire contraption was connected together and wrapped with gray duct tape ... someone in the control room said I was a good seamstress, and Sally Ride reminded them that I was a good surgeon. I wish I'd been there to thank her for that.” —*Go for Orbit* 1

Apollo 12, Skylab 3

Alan Bean

On keeping track of your belongings in zero gravity:

“If you wait long enough, everything lost will float by.”

—*Homesteading Space: The Skylab Story* by David Hitt, Owen Garriott, and Joe Kerwin 2

Gemini 12, Apollo 11

Buzz Aldrin

On returning to earth:

“The ten years since my moonwalk were not filled with achievements, bold accomplishments, and grand acclamations. It had been my decade of personal hell.”

—*Magnificent Desolation* (with Ken Abraham) 3

Gemini 10, Apollo 11

Michael Collins

On flying around the moon, alone:

“If a count were taken, the score would be three billion plus two over on the other side of the moon, and one plus God only knows what on this side. I feel this powerfully—not as fear or loneliness—but as awareness, anticipation, satisfaction, confidence, almost exultation. I like the feeling. Outside my window I can see stars—and that is all. Where I know the moon to be, there is simply a black void; the moon's presence is defined solely by the absence of stars.” —*Carrying the Fire* 4

Gemini 12, Apollo 8, Apollo 13

Jim Lovell

On his damaged spacecraft:

“That entire door was gone, ripped free and blasted away from the ship. Trailing from the gash left behind were sparking shreds of Mylar insulation, waving tangles of torn wires, tendrils of rubber liner.”

—*Lost Moon: The Perilous Voyage of Apollo 13* (with Jeffrey Kluger) 5

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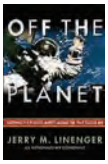

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Space shuttles Discovery & Atlantis (2), Mir

Jerry Linenger

On a fire that almost killed him:

"Because the fire extinguisher acts almost as a thruster in space, I grabbed Korzun around the waist to stabilize him. I would also periodically shake him, he would shake back—a signal that we were both still conscious. The flame was five feet in front of my face, the smoke so dense that I could not count the fingers in front of my face."

—*Off the Planet: Surviving Five Perilous Months Aboard the Space Station Mir* 6

Space shuttles Atlantis (2), Discovery (2), Endeavour

Scott Parazynski

On fixing the International Space Station:

"I can't really toss and turn in my snug sleeping bag, but if I could, I would. An army of brilliant NASA rocket scientists is sending Wheels and me out tomorrow to suture the space station back together … We never anticipated this crazy scenario, so we certainly aren't trained, in the traditional sense, to do this repair."

—*The Sky Below* (with Susy Flory) 7

Voskhod 2, Soyuz 19

Alexei Leonov

On watching his rivals beat him to the moon:

"Very soon this atmosphere of celebration was overtaken by professional talk. We cosmonauts began discussing how easy it appeared to walk on the surface of the Moon, how easy it was to jump. We would have to take this into account, we agreed, when we went there ourselves."

—*Two Sides of the Moon* (with David Scott and Christine Toomey) 8

Apollo 7

Walter Cunningham

On reaching orbit:

"Once the initial activity subsided, my first sensation of space was simply one of belonging. I had lived with the thought for five years … it all went so smoothly, so uneventfully, that any preflight doubts seemed almost foolish." —*The All-American Boys* 9

Apollo (did not fly)

Brian O'Leary

On quitting the space program:

"It suddenly occurred to me I wanted to quit the astronaut program at once. It was as clear to me as the sky over Grizzly Park. I no longer wanted any part of it, and it took a change of environments to catalyze the process. Pros and cons, pros and cons—how could I possibly sit in Houston for a decade in an environment of flat plains, murky air, unimaginativeness and nonscience?" —*The Making of an Ex-Astronaut* 10

BURNING AMBITION

SPACE TRAVEL MEANS GOING FAST—VERY FAST. HOW DO YOU SLOW DOWN AGAIN?

For months on end, the samples kept melting. This wasn't exactly surprising—the cork-filled fiberglass honeycomb was being subjected to a blast of heat four times more intense than what the space shuttle's leading edge withstood on reentering Earth's atmosphere. It was like putting the world's hottest oven in the middle of its most powerful wind tunnel.

The same materials had already protected all America's previous Mars landers from the heat of hitting the Martian atmosphere at nearly 10,000 miles (16,000 kilometers) per hour. But that wasn't going to be good enough anymore. The shield for the Mars Science Laboratory (MSL) would need to withstand about 250 watts of energy per square centimeter—about 10 times the heat experienced by the Viking, America's first Mars lander, which touched down on the planet in 1976. That's because MSL, scheduled to launch in August 2009, would be three times heavier than the Viking. The Curiosity rover that MSL would carry was about five times heavier than the Spirit and Opportunity rovers, which had landed safely on Mars in 2004. MSL's size and weight weren't insoluble problems in themselves. But computer simulations showed that the probe's huge weight would result in heavy turbulence, leading to more severe conditions than any previous Mars entry heat shields would have endured. And when they turned the heat-shield material sideways to the oncoming flow of hot air to simulate turbulence, honeycomb cells in it would "pop," leading to a chain reaction of failures. "The test looked unlike anything we had ever seen before," remembers Helen Hwang, a researcher at NASA's Ames Research Center in Silicon Valley who was in charge of MSL's thermal protection system at the time.

In the wake of those failures, Hwang's team faced a serious time crunch. It was 2007, and launch was scheduled in less than two years. There were two options, as she saw it: redesign the mission to try to reduce heating conditions, or come up with a new heat-shield material. The first option would limit where the rover could land and the scientific instruments it could carry. The second option meant that

BY BECKY FERREIRA

PHOTOGRAPHS BY JESSICA CHOU

they would have to design, develop, test, and build a new heat shield in less than 18 months. That option was risky, but it would allow the mission to do all the science it was meant to do.

They chose the second option.

As human ambitions grow in space, our ingenuity will have to match them. To explore the dense atmospheres of planets like Venus or Saturn, we need ultra-robust heat shields that can handle intense pressures. To send Martian samples back to Earth, we need indestructible heat shields that will prevent any alien life forms from contaminating our planet, or vice versa. Landing humans on other planets will require supersizing aeroshells, the entry capsules protected by heat shields, to diameters of almost 20 meters (66 feet) across, or more. Nothing close to that scale has ever been flown to Mars before.

The challenges of developing these technologies will be immense, but so will the rewards if they safely deliver robots and humans to new frontiers. Without cutting-edge advances in aeroshells and heat shields, such missions will be pointless—they'll just burn up in the atmosphere.

If you go into space, there are two reasons to slow down: to return to Earth or to stop at another celestial body. One way to slow down is to use the same method you used to speed up: rockets. But this means carrying more rocket fuel, which adds weight. As a practical matter, it makes sense to use the atmosphere, if there is one. But surviving the resulting heat requires clever materials and cleverly shaped spacecraft.

The clever shapes originated in the 1950s at Ames Research Center, the same place where Hwang would later work to develop the MSL heat shield. Harry Julian "Harvey" Allen, who headed the Ames High-Speed Research Division during the early 1950s, devised the so-called blunt body, which would have a flat, broad side to take the brunt of the heat. Allen and a colleague worked on the theory over the next year. They realized that a blunt body would create a strong shock wave in front of it, which deflected much of the heat away from the vehicle. They then put together the second piece of the puzzle: ablation. This means using materials that are designed to decompose and erode on entry, creating a charred layer that effectively pushes heat away from the vehicle.

The blunt-body concept was initially met with skepticism, and it remained classified until 1957. But by May 1961, when Alan Shepard became the first American to visit space, his Friendship 7 capsule used a conical blunt face to safely return to Earth.

Because of the Apollo program, new ablative materials were a very active research area in the 1960s. For Apollo, NASA turned to a company called Avco, which specialized in materials for long-range missile warheads. A 2.7-inch-thick layer of "Avcoat," a heat-shield material made of epoxy resin in a fiberglass matrix, absorbed the worst of the heat on Apollo's reentry.

For the Viking missions—which would launch the first successful Mars landers in the 1970s—NASA used a new material called SLA-561V. Like Avcoat, SLA (for "super-lightweight ablator") is based on a honeycomb structure filled with gobs of ablative resin. But the engineers at Martin Marietta, the company that devised the material, also integrated lighter constituents, such as silicon and cork, to reduce its density.

The space shuttles, first launched in the 1980s, needed an entirely new approach. The shuttles were meant to be reusable, and that went for the heat shields as well. Instead of a substance like SLA, the shuttles were protected with reinforced carbon-carbon on the nose cap and the leading edges of the wings, and by ceramic tiles on their belly.

Hwang (previous spread) with HEEET, a new heat-shield concept.

HEEET (right) is intended for entry into extreme environments, like those on Saturn or Neptune.

Hwang, who grew up in a small town in Iowa, remembers handling a space shuttle tile in a school presentation. The experience planted the desire to one day work on heat-shield technologies. After earning her doctorate in plasma physics at the University of Illinois, Urbana-Champaign, she took a job at Ames Research Center, but one that had nothing to do with heat shields. For several years, she worked on using plasmas to etch circuits in microchips. When funding ran short, she switched to heat shields, realizing her childhood ambition.

When Hwang was given the task of creating a heat shield for the MSL project in 2006, she initially turned to SLA. But it became clear pretty fast that SLA wasn't going to work. "We were never really able to isolate what was causing the failure," Hwang says, "but the failure was repeatable; we tested in many different facilities, and we saw the same failure in different conditions."

There weren't many other options, though. The only viable choice was something called phenolic-impregnated carbon ablator (PICA), which had been developed at Ames in the 1990s for the Stardust mission—the first to return samples from a comet, and the fastest atmospheric reentry in history. Stardust had used one continuous piece of PICA, but MSL was too large for that approach to be practical. They instead had to create tiles of the material and designed the Mars probe to be covered with them, doing so in a way that didn't allow the streamlines of gas to flow along the potentially vulnerable seams between the tiles. It was the first tiled ablative heat shield, and the largest aeroshell ever flown. (The same solution is now being used by SpaceX for its Dragon capsule. NASA loaned Dan Rasky, one of the designers of PICA at Ames, to SpaceX to

"I want to explore our solar system. We've only been to a handful of destinations. I want to go to all of them."

help design the Dragon's heat-shield material, known as PICA-X.)

As the MSL launch deadline loomed, Hwang and her team blasted PICA samples in the Arc Jet Complex at Ames, improving their understanding of the material and gap fillers with each new test. They perfected their shield in time for the 2009 launch—only to see the mission delayed until 2011 to make sure other systems were ready. The MSL eventually landed on Mars in August 2012. Curiosity is still active on Mars, and has been so successful that NASA is now developing another mission, the Mars 2020 rover, based on a similar design. Hwang has reprised her role managing the thermal protection system, which will again use PICA to shield the spacecraft as it descends to Mars in early 2021.

One of the Mars 2020 rover's most important duties will be gathering samples that may one day be rocketed back to Earth by a future lander. Even as scientists learn how to land the next generation of spacecraft on other worlds, they are also working out how to bring tantalizing alien environments back to Earth.

If humans want to land on Mars, it will require heat shields at least four times the diameter of the one on MSL. That's why NASA is now developing concepts for expandable aeroshells that can be tucked inside the launch vehicle shroud and deployed into a larger shield in space. Much of that work is being done at NASA's Langley Research Center in Virginia. On the morning of July 23, 2012, a sounding rocket blasted off from NASA's Wallops Flight Facility, across the Chesapeake Bay from Langley, on Virginia's eastern shore. The rocket carried a deployable aeroshell known as a hypersonic inflatable aerodynamic decelerator (HIAD), a broad, shallow cone consisting of an inflatable structure of doughnut-shaped tubes. The HIAD was less than a half meter in diameter, but once in space it deployed to three meters. Making the shield wider spreads the heat of reentry out across a larger area.

The rocket went 290 miles up—well above the boundary of space—and then the HIAD inflated to its full size. Onboard cameras captured a view of the Atlantic Ocean as the structure dropped through the atmosphere. The HIAD concept has performed well in these flight tests, but some people still balk at the idea of protecting Mars-bound astronauts with a blow-up aeroshell. "A lot of people say: 'Oh, you have an inflatable structure—it's going to bend up like a pool toy,'" says Robert Dillman, an aerospace engineer at Langley and a member of the HIAD team. "This thing is pretty solid. It rings when you tap it."

Larger aeroshells push shock waves farther away from the spacecraft, providing more protection from entry heat. The remaining heat is warded off by a flexible thermal protection system that covers the inflatable structure with durable outer fabrics and insulation.

The next HIAD scheduled to fly will reach low Earth orbit and expand to six meters. But these inflatable concepts are not the only expandable aeroshells in the works. A team at Ames is developing a foldable shield called the Adaptable, Deployable Entry and Placement Technology. Made from flexible 3D-woven carbon fibers, the shield pops open like an umbrella and is held steady by metal struts.

Hwang is also involved with the development of something called the Heat Shield for Extreme Entry Environment Technology (HEEET), which could accommodate missions to Venus, Saturn, Uranus, and Neptune. HEEET is far more robust than PICA and SLA-561V, and thus better suited for dense atmospheres. Traditionally, each mission has had a unique heat shield, but this makes things more expensive. Hwang hopes to achieve economies of scale—a sort of Ford Model T of reentry.

"I want to explore our solar system," she says. "We've only been to a handful of destinations. I want to go to all of them."

Becky Ferreira is a science reporter based in Ithaca, New York. Her work has appeared in Wired and the New York Times.

The SOUNDS of SILENCE

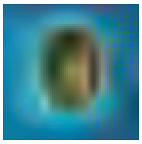
How the idea of space travel shaped rock music

The rock era and the space age exist on parallel time lines. The Soviets launched *Sputnik* in October 1957, the same month Elvis Presley hit #1 with "Jailhouse Rock." The first Beatles single, "Love Me Do," was released 23 days after John F. Kennedy declared that America would go to the moon (and not because it was easy, but because it was hard). *Apollo 11* landed the same summer as Woodstock. These specific events are (of course) coincidences. Yet the larger arc is not. Mankind's assault upon the heavens was the most dramatic achievement of the 20th century's second half, simultaneous with rock's transformation of youth culture. It does not take a deconstructionist to see the influence of the former on the latter. The number of pop lyrics fixated on the concept of space is massive, and perhaps even predictable. It was the language of the era. But what's more complicated is what that concept came to signify, particularly in terms of how the silence of space was somehow supposed to sound.

By
CHUCK KLOSTERMAN
Illustration by **KEITH RANKIN**

Far above the moon

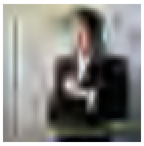
A space song playlist



Space Oddity

DAVID BOWIE

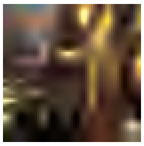
David Bowie, 1969 – This oddly pessimistic portrait of fictional astronaut Major Tom set the standard for rock musicians writing about space travel.



Major Tom (Coming Home)

PETER SCHILLING

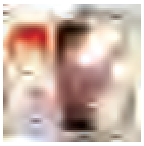
Error in the System, 1983 – Penned by a German one-hit wonder, this is the unofficial synth-pop sequel to Bowie's genre-defining single.



Starman

DAVID BOWIE

The Rise and Fall of Ziggy Stardust and the Spiders from Mars, 1972 – The lead single from the concept album about an alien who becomes a rock star.



Ashes to Ashes

DAVID BOWIE

Scary Monsters (and Super Creeps), 1980 – Bowie revisits the character of Major Tom, who is now a drug addict.

Theme to *Star Trek*

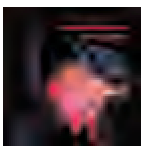
COMPOSED BY ALEXANDER COURAGE

TV debut 1966 – The sound of the ondes martenot—a keyboard that vaguely simulates a human voice—helped shape what we think of as "spacey."

4'33"

COMPOSED BY JOHN CAGE

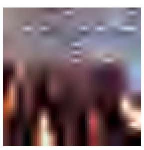
Premiered in 1952 – Space is a vacuum: the only song capturing the verbatim resonance of space is, well, perfect silence.



Planet Caravan

BLACK SABBATH

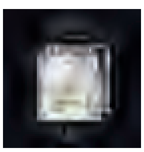
Paranoid, 1970 – Lead singer Ozzy Osbourne's vocals are processed through a Hammond organ to create a sprawling sense of ethereal distance.



Space Truckin'

DEEP PURPLE

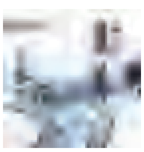
Machine Head, 1972 – Organ harmonics distorted through a ring modulator simulate a colossal spacecraft traveling at high speed.



No Quarter

LED ZEPPELIN

The Song Remains the Same, 1973 – The drone of John Paul Jones's mellotron and Jimmy Page's ultra-compressed guitar evoke an alien landscape.



Paranoid Android

RADIOHEAD

OK Computer, 1997 – The lead single from the last major rock album to use the instruments, tunings, and tempos associated with space-age pop.

The principal figure in this conversation is also the most obvious: David Bowie. In a playlist of the greatest pop songs ever written about life beyond the stratosphere, 1969's "Space Oddity" would be the opening cut, a musical experience so definitive that its unofficial sequel—the 1983 synth-pop "Major Tom (Coming Home)" by German one-hit wonder Peter Schilling—would probably be track number two. The lyrical content of "Space Oddity" is spoken more than sung, and the story is straightforward: an astronaut (Major Tom) rockets into space and something goes terribly wrong. It's odd, in retrospect, that a song with such a pessimistic view of space travel would be released just 10 days before Neil Armstrong stepped on the lunar surface. That level of pessimism, however, would become the standard way for rock musicians to write about science. Outside of Sun Ra or Ace Frehley, it's hard to find serious songs about space that aren't framed as isolating or depressing.

Bowie wrote about outer space a lot throughout his career, often brilliantly and seemingly any time he couldn't come up with a better idea. The character of Major Tom was revisited in 1980's "Ashes to Ashes," except Tom was now a drug addict. "Life on Mars?" certainly seems like a space song, but the lyrics are too surreal to denote anything literal. Bowie made an album in 1997 titled *Earthling* that used the cosmos as context for where we already were. The most notable entry in his entire catalogue is *The Rise and Fall of Ziggy Stardust and the Spiders from Mars*, a 1972 concept album about an alien who becomes a rock star. It would earn Bowie the unofficial position of poet laureate of outer space.

Still, there are three details about Bowie's cosmological obsession that complicate the conventional wisdom. The first is that "Space Oddity" was not inspired by NASA, but by Stanley Kubrick's 1968 movie *2001: A Space Odyssey*. It's fiction based on fiction. The second is that Bowie's space fixation usually focused on aliens coming *to* our world (as opposed to us going to theirs). This is the case not only in his music, but also in his 1976 film *The Man Who Fell to Earth*. The third detail is that Bowie generally used space as a narrative device. He did not try to give his music a distinctly non-terrestrial feel (half the songs on *Ziggy Stardust* are about aliens, but the music is textbook glam). The only time he directly tried to interpret the imaginary sonics of space—cold, mechanical chords devoid of hooks—was on the original version of "Space Oddity." Still, the singularity of that interpretation can't be minimized. The influence of his attempt had real ramifications. It remains ground zero for the ungrounded.

Space is a vacuum: the only song capturing the verbatim resonance of space is John Cage's perfectly silent "4'33"." Any artist purporting to embody the acoustics of the cosmos is projecting a myth. That myth, however, is collective

COURTESY IMAGES

and widely understood. Space has no sound, but certain sounds are “spacey.” Part of this is due to “Space Oddity”; another part comes from cinema, particularly the soundtrack to *2001* (the epic power of classical music by Richard Strauss and György Ligeti). Still another factor is the consistent application of specific instruments, like the ondes martenot (a keyboard that vaguely simulates a human voice, used most famously in the theme to the TV show *Star Trek*). The shared assumptions about what makes music extraterrestrial are now so accepted that we tend to ignore how strange it is that we all agree on something impossible.

The application of these clichés is most readily seen in the dawn of heavy metal. The 1970 Black Sabbath song “Planet Caravan” processed Ozzy Osbourne’s vocals through a Hammond organ to create a sprawling sense of ethereal distance. Deep Purple’s 1972 “Space Truckin’” used ring modulation to simulate a colossal spacecraft traveling at high speed. The lyrical content of Led Zeppelin’s “No Quarter” is built on Norse mythology, but the dreamlike drone of John Paul Jones’s mellotron and Jimmy Page’s ultra-compressed guitar mirrored the sensation of exploring an alien landscape. Unsurprisingly, the ambiance of these tracks merged with psychedelic tendencies. The idea of “music about space” became shorthand for “music about drugs,” and sometimes for “music to play when you are taking drugs and thinking about space.” And this, at a base level, is the most accurate definition of the genre we now called space rock.

More ideologically intertwined with ’60s prog than ’70s metal, the qualities of space rock are delineated by the mood they manufacture: hypnotic song structures, punctuated by distortion that’s heavier than the riffs. The lyrics tend to be low in the mix and not particularly essential, but the focus on the galactic is overt: Hawkwind’s 1973 live album *Space Ritual* featured voice narration from sci-fi poet Robert Calvert. Because space rock songs tended to be long, meandering, and performatively trippy, they weren’t much played on commercial radio, with one notable exception: Pink Floyd. That exception, much like Bowie’s “Space Oddity,” culturally dwarfs the totality of its competition.

When rock was new, space was new—and it seemed so far beyond us. Anything was possible.

Dark Side of the Moon, Pink Floyd’s eighth studio album, is the most durably popular rock album ever recorded, selling nearly 50 million copies and remaining in the Billboard Top 200 for 917 weeks after its release in 1973. It’s a concept album, and it’s not about the moon. It does, however, allow a teenager lying in a dark room to feel as though that is where he’s going. The apotheosis of all the fake audio signifiers for interstellar displacement, *Dark Side of the Moon* (and its 1975 follow-up *Wish You Were Here*) perfected the synthesizer, defining it as the musical vehicle for soundtracking the future. Originally conceived as a way to replicate analog instruments, first-generation synthesizers saw their limitations become their paradoxical utility: though incapable of credibly simulating a real guitar, they could create an unreal guitar tone that was innovative and warmly inhuman. It didn’t have anything to do with actual astronomy, but it seemed to connote both the wonder and terror of an infinite universe. By now, describing pop music as “spacey” usually just means it sounds a little like Pink Floyd.

If America’s obsession with the space race during the 1960s explains the rise of space rock in the ’70s, it follows that waning public interest in NASA (post-Apollo) led to a decline in space-related music in the ’80s and ’90s. Tunes like “Space Age Love Song” by Flock of Seagulls or “Space Is the Place” by Spacehog did not seem inspired by anything unworldly; they just seemed to use the word “space” as a meaningless monosyllabic placeholder. Soundgarden’s “Black Hole Sun” derived not from an interest in the sky but from a misheard TV report. Even the most serious attempts contained elements of kitsch and caricature: the UK outfit Spacemen 3 was maybe the best of the bunch, but the group’s music was overshadowed by their comedic self-awareness. The last major rock album that felt like music from space was arguably Radiohead’s *OK Computer*, but the connection was ancillary. The band was simply using the instruments, tunings, and tempos that have become associated with space-age pop. The audience felt the correlation more than the artist.

What has happened, it seems, is that our primitive question about the moon’s philosophical proximity to Earth has been incrementally resolved. What once seemed distant has microscoped to nothingness. When rock music was new, space was new—and it seemed so far beyond us. Anything was possible. It was a creative dreamscape. But you know what? We eventually got there. We went to space so often that people got bored. The two *Voyager* craft had already drifted past Pluto before Nirvana released *Nevermind* in 1991. You can see a picture of a black hole in the New York Times. The notion that outer space is vast and unknowable has been replaced by the notion that space is exactly as it should be, remarkable as it is anodyne. In 1997, one of the former members of Spaceman 3, Jason Pierce, made an album with his new band, Spiritualized, titled *Ladies and Gentlemen, We Are Floating in Space*. That title was a reference to a Norwegian novel, but it accidentally illustrated precisely how much perception had changed. Space was no longer somewhere to go. Space was where we already were, all the time, and we were just floating along for the ride.

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In her light

By Deji Bryce Olukotun

First NASA launched a few nanosatellites as experiments. Then a private space company sent up 300. Soon every government and major corporation had its own satellite network, and nearly a million nanosats were sprayed throughout low Earth orbit in twinkling constellations. No one wanted to talk about the sexual symbolism, because it was crude, which meant no one remembered that men left by themselves who are inflamed with passion can create quite a mess.

Someone needed to clean it up, and I was happy to sign up for the job. I had lingered on the B-list of human spaceflight for two decades after completing my service with the Royal Canadian Navy, supposedly because of my poor scores in leadership potential. This bothered me because not everyone needs to be a leader, to stick out their chest and tell others what to do. Thankfully, Bass-Xianhou Limited found my skills highly desirable—in particular, my work running a salvage operation for a decommissioned submarine in Baffin Bay. I joined a hundred other candidates from around the world to become an orbital ballistics control operator, or OBC—a sanitation worker of the stars.

My partner at Bass-Xianhou was Nanjira Yego, an aspiring astronaut from Mombasa with dyed blue braids who liked to wear heat-sensitive midriff tees and sparkling sneakers. During our training in French Guyana, Nanjira was a quiet, introspective loner who spent her free time jacked into StarWorlds, a massive online game. While I still harbored fantasies of finding the Right Stuff and becoming a Mars explorer, Nanjira visited imagined planets without any sense of embarrassment about our real-life jobs.

But in space, Nanjira transformed into a confident OBC operator who liked to question authority. She even sewed political patches onto her flight suit: *FREE UBUNTU! LIGHT BRIGADE. QUANTUM SPIN CLASS*. I found her brashness appealing, as if she could make up for my own conformity and meekness. She was a kind of anti-leader I wanted to follow, if that makes any sense. On the station I would try to work up the courage to invite her out, but we had little privacy under the banks of LED lights, so I would inevitably do nothing. Back on the surface, though, she would immediately immerse herself in StarWorlds, leaving me to bury my feelings for her through the intensive workouts they made us do to counter the effects of the time we spent weightless.

There was no press release or fanfare before our first mission. No endorsements of breakfast cereals or underwear. Bass-Xianhou booked us on an Ariane 6 out of French Guyana and hurled us into space along with three other sanitation teams. Once at the station, we docked for 24 hours to acclimatize, slept as much as we could, and then headed out to work.

Nanosats orbited closer to Earth than heavy satellites, which meant they offered

TIM PEAKE/JSC/NASA

lower latency and more stable communication. The latest ones adjusted dynamically to transmit data like a mesh network, but no common protocol had been developed between competing manufacturers, so sometimes they careened dangerously out of orbit. There were already millions of pieces of debris in orbit before the nanos, from discarded rocket stages to loose screws and lost tools, but the little satellites worsened the problem because many of them failed, adding to the detritus. The most legendary constellation belonged to Estée Lauder: a network of nearly a thousand gold-plated nanos that had immediately malfunctioned upon launch, and yet were rumored never to have fallen out of orbit. The talk amongst us OBCs was that if you caught them, you only had to extract the gold and you would retire in luxury.

Our job was to clean out the various giant nets that Bass-Xianhou had launched into different orbital planes. These nets had their own stabilizer jets that held them in orbits with known accumulations of debris. Like lobster fishermen, Nanjira and I would visit each "trap" on a prescribed route, spacewalking in tandem to the nets to extract the debris that had accumulated over weeks. Nanjira would bark instructions—"Up 20 degrees! Reverse, and four to the right!"—and I learned to listen to her. The general principle was to haul the debris back to the station, fish out the nanos, and repair the ones that still had some life in them, which reaped Bass-Xianhou extra revenue. The rest of the debris we would jettison to burn up in the atmosphere.

If it seems like a strange job, that's because it was. Bass-Xianhou had never planned to launch humans into space, only automated drone sanitation systems. Their prototypes, however, weren't nimble enough to pick the debris out of the nets. They had already secured several billion dollars' worth of contracts, so they sent us OBCs as a stopgap. I didn't gripe—the pay was good, and it beat salvaging submarines.

We catalogued each nanosat we collected. Many were from the so-called Third Tier of spacefaring nations—even minuscule São Tomé and Príncipe had managed to lob a few up. Some were labeled or had a scannable bar code, but other models—especially those that had been irradiated or damaged by a flare—did not show clear ownership. We were supposed to return unclaimed nanos to orbit, but sometimes, after taking a few plugs of whatever booze someone had smuggled aboard in French Guyana, we'd toss them out of the airlock to watch them burn up in the atmosphere. Nanjira liked to sprinkle different chemical compounds atop them like sesame seeds so that they would pop with bright colors.

It was juvenile, to be sure, but such moments helped us let off steam, because our work was dangerous. One time, a crew member returned from a spacewalk with his leg mashed by a chondrite meteoroid. His superkevlar suit had prevented it from being severed, but it flopped about like a tube of jelly. We had to put him into a partial coma and dispatch him back to the surface in an escape pod.

The station was skirting above the bleached white crust of the Great Barrier Reef one night when I noticed that Nanjira had disappeared into the toilet for longer than usual.

"You all right in there?" I shouted.

"Yes, why?"

"You've been in the head for a while."

"You need to go?"

"No."

"Okay, so wait your turn."

I busied myself by sorting the nanosats we'd collected: REPAIR, RETURN, or DISCARD. I logged seven Safaricoms and four Dancoms in the REPAIR category, at about a $500 bonus for each; 30 miscellaneous (mostly Iroko) in the RETURN pile; and then eight for the DISCARD pile, which we would jettison.

After Nanjira returned from the bathroom, I re-counted our haul and found that we now had 12 in the REPAIR bin.

"Where did you find that extra nano, Nanjira?"

"We got it outside."

"I don't remember grabbing it."

"Leave me alone, Marcus."

I decided not to press her. Instead, I examined the nano, made a few minor repairs, and relaunched it into orbit the next day. Still, I found it suspicious that Nanjira would keep secrets from me on the station. We could activate privacy screens that shielded out sound and light, but we knew each other intimately. After the gravity centrifuge stopped working one day, we had to race through the station to catch turds that had escaped from the toilet. When your fellow crew member's poo gets on your face, there's not much else you can be embarrassed about.

The next haul was a lucrative one. Nanjira and I maneuvered together, balletic in our coordination, to collect our haul from a net on an especially difficult orbital plane. Yet the moment we docked, she disappeared into the toilet and stayed there for 15 minutes. I barged in to find her dismantling a Dajiang MS142, a variant of a common Asian nanosat.

"Why are you doing that in here?"

"No cameras," she said, pointing at the walls. It was true—the toilet was the one area of the station that even Bass-Xianhou did not observe. She inserted a tool that looked just like the one we used to plug in to nanos so the system could analyze them. Then she adjusted a piece inside the satellite, and screwed the plate shut.

"Will you tell me what you're doing?"

She shook her head. "It's better if you don't know."

Back on Earth, I grew nervous when the management at Bass-Xianhou called an emergency meeting, thinking that perhaps Nanjira's tinkering in the toilet had been discovered. Instead, our route planner explained to us that an Israeli-French firm had cracked the so-called automation problem and was expected to launch its first products within a year—drone sanitation systems with no need for a human crew. To cut back on costs, Bass-Xianhou was reducing our bonus pay for fixing REPAIRS. We would also be subjected to random audits.

WE WATCHED THE JAGGED HORN OF AFRICA SLIDE BENEATH US, PINPRICKS OF LIGHT SPREAD ALL OVER, WITH CORRIDORS OF ILLUMINATION LINKING THE CITIES ACROSS THE REGION. "THERE—WHAT DO YOU SEE, MARCUS?"

"You've all signed noncompete clauses," the vice-president of the company growled. "So don't bother selling out to those copycats, or we'll sue your ass."

But on our very next route, once again I found Nanjira squirreled away in the toilet fixing a Dajiang.

"Aren't you afraid of being caught, Nanjira?"

"No," she said, shaking her head. "I'm almost done."

"Almost done with what? Can you at least tell me? We've worked together for nearly three years now, and for all I know we're about to lose our jobs. What are you doing to those nanos? Spying for the copycats?"

"You really want to know?" Nanjira asked.

"Yes."

"Follow me."

We climbed some handholds to the small cafeteria, actually just a table folded into the wall, and she pointed through the large observation porthole. I could smell the geranium-scented wipes she used to mop her brow after we completed a route. We watched the jagged Horn of Africa slide beneath us, pinpricks of light spread all over, with corridors of illumination linking the cities across the region. "There—what do you see, Marcus?"

"Maglev lines."

"You see the connections. Your eyes are drawn to the light. But what's in the dark?"

"I don't know," I said. "Desert. Mountains."

"Many people," Nanjira said, wistfully. "Many people live in that darkness."

"That's why we're up here," I said. "To service the nanos. To help those people stay connected." This was our sacred responsibility, instilled in us by Bass-Xianhou on our first day.

But she had a determined look in her eye. "Connected to what? What are they connecting to?"

"To each other," I blurted. "To information. To knowledge. Knowledge about their lives and how they can live them better. It's why everyone has the right to a node now."

She gave me a look that I wanted to interpret as fondness.

"The right to a node? Sure. A node that harvests their data, feeds them ads and propaganda, filters out what they aren't supposed to see." She swept her hand across the Earth beneath us. "Think of all this spectrum, Marcus. All of that light beaming information down to the planet from the nanos. All I'm doing is taking a little slice of that spectrum. A tiny, infinitesimal sliver that's rarely used."

"You're talking about stealing."

"I'm talking about untapped potential."

"Our job is to maintain the network. You shouldn't get your hands dirty in all this."

"*My* hands are dirty?" she said, smiling. "Take a look at our catch next time and tell me if you really believe that."

I did take a look the next time, and I didn't see anything particularly strange about our catch. In fact, we had a bumper crop: nearly 100 nanos, with three dozen Standard Bank crypto-nanos in prime REPAIR condition, and 12 Mo-Cola energy drink nanos that seemed serviceable. Nanjira did her thing and disappeared once again into the toilet after fishing a Dajiang from the spoils.

We were fortunate to have made that haul, because we soon received notice from Bass-Xianhou that our program was going to go through "slimming." The French-Israeli competitor had underbid us on a major contract and our company was now planning to shift to servicing government-owned nanos, which were much less lucrative but would offer a stable source of income, according to our executives.

Strangely, Nanjira didn't seem bothered by the news. In fact, she laughed more easily and joked with the other crew members without a care in the world. I wondered if she had taken too many stims, and whether there would be enough left over for me—we'd been working for nearly 72 hours straight.

"It's finished," she announced, happily.

"You mean you're done with your thieving," I goaded.

"Marcus, no one should own the light. The nodes are corrupted. Every single one is owned. We need a pure band, not an on-ramp to some bullshit data mining or shopping experience. It's what we deserve."

"That's how the internet was in the beginning," I said, "and it was polluted. That's why we controlled it. Humanity wasn't ready."

"This is different, Marcus. We're building it within—tunneling through the very heart of the beast. This spectrum will live in the center, hidden as if behind a cloud, and belong to anyone who can find it."

Her passion for the cause made me want to kiss her, but she was looking at me as if I were a poor student who might one day, with a little extra effort, catch on.

We didn't speak much before our next route, yet we behaved like total professionals as soon as we left the airlock. Nanjira barked instructions and I swiftly complied, even more eager to please her than before, as if I could reconcile our differences that way. We extracted over 50 nanosats from the net in record time. I managed to grab one in my glove. It was about five centimeters wide and coated in shimmering gold. It was clear its stabilizing propulsion system was still active, giving off light puffs of air like a perfume bottle. Only its uplink was switched off.

I FOUND MYSELF LINGERING IN THE LIVING ROOM OF HER FAMILY'S COMPOUND, TRYING TO MAKE SENSE OF HER JOURNEY FROM KENYA TO THE STARS.

"Nanjira!" I shouted. "We found them!"

"What?"

"The Estée Lauder constellation! We hit pay dirt!"

"Are you sure—" she began, and then it sounded as if someone had punched her in the gut.

"Nanjira?"

I looked along the net. She had crumpled over in her propulsion chair and was trying to remove her boot, her fingers fluttering at the straps. Her chair suddenly began accelerating toward the net.

"Watch it, Nanjira! Shut off your jets!"

Except she kept on trying to unstrap her boot, as if it were the most important thing in the world.

"Home!" I shouted to the station. "Status on Nanjira."

A voice crackled back. "Heart rate spiked. Air is intact."

Her chair had now pushed into the center of the net, which was starting to coil and swoop down upon her like a giant wave. If she became entangled, it would be almost impossible to extract her.

"Marcus ..." I heard her whisper.

"Roid shower!" home announced. "Escape protocol."

"There's something wrong with her."

"Escape protocol!"

"I'm telling you she's not responding!"

I could see the streaks in the corner of my vision, some of the meteoroids catching in the net, while the microscopic ones pushed right through it and flamed into the atmosphere. I launched myself toward my partner.

"Nanjira!" I yelled. "I'm coming!"

A roid slid past my visor as I unfastened her from her chair and clipped her to my own. Then my escape jets flung us away and back toward the station.

"We hit pay dirt, Nanjira," I found myself saying over and over again. "Pay dirt." But she only moaned. Back in the airlock, she slumped against a wall as I disrobed from my suit. Now I saw why she was trying to unstrap her boot—it was bulging as if it had filled up with water. But when I released the strap, blood gushed into the airlock.

"No!" I shouted. "No! No!"

The medic entered the airlock, unbolting Nanjira's helmet, her blue-dyed braids drifting up around her head. Her eyes were open as if she were staring into a brilliant light. I began waving my hand in front of her face. "Nanjira! Wake up. Wake up!"

"Sensors 14 through 45 were triggered. Traumatic impact."

"No!" I said. "It's just blood. We can fix this. Snap out of it, Nanjira!"

"She's dead, Marcus."

Through the porthole, I saw the net filling up with meteoroids and starting to fall slowly, inexorably, toward the planet.

At her funeral in Mombasa, Nanjira's family probed me with questions to determine if we had been lovers, as if such intimacy, even unsanctioned, would impart some dignity to her passing. I felt ashamed that I couldn't even offer them that, when she herself had mustered the strength to utter my name in the midst of all that pain. I found myself lingering in the living room of her family's compound, trying to make sense of her journey from Kenya to the stars. She was by no means poor, as I had stupidly assumed, and clearly came from a prosperous and loving family.

Her kid sister tugged at my arm and pulled me toward Nanjira's bedroom. "Nanjira wanted you to see this," she said.

Her sister had set up a node for me, and hooked me into the game. My entire field of vision was filled with ships: dreadnaughts, cruisers, fighters, battle destroyers, transports, ice tugs, seemingly every ship ever imagined or built in StarWorlds. In the vastness, a spinning wheel of white light opened and the ships began moving toward it. It looked like an event horizon with a beautiful corona. This was it, I understood. This was the spectrum Nanjira had sliced away from those nanos, her tunnel into a new, unfettered place where our words could mean what we wanted them to mean. One by one the ships began to approach the corona and disappear. I joined them, moving toward the light.

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