Bloomberg Businessweek
July 30, 2018

Special Issue

THE NEW SPACE AGE

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COUNTDOWN

A crowd on the beach in Titusville, Fla., watches the launch of Apollo 11, the first manned mission to land on the moon, on July 18, 1969.

Photo © David Burnett/ Contact Press Images

■ They say there are only two plots: Species goes on a journey, and aliens arrive in town. UFO sightings aside, humans have been living the first story for decades. The first stage of the trip began in 1957, when *Sputnik 1* arced its way around the world, and ended in 1972, when Apollo 17 Commander Gene Cernan traced his daughter's initials in moondust and stepped off the lunar surface. The second big stage is upon us now.

A trail marker was laid down in February, when SpaceX equipped a Falcon Heavy rocket with a Tesla Roadster and a data crystal containing Isaac Asimov's *Foundation* trilogy and fired it toward Mars, then landed two of the Falcon's boosters in synchrony at Cape Canaveral. At least 2.3 million people watched the YouTube livestream—high by internet standards, if far short of the hundreds of millions who tuned in for the first moon landing. Where the Apollo era was marked by singular, cost-is-no-object technological feats and suffused with political and cultural meaning, the new one has been more diffuse and democratic, fueled by ever-cheaper launches that have opened space to startups, researchers, and smaller countries. A full-fledged space economy is within reach, and with it, perhaps, a permanent human presence above.

Technology has, in stunning fashion, shown us that we can become a spacefaring species. But those of us who don't speak vector calculus will be more than gawkers. We'll help to determine how we go. The shift to a more accessible, urgent, and potentially profitable era of space exploration means there are decisions to make about ownership, environmental impact, and more.

The groundwork for these debates was laid by the Outer Space Treaty, which went into force in 1967, almost exactly 10 years after *Sputnik 1* was ▶

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Photo ☐ Courtesy Smithsonian's National Air and Space Museum

A UV image of the glove Neil Armstrong wore when he left the Apollo 11 lunar module to walk on the moon.

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1

◀ launched. The pact's full name—the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies—captures its spirit. With its first article, the accord held that space exploration "shall be carried out for the benefit and in the interests of all countries, irrespective of their degree of economic or scientific development, and shall be the province of all mankind." It also banned weapons of mass destruction in space, forbade national appropriation by claim of sovereignty, and made parties to the treaty responsible for nongovernmental actors based on their soil.

At the time, the pact was seen as a way to head off some of the dystopian nightmares fed by the Cold War and the nuclear arms race. But it also created an optimistic road map, casting spacefaring as a collective project, led by the great powers yet leaving no one behind. Signing the document, the famously combative Lyndon Johnson sounded downright un-Johnsonian. "It means that astronaut and cosmonaut will meet someday on the surface of the moon as brothers," he said, "and not as warriors for competing nationalities or ideologies." Of course, Johnson had just dramatically escalated the Vietnam War. Nationalities and ideologies die hard.

In the wake of the Apollo missions, the United Nations forged an even more idealistic pact, the Moon Treaty of 1979. Although Armenia became the latest country to accede to it earlier this year, it has mostly foundered, with only 18 parties. Partly this is because the U.S. backed off, under pressure, according to news reports of the day, from the L5 Society, a 3,600-member collection of space-colony enthusiasts. A lobbyist for the group testified that the treaty—which cast the moon and its resources as "the common heritage of mankind"—would create "a ▶

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Photo □ Michael Friberg

The Soyuz launch pad at the European Space Agency's spaceport in French Guiana.

◀ system of international socialism" and "foreclose the commercial uses of outer space by American private enterprise."

Since then, U.S. governments have carved out a bigger role for space capitalism. Under Ronald Reagan, NASA created a commercial programs office. George W. Bush released a policy that emphasized private contracting. Barack Obama signed the U.S. Commercial Space Launch Competitiveness Act, which held that American citizens could keep anything they brought back from space. (One asteroid-mining executive called this "the single greatest recognition of property rights in history." Others saw it as potentially contravening the Outer Space Treaty's prohibition on national appropriation.) And Donald Trump issued a directive establishing a regulatory "one-stop shop" under the Department of Commerce for companies seeking to launch satellites, land on asteroids, or build fuel stations on the Saturnian moon of Mimas.

Just how big a space economy could get is impossible to know, though Morgan Stanley released a study last year estimating that revenue from the global industry will increase to at least $1.1 trillion by 2040, more than triple the figure in 2016. The company ascribes much of that future growth to satellite and rocket services, anticipating products such as orbital internet and even rocket package delivery. It doesn't account for the more aspirational possibilities presented by tourism or mining, nor by megaprojects such as NASA's Lunar Orbital Platform-Gateway, a proposed staging ground for lunar and other deep-space missions.

The moment has echoes of the early seafaring and railway eras. Forge the infrastructure, the thinking goes, and ingenuity will take it from there. The innovations—and abuses—of those eras argue for careful thought as the tracks go down, though. Will the Commerce Department take care to ▶

Data ☐ Morgan Stanley

Global space economy

Photo ☐ Sean Lemoine

A man and his rocket in the Mojave Desert for LDRS, an annual rocketry event, in June 2016.


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◀ prevent space-junk proliferation and ozone-layer depletion? Will it favor the concerns of the wealthy over the interests of the public at large? The megarich are naturally champing to chart humankind's exploratory course. Jeff Bezos, the centibillionaire Amazon.com founder, wants his startup Blue Origin to land on the moon by 2023, in advance of human settlement. Elon Musk's SpaceX hopes to put people on Mars the following year.

Americans are skeptical about who will benefit from space and how far our ventures should go. A survey conducted by Morning Consult for *Bloomberg Businessweek* found that only 37 percent of respondents—drawn from a spectrum of backgrounds and political affiliations—thought private companies should play a major role in space exploration. Some 45 percent thought they should play a minor role, and 18 percent said they should play no role at all. Asked whether they thought humans should colonize the moon, those surveyed were almost evenly split; asked who should oversee any colonization of other planets, 58 percent said a coalition of global governments.

The results suggest a persistent idealism about space—a belief that it's a place to which humankind has a common claim (at least until those aliens show up). But that vision won't be realized by default. It requires considered decisions: boring committee discussions and multilateral negotiations informed by public interest, public pressure, and public consent. Governments are constantly interpreting the Outer Space Treaty, asking themselves how to conform to it and what values it expresses. It's a good foundation. In so many realms, from climate change to economic inequality and more, we've seen how hard it is to fix the problems we create. In space, we have a chance to get it right from the start. Ⓑ —*Jeremy Keehn*

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Data ☐ Morgan Stanley

Photo ☐ Courtesy ESA

The surface of a comet, seen from 1.7 miles above. The image was captured by the *Rosetta* space probe on Sept. 2, 2016.

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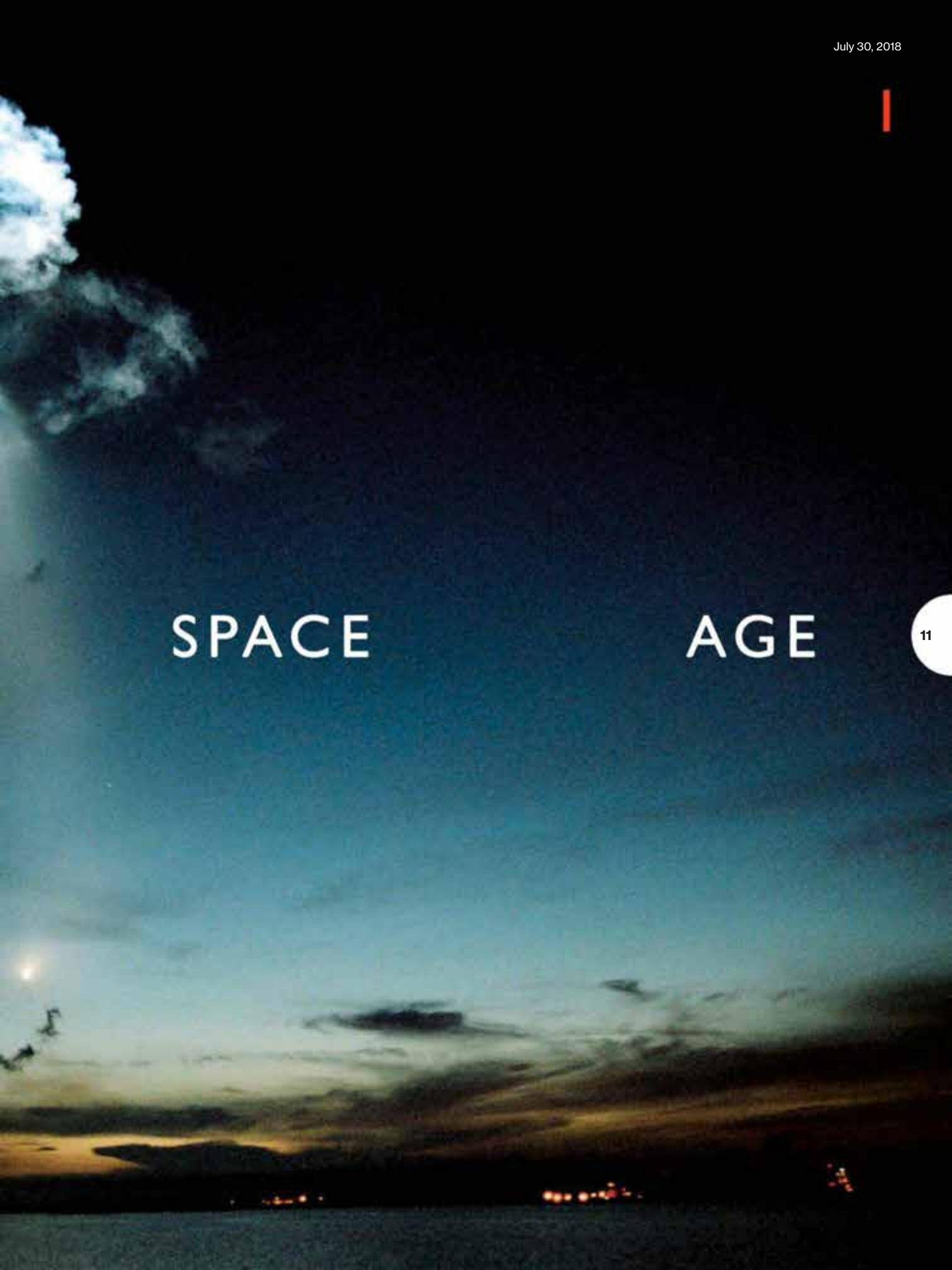
THE NEW

A SpaceX Falcon 9 en route to rendezvous with the International Space Station on June 29.

Photo ☐ Steven Brahms for Bloomberg Businessweek


SPACE AGE

LAUNCH

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Photo ☐ Courtesy World View

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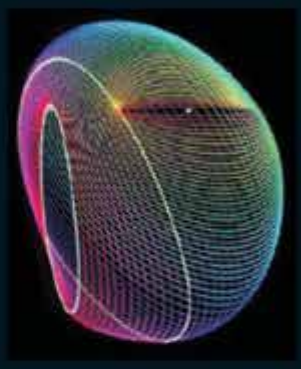
SpaceX Falcon 9 launch on April 18, 2018, Cape Canaveral, Fla.

Photo ☐ John Kraus

Photograph by Steven Brahms

Photograph by John A. Chakeres

II ORBIT



Satellite image ☐ Courtesy Iceye. Rendering ☐ Courtesy Purdue University School of Aeronautics and Astronautics, Ai Solutions

Photograph by Tony Luong

III FAR OUT

Photo ☐ Raffaele Petralla/ Prospekt

Image ☐ Courtesy ESA

I LAUNCH

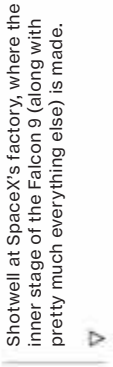
Photo ☐ Courtesy NASA

The space shuttle *Endeavor* blasts off from Kennedy Space Center on May 25, 2011.

"WE'VE

Launching spaceships, selling $60 million rockets, dealing with Elon Musk, and other amazing feats of SpaceX's Gwynne Shotwell

By Max Chafkin and Dana Hull
Photographs by Steven Brahms



Shotwell at SpaceX's factory, where the inner stage of the Falcon 9 (along with pretty much everything else) is made. ▷

■ In early February, Gwynne Shotwell arrived in Saudi Arabia for a bit of last-minute cleanup. SpaceX, the rocket company where Shotwell serves as president and chief operating officer, was days away from its most ambitious launch yet. Its new rocket, Falcon Heavy, would have a larger capacity than any that had lifted off in the U.S. since the Apollo era. And unlike NASA's Saturn V, which last flew in 1973, the Falcon Heavy would be reusable, capable of bringing its three boosters back from the edge of space and landing them vertically. To make the rocket's first flight even more memorable, Shotwell's boss, SpaceX founder and Chief Executive Officer Elon Musk, wanted the experimental payload to include his own sports car.

If all went well, Musk's cherry-red Tesla Roadster would be propelled toward Mars with a spacesuit-clad dummy behind the wheel and David Bowie's *Life on Mars?* playing on the stereo. "Destination is Mars orbit," Musk tweeted in early December. "Will be in deep space for a billion years or so if it doesn't blow up on ascent." News organizations around the world were soon scrambling to cover the launch. "It's either going to be an exciting success or an exciting failure," Musk told CBS News on Feb. 5. "One big boom! I'd say tune in."

But Shotwell wasn't thrilled about the buzz Musk was generating. SpaceX's customers pay the company tens of millions of dollars to ferry their $100 million satellites thousands of miles into space. As a general rule, it's unwise to have them envisioning big booms. And so, with just two days to go before the launch, Shotwell was paying a visit to the Riyadh headquarters of the Arab Satellite Communications Organization (Arabsat), which had reserved a Falcon Heavy launch. "I needed to get way more across than what was in the tweets," she says.

This was familiar territory for Shotwell. The ▶

GOT

THIS"

◀ 54-year-old engineer has worked with Musk since SpaceX's founding in 2002, longer than almost any executive at any Musk company. She manages about 6,000 SpaceX employees and translates her boss's far-out ideas into sustainable businesses—whether it means selling customers on a rocket or telling them not to read too much into @elonmusk.

She's succeeded remarkably. In fact, SpaceX, the business, might be as impressive as SpaceX, the showcase for Muskian wizardry. The company is privately held—Musk owns a majority stake, alongside investors such as Google, Fidelity Investments, and Founders Fund—and doesn't disclose revenue. But last year its workhorse Falcon 9 rocket reached orbit 18 times, more than any other launch vehicle in the world. SpaceX, which now has more than half of the global launch market, has signaled it would do about 30 launches in 2018, including at least one more Falcon Heavy launch later in the year. The company is worth $28 billion, making it the third most valuable venture-backed startup in the U.S., after Uber Technologies Inc. and Airbnb Inc.

Shotwell has rarely taken credit for any of this. "I try to run the company the way I think Elon would want me to run it," she says. "He makes great decisions with good data. It's irritating that he is right as often as he is." That's not to say he's always right. Years earlier, Musk ordered Falcon Heavy canceled, forcing Shotwell, who'd been tipped off by another SpaceX employee, to sprint to a conference room and remind him that the U.S. Air Force, a critical customer, had already purchased a launch.

In Riyadh she told Arabsat that though Musk had evoked the prospect of a fiery failure, he didn't mean exactly that. "I said, 'Look, Elon is just trying to set the stage to make sure that people understand that this is a demo flight,' " Shotwell says. "We are not going to lift off if we actually think the probability is as bad as 50-50."

She acknowledged, though, that Falcon Heavy was a new rocket and thus carried some risk. She described the key areas SpaceX was hoping to test—for instance, the separation mechanism that allowed two side boosters to detach from the rocket's center stage and land. "If this one doesn't work," she told them, then the next one would. "We've got this."

After the Feb. 4 meeting in Saudi Arabia she flew to London for a meeting the following day with Inmarsat Plc, Falcon Heavy's other big customer. Then she boarded a plane to Florida to survey the launch pad at Cape Canaveral, then another to California for the Feb. 6 launch. She arrived at SpaceX's headquarters in Hawthorne, 15 miles south of downtown Los Angeles, only 40 minutes before scheduled liftoff, settling herself into mission control in a large auditorium separated from the main factory by enormous glass walls.

The launch didn't go perfectly—the center booster crashed into the Atlantic Ocean and was destroyed—but few of the people watching even realized SpaceX had planned to land it. Most were captivated by the pictures of Musk's sports car sailing into oblivion, with Bowie blasting and the blue Earth in the background. Then they saw the two side boosters execute a perfectly synchronized landing.

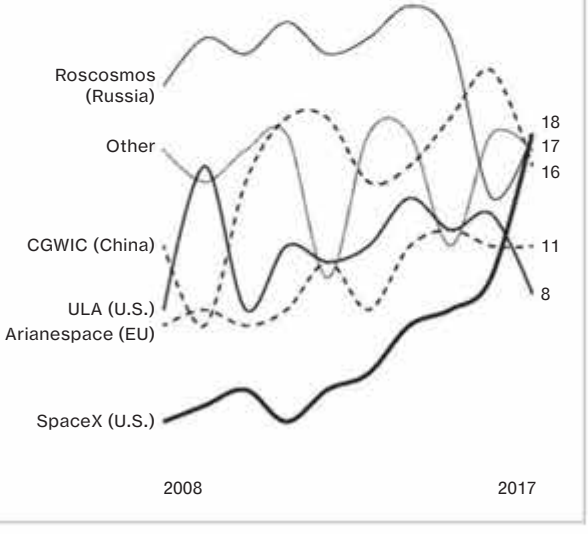
That night, President Trump tweeted a video of the launch with a note of congratulations to Musk. He called Falcon Heavy "American ingenuity at its best." Musk responded, "An exciting future lies ahead!" Shotwell made no public statement, but in a SpaceX video she could be seen standing up in the control room, pumping her arms. "Gwynne has been able to provide this constant, consistent, positive leadership for SpaceX," says Lori Garver, a former deputy NASA administrator and the co-founder of the Brooke Owens Fellowship, which supports young women in aerospace careers and counts Shotwell as a mentor. "The public may not be as aware of her, but in the space community she is as big of a rock star as he is. If someone wants a keynote speaker or someone to testify at a congressional hearing, it's always, 'Let's get Gwynne.' "

■ For someone who's spent much of her career behind the scenes, Shotwell is less restrained in person than one might imagine. She drives a red Tesla with space-themed vanity plates and favors designer boots. During a rare interview with *Bloomberg Businessweek* in June, she jokes about the flamethrower she shipped to her family's Texas ranch as a Valentine's Day gift for her husband, Robert. "We're going to use that to light our burn piles," she says, grinning.

The anecdote comes across as strategic, marking Shotwell as no less capable than Musk of a little calculated craziness while also promoting her boss's work. Her flamethrower was one of 20,000 sold as part of a surreal promotion for Musk's tunneling side project, the Boring Co.

Shotwell grew up in a small town 40 miles north of Chicago, the middle child of three girls. "This is going to

Number of Rocket Launches



Data ☐ Northern Sky Research

43 feet

Having landed and reused rockets, SpaceX wants to recover the rocket's nose cone.

sound terrible," she says. "I was kind of the boy in the family. I was the hands-on kid." In grade school, she helped her dad, a neurosurgeon, build the fence around the family's suburban garden and made a basketball backboard out of plywood. She also fixed her own bicycles.

Shotwell studied mechanical engineering at Northwestern University and took a job in Chrysler Corp.'s management training program. She liked the starting salary but wasn't crazy about the conservative culture. On the first day of her first rotation, at Chrysler's mechanic training school, an instructor singled her out for wearing what he deemed a skimpy outfit, then made her stand before the class while he berated her. "I was too young to be offended," she says. She lasted 18 months and went to grad school.

She moved to L.A. and spent a decade at the Aerospace Corp., a large defense contractor, before going to Microcosm, a private space startup that designs and builds low-cost rockets and rocket parts, for a few years. She was introduced to Musk in 2002 by Hans Koenigsmann, a former Microcosm engineer who'd gone to work at SpaceX. By that time she'd had a taste of the nascent movement of entrepreneurs who were trying to dramatically lower rocket launch costs. But companies like Microcosm subsisted largely on small government contracts, making it hard to try new things (and forcing the small company to waste precious resources dealing with the government-contracting bureaucracy). Private rocket companies, as far as she could tell, essentially had the worst of both worlds.

"The commercial stuff that had gone on was failing," Shotwell says. What excited her about SpaceX was that Musk, then best known as a co-founder of PayPal, was proposing to sell launch services to private satellite providers for very low prices from the get-go. He wanted to use proven launch technologies and manufacture them as cheaply as possible, eventually reusing rockets to save even more money. Shotwell, who'd recently divorced her first husband and had two young children, knew she was taking a huge risk, but she was charmed by the audacity of Musk's plan. She signed on as SpaceX's seventh employee, becoming head of business development. "I thought, Let's see if I can go sell rockets," she says.

■ Not long after starting at SpaceX, Shotwell finagled a meeting for herself and Musk with Peter Teets, director of the National Reconnaissance Office, the U.S. intelligence agency responsible for satellites under President George W. Bush. "He kind of hugged-slash-patted Elon on the back and said, 'Son, good luck to you, but this is really hard,' " she says. "I saw Elon physically respond to that. His resolve firmed up in that moment. Like, 'I absolutely am going to prove you wrong.'" Teets could not be reached for comment.

In recent years, SpaceX has pulled off a number of impressive technical breakthroughs, most importantly landing rockets vertically and then safely using them again. But some key innovations were as much about its

business model as its rockets. When Musk founded the company, most other aerospace contractors made money through so-called cost-plus government contracts—that is, the government would come up with a spec and the contractor would meet it, usually with the help of armies of subcontractors and suppliers, then add a fixed percentage fee on top of its total cost. Unable to win (and uninterested in) this kind of business, Musk focused on developing standard products and offering them for as little money as possible. The company's first rocket, a slender single-engine missile known as Falcon 1, was sold for less than $7 million per launch, a fraction of the price of a ride with the United Launch Alliance (ULA), a joint venture between Lockheed Martin Corp. and Boeing Co. that is now SpaceX's fiercest competitor.

Musk's strategy made Shotwell's job crucial. She had to sell a rocket to satellite companies, even though the rocket had never actually flown, and she had to persuade NASA and the military to fund SpaceX's demonstration flights. The company's early customers: the Defense Advanced Research Projects Agency, the U.S. military's research arm, which paid for its first three launches, and a Malaysian state-owned satellite startup, which paid for a fourth. The final and most important early backer: NASA, which in 2006 awarded SpaceX a $400 million contract to develop a larger rocket, Falcon 9, that would be capable of bringing cargo and people to the International Space Station. "That astonished people," says Koenigsmann, SpaceX's vice president for mission assurance and a longtime friend of Shotwell's. "She was selling stuff to NASA at a time when we had a little rocket on an island. That takes bravery and vision."

The first and second launches of Falcon 1, in 2006 and 2007, failed. So did the third, in 2008, which went down ▶

◀ a few minutes into the launch sequence. The first stage of the rocket normally runs out of fuel and detaches, leaving a second, smaller engine to finish the trip, but after detaching, the first stage kept going and crashed into the second. "It was almost Monty Pythonesque," Shotwell says. "We rear-ended ourselves." Musk was devastated, but she spun the launch as a success in conversations with customers. Yes, it had ended in failure, but the only fix Falcon 1 needed to get successfully into orbit—to be shot well, as it were—was to allow a little more time before the stages separated. "When I saw the video, it was like, 'OK. We can figure it out,'" she says.

Amazingly, her assurances worked. The Malaysians didn't dump SpaceX, though the company did launch a dummy version of the Malaysian satellite before shooting off the real thing. Falcon 1 reached orbit for the first time in September 2008. Three months later, NASA, satisfied with the company's progress, awarded it a $1.6 billion contract that called for SpaceX to develop a capsule that could dock with the International Space Station. NASA bought 12 missions using Falcon 9 and the new spaceship, Dragon, to take cargo there.

The flights cost NASA about $133 million each, compared with $450 million for a shuttle launch. "The holy grail has always been about lowering the cost to orbit," says Garver, who was the agency's deputy administrator from 2009 to 2013. "When it's so expensive to launch a rocket, you can't get many things up there. SpaceX has done it, in the face of a lot of opposition." About the same time SpaceX won the NASA deal, Musk offered Shotwell a promotion, to president and COO. A few months after that, she joined SpaceX's board of directors. "Gwynne is a wonderful person and an outstanding leader," Musk says. "We would not be where we are today without her."

At SpaceX, she's built a reputation with customers and employees for unflappability. Musk is prone to bouts of distress and elation, and he's renowned for his hair-trigger temper, especially when challenged on technical matters. This was in evidence recently, when he lashed out at a diver who participated in the rescue of a Thai soccer team trapped in a cave. After the diver criticized a minisubmarine Musk had designed and sent to the rescue site, Musk called him a "pedo." (He later apologized.)

Shotwell eschews Twitter, and aerospace insiders commonly use the word "normal" to describe her, in a barely veiled comparison to her boss. "Gwynne is the steady hand," says Matthew Desch, the CEO of Iridium Communications Inc., SpaceX's largest commercial customer. "She's got the technical savvy, and that underpins her being a great salesperson. But she never tries to oversell, and she's always open and honest."

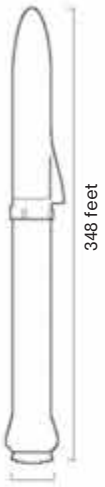
Desch began negotiating with SpaceX in early 2010, as part of a plan to put 75 satellites into space aboard Falcon 9s. The satellites would replace Iridium's existing array, allowing it to handle broadband communications, and would be financed in part by a $1.8 billion loan. According to Desch, the company's lenders "liked the price" of Falcon 9—currently $62 million per flight, a little less than half what a ULA launch charges for a flight on its comparable Atlas V. But they were concerned that Falcon 9 had yet to fly. In June, just days after the rocket reached orbit for the first time, Shotwell flew to Paris to make her case before 50 or so skeptical investors at the Four Seasons Hotel. Her presentation included a video of the successful flight. "Gwynne mesmerized the bankers," says Desch, who closed the deal shortly afterward.

■ Rocket launches are eerily quiet, at least at first. You see the flash of fire as the engines ignite, but it takes a moment for your eyes and brain to absorb that the thing is actually leaving the pad. It seems impossibly slow at first. By the time the rocket is really moving, the rumble hits your ears. It feels a lot like thunder—distant and then getting closer and closer, until it electrifies your entire body. The rocket hurls itself upward, receding above until it looks like an upside-down matchstick, then it's gone.

The experience is thrilling if you're a spectator but downright terrifying if your satellite is on top of the matchstick. "Every launch you go to, you're worried about it,"

Photos ☐ Courtesy SpaceX

SpaceX's Falcon 9 rocket landing on a drone ship in the Pacific Ocean as part of a mission for NASA on April 8, 2016.



New York to Shanghai: 39 minutes

Earth to Mars: 80 days

"Big Fucking Rocket" (BFR)

says Bryan Hartin, an executive vice president at Iridium. Many in the industry were initially uncomfortable with SpaceX's breakthrough addition of a set of four retractable legs to Falcon 9 so it can land vertically and be reused. "I was thinking, I hope the rivets are tight," Hartin says.

Even so, after SpaceX successfully landed and reused a rocket in 2017, Iridium agreed to a launch on the company's "flight proven" rockets—the aerospace industry equivalent of a "certified preowned vehicle"—because they're slightly cheaper and, more important, because SpaceX can prep them faster. The concept of reusability, pioneered by SpaceX, has since been embraced by most launch providers, including ULA. Musk has said that next year SpaceX will take advantage of upgrades to Falcon 9, including improvements to its legs and heat shield, to land a booster and launch it again within 24 hours. The idea is to make going to orbit as routine as flying from L.A. to New York.

Even after all this practice, Shotwell still gets nervous before launches. "Candidly, there is a healthy tension," she says. "Everything has to be right in order for things to be successful. It's a very unforgiving technology."

Falcon 9 has suffered two launch failures, most recently in 2016, when a rocket exploded mysteriously on the launch pad, destroying an Israeli satellite Facebook Inc. had planned to use after SpaceX sent it to orbit. "The Falcon fireball investigation," as Musk called it, may have led to a public feud between Musk and Facebook co-founder Mark Zuckerberg, who appeared to anger Musk by failing to show appropriate sympathy. Musk grieved openly. "Turning out to be the most difficult and complex failure we have ever had in 14 years," he tweeted.

The explosion marked a different kind of turning point for Shotwell. In the immediate aftermath, she says, "I ran around the company with a frumpy frowny face." But she quickly realized that she needed to project confidence. "You forget that people look to you for not only guidance but for inspiration," she says. "When I walked around with a worried face, it was not helpful to the company." An investigation ultimately traced the fireball to a faulty fuel tank. SpaceX returned to flight three months later.

"She realized, probably more than anybody else on the team, that people look at us," says Koenigsmann. "It's important that you carry yourself with a certain level of confidence." Over the years, Shotwell has earned a reputation as the person who can translate Musk's visions into reality. "She's the bridge between Elon and the staff," Koenigsmann continues. "Elon says let's go to Mars and she says, 'OK, what do we need to actually get to Mars?'"

Shotwell's leadership—less emotional than Musk's, perhaps a bit more assertive—came to the fore again in January, when a U.S. spy satellite mysteriously disappeared shortly after being launched into orbit by a Falcon 9. With no official explanation forthcoming and speculation mounting that SpaceX had screwed up, it was Shotwell who took the reins. "Falcon 9 did everything correctly," she said in a statement two days after the launch. The Air Force released a similar statement backing her up. (The *Wall Street Journal* reported, by way of anonymous sources, that investigators had found a flaw in a piece of equipment the U.S. had purchased from Northrop Grumman Corp. Northrop Grumman didn't return a request for comment.)

"Elon says let's go to Mars and she says, 'OK, what do we need to actually get to Mars?'"

SpaceX is now developing a plan to launch thousands of satellites that would blanket the Earth with internet access and is designing an even larger rocket, which Musk introduced to the world in 2016 as BFR (for "Big Fucking Rocket"). The BFR is designed to take passengers and cargo to Mars, but Musk has said it could be used to replace long-haul air travel—New York-Shanghai in 39 minutes, for instance.

Shotwell has tweaked the F in BFR to "Falcon." She says that prototype production has already begun at a factory at the Port of Los Angeles. The rockets can't be built at SpaceX's main facility in Hawthorne because they'll be 30 feet in diameter, way too fat for a truck to transport to launches. BFRs will have to travel by boat.

The company plans to begin test flights next year, even though it doesn't have any customers yet. "We're working on that," Shotwell says. Satellite companies and defense contractors will "need to figure out how to fill it up," she says. "I can help with that."

In the meantime, she's focusing most of her attention on the latest upgrades to Falcon 9 and Dragon. The latter is scheduled to carry astronauts to the International Space Station as early as December. SpaceX will share that milestone with Boeing, which has also designed a crew-carrying rocket launch system; this marks the first time NASA astronauts will fly on a private rocket. It's unclear whether Boeing or SpaceX will get to the station first, but SpaceX seems to be in the lead at the moment. In late July, the *Washington Post* reported that Boeing and NASA had discovered a fuel leak during a test, potentially delaying Boeing's launch. Vice President Mike Pence is expected to announce the schedule on Aug. 3.

The four American astronauts who could ride Dragon—Robert Behnken, Eric Boe, Douglas Hurley, and Sunita Williams—have been fixtures in Hawthorne this year, preparing for the mission. Two of them will fly with SpaceX, while the other two will fly with Boeing. Shotwell calls it SpaceX's "toughest launch." With humans on board, the stakes will be higher than they've ever been.

If it works, though, her job will get easier. "Hopefully the public looks at SpaceX and says, 'They do what they say they're going to do.' Even when it sounds completely insane at the beginning," she says. "It might take longer. It almost always takes longer. But yeah, we're doing really cool stuff." B

WHAT ABOUT BEZOS?

Blue Origin, the other space-obsessed billionaire's rocket company, isn't *that* far behind SpaceX

By Brad Stone

Photos ☐ Courtesy Blue Origin

Blue Origin launch on June 19, 2016.

Bezos

■ On July 18, outside the West Texas town of Van Horn, hundreds of Blue Origin employees and their families and friends gathered to watch the New Shepard rocket blast off toward the edge of space. The rocket performed the kind of feat that was once the province of sci-fi stories and discarded NASA white papers. It took off vertically like a conventional rocket, rose 66 miles above Earth to jettison a parachute-equipped crew capsule carrying a test dummy, then returned to the same tract of land and gracefully landed upright, drag brakes deployed, retro booster flaming. The capsule touched down nearby, raising a cloud of dust. Thousands watched this precise interplay of physics and chemistry online, and for those listening closely, 39 minutes and 15 seconds into the broadcast, a familiar, staccato laugh could be heard emanating from the control room: It sounded as if Blue Origin's founder, Jeff Bezos, was having a very good day.

He's been having a lot of those lately. With a fortune of about $150 billion, according to the Bloomberg Billionaires Index, he's the wealthiest person in the world. By a lot. He's worth approximately one Bill Gates and two and a half Elon Musks. One of his other companies, Amazon.com Inc., is now the world's second-most valuable corporation and has turned an otherwise dreary summer day in retail into Prime Day, one of the busiest shopping events of the year. President Trump is attacking Bezos again on Twitter for, as Trump tweets it, using the *Washington Post* as a lobbying arm; cities are courting him to secure Amazon's second headquarters; and investors have bid its stock up almost 150 percent over the past two years.

Yet guiding Blue Origin LLC "is the most important work I'm doing. It's crucial," Bezos told an audience in May at the National Space Society's International Space Development Conference. He founded the rocket company 18 years ago in an old warehouse south of Seattle, originally stocking it with tinkerers and science fiction authors who could help reimagine space travel. Now the company, known in the space business as Blue, employs more than 1,500 software engineers and rocket scientists, most of them at its headquarters in Kent, Wash., and the West Texas launch site. It plans to launch New Shepard with test pilots on board as soon as this year, and in 2019 it will sell tickets to brave tourists who want to sit atop a tank of combustible liquid hydrogen and oxygen to experience four minutes of sublime weightlessness in suborbital space. The ticket price has yet to be revealed. But unlike other space startups that have to make the numbers work, Bezos largely funds the company himself by selling $1 billion in Amazon stock every year.

Blue Origin's eventual goal is "millions of people living and working in space," Bezos has said. He plans to get there "step by step, ferociously," according to Blue Origin's motto ("*gradatim ferociter*"), which adorns its coat of arms. New Shepard is the first step. The rocket is tall, thick, and cone-tipped—its shape strenuously suggests off-color metaphors that shall not be deployed here. The crew capsule has a half-dozen large windows, so its astronaut-tourists will have a fantastic view of the gentle curvature of Earth. Unlike passengers on Virgin Galactic's SpaceShipTwo, which will be dropped from an airplane before its rockets send it soaring upward, Blue's astronauts will endure the same blastoff and parachute landing experienced by space pioneers like the vessel's namesake, Alan Shepard.

Bezos' plans get more ambitious from there. Another Blue Origin rocket, New Glenn, will take astronauts and commercial payloads such as telecommunications satellites to low Earth orbit and beyond, with tests starting in 2020. Bezos has also hinted at a future design called New Armstrong, which presumably will voyage to the moon. Bezos says lunar villages can be set up there to mine water ice and other deposits that can be used to manufacture rocket fuel, facilitating travel elsewhere in the solar system. Those big rockets will eventually compete with partially reusable launch vehicles such as the Falcon Heavy and forthcoming BFR, both made by SpaceX, which is owned by that other high-profile spacefaring tech billionaire, Elon Musk.

On the surface, Bezos and Musk have plenty in common, including a steadfast belief that reusing rockets can dramatically bring down the cost of getting to space. Beyond that, though, their styles and visions dramatically diverge. Bezos has said relatively little about Blue Origin outside the occasional speech and company promotional video. Musk has almost single-handedly pried open the space business to new entrants by noisily suing the federal government over its exclusive contracts with Boeing Co. and Lockheed Martin Corp., driving a space capsule around Washington on the back of a flatbed truck to get Congress's attention. Unlike Blue Origin, which to date has been something of a personal passion project, SpaceX has been funded by revenue from paying customers, including NASA, the U.S. Air Force, and commercial satellite companies.

Even so, Bezos looms so large in space circles, insiders joke that one day, with much fanfare and media attention, Musk and his crew will set off on what they believe is the first manned expedition to Mars. Upon landing, they'll be greeted there by Bezos and his crew, who've quietly been living there for months. But that belies another stark difference in their philosophies. SpaceX defenders will point out that Blue Origin's rockets have yet to reach orbit, a milestone SpaceX passed a full decade ago. And Musk has his eyes on distant planets in a way that Bezos doesn't. By the time Blue Origin sends a rocket to Mars, it may well be called New Musk.

But it's not even clear Bezos wants to go there. As a child, he devoured sci-fi books at the local library outside his grandfather's ranch in South Texas and eventually discovered the writings of Gerard K. O'Neill, who spun visions of people living and working in space habitats. Bezos later gave the valedictorian speech at his Miami-Dade high school on the topic, describing a future in which polluting heavy industry is moved into orbit, to be powered 24/7 by solar power, while Earth is rezoned into something resembling a giant nature preserve. Thirty years later, he's still remarkably consistent, captioning a recent Instagram photograph of the Perito Morena Glacier in Patagonia: "We've sent robotic probes to every planet in this solar system. Earth is BY FAR the best one. We go to space to save the earth."

Compared with Amazon, famous for moving fast and pioneering new industries, Blue Origin seems un-Bezos-like. "Blue Origin has been very methodical and a little more cautious and patient than others," says Marco Cáceres, a senior space analyst at the Teal Group. "Their primary thing is to do it right and avoid any failures."

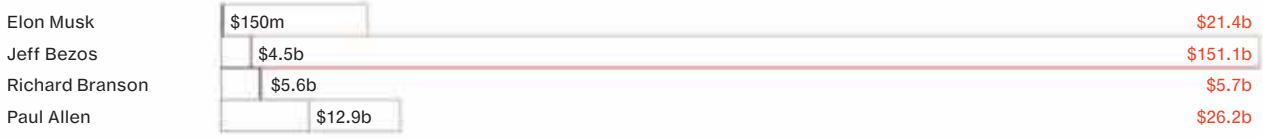
But while Blue Origin proceeds carefully—the recent test of New Shepard was its ninth—Bezos speaks with urgency about humanity running out of resources and hitting the limits of growth. As he told the National Space Society gathering, opening up space for both heavy manufacturing and exploration is essential. "You might not need it, actually," he said. "You might be fine. You're going to live out your life on this Earth, and it is going to sustain you, and you're not going to have to do weird things. That won't be true of your grandchildren or their grandchildren." Ⓑ —*With Karen Weise and Spencer Soper*

Into Bezos? You might also like: Amazon.com *Washington Post* Seattle Museum of History & Industry Bezos Expeditions Breakthrough Energy 10,000 Year Clock Princeton Neuroscience Institute Community Banana Stand

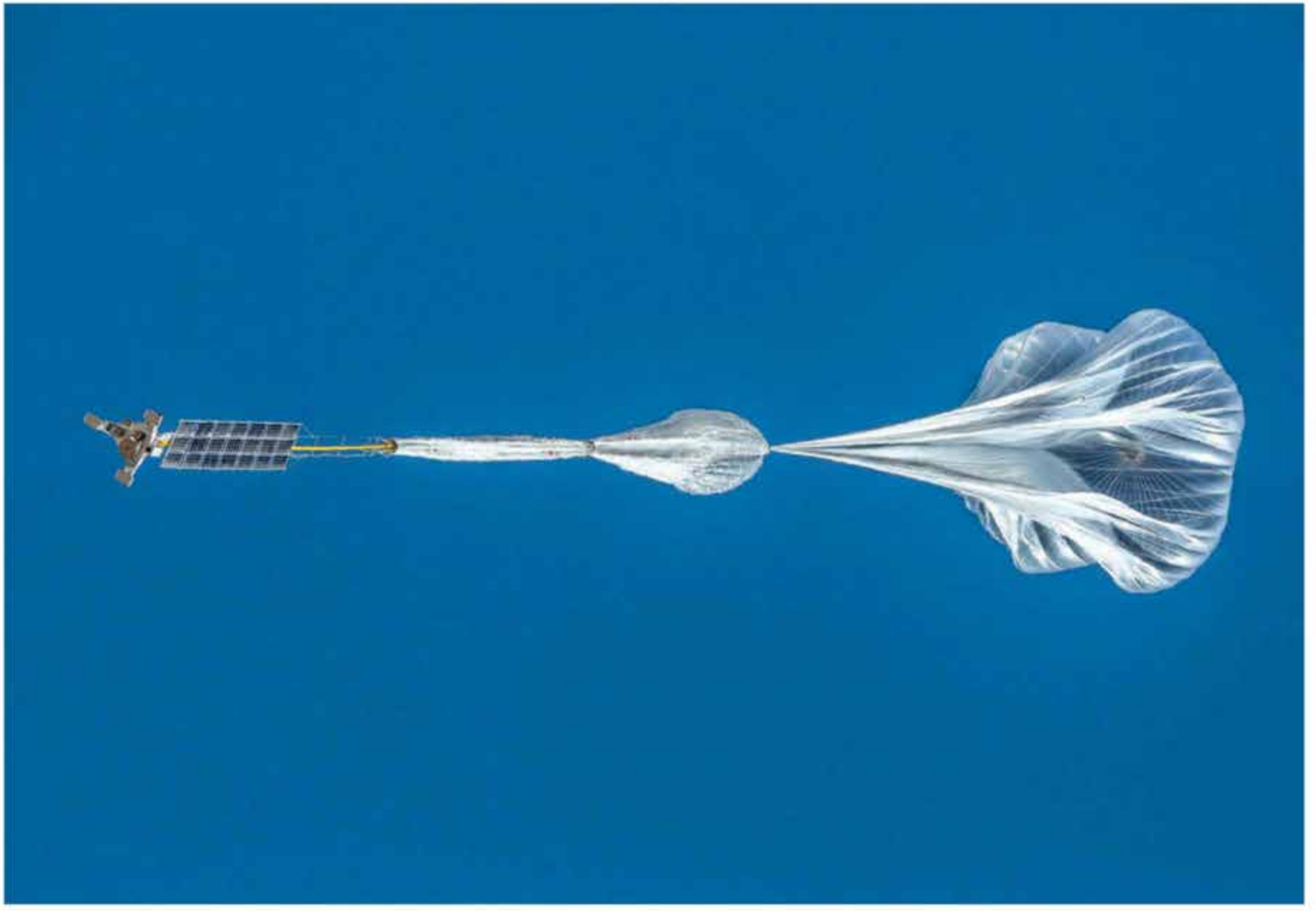
Billionaires in the space industry

Net worth when starting space ventures (Musk's SpaceX, Bezos' Blue Origin, Branson's Virgin Galactic, Allen's Mojave Aerospace Ventures)

Net worth as of July 24



Data ☐ Bloomberg Billionaires Index, *Sunday Times* Rich List 2005 (Branson)



A Stratollite rises above Spaceport Tucson in October 2017. From top to bottom: the primary lift balloon, a secondary balloon for altitude control, a solar panel, and the payload.

Photo ☐ Steven Meckler

MASTERS OF THE STRATOSPHERE

World View has figured out how to keep a balloon stable in near space. Interested in a ride?

By Ashlee Vance

■ The chicken sandwich has to get to space.

This is what everyone at World View Enterprises Inc. was thinking as they set to work in the predawn hours of June 29, 2017, at the Page Municipal Airport in Arizona. KFC Corp. had hired World View, a maker of high-altitude balloons, to ferry a Zinger, which consists of a spicy breaded chicken fillet topped with lettuce and a little mayonnaise on a sesame seed bun, through the upper reaches of the atmosphere and into the heavens. The publicity stunt would result in glorious images of the sandwich set against the stark black backdrop of space, and it would announce World View and its balloons to the paying public. "At first we thought it might not be a good idea," says Andrew Antonio, director for business development at World View. "People would think we're the chicken sandwich company, and that would be really bad. But we were just starting out, and ultimately this seemed like the perfect opportunity to use millions of dollars in KFC's ad budget to tell our story."

The Zinger launch preparations were intense. In the months leading up to the flight, nondisclosure agreements were put in place and signed. Rob Lowe was hired as a spokesman. A team of engineers built a solar-powered, animatronic KFC bucket that could tweet, take selfies, and house the sandwich beneath a protective glass dome. Zingers were tested in thermal vacuum chambers to see how they would react to pressure and temperature extremes. Then, just ahead of the launch, a group of food artists took over a local KFC and cooked dozens of Zingers, coating them with strange substances to make them beautiful. The Zingers were lined up and judged like pageant participants, and one was finally anointed the hero sandwich, the one with the fowl charisma and fast-food fortitude to brave the rigors of space in the name of over-the-top marketing. ▶

On launch day, the World View team attached the Zinger payload to the end of a long strip of polyethylene laid out on the tarmac. Against a desert backdrop of thirsty grasslands and burnt-orange plateaus, the plastic slowly filled with helium and started to take the shape of a massive teardrop. Lowe, doing his voice-over work, went through a countdown sequence. "Stand by to give status report when called. Launch systems? Aerodynamic descent systems? Balloon systems? Digestive systems? Roger, we are a go for launch for the Zinger 1 bucket satellite." And up the Zinger went, to 67,143 feet, streaming video as it rose. Did it make it all the way to space? Not quite. Did it stay up for only 17 of the planned 96 hours? Yes. But who cares? KFC got its ad campaign, and World View got a heck of a lot more than that.

Founded in 2012, World View had only ever flown its balloons, called Stratollites, for a few hours in one go. The chicken sandwich mission represented its maiden voyage toward something more significant—a time when its balloons could sail the winds of the stratosphere for thousands of miles and then hover over a point on Earth for days or even months. The KFC test helped fund research and development around the Stratollite's avionics systems, solar panels, and communications. In the year that's followed, World View's researchers have come up with techniques to build durable balloons and software and sensors that exploit previously unknown nuances of the stratosphere. The company has also raised $42 million from venture capitalists hoping it will alter the way we take images of Earth, predict the weather, and, one day, get tourists into space.

"Balloons have been around for decades but have never really been used in a way where there is navigational control," says Jane Poynter, World View's co-founder and chief executive officer. "Our rather genius engineers have figured the winds in the stratosphere out."

■ The history of high-altitude balloons goes back to the late 18th century, when the French, in particular, demonstrated a gift for releasing huge volumes of hot air into casings of rubberized silk that would float up into the skies. One of the first flights took place in 1783, with a sheep, a duck, and a rooster hovering for 8 minutes at 1,500 feet over Versailles. Not long after that, humans decided to attach themselves to the things, giving the public and militaries around the globe a new frontier to explore—and a new way to look at their home.

Things really started to get interesting in the middle of the 20th century, as a series of adventurous, brilliant, foolish people decided to see exactly how high balloons could go and what a human body hanging beneath them could take. The U.S. and Russia took to endurance ballooning with the same competitive fervor they would later display with rocketry. Without some protection, people tend to lose consciousness from oxygen deprivation at 50,000 feet, and bodily fluids boil at 63,000 feet, but these factors were apparently only mild deterrents. Individuals were initially crammed into tiny, crude gondolas with often untested safety systems. Many of the results were as expected, with people passing out during their journeys, freezing, and generally being tortured for hours or days—that is, when they didn't die.

Photograph by Ilona Szwarc for Bloomberg Businessweek

MacCallum and Poynter at World View headquarters in Tucson

One of the great heroes of this era was Joe Kittinger, a pilot in the U.S. Air Force. He was the kind of guy willing to have a rectal thermometer inside him for 48 hours, or chew his way out of a safety harness—yes, these things happened—if that's what it took to get his ballooning job done. In 1957 he was packed into a gondola beneath a balloon for a mission dubbed Manhigh. Despite a major mishap with his oxygen supply system, Kittinger set a record by rising to 96,000 feet. In 1960 he topped himself by going to 102,800 feet and then jumping out of his gondola. He dropped for four and a half minutes before engaging his parachute, reaching 614 miles per hour at one point, and repeated the same words over and over as he neared the ground: "Thank you, God. Thank you."

As the space race heated up, interest in ballooning waned. Great advances had been made in gondolas, safety systems, and balloon materials, and much of this

"We're solar-powered and mostly autonomous and just sit there at this high altitude looking down"

technology would aid astronauts. The public, however, was no longer as moved by ballooning feats, and the militaries of the U.S., Europe, Russia, and Japan invested their time and money elsewhere. Tourists still dabbled with hot air balloons, and high-altitude balloons continued to be used as scientific instruments, but Kittinger's altitude record held until the turn of this decade, when two risk takers decided to put their lives on the line.

Red Bull GmbH, naturally, was involved in the first attempt to best Kittinger, because nothing says "energy drinks are cool" like sending someone plummeting to his possible death at high speed. It sponsored the daredevil Felix Baumgartner in his 2012 jump from a helium-filled balloon at 128,000 feet.

In 2014, Alan Eustace, a computer scientist who was then a senior vice president at Google, tried to top Baumgartner. Eustace saw the feat as an engineering challenge. "It made no sense to build a giant capsule or gondola," he says. "They had caused more problems than they had solved." (People had died after hitting their gondolas during jump attempts.) He chose to dangle from the end of a balloon wearing a pressurized suit before being dropped from 135,908 feet, basically the edge of space. The balloon and the life-sustaining suit were made by World View.

■ From Mojave, Calif., to Midland, Texas, it's fashionable these days for scrubby Southwestern locales to have spaceports. Not the kind of city to be left out, Tucson erected Spaceport Tucson in late 2016, part of a $15 million incentive package meant to keep World View in town. The 142,000-square-foot office and manufacturing facility and accompanying 700-foot launch pad abut Tucson's international airport, ringed by mountains, cactus, and miles of ruddy desert.

Compared with flying humans and sandwiches, World View's most immediate, commercial mission is somewhat prosaic. It offers customers the ability to fly cargo weighing from 100 pounds to 20,000 pounds as high as 19 miles into the stratosphere, where it can hang out—or "station keep," in balloon lingo—for days, weeks, or months. Some of the earliest customers have been governments and companies looking to take precise pictures of a specific location. Satellites and drones can do this type of work, but World View has time, precision, and cost advantages. "Over time, we operate for less than a 10th the cost of a drone," says Taber MacCallum, co-founder and chief technology officer for World View. "We're solar-powered and mostly autonomous and just sit there at this high altitude looking down."

Photo ☐ Look at Sciences/ Science Source

The Biospherians, including MacCallum (third from left) and Poynter (far right), in the almost completed dome in 1990.

Because World View can affix all manner of objects to the end of a balloon, it can do more than take spy photos. Scientists can send up complex measurement systems. Militaries and aid organizations can position communications systems to provide internet and phone services in remote locations. And weather forecasters can place instruments directly into interesting spots. "We are jonesing to get one of these things into a hurricane and see if we can stabilize in the eye," MacCallum says. The company's long-term goal is to have dozens of balloons flying in shifts all around the world, reporting back and building the most detailed view ever of the world's weather.

Until recently, the prevailing wisdom among balloon aficionados was that these types of missions weren't possible. People believed the stratosphere had billowing, jet stream-like winds that flowed in one direction and would shove a high-altitude balloon around too much for it to stay in one place long enough to do anything useful. But, through much trial and error, companies such as World View and Loon LLC have discovered new facets to the stratosphere. Crucially, World View found that at the right heights, there are crisscrossing winds. This makes it possible for a balloon to remain relatively stationary by, in effect, flying in a figure-eightish pattern, bobbing up and down. "The circle you rotate around is five miles in diameter," Poynter says. "You go up a bit and down a bit, and find these winds that take you around and around."

■ On a November morning at about 3 a.m., World View's engineers and technicians begin showing up for a launch at Spaceport Tucson. They're months past the Zinger extravaganza and are setting out to put up a military imaging system and fly it from Arizona to Mexico, where it will hang out for a few hours before coming back for a landing. It's the desert, so the air is cold and crisp as they begin setting up fueling tanks, communications gear, and calibration equipment beneath three floodlight towers aimed at the pad.

The first step of a launch involves carting a folded balloon out to the pad and unfurling it. A car drives very slowly for 30 minutes, spreading the long stream of polyethylene across the ground. At the base is a white case called a stratocraft, which looks like a pyramid with its top cut off; it holds the payload. Next up the line are some solar panels, and then a yellow tube that carries helium to the balloon. A couple of men connect large, cylindrical guns to the base of the balloon and begin pumping in the gas. As the tip of the balloon fills, the ▶

big plastic snake stands up like a 400-foot-tall cobra.

MacCallum paces around the launch pad. Like a rocket launch, a balloon launch comes with a mix of tedium and tension—so many things must be checked and rechecked. The procedure manual for this mission runs 118 pages. There's the wind to worry about and, of course, the safety of the people on the ground.

The actual event, though, is nothing like the percussive, soul-tingling blast of a rocket catching fire and roaring against the chains of gravity. It takes 90 minutes to fill the balloon, at which point there's a mild jolt as the full tension of the thing travels up to the top and back again. Then the helium hoses are detached and the balloon jumps into the air like an excited jellyfish. Once it picks up speed, it floats up at 1,000 feet per minute and will take 75 minutes to get to a working altitude.

"It's pretty graceful and always seems miraculous to me," MacCallum says. Engineers use telescopes to watch the balloon's ascent and check for any problems or, God forbid, leaks. None of this is subtle. Anyone near the airport can see the giant plastic mass making its way up. "I will get at least three UFO spotting calls today," Antonio says.

In mission control, seven people track the balloon's path and help steer it via software. The amount of helium stays fixed, but ballast controllers adjust the balloon's overall mass via the intake and expulsion of air. It's this technology—the exact details of which remain secret—that makes World View unmatched in controlling altitude changes. On this mission, the balloon does as planned. It catches some strong winds and sails to Mexico and back. When World View is ready for it to come down, some onboard machinery springs into action. The cord connecting the payload to the balloon is chopped and a steerable parachute unfolds. Then mission control sends signals to levers to guide the payload, which travels at speeds as fast as 250 knots, to a location of World View's choosing. The balloon can't be steered, but it usually lands within a few miles of a predicted area.

Photo ☐ Courtesy World View

An image of an electrical substation taken last year from a Stratollite at 65,000 feet.

Things don't always run smoothly. For safety reasons, World View picks remote spots for the return to Earth, and its team doesn't always reach the goods first. During an early mission, a payload was taken hostage on its return by someone in the desert. The man claimed it had killed his dog and hurt his grandmother, and he asked for money to give it back. (World View's video showed the payload had landed safely.) On another occasion, a scavenger was seen on camera debating whether to hold the payload for ransom or strip it for parts. This caused World View to add a "call for reward" sign to its hardware for a spell, though the landings have recently become much more precise and the sign is no longer needed.

More distressingly, a balloon exploded on the launch site in December, creating a massive boom and fireball. World View mostly uses helium, but on this day it was running a test with hydrogen, which is cheaper and easier to get. Engineers were testing a venting mechanism when static electricity built up and sparked the gas. "The employees were a bit frightened," Poynter says. "We're not supposed to blow things up." No one was hurt in the incident, but Tucson officials were unimpressed, noting extensive damage to walls, doors, and windows at the company's headquarters. Meanwhile, the explosion reinvigorated critics of the sweetheart deal World View got on the property and building.

The explosion has done little to slow the company's operations. Since the Zinger, it's conducted more than 50 flights, primarily for the U.S. government, and kept its balloons up in the air for many days at a time. The company is in the process of preparing launches that will take balloons to the equator, Hawaii, Puerto Rico, and across oceans. "People want us to do things like sit over the Red Sea and Indian Ocean and look for pirates," MacCallum says. The company plans to start flying for commercial clients early next year. "Basically, our mission is to take over the stratosphere," he says.

Experts contend that winds—or, really, the lack of them—at some latitudes will limit what sorts of routes World View can fly and when it can conduct missions. Poynter dismisses such criticisms, saying it will be possible to get consistent coverage everywhere the company wants by using teams of balloons. "The doubters make me happy," she says.

■ In a back corner of World View's immaculate factory, there's a red-and-white canister big enough to hold eight people. It's cylindrical, with rounded bulges on both sides and at both ends, each with nine windows arranged in a circular pattern. Even though Poynter and MacCallum spend most of their time talking up commercial applications for their balloons, their real dream—their life calling—is to take this capsule into space and let people see Earth with fresh eyes.

Poynter, 56, and MacCallum, 54, are wife and husband.

A parachute rigger at World View. Photograph by Ilona Szwarc for Bloomberg Businessweek

She's a Brit; he's a Yank. Growing up, they were both free-spirited adventurers fascinated by the question of how people could live in space. They met in the 1980s while doing research missions at sea, and both ended up living inside the Biosphere 2 enclosed habitat from 1991 to 1993. "I went in because it seemed like such a forward-thinking idea to recreate planet Earth's biosphere in miniature and then use that to sustain life elsewhere," Poynter says. "I thought it was the closest I would ever get to doing something like actually being on Mars."

Biosphere 2 was plagued by personal and technical issues, but the romance between Poynter and MacCallum survived. Before they had even left the bubble, they'd decided to start a company called Paragon Space Development Corp. It would become well-known for engineering all manner of oddities meant to hold up under extreme conditions. NASA had Paragon make a breeding system for animals on the space station; the U.S. Navy asked for a specialized suit that would let divers go into sewage or chemical-laden water; Elon Musk asked the company to develop plans for a greenhouse on Mars.

As they worked on these projects, MacCallum kept thinking back to his childhood. He grew up in New Mexico and spent time around big balloons as a kid. His father worked as a scientist at Sandia National Laboratories and was part of a team that discovered a black hole at the center of the Milky Way by attaching gamma ray-hunting telescopes to balloons. "I would go out and see these huge things with their massive payloads, and it stuck with me," MacCallum says. "I have always been a space head." One day he walked into Poynter's office at Paragon and brought up the idea of doing some big balloons of their own. "I'm like, 'Absolutely. That's exactly what we're doing,'" Poynter says.

The driving idea is to make space truly accessible. "We wanted to give people that seminal experience that astronauts talk about where you see the curvature of the Earth, the blackness of space, and have the mental space to really experience the planet," she says. Instead of being strapped into a rocket, however, World View's passengers will float into space slowly and peacefully inside a pretty roomy cabin without the need for a spacesuit or any special training. There will be a bar and a bathroom. People will reach 100,000 feet and hang out for two hours before being piloted down with the steerable parachute. Philippe Bourguignon, former head of Euro Disney and Club Med SAS, is an investor in World View and will be one of the first people to head to space when—if?—the $75,000-a-person flights begin in the next few years. "I bought tickets for my whole family," he says. "But the company needs to hurry up, because my family is growing and there are more grandkids coming."

As for exactly what the ride will be like, we could turn to a chicken sandwich for an answer or, better yet, to Eustace. "It will be a beautiful experience," he says. "It will be the most peaceful ride you could imagine in this totally quiet environment instead of with a rocket shooting off and vibrating behind you. This will appeal to a huge number of people that want to see things from a different perspective. That's all I can really say. You know something is good when it's almost impossible to describe." B

Solutions

A Cancer Cure Could Start in the Thermosphere

The advantages of pharmaceutical research on the International Space Station

By Cynthia Koons and Jared S. Hopkins

■ Shou-Ching Jaminet, a molecular biologist and former researcher at Harvard Medical School, spent almost a year preparing an experiment for her small biotech startup, Angiex, to study the effects of weightlessness on a potential cancer drug. By June she was nervous with anticipation, readying her project for launch on an International Space Station resupply mission powered by a SpaceX Falcon 9. But before it blasted off, she wanted to lay eyes on a dolphin. In rocketry, she'd been told, it's good luck to see one (and bad luck to see a pig) prior to liftoff. So the night before launch, she and her family headed to a waterfront restaurant near Cape Canaveral Air Force Station in Florida. It was an auspicious dinner: She spotted not one dolphin but four.

At precisely 5:42 the following morning, plumes of fire lit up the sky, and the rocket took flight without a hitch. Angiex Inc. was in space. The company, which Jaminet co-founded with her husband and a former Harvard colleague, would soon be among the more than 2,400 research projects started on the ISS since it went into service in 1998. Orbiting about 250 miles above Earth, the station has provided a coveted platform for scientists to conduct experiments in the microgravity and extreme temperatures of space. Their work is monitored by a crew drawn from around the world. (Resupply missions also ferry food; Angiex's flight included maple-smoked salmon at one astronaut's request.)

Jaminet's drug is intended to cut off the blood supply to tumors, thereby killing them. In space, she wants to observe how endothelial cells, which provide this blood, behave in microgravity. When a person has cancer, these cells can proliferate, promoting tumor growth. But it's not possible to run tests on them in a nonproliferating state on Earth. Jaminet's hypothesis is that they won't grow in culture aboard the ISS, making them similar to the cells in a healthy person's blood vessels. Then, if the drug doesn't harm these dormant endothelial cells, she'll have evidence that it won't damage patients' blood vessels on Earth, either, adding to the likelihood that the treatment will be safe. Bonus insight: "If the changes we are seeing in cells in culture also occur in the cells of astronauts' bodies," Jaminet says, "then it seems likely that tumor growth will slow down under microgravity."

Lobbing drugs into near-zero gravity isn't likely to produce immediate, radical results. But drug companies large and small see the practice as a valuable tool in early stage development. Merck does it, Amgen has done it, Novartis and Eli Lilly, too. Space research is appealing for a number of reasons. According to Paul Reichert, a scientist at Merck, it's easier to maintain uniform temperatures in space, which makes the process of growing crystals more precise. Particles in solutions also tend not to settle, keeping liquid formulations more evenly distributed. And matter moves more slowly in space, giving scientists time to improve their experiments by filtering out impurities along the way.

"There's a unique environment on the station that allows you to explore different aspects of life that you wouldn't normally see on Earth—or you'd never see on Earth," says Ken Savin, a former Eli Lilly scientist who's now with the Center for the Advancement of Science in Space (Casis), which manages the U.S. National Laboratory on the ISS. "It's like Christopher Columbus has gone to the New World and people are saying, 'Hey can we go back? What else is there? What are the new opportunities?'"

Much of this activity can be traced to Reichert, who's been sending experiments into space since the 1990s. His early work sought to induce crystallization there. Hoping to create large crystals, he was surprised to find small, uniform ones when his experiment returned from orbit. For drug delivery, uniformity is ideal, but it will still

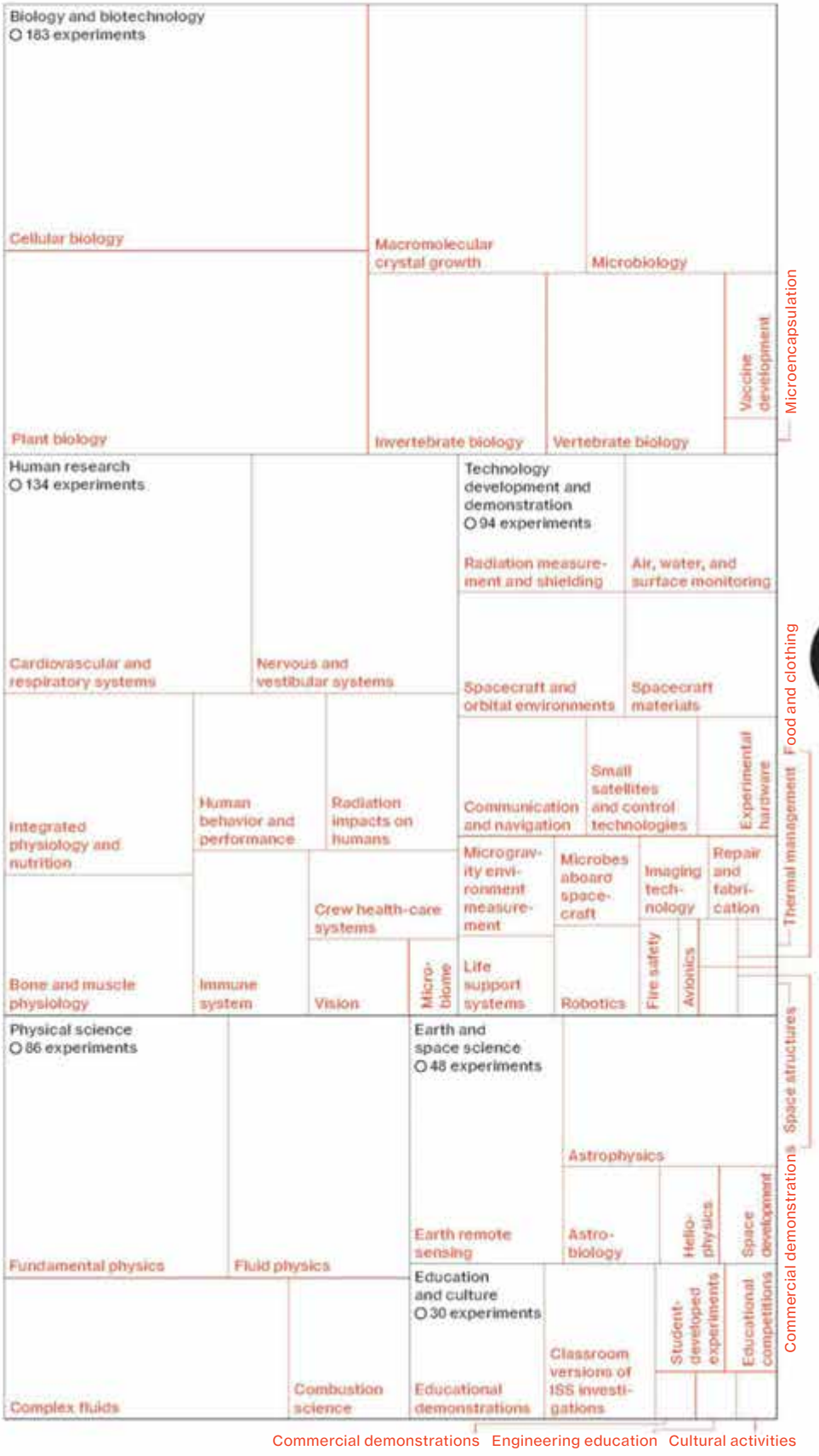
be some time before Merck is manufacturing drugs in space.

After the main assembly of the ISS was completed in 2011, the astronauts had more time for experiments, and Casis stepped in to help facilitate the work. Reichert began studying the effects of near-weightlessness on Merck's Keytruda, a multibillion-dollar drug that marked a major advance in the treatment of melanoma and other cancers. The aim is for those smaller, more uniform crystals to help turn the dose from an hours-long infusion into a simple shot, cutting down on the time physicians spend administering the drug and easing the burden on patients.

Much ISS pharma research is being funded by the U.S. government, which in 2017 allotted almost $350 million of the station's $2.8 billion budget for the purpose. President Trump has said he wants to end funding for the station by 2025 to free up money for NASA to use in other ways. Casis estimates each trip currently costs about $7.5 million per experiment, but the price of going into space is coming down. By 2025, drug companies might be better able to bear the costs. The hope, Savin says, is that they'll conclude, "Hey, there are good biological models that can be run in space, and it's worth the premium."

Three days after Jaminet's experiment launched, the SpaceX craft docked with the ISS. She's been in contact with the doctor-astronaut who's handling her experiment, Serena Auñón-Chancellor, ever since. The results so far, Jaminet says, are encouraging. Back on Earth, she's running a "ground control" experiment to compare how cells react in a normal-gravity environment with how they behave in microgravity. So far, her hypothesis is panning out: The endothelial cells are growing more slowly in space. B

Experiments aboard the International Space Station



Data ☐ NASA







Forgotten Images From







Stills from a book showcase the work of a space-obsessed photographer who spent the early- and mid-1980s capturing launches at Kennedy Space Center, only to stash his work for almost three decades after the *Challenger* disaster

Photographs by John A. Chakeres

the Shuttle's Glory Days

△ *Discovery* launches for the first time, Aug. 30, 1984.

■ As a kid growing up in the 1960s, John A. Chakeres would persuade his mother to let him stay home from school to watch space launches; using his father's Rolleiflex camera, he'd take pictures of the TV. This was the beginning of his obsession with NASA, and it would lead him to get his B.F.A. in photography in 1975. The next manned spaceflights wouldn't happen for six years, however.

Chakeres's first successful attempt at photographing a launch—after a couple of false starts—came on March 22, 1982, the third voyage of *Columbia*. Over the next four years he shot *Discovery*, *Atlantis*, and *Challenger* multiple times at the Kennedy Space Center in Florida. But he didn't shoot *Challenger*'s last mission. The launch was delayed repeatedly because of cold weather, and the day before the shuttle finally took off on Jan. 28, 1986, he decided not to shoot since he had plans to go out ▶

Challenger backing out of the Orbiter Processing Facility in 1985 for transport to the Vehicle Assembly Building (VAB), where it would be mated to the "stack," the external tank and the solid rocket boosters.

Atlantis arrives at Kennedy Space Center aboard the Boeing 747 that transported it from California, April 13, 1985.

△ *Challenger* heading to the VAB.

▽ *Atlantis*'s vertical stabilizer, which helped control its descent upon reentering Earth's atmosphere.

◀ of town. More cold weather was expected that morning, and Chakeres was sure NASA wouldn't proceed. But when he awoke and learned that the agency was moving ahead, he went to watch—without his cameras. *Challenger* exploded 73 seconds into its 10th mission. "It was hard to continue the work after witnessing this accident, and I decided to set the project aside. For more than 25 years these negatives were kept in storage," Chakeres writes in *First Fleet: NASA's Space Shuttle Program 1981-1986*, a book of his work to be published in September (Daylight Books, $50). ▶

◀ He writes that he was drawn to the space shuttle because it was "the most complicated machine ever created." It also carried on the spirit of past NASA missions, which were always meant to make America first at *something*. The shuttles were the first reusable manned crafts, the first ships to launch and retrieve

Exhaust and steam clouds from *Discovery*, 1984.

△ "Climb out" phase of *Challenger*'s fourth flight, Feb. 3, 1984.

satellites while in space, and the first to take an American woman beyond the stratosphere.

Chakeres had to innovate to capture the shuttles on film. He shot with a Hasselblad EL/M protected by a custom aluminum housing painted white to reflect heat. NASA allowed photographers to place ▶

their cameras quite close to the launchpad—1,000 feet—but the nearest any photographer could be was 3½ miles away. Using the original Apple Macintosh, he designed a remote camera trigger that took its cues from sound and light. He called it the Omni Trigger because it could work with any camera, and soon news organizations wanted one for themselves.

Looking at these photos in the SpaceX era—when booster rockets fall back to Earth and reverse-thrust onto platforms in sync—makes *First Fleet* feel very much like a document of the past. But Chakeres says he had a "front-row seat to the future" and that, by treating the shuttles less as pieces of technology than as modern sculpture, he sought to preserve the sense of awe they once evoked. "*First Fleet* is my way of paying homage to all the men and women who built and flew the Space Shuttle," he writes, "and how they inspired me to live a creative life." B

Discovery approaches Runway 15 at Kennedy Space Center, Jan. 27, 1985.

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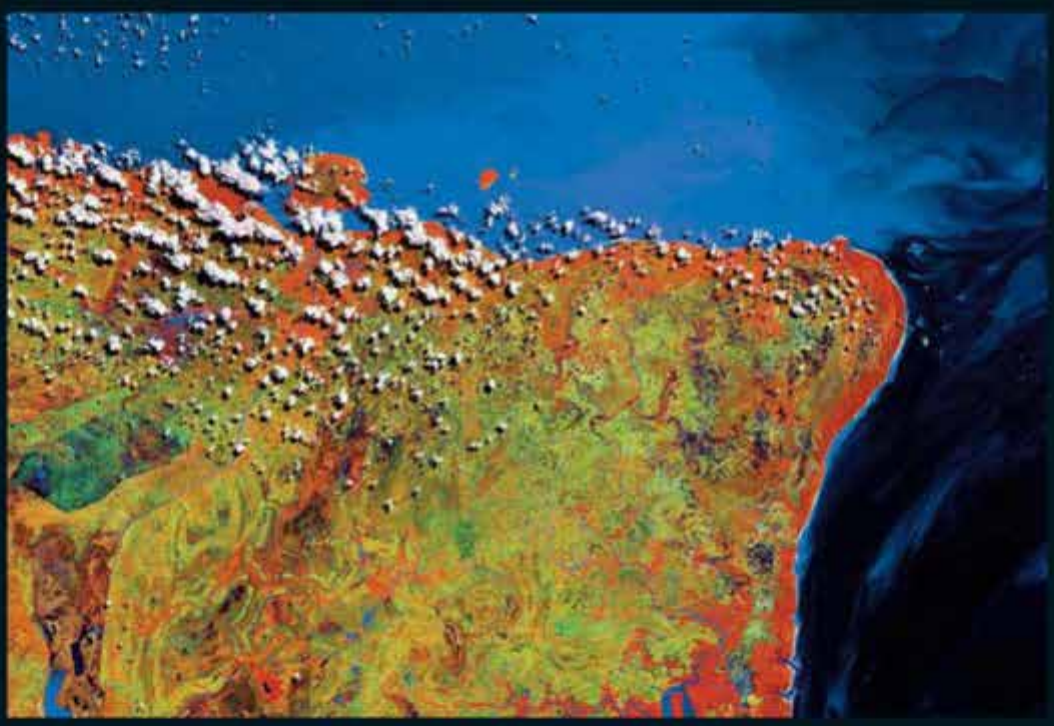
II ORBIT



A view of northern Brazil's Marajó island from the *Copernicus Sentinel-2A* satellite.

Photo ☐ Courtesy ESA

AN ENGINEER'S GUIDE TO DISRUPTING THE GALAXY

Natalya Bailey's tiny engines could change the economics of space exploration, much as the jet engine altered commercial air travel

By Kyle Stock
Photographs by Tony Luong

■ There's a sweet spot about 22,000 miles above the planet. Only in this narrow band of space can an object achieve geosynchronous orbit, moving at the same speed as Earth's rotation and staying fixed above one point on the surface. It's beachfront real estate in the void.

This part of space came of age with the baby boomers in the 1960s. It's been dominated by the few governments, aerospace giants, and telecoms with enough money and expertise to build a complex SUV-size object and lob it almost a tenth of the way to the moon. Everything in this stratum is highly planned and expensive; a satellite here can cost more than $300 million to produce.

Far below, at an elevation of about 370 miles, is the cheaper and riskier near-Earth orbit that has matured in step with millennials. It's a free-floating, unruly mess populated by a new generation of miniature satellites that can be as small as toys and made for as little as $10,000. Already, they're being stuffed aboard launch rockets like Tic Tacs.

The falling cost of building space tech and putting it into orbit has entrepreneurs, researchers, and oil-tanker-tracking hedge fund analysts lining up to claim their corner of the upper atmosphere. About one-third of the 4,600 man-made objects in Earth orbit went up in the past decade, including a record 553 last year, according to the United Nations.

All of this activity poses a problem: There's no efficient way to position these objects once they've been launched. The result is something like thousands of boats adrift at sea. Until now, there was little reason for engineers to streamline satellite propulsion, because geosynchronous satellites were large enough that they could devote a few extra pounds to bulky, chemical-driven engines. Smaller space objects in near-Earth orbit mostly just float along without propulsion, descending eventually, as NASA requires, into a so-called graveyard orbit, where they will burn up within 25 years. A tiny satellite or lab that could scoot itself around would be able to go higher, into less-dense layers of space, then steer into a fiery atmospheric death once obsolete. It would also be nimble enough to dodge the 18,000 or so pieces of man-made junk zipping around the globe like a hypersonic trash dump.

The frantic new space race needs an engine. Preferably a tiny one.

■ Inside an old brick candy factory north of Boston, 30 young rocket scientists with scruff fringing their ▶

Bailey in the lab at Accion Systems in Boston. ◁

hairnets shuffle among machines and curl over microscopes, tinkering with tiny tools like watchmakers. Accion Systems Inc. essentially makes one product, a device about the size of a deck of cards that's designed to slowly and silently nudge satellites, spacecraft, and other galactic ephemera through the blackness. Technically, the Tile—an acronym for tiled ionic liquid electrospray—is an ion engine, which is to say it runs on a stream of charged particles, much like a battery. Stick enough of them onto a giant craft, and you can putter out to Mars.

At least, that's Natalya Bailey's hope. Her company's little engines haven't yet left the ground. The 31-year-old chief executive officer travels in a tight orbit around Accion's office. She spends most of her time amid a scrum of desks, occasionally swinging by the lab to see how the Tile is faring against a phalanx of machines that squeeze and shuffle it to approximate the violence of a rocket launch and the vacuity of space. The only significant time she spends in her private office is to pump milk for her 9-month-old daughter, who goes to the day care next door. "The world needs this technology," Bailey says of her engine. "And it isn't very clear that someone else can do it better."

The cost of launches is shrinking as quickly as the cost of satellites, with a rash of startups developing rockets for lighter, unmanned payloads. Some are producing designs using 3D printers or filing patents for space catapults. One company, Vector Launch Inc., plans to build a fleet of simple rockets and sling them by the hundreds from a mobile launch pad. Vector CEO Jim Cantrell says that in the not-too-distant future, two or three launches will take place around the world every day. He estimates they'll cost $1.5 million to $3.5 million apiece, far below the already groundbreaking $60 million that SpaceX charges for a resupply run to the International Space Station. "It consumerizes space," says Cantrell, a SpaceX alumnus. "I've got neighbors that can write a $1 million check."

At that price, doing business in orbit becomes much more tempting for a wide range of industries. The gold rush is on, and Accion is poised to become a premier shovel supplier. "They're pretty core to what the future is," Cantrell says.

The Tile is a rectangular piece of silicon and plastic whose smallest incarnation measures about 3 inches wide. It's built in layers, cakelike, with an electric plate atop a tank of liquid-salt propellant atop a membrane with hundreds of holes. When the engine fires, propellant particles jet away from the charged plate, stream through the holes, and shoot out into space like subatomic pingpong balls. Whatever the Tile is attached to—be it shoebox-size satellite, robot, or astronaut—is gently and silently pushed in the other direction. "It's a mix of plasma physics [and] fluid dynamics," Bailey says. The effect is subtle: "When some are operating efficiently, you visually can't even see that they're on."

"The world needs this technology. And it isn't very clear that someone else can do it better"

The beauty of the Tile is in what it lacks. It contains no pressurized tanks, no bulky valves, no chemicals that could cause a costly launch accident. It's also tireless. Right now, a Tile can run for about 42 days straight. Bailey is shooting for 417 days—10,000 hours—though Accion won't know how quickly it can reach that goal until after its first engines leave the planet. "That would get us the entire Earth-centric space market," she says.

■ Much of today's cosmic clamor is coming from busy billionaires, the Musks and Bezoses who bring competition to NASA and its cozy network of defense contractors, then retire for the evening to nibble roast iguana and wage Twitter wars. Even less-moneyed rocketry upstarts hew to a certain machismo: When Cantrell isn't building rockets, he's racing Porsches. Bailey refers to this group as "the billionaire cowboys," and she's most decidedly not among them. For one thing, she looks like Audrey Hepburn, with a preppy sense of style. She's also an introvert and a quiet, calculating problem solver.

For as long as she can remember, she's puzzled over what's out there. As a kid drifting off to sleep on a trampoline outside her family's home near Portland, Ore., she would track the International Space Station. She remembers cobbling together a preteen version of the Drake Equation on those nights and realizing that the likelihood of intelligent alien life was something greater than zero. *Star Trek* marathons with her father catalyzed her cosmic thinking, as did her mother's unexpected death when Bailey was 8. The house lost some of its order—some of its gravity—which led to more nights gazing skyward on the trampoline.

In college, Bailey got a hard-won paid internship at now-merged aerospace giant Hamilton Sundstrand and joined a team repairing turbine engines. She hated it. "It was the opposite of pushing the envelope," she says. "Nothing new ever went into that building. Nothing new ever left that building."

By the time she set off to get a master's degree in mechanical engineering at Duke University, the idea of logging 30 years at a place like Boeing Co. or NASA had lost all appeal. She tried her hand at finance and later law, and was unlucky enough to excel at both. "I made it pretty far down that path, but then I thought, Wait, if I become a lawyer, then I'm a lawyer and that's what I do," she recalls. "What if I don't want to do that on Tuesdays?"

Eventually, Bailey's Duke adviser bought her a plane ticket to Boston so she could start a doctorate at the Massachusetts Institute of Technology. The LSAT was old news; she was going to rocket-engine school.

Impulse and warp-engine milestones for the USS *Enterprise*:

2346: Systems pass design review

2351: Major impulse-engine installation complete

2352: Warp-engine core completed

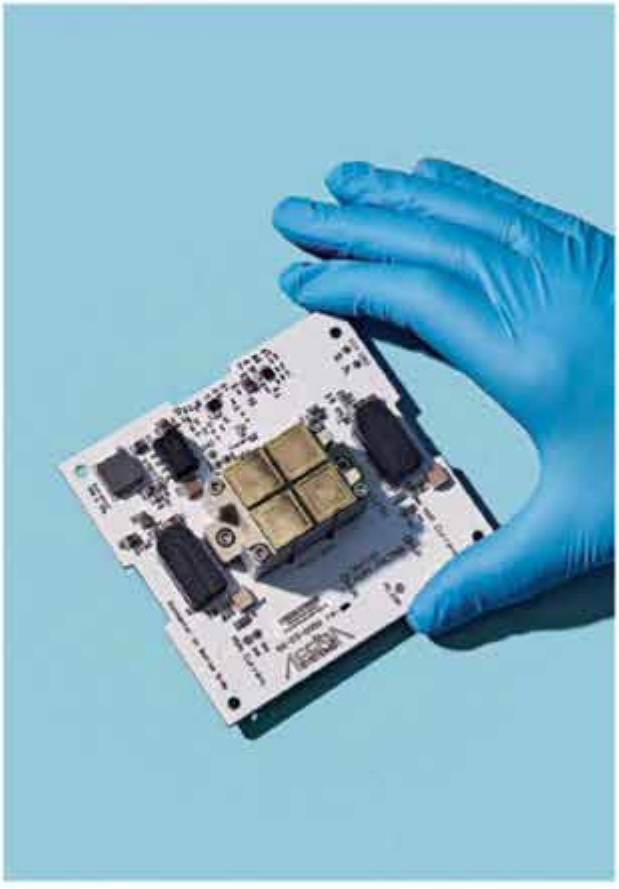
2355: Impulse-engine testing completed

2359: *Enterprise* declared warp-capable

2360: *Enterprise* achieves warp flight in outer solar system

2363: *Enterprise* is officially commissioned

Source ☐ *Star Trek: The Next Generation Technical Manual*, by Rick Sternbach and Michael Okuda



Tile stands for tiled ionic liquid electrospray and is used for scalable electric propulsion for satellite platforms.

■ One theory for why NASA and its corporate partners haven't perfected an ion engine is that the space behemoths are too big to try. Their missions are so grand and expensive that risk is squeezed out, along with much of the drive for innovation. "It's the opposite of a virtuous cycle," says Rob Coneybeer, a venture capitalist and early Accion investor who cut his teeth in the 1990s at Martin Marietta. "It's a negative spiral."

But there's another reason satellite propulsion has been slow to evolve: It's boring. Some of the best and brightest minds in rocket science are in it for the bang. They like a big burn, the high stakes of a 10-story tower quivering with liquid hydrogen and a computationally complex 18,000-miles-per-hour flight.

At MIT, Bailey worked with Paulo Lozano, a professor of aerospace engineering who started looking into the potential of ion engines about two decades ago. He found he had trouble getting funding. At one of his conference presentations, three people showed up. "It's hard to convince people that this is something interesting," he says. "It was even hard for me to convince academia that this is something to look at." Bailey was attracted to it because it was subtle and largely overlooked by the space establishment.

When she arrived, Lozano's team was working through two major technical problems: The charged metal would corrode quickly, causing the whole thing to short-circuit in a small explosion. Bailey and Louis Perna, a fellow student who eventually co-founded Accion with her, took the research in a new direction by replacing the metal with a charged liquid, insulating the process and making it ultra-efficient and far less volatile.

As Bailey was preparing to defend her doctoral thesis, she was also raising funds for Accion. (The name is a reference to a summoning charm in the *Harry Potter* books.) "Somewhere in there we decided I was making more of the decisions and going to more of the meetings," she says of her relationship with Perna. "So when it came time to form the C-corp, we put my name down." Accion wants to change the economics of space exploration in much the same way the jet engine altered commercial air travel.

Sometime in the next few weeks, a Rocket Lab launch vehicle will thunder skyward from a tiny peninsula on the heel of New Zealand. Its payload will include a shoebox-size space lab built by students at a California high school, which will feature the first of four Accion units heading to space in the next year or so.

Although its first customers make small satellites, Accion is building its business plan around midsize machinery, which tends to be owned by corporations and countries with more money than high school students have. The company has already secured $7 million in contracts from the U.S. Department of Defense, in addition to $10.5 million in venture capital. Accion is cagey about prices, but it touts its products as 10 to 100 times cheaper than existing options. One virtue of the Tile is that, simply by adding a few more engines, you can move a larger object or go farther and faster. That could be useful for machines doing detailed weather research, defense surveillance, or communications.

"My personal hope and ambition is that they become the in-space propulsion company," Coneybeer says. He and Accion's other investors are most excited about the Tile's potential to scale, Silicon Valley's magic word. The market is expanding quickly, and Accion can theoretically serve everyone. Bailey's team has already prepared a straightforward manufacturing plan, not unlike a smartphone factory workflow, with the heart of the machinery baked into a tiny chip. Assuming Accion gets the Tile right, the process will be easy to replicate.

Bailey is thinking even bigger than near-Earth orbit. Someday, she wants to sell explorers and scientists a one-way trip to Mars, even to other solar systems—a level of ambition she shares with the billionaire cowboys. She's also thinking about her own trajectory: What, if anything, comes after Accion? In her free time, she's been taking flying lessons, strapping into a small plane with her baby. "It's kind of like our family car," she says. A pilot's license is one of the only remaining qualifications that would buttress her application to become an astronaut. NASA has already rejected her twice.

"I don't know why," she says. "I'm a pretty good specimen. I even have great vision." B

The View From Way Up

Satellites are orbiting in record numbers. These are just some of the companies, government agencies, and NGOs putting them to use

1 World Bank

- Monitoring high-risk urban development
- Sierra Leone

In 2017 at least 400 people died in Freetown after torrential rains set off a mudslide. Using images from NASA's Landsat and the European Space Agency's Sentinel-1 satellite programs, overlaid with census and other data, World Bank researchers demonstrated how the city's haphazard development bore some blame for the loss of life.

Almost two-fifths of Freetown's expansion since 1990, they found, was in areas at medium to high risk of natural disasters, such as on steep hillsides or below sea level, despite laws designed to prevent just that. What's more, from 1975 to 2015 just 3 percent of the city's construction was within existing neighborhoods. The farther the city sprawls, the harder it is for public authorities to provide vital infrastructure and services, including sanitation and public transit.

While the World Bank has studied cities' development since at least 2011, its work on urban fragmentation in Africa started around 2016. "For a while there was a perception within the World Bank that investments in geospatial skills, like remote sensing and satellite imagery, was more of a nice-to-have that didn't really have widespread utility," says Megha Mukim, a senior economist at the bank. "Most people now agree that this is a critical decision support capability."

Researchers with the bank now use satellite data to create policy recommendations for clients such as officials from developing nations and urban planners. They plan to publish their findings on Freetown's development later this summer. —*Andre Tartar*

2 Ursa

- Estimating oil stockpiles
- China

Ursa Space Systems' main mission is to shine a light on the dark corners of the global supply chain—specifically countries where official statistics are incomplete or untrustworthy. To do so, it buys synthetic-aperture radar imagery (for more on SAR, see ❹) of 10,000 oil tanks worldwide, focusing on the heights of the lids to measure fluctuation in the oil levels underneath. Ursa then sharpens the images and feeds all the data into a proprietary machine-learning algorithm. The company has found that the market may be underestimating demand in China, the world's largest oil importer.

Economic forecasters are major buyers of satellite data. In June, Ursa formed a data-sharing partnership with S&P Global Platts, a provider of commodity indexes and key oil prices. "As satellite data become more prevalent for all industries, market participants will use it to supplement and verify traditional fundamental indicators," Barclays Plc said in an October report—its first to incorporate satellite data, which was also from Ursa.

The company has rivals. Planet Labs Inc. recently unveiled a platform, Queryable Earth, that customers can use to track planes, ships, roads, buildings, and forests worldwide. Orbital Insight Inc. has its own oil storage tracker and does daily automobile counts for 80 U.S. retailers.

Oil storage monitored by Ursa. Photo ☐ Courtesy Terrasar-X

Satellite measurement is by definition far removed from what's happening on the ground. Given the opaque markets Ursa targets, it has to sell clients on data that are often unverifiable. Co-founder Derek Edinger, who's helped build satellites for the likes of Raytheon Co. and Lockheed Martin Corp., says the company's findings go through automated checks and human verification, and its algorithms get better with each image it processes. —*Jeff Kearns*

3 EarthCast

- Providing in-flight forecasts to pilots
- Earth's atmosphere

When one of the more than 10,000 pilots flying for a certain large commercial U.S. airline needs to know whether that dark cloud bank ahead will affect their flight, they can power up an iPad, tap in their flight number, and see a weather forecast tailored for their particular plane. The company behind this application is EarthCast Technologies LP, founded in 2011 by NASA veteran Greg Wilson. (The airline declined to be named.)

Pilots have long had access to basic weather information for their departure and arrival airports, but EarthCast has given them the ability to map out conditions along a particular flight path. The company pulls data from a constellation of 60 mostly government-operated satellites, overlaying that with information from ground- and aircraft-based sensors tracking everything from lightning strikes to turbulence. This fully localized, real-time capability sets EarthCast apart from consumer-facing services such as the National Weather Service and the app Dark Sky; in addition to airlines, EarthCast's clients include government agencies and other commercial weather companies. In theory, EarthCast could customize forecasts for everything from hot air balloons to drones. —*A.T.*

Global radar forecast. Photo ☐ Courtesy EarthCast Technologies

Sea ice between Helsinki, Finland, and Tallinn, Estonia. Photo ☐ Courtesy Iceye

4 Iceye

● Mapping sea ice
■ Arctic Circle

Shipping and oil companies are rushing to exploit Arctic seas newly freed by melting ice caps—but to do so, they need up-to-date information on the location of remaining frozen hazards. The task is well-suited to synthetic-aperture radar, which uses electromagnetic pulses transmitted by satellite-mounted antennae to build detailed three-dimensional images.

SAR satellites used to be two-ton behemoths the size of city buses, so expensive to build and hurl into orbit that they were controlled almost exclusively by governments. Iceye Oy, which started in 2012 as a student project at Aalto University in Finland, set out to upend that model. "We had to rebuild every part of [the SAR satellite] down to the transistors," says co-founder Rafal Modrzewski.

Iceye's SAR is 10 times smaller than the standard version and weighs just 80 kilograms (176 pounds). In January the company sent its first SAR microsatellite into orbit. Because of its size, its low-cost construction, and the relative ease in launching it, Iceye's SAR can provide raw image data at a cost of about $1 per square kilometer, a 10th of most other SAR image providers.

There are a few drawbacks to mini-SAR satellites, including image resolution that's 10 percent to 20 percent less acute than their full-size cousins'. And their life spans are less than half that of the giant versions, but Modrzewski says you could afford to build 100 mini-SARs for the cost of a single large model.

So far, Iceye's customers include Exxon Mobil, Sweden's Saab, the Finnish and U.S. militaries, and Arctia, which operates ice breakers that escort ships through the Arctic. To make its data more readily interpretable, Iceye uses machine learning to detect features such as ice, water, forests, and agricultural cover. It plans to assemble a constellation of 18 satellites that will allow it to capture images of almost any spot on Earth once every three hours. The next launch is planned for October. —*Jeremy Kahn*

5 NASA

● Measuring the effects of Hurricane Maria
■ Puerto Rico

Since 2011, much of the best nighttime imaging has come from a satellite called *Suomi National Polar-orbiting Partnership* (*NPP*), a joint project of NASA and the U.S. National Oceanic and Atmospheric Administration. In the days following Hurricane Maria's landfall in Puerto Rico last September, a team led by Miguel Román of the NASA Goddard Space Center worked with *Suomi NPP* images, using software tools to filter out nonelectric light and producing a powerful set of before-and-after images that revealed the devastating extent of power outages and other infrastructure damage.

This analysis was made possible in part by an earlier effort to understand and measure the accuracy of *Suomi NPP* imagery. Last spring, Román traveled with a team to Puerto Rico, where they pointed LED lamps with predetermined power levels at reflective targets, creating a baseline they could use to quantify errors based on cloud cover and other factors. He calls the trip "a ▶

◀ first step to develop a new set of guidelines to assess the quality and stability of nighttime satellite measurements." A final analysis of Hurricane Maria's impact using the nighttime lights data is expected later this year. —*A.T.*

6 SpaceKnow

- Counting cars in Six Flags parking lots
- U.S.

San Francisco-based analytics company SpaceKnow Inc. can identify and track everything from planes at John F. Kennedy International Airport to shipping containers in the Port of Hamburg, which it does by tapping data from about 200 public and private satellites.

SpaceKnow prides itself on being a "DIY spatial analytics platform," says Chief Executive Officer Jeremy Fand. (SpaceKnow provides certain indexes to Bloomberg terminal subscribers; Fand was a senior product manager at Bloomberg LP before moving to SpaceKnow.) Anyone so inclined can go to its website and select a geographic area to zero in on. Those interested in specific companies or industries can order custom reports. "Say I'm a trader who's responsible for trading Six Flags stock," Fand says. "I would want to use SpaceKnow analytics to look at all Six Flags parking lots all the time." Prices start at $10 per square kilometer analyzed and vary depending on the computational and labor demands. If the customer wants exclusive access to the reports, that also adds to the cost.

One area the company's clients are particularly interested in is infrastructure development—whether there are new mines in the cobalt-rich Democratic Republic

of Congo, say, which could indicate an imminent rise in minerals prices or an increase in production of electric car batteries. —*A.T.*

7 Imazon

- Policing Amazon deforestation
- Brazil

Ten years ago, Carlos Souza, senior researcher at the Amazon Institute of People and the Environment (Imazon) in Brazil, started using satellite data to develop a picture of Amazon deforestation. The images were relatively low-resolution, so Souza layered in other sources of data to produce a detailed, acre-by-acre portrait of Amazon rainforest cover.

Today, scientists and engineers at the European Space Agency make Souza's job much easier. One of the agency's Sentinel satellites provides him with optical and infrared imagery, while another uses radar to cut through cloud cover and fill in any gaps. Imazon can now spot changes in forest cover from one month to the next. "Our goal is to get as close to real-time information about deforestation as possible," Souza says.

Deforestation spiked in Brazil in 2004, prompting new laws that partially clamped down on the practice. But enforcement is a nagging problem, and in recent years the government has tried to roll back environmental laws. The deforestation rate has stayed steady, but Souza considers that bad news. "We are still losing a lot of forest to illegal deforestation," he says.

Imazon makes its tree-clearing images available to the public as well as to local law enforcement, and so far that's led to some raids on illegal sawmills. Souza believes officials can do more. He's focused on getting data into the hands of local governments through Imazon's "green municipalities" program, which trains officials to identify deforestation. —*Shannon Sims*

8 TellusLabs

- Tracking global crops
- Turkey

TellusLabs Inc. is among the companies that rely on their expertise sifting through and enhancing satellite images rather than collecting the images themselves. Co-founded two years ago by a former NASA scientist, the agricultural-data startup relies primarily on NASA and European Space Agency satellites to power prediction models for millions of acres of wheat, rice, and other crops. What these older government satellites lack in precision, they make up for in their ability to measure thermal infrared bands, which show whether something is alive and radiating heat. "The pixels are much larger," says general manager Fernando Rodriguez-Villa, "but they're incredibly rich from a spectral perspective."

Photo ☐ Courtesy SpaceKnow

Over Six Flags, Castaic Junction, Calif. ◁

Photo ☐ Courtesy ESA

Northern Brazil, where the Amazon River meets the Atlantic Ocean. ▽

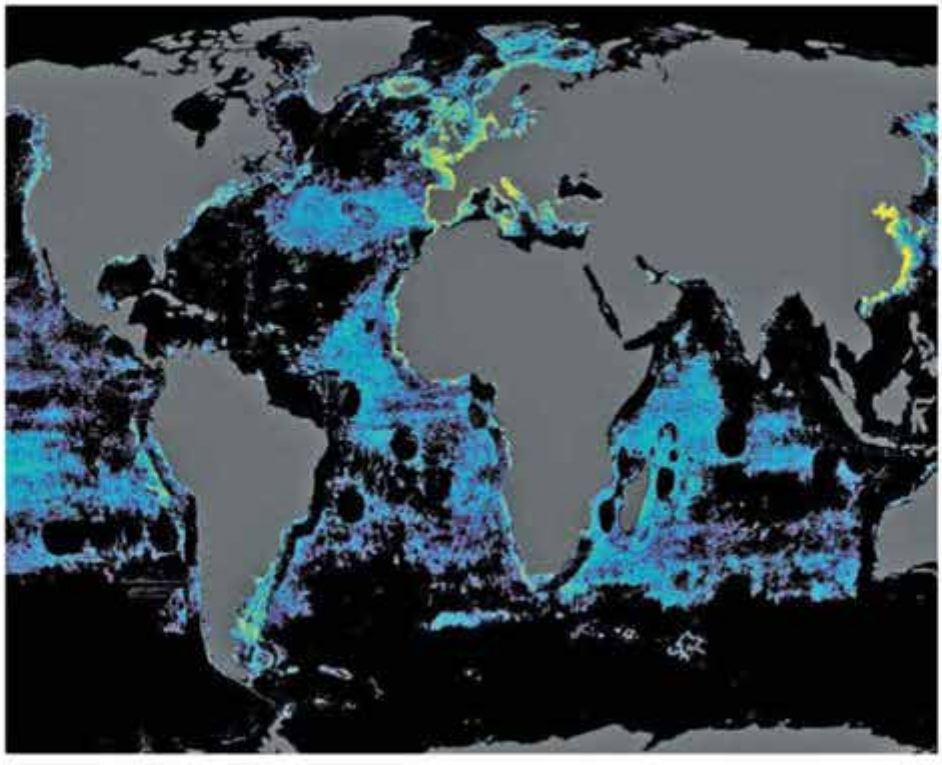


Photo □ Courtesy Global Fishing Watch

Global fishing activity. The round dark spots are exclusive economic zones of island states.

Having started out measuring U.S. corn and soybean output, the company is expanding into more categories and countries to serve a multinational client base—including the likes of Unilever Plc. Palm oil, coffee, and cocoa are all growth areas; TellusLabs has detailed predictive models in 10 countries, with crop health statistics in dozens of others. One area of increasing interest is Turkey, where advances such as higher-quality seeds have boosted wheat harvests, but where political uncertainty is seen as a possible obstacle to progress. ——*A.T.*

9 Global Fishing Watch

- Stopping illegal fishing
- Indonesia

The fish-filled waters around the Indonesian archipelago have long been fertile territory for foreign poachers, and until recently they've been all but impossible to police. Led by fisheries minister Susi Pudjiastuti, the government made a breakthrough last year when it teamed up with the international nonprofit Global Fishing Watch, which processes satellite-gleaned ship-tracking data to help identify where and when vessels are fishing illegally.

To avoid collisions, ships over a certain size are required to broadcast their location using the automatic identification system (AIS), a GPS-like program that relies on satellites and terrestrial receivers. Global Fishing Watch analyzes those transmissions alongside data from other sources, including infrared imaging and radar, deploying machine learning to determine which vessels are fishing boats.

The group was jointly founded by three separate companies: SkyTruth, which uses satellites to monitor natural resource extraction and promote environmental protection; Oceana, an international ocean conservation organization; and Google, which provides data-analytic muscle. (Bloomberg Philanthropies is a funding partner of Global Fishing Watch.) Indonesia is the first and only government to provide it with additional data from the vessel-monitoring systems used by smaller boats that aren't required to carry AIS. With this information, Global Fishing Watch can see when these boats rendezvous with cargo ships to transfer their catches rather than return to port, which is often a sign of illegal activity.

The program is part of a crackdown that began in 2014 and delivered swift results for Indonesia: Government revenue from fishing was up 129 percent last year, compared with 2014, according to the ministry. Global Fishing Watch now tracks about 65,000 vessels globally, and while its partnership with Indonesia is still new, the organization expects the aggressive approach to spread. "Within the next decade, we can be tracking the vessels that are responsible for about 75 percent of the world's catch," says its chief executive officer, Tony Long. Peru and Costa Rica have committed to join the program. ——*Karlis Salna and Aaron Clark*

10 World Health Organization

- Refining detection of airborne particulate matter
- India

Carbon dioxide gets all the attention these days—not only because it's the main driver of climate change but also because its effects are global and long-lasting. Old-fashioned air pollution is a more local affair. Also known as particulate matter, it's heavier, doesn't mix as well with air molecules, and succumbs over time to gravity, rain, and other forces that remove it from the atmosphere.

Harvard scientists showed in a landmark 1993 report that particulate matter is "positively associated with death from lung cancer and cardiopulmonary disease." That finding has since been backed up by numerous studies, generally relying on ground-based pollution sensors. But such systems provide only spotty coverage. In recent years, the World Health Organization has drawn on satellite data to produce its annual *State of Global Air* report, running the data through an algorithm that divides the atmosphere into a million "boxes," then calculates how weather moves from box to box, producing a simulation of how air—and pollution—move around the planet.

In the most recent edition, published in April, researchers showed that 95 percent of humanity lives in areas with unhealthy air. The proportion of North America with high levels of the most dangerous fine particulate matter fell from 62 percent from 1998 to 2000 to 19 percent from 2010 to 2012, in no small part due to amendments to the U.S. Clean Air Act passed in 1990. In India the concentration of the same size particles has jumped almost 20 percent since just 2011. ——*Eric Roston*

SCREWED IN A MILLISECOND

The world economy runs on the shockingly vulnerable GPS network. It needs a backup plan

By Paul Tullis

■ Duke Buckner was enjoying his breakfast at the Renaissance Tel Aviv Hotel, looking out on the city marina, on the day that time stuttered. Buckner oversees marketing and business development for Microsemi Corp., an American communications and defense contractor, and he gets a copy of emailed error reports for its equipment. It's rare to get more than one in a given day. But on the morning of Jan. 26, 2016, they flooded his inbox. He forgot about breakfast.

The complaints had to do with Microsemi's timing receivers for the Global Positioning System, the ubiquitous satellite navigation technology that was built for the U.S. military and has found its way into all our pockets. GPS isn't just for maps. It's also a kind of vast, spaceborne clock. Computers all over Earth use it to determine what time it is, down to billionths of a second. When there's the slightest disagreement among those computers, things fall apart.

Microsemi's timing receivers were frantically issuing error messages because of just such a discrepancy. "In normal operation, these things don't generate alarms for years," Buckner says. "So when one goes off a lot of times, people don't know what to do." Over the next 11 hours, cellphone towers lost their connections, U.S. police and fire stations reported communications errors, BBC radio signals were interrupted, and the telescope that tracks asteroids in Earth's orbit went offline.

The cause was a bug in the GPS network. When the U.S. Air Force, which operates the 31 satellites, decommissioned an older one and zeroed out its database values, it accidentally introduced tiny errors into the database, skewing the numbers. By the time Buckner's inbox started blowing up, several satellites were transmitting bad timing data, running slow by 13.7 millionths of a second.

Each satellite carries several atomic clocks that are supposed to measure time by tracking how often the electrons at its core jump from one energy state to another. The satellites then transmit that data, along with their locations in orbit, toward Earth. On the ground, the GPS receiver in your phone relies on the consistency of those ultraprecise calculations to determine where you are, where the nearest decent bowl of pho is, and so on. (Yes, Einstein fans, the receiver accounts for the space clocks ticking a little slower than the ones on Earth.)

It's tough to overstate how GPS-dependent the world economy has become since the U.S. Department of Defense started giving the service away to the public in 2000. There are 2 billion GPS receivers in use around the world, a number that Europe's satellite navigation agency estimates will hit 7 billion by 2022. Along with the telecommunications industry, banks, airlines, electric utilities, cloud computing businesses, and TV broadcasters require constantly precise GPS timing. Emergency services do, too, as do military forces. The U.S. Department of Homeland Security has designated 16 sectors of infrastructure as "critical," and 14 of them depend on GPS.

Most critical services, and financial markets, have backups—their own atomic clocks, perhaps, or connections to slightly less precise tools. But some of those backups depend on GPS timing, and might last only a few minutes. "GPS is the single point of failure for the entire modern economy," says Representative John Garamendi, a California

Democrat who's been warning about the hazards for years as a member of the House committees on armed services and on transportation and infrastructure. "No cellphone, no ATM machine will work."

The 11-hour run of intermittent chaos that ruined Buckner's breakfast was just a hint of what's possible. That was an innocent mistake, after all, not a concerted attack on the GPS network. Yet U.S. politicians have done little to safeguard the system since then.

Besides Garamendi, one of the loudest voices pleading to shore up GPS vulnerabilities is Dana Goward, who runs the nonprofit Resilient Navigation and Timing Foundation. (Founded in 2013, it's backed by defense contractors and related companies.) A former Coast Guard helicopter pilot, Goward doesn't equivocate when asked what a widespread GPS outage would mean. It's like ignoring warnings to reinforce airplane cockpit doors before Sept. 11, he says, or the alarms about New Orleans's creaky levees before Hurricane Katrina: "People will die."

■ Schriever Air Force Base, a few miles east of Colorado Springs, is home to the 2nd Space Operations Squadron. 2SOPS, as the squadron is known, operates the GPS network from a single room behind two passcoded doors, an armed guard, barriers that can rise from the driveway to block vehicles, and three chain-link fences topped with razor wire.

In the operations center one day in June, eight uniformed airmen and two civilian contractors are getting ready to conduct a "pre-pass," a routine test to ensure the satellites can communicate. Each of the airmen has secret or top-secret clearance, and visitors must pass a background check. The language of 2SOPS is, unsurprisingly, heavy on acronyms.

"Pre-pass SV 15!" says the satellite system operator.

"C/L1-8 Step 4 listen up for prepass," responds the mission chief.

"Active now, SV 15, CAPE A string, SSO 1, alternate visibility at DIEGO, VSOH/NAV/MOD/GBD, no applicable CIFs/TPs," says the system operator.

2SOPS typically relays a new navigation message to each satellite once every 24 hours to make sure it's accurate, using a network of 11 antennas around the world. In between, the unit monitors the GPS network for quirks and defects, based on precise navigation and timing signals the airmen send the satellites every 1.5 seconds. It's repetitive work that runs the risk of becoming mindless, says Lieutenant Colonel Stephen Toth, who runs 2SOPS. "With repetition can come complacency," he says. "You need to pay close attention to make sure it doesn't creep in."

Lots of things can scramble the satellites besides some stray numbers in a database. Solar flares. Space debris. And, perhaps, a hostile foreign power. The Pentagon started to regard the satellites themselves as a potential target in 2007, when China obliterated one of its own aging weather satellites using a missile. North Korea, Iran, and Russia are also said to have developed satellite-busting weaponry. In an effort to guard against hacking, 2SOPS has added the position of cyberdefense operator, and the military is expanding related training for the satellite operators.

In June, President Trump surprised a meeting of the National Space Council, a committee so new it doesn't have a website, by announcing his intention to create a Space Force, a sixth division of the military to complement the Air Force. This was over the objections of his defense secretary, and it may have a tough time winning approval from Congress, which last year rejected just such a proposal. But the threats aren't difficult to imagine, and the U.S. is ill-prepared for them. While there are protocols and international agreements that dictate what to do when a Russian fighter jet flies too close to an American jet over Syria or a U.S. Navy vessel runs aground in Chinese waters, there's no rulebook for what happens when a foreign satellite's activity appears potentially hostile.

On the receiver side, GPS signals are weak enough to be clouded by pigeon poop on cellphone towers—or jammed by miscreants using hardware that's surprisingly easy to obtain. Although the hundreds of varieties on the market are illegal in most countries, the European Global Navigation Satellite Systems Agency tallied roughly 50,000 incidents of deliberate jamming in the last two years, mostly truckers and ride-hailing drivers trying to hide their locations from employers during breaks. It's assumed jamming was the cause of more than 40 airliners' loss of GPS when nearing runways at Manila's Ninoy Aquino ▶

A few other satellite navigation systems have backups in place:
● Galileo (operated by the European Union) ● GLONASS (Russia) ● BDS (China)
└ The only non-U.S. system that claims global coverage

◀ International Airport in July and August of 2016. All landed safely by eyeballing their approaches, but the weather isn't always so forgiving.

The most insidious tactic on the ground is GPS spoofing, using malicious software to broadcast phony signals and fool the receiver on, say, an aircraft into thinking it's somewhere, or somewhen, that it isn't. Such methods "would certainly work against Ubers, Waymo's self-driving cars, delivery drones from Amazon," and more, says Todd Humphreys, an aerospace engineering professor at the University of Texas at Austin.

In the world of finance, subtle spoofing could foul up everything from a convenience store's credit card reader to the entire New York Stock Exchange. "If you change the reference time dramatically, everybody's going to notice," says Andrew Bach, who used to oversee the NYSE's network services. "The thing people get concerned about is, what if someone very gently drifts time ahead or back for the purpose of injecting confusion into the operations of the financial industry?" Even though most major Wall Street companies have their own atomic clocks to backstop GPS timing, introducing subtle anomalies could spook the algorithms that run the world of high-frequency trading, sparking a mass sell-off.

Spoofing by hostile foreign powers is a concern for the Pentagon, too. In 2012 stunned Homeland Security officials watched as Humphreys and colleagues hijacked a drone by giving it false GPS coordinates and leading it away from its intended path. Russian military forces are able to spoof drones over Syria and the Black Sea, says a person familiar with the matter.

The Air Force says spoofing isn't really its responsibility, that the job of 2SOPS is just to maintain the signal from the GPS network, not ensure that receivers can read it accurately. Yet no other government agency is in charge of trying to mitigate the effects of jamming and spoofing. It's been left to businesses like Microsemi to develop relevant antispoofing firewalls and keep them updated. DHS says it provides support and technical expertise to operators of critical infrastructure, but only on request. Mostly, the department says, it's up to businesses to make sure they have backup plans.

That's unrealistic, according to Goward, the lobbyist. "Everyone we've talked to in all industries sees this as a government responsibility, and none that we know of, other than core financial services, is able to withstand any significant disruption for any significant period of time," he says. The corporate attitude seems to be one of mutually assured destruction, he adds, as in, "I'm not gonna get blamed. The Air Force or the government's gonna get blamed. So why should I spend money on it?"

■ An hour north of the Air Force base, in Waterton, Colo., sprawls a Lockheed Martin Corp. facility that dates to 1955, when it was isolated enough for missile testing. Today, Denver's suburbs edge up almost to the fence around its 5,600 acres. Among the 185 structures onsite, the company recently built a $128 million, 40,000-square-foot cleanroom. Inside, past the armed guards, a half-dozen workers in calf-length jackets, hairnets, and shoe coverings, all antistatic and lint-free, are assembling the next generation of GPS satellites.

The Air Force has approved the first GPS 3 satellite for launch, and Lockheed expects another to get the OK this summer, once it completes vacuum tests behind a three-story door just off the cleanroom. The tests mimic the conditions of outer space using pumps and cold or hot air, yielding low pressures and temperatures ranging from -238F to 302F.

The GPS 3 satellites are designed to last 15 years, 25 percent longer than those in the current generation, which have far exceeded their life expectancy thanks in part to careful fuel management. The GPS 3s also provide a signal eight times stronger, which makes it tougher to jam, with triple the location accuracy. But they still lack the two strongest antispoofing technologies on the market, both essentially extra layers of security to detect attacks and prove signals and navigation messages are legit. Two colonels with Air Force Space Command agreed to discuss GPS vulnerabilities in an interview but canceled the day before it was scheduled. A spokeswoman says the change was "due to the current environment and the sensitivity around some of the questions" and that one of the encryption methods "is currently being examined."

Although it would help if the government went with the better encryption techniques, it would be safer to reduce the world economy's dependence on GPS, says Garamendi, the Democratic congressman. He's been pushing for years for the federal government to build a backup ground-based radio network called Enhanced Long-Range Navigation (eLoran). It would deliver stronger signals than those from GPS, and Congress estimates it would cost taxpayers $200 million. South Korea says it will have eLoran coverage by 2020.

There's been no serious effort to set up the backup system in the U.S., even though military officials briefed members of Congress on GPS vulnerability by 1997. George W. Bush's Homeland Security team announced plans for an eLoran system in 2008, but the funding fell out of Barack Obama's recession-strapped first budget the following year and hasn't reappeared since. James Platt, director of the DHS position, navigation, and timing office under Trump, says his office ought to define the requirements for a backup system before it begins evaluating whether eLoran is the best option.

Garamendi has been left to try to fold the funding into military spending bills without DHS support. "It's just organizational reluctance of federal agencies to pick up a new task," he says. If they don't, Trump's Space Force may well be flying blind—and Duke Buckner can sell lots of atomic clocks. Not that he's super excited about it. Ⓑ

Solutions

Kathleen Howell's Exotic Orbit

By Peter Coy

Using math she pioneered, NASA wants to get Americans back to the moon and one day to Mars

■ Kathleen Howell never aspired to walk on the moon. When she watched the first lunar landing as a teenager in 1969, she was more intrigued by the looping route that brought the Apollo 11 astronauts from Earth to the Sea of Tranquility and back. Orbits became her life's passion. In 1982 she wrote a doctoral thesis on orbits in "multibody regimes" that earned her a Ph.D. from Stanford. She soon received a Presidential Young Investigator Award.

Howell's world-leading expertise in unconventional orbits is in fresh demand. NASA has decided that a near-rectilinear halo orbit (NRHO)—a specialty of hers—would be an ideal place to put the Lunar Orbital Platform-Gateway, a planned way station for future human flights to the moon and eventually Mars. Mission planners have already brought her in for advice.

Unlike an ordinary flat orbit, an NRHO can be slightly warped. Also, it stands on end, almost perpendicular to an ordinary orbit—hence "near rectilinear." The plan is for the Gateway's circuits to pass tight over the moon's north pole at high speed and more slowly below the south pole, because of the greater distance from the moon. Imagine moving your hand in circles, as if washing a window, while you walk forward. Except you're making hand circles around the moon while walking around Earth.

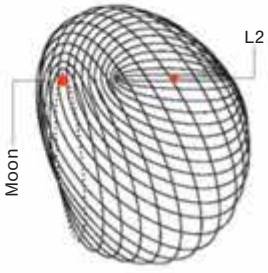
Although an NRHO appears to be an ordinary circuit of the moon, it's actually part of a family of orbits centered on an empty point called L2, or Lagrange Point 2, about 45,000 miles beyond the far side of the moon, where the gravitational forces of Earth and the moon are in balance with the centrifugal forces on the spacecraft.

Contrary to what you were taught in school, it's quite possible to orbit around nothing, as long as that nothing is a Lagrange point, says Howell, now a chaired professor at Purdue University, which calls itself "the cradle of astronauts." "It is elegant and very rich," she says. "All the forces come together to produce an unexpected path through space." She likens the competing gravitational fields that influence a spacecraft in an NRHO to the effects of a tricky green on a golf ball. Space scientists need to work with those contours like a skilled putter. "I need to build the nuances of the green into my mathematics, to take advantage of the green," Howell says.

Her work builds on an 18th century discovery. In 1760 the Swiss mathematician Leonhard Euler theorized that for any pair of orbiting bodies, there are three points in space where gravitational and centrifugal forces precisely balance. In 1772 his protégé Joseph-Louis Lagrange found two more such spots. He apparently won naming rights: All five are now known as Lagrange points, or sometimes as libration points. For a space station or a satellite, a Lagrange point is like a mooring in a safe harbor. An object parked at one of these sweet spots can remain in lockstep with the smaller body as it orbits the larger one. Observation satellites have been positioned near Lagrange points, and sci-fi writers have imagined colonies stationed at them.

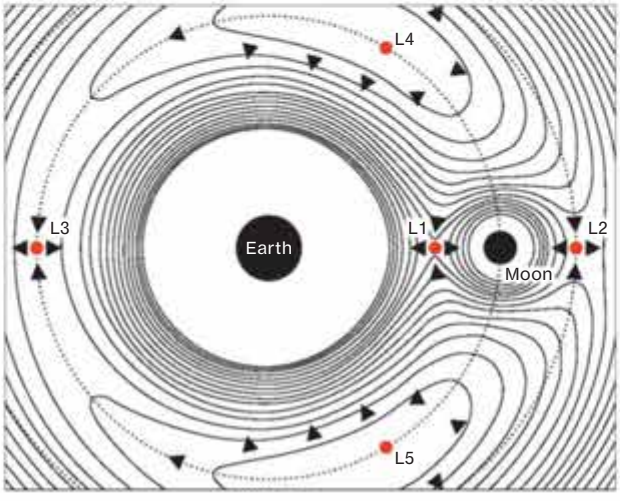
Howell's doctoral thesis explored a family of orbits around Lagrange points, called halo orbits because from Earth they appear to form a halo around the moon. A satellite or spacecraft in a halo orbit can be constantly in Earth's sight and can therefore maintain communication between astronauts on the far side of the moon and control rooms back home. Each circuit around the moon is slightly different, like a spinning plate wobbling on a tabletop.

The few people who knew anything about halo orbits in the early 1980s perceived them as interesting but erratic. Howell found a subset that was more stable. In simulations, she tipped her orbit upward,



dragging it so it would be more vertical and less "bent," and also pulled it nearer to the moon. When the orbit got close to the moon, it became "metastable." That meant it could stay on course with minimal use of thrusters—extending its useful life and saving NASA and other would-be spacefarers money. "If I run out of propellant, I'm done," she says.

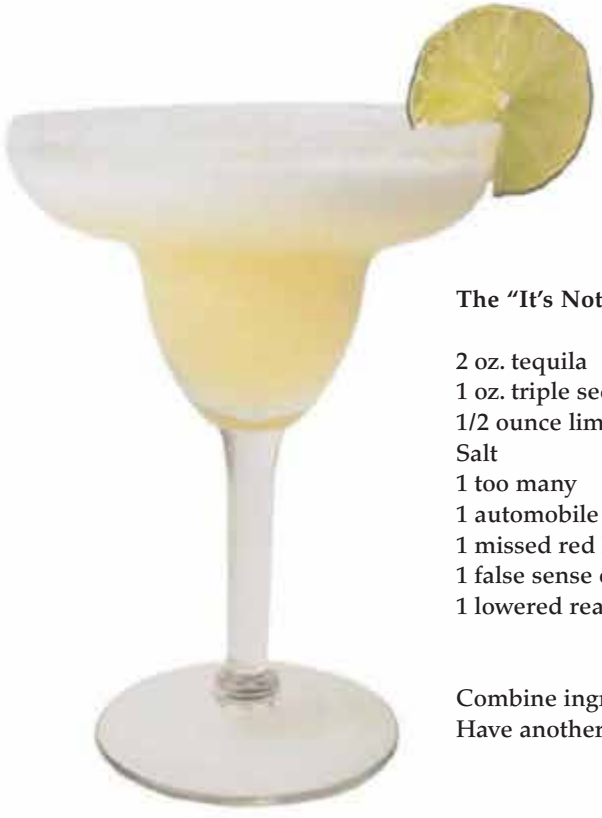
President Trump has proposed spending $500 million in fiscal 2019 and $2.7 billion over the next five years for the Gateway. Its first module, a "space tug," is slated to be put into orbit in 2022, with American astronauts returning to lunar orbit a year later. The orbital math the Gateway will use is complex, because it must account not just for Earth and the moon, but the pull of the sun and even Jupiter. Howell's computer simulations offer a close approximation of the craft's path; perfect prediction is in principle impossible. "You can't include everything in the universe in your calculation," she says, "but we do amazingly well for what we don't know." B



The orbits shown are centered on L2, a Lagrange point on the far side of the moon. The most vertical one is planned for NASA's Lunar Gateway.

Not to scale. Data □ NASA, Purdue University School of Aeronautics and Astronautics, A.I. Solutions

The thick black dots show Earth and the moon. The small red dots are Lagrange points, where gravitational and centrifugal forces are balanced.



The "It's Not Like I'm Drunk" Cocktail

2 oz. tequila
1 oz. triple sec
1/2 ounce lime juice
Salt
1 too many
1 automobile
1 missed red light
1 false sense of security
1 lowered reaction time

Combine ingredients. Shake.
Have another. And another.

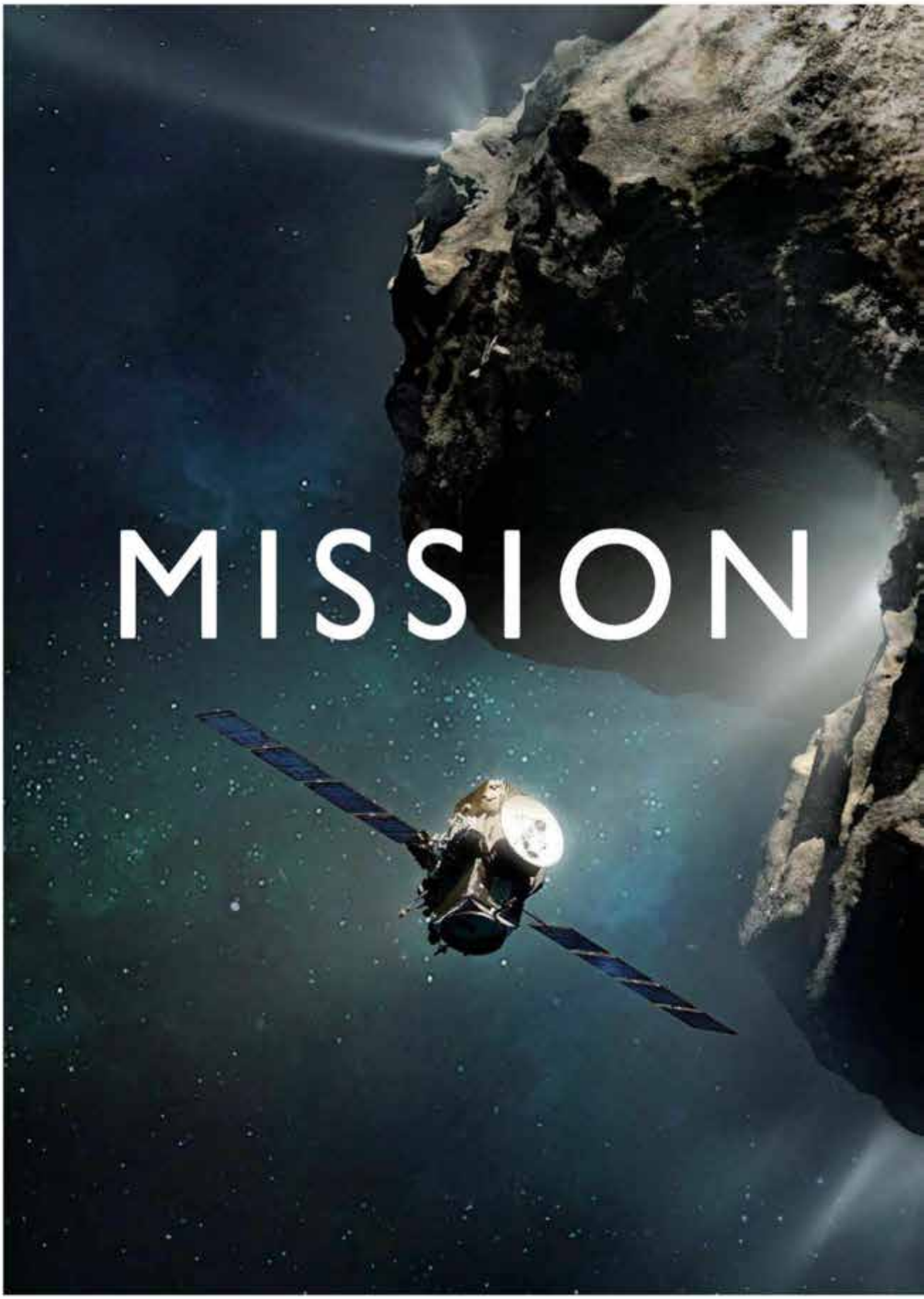
Never underestimate 'just a few.'
Buzzed driving is drunk driving.

III

FAR OUT

Photo ☐ Courtesy NASA

The Lagoon Nebula, a vast stellar nursery 4,000 light-years from our solar system.


MISSION

TO 67P

By Dimitra Kessenides
Illustration by Emmanuel Shiu

The secret to the beginning of life could be found on the surface of a comet

■ Steve Squyres was feeling restless. It was late fall 2013, and the semester was wrapping up at Cornell, where he'd been a professor for more than 25 years. As head of NASA's Mars Exploration Rover mission, he'd just marked 10 years tracking *Spirit* and *Opportunity*, two six-wheeled robots that went to the red planet. They'd been designed to roam the surface for just 90 days, scratching and drilling into rocks and examining soil in search of evidence of water. Nearly a decade later, *Opportunity* was still rumbling along. Squyres wasn't bored by its persistence, but there wasn't much left for him to do.

He called Stephen Gorevan, a longtime friend and a co-founder of Honeybee Robotics Ltd., which specializes in drills and sampling tools for planets and smaller bodies. Squyres had included a Honeybee tool on the rovers, and he figured Gorevan might have something new and cool to show him. Squyres proposed a visit to the company's New York headquarters.

Over the course of a day, Gorevan talked up a dozen or so projects. One in particular stood out: a nearly 18-foot-long pogo-stick-like retractable arm that Honeybee envisioned sending to a comet. The robotic "touch and go" system would grab a small chunk from the comet's surface, about 100 grams' worth, store it in a capsule, and return it unspoiled to Earth.

Squyres was captivated. Comets are icy bodies loaded with organic material—including carbon, hydrogen, nitrogen, and oxygen—that astronomers believe may have collided with Earth billions of years ago, starting the chain of events that led to the earliest forms of life and, eventually, to us. This primordial matter, which doesn't exist anywhere else, remains frozen in comets, kept in a primitive condition since the birth of the solar system. "If you want to understand the emergence of life, comets get us closer than anything we can get our hands on," says Squyres, a fit 62-year-old with short gray hair.

Of course, humans have never gotten near the dust and ice that make up comets. Driving back to Ithaca, N.Y., Squyres began working out how to rectify that. "A couple of neurons that hadn't fired in well over a decade got me thinking," he says. "I knew how important comet sample return was scientifically, and I knew that past attempts to propose it had failed."

At the time, astronomers were waiting for images from the *Rosetta* mission, a probe launched to the comet 67P by the European Space Agency in 2004. Its photos were supposed to start beaming back to Earth in 2014. In theory, they'd give Squyres much of the data needed to design a mission to send Honeybee's touch-and-go instrument there. So would Osiris-Rex, a NASA-sponsored asteroid study scheduled to launch in September 2016 that would also use touch-and-go technology.

Four and a half hours after leaving Honeybee, Squyres pulled into his driveway with an outline for his next big project. It would be expensive, but he knew NASA would be soliciting proposals in December 2016 for its periodic New Frontiers program, which sponsors space exploration missions with a budget of about $1 billion.

Squyres's comet proposal—ultimately dubbed Caesar, for comet astrobiology exploration sample return—was selected late last year as one of two finalists. If it wins, it will give researchers their first chance to bring some of the organic stew from a comet's surface back to Earth.

■ Comets are named either for the astronomers who identify them or with an alphanumeric code describing their orbit. 67P is also known as Churyumov-Gerasimenko, for the Ukrainian astronomers, Klim Ivanovich Churyumov and Svetlana Ivanovna Gerasimenko, who discovered it in 1969. With two misshapen lobes, the comet resembles a lumpy rubber duck spinning through space at 84,000 miles per hour. A day on 67P lasts a bit more than 12 hours;

Single-frame enhanced NavCam image
Date: 03/27/2016 Distance to 67P: 329km

Rosetta images □ Courtesy ESA

a revolution around the sun, nearly six and a half Earth years. It's about 2.5 miles wide, with an orbit that goes beyond Jupiter at its farthest point from the sun. Thanks to *Rosetta*, we know more about 67P than any of the thousands of cosmic snowballs (as NASA sometimes calls comets) that have been identified.

Getting a spacecraft to a comet and collecting a sample is a complicated proposition. Irregularly shaped and small, comets spin quickly, and because of their size, they have almost no gravity. We know they're frozen, and we know something of their chemical composition, but we understand almost nothing about their topography. A comet might be hard, like an ice cube, or it might be soft, like the slush pile at the base of a ski lift. "The environment of space is relatively easy if you don't have to interact with a surface," says Kris Zacny, a Honeybee engineer. "It can be anything, from very cohesive to very loose."

Despite the challenges, NASA has made collecting such a sample a top priority. Comets are scientifically intriguing—the whole origins-of-life-itself thing—but some people think bringing celestial matter to Earth will someday be a big business as well. Commercial efforts, such as Deep Space Industries Inc. and Planetary Resources, an asteroid-mining startup backed by Google co-founder Larry Page and others, have promised investors enormous payoffs by accessing untapped resources in space. These efforts are widely seen as speculative—so

Photo □ Courtesy NASA

The aquanauts were using the water's low gravity to simulate field geology tests on asteroids.

Squyres spent two weeks in 2012 in a lab submerged off the coast of Florida, as part of NASA's Neemo16 mission.

Distance to 67P: 30.8km

Date: 06/17/2016

speculative that, earlier this year, Planetary Resources had to lay off most of its employees after its funding dried up.

The challenge in space mining, according to Jim Keravala, a co-founder of OffWorld, a privately owned robotic mining and construction company in Pasadena, Calif., is that a scaling market doesn't yet exist. OffWorld is developing AI technologies to be used in traditional mining, infrastructure repair, and construction. Eventually the technologies will be configured for use in space. "We're treating Earth as our first celestial body," Keravala says.

OffWorld supersedes another company he founded, Shackleton Energy, which sought to extract water ice from the moon. Shackleton wasn't viable, he says, and ceased operations three years ago. "There is a 20- to 50-year arc before you start, and your average space-mining entrepreneur is an enthusiastic zealot–I speak as part of that crowd." OffWorld will draw on data from missions like Osiris-Rex and Caesar. "Until you can touch bodies in space extensively, you don't have a business," Keravala says.

In the near term, Honeybee is designing robotic drilling and mining equipment for research projects. Over 35 years, it's grown from a few engineers working on New York's Lower East Side to about 150 employees, with offices outside Denver and in Pasadena, across from NASA's Jet Propulsion Laboratory. "Our niche is tiny, but someday it will have value when these commercial missions come together," says Gorevan, who's also Honeybee's chairman. "We get most of our rare metals from China now. If we brought back one asteroid that was preexamined for having rare-earth metals, we'd never have to get anything from China again."

Distance to 67P: 84.3km

Date: 01/17/2016

■ Like many scientists, Squyres prefers not to think about commercial potential. He studied geology at Cornell but switched his focus after taking an astronomy class with Joseph Veverka, a member of the science team on NASA's Viking mission, which sent two probes to Mars in the mid-1970s. "There weren't many blank spots on the map," Squyres says of studying Earth's surface. "Geology is a compelling scientific discipline, but it didn't have that 'nobody's ever been there' appeal." After taking Veverka's class, he shifted to space.

As an undergrad, he studied images from the Viking mission, which showed, among other things, evidence of water on the planet–dried-up lakes and riverbeds. Shouldn't mankind try to figure out what happened? Squyres went on to grad school, then took a job with NASA as a researcher at the agency's Ames Research Center in Mountain View, Calif. Five years later he joined the faculty at Cornell alongside Veverka and Carl Sagan, the late renowned astronomer. Squyres maintained his NASA contacts and participated in missions whenever he could. "I spent 10 years writing unsuccessful proposals," he says.

In the early 1990s, under then-Administrator Dan Goldin, NASA launched its Discovery Program, a lower-cost way to explore the solar system. The missions were competitive–"faster, better, cheaper" was Goldin's mantra–and run by scientists or principal investigators. Mars got little attention, though, until the summer of 1996, when a paper in the journal *Science* raised the possibility that an Antarctic meteorite believed to have come from the red planet contained fossils. The findings suggested the existence at one

time of living creatures on Mars, prompting President Bill Clinton to commit to exploring the planet. His announcement "cemented NASA's commitment to search-for-life research and made it appealing in a whole new way," says Laurie Leshin, president of the Worcester Polytechnic Institute and a co-investigator on Caesar.

Spirit and *Opportunity* were launched in the summer of 2003, successfully touching down on Mars about seven months later. *Spirit* phoned home first, with *Opportunity* following three weeks later. The robots found craters suggesting Mars once had enormous lakes. They also captured spectacular images of dust devils and sandstorms and discovered minerals previously unknown to scientists.

Squyres had expected the rovers' solar panels to eventually become so dust-laden that they'd shut down. *Spirit* last contacted mission control in March 2010, but it wasn't dust that killed it–it had gotten lost after being stuck in a sand trap. Windstorms did blow the dust off *Opportunity* until late May of this year. Since then, one of the most severe Martian dust storms in decades has posed the greatest threat to the rover, and it's gone silent. "*Opportunity*'s fate as a consequence of this storm will be either a miraculous recovery or an honorable death," Squyres says, adding that there's no telling when the weather will clear.

■ The budget for Caesar is about $1 billion, which, if the mission goes forward, would make it ▶

medium-size by NASA standards. It's competing against Dragonfly, a mission led by Elizabeth Turtle, a planetary scientist at Johns Hopkins University, that would explore the chemistry and possible habitability of dozens of sites on one of Saturn's moons.

The two teams are formulating their proposals, working out details. Honeybee has already started testing early designs of Caesar's sampling system. At NASA's Glenn Research Center in Cleveland, the instrument is dropped 500 feet into a giant vertical tunnel that's essentially a vacuum. Aerated concrete, or aircrete, which has the density of light pumice, approximating that on 67P, is attached to the instrument, without touching it, so engineers can simulate sampling the material in zero gravity.

The next big milestone for the roughly 200 members of Caesar's team will occur in 2019, when NASA will select the winning project. If theirs is chosen, they'll spend about five years building and testing a spacecraft—Northrop Grumman Innovation Systems is designing one—and send it into orbit. It would take almost another five years for the craft to reach 67P. The launch is planned at the earliest for August 2024, with a tentative arrival date of March 2029. "Every mission is years in the making," says Christopher Scolese, director of the Goddard Space Flight Center in Greenbelt, Md., which is managing Caesar and Osiris-Rex. "It's not like the movies, where it takes 90 minutes and a couple of nice words."

Nor is it always heroic. For all the awesome tech that would make Caesar possible, Squyres talks a lot about meticulous preparation and "margin on top of margin on top of margin." To him, risk reduction is almost a mantra and a way to meaningfully lower costs. In addition to drawing on the research from *Rosetta* and Osiris-Rex, Caesar would use solar electric propulsion to get to the comet, rather than chemical propulsion. This would allow the spacecraft to fly trajectories that wouldn't

otherwise be possible, Squyres says. "With chemical propulsion you do very short, intense burns that are followed by long periods of coasting. With solar electric propulsion you can do very long, gentle burns." Those trajectories will reliably get Caesar to 67P and back. And since *Rosetta* has already studied 67P, Caesar's spacecraft would carry few instruments, dramatically reducing its power needs and weight.

Once the craft enters 67P's orbit, in early 2029, the plan calls for six cameras to start snapping thousands of pictures that would help identify promising sampling spots. Site selection would begin almost immediately. The spacecraft would first get close enough to allow Honeybee's touch-and-go arm to make trial contacts with the comet. Eventually, it would dig into the surface for several seconds to grab material. If the first attempt acquires enough—80 grams or so—then, Squyres says, "we're out of there." But the mission is designed to allow for two more touches; all told, the Caesar craft could spend as much as four years orbiting the comet.

The robot arm would seal off the sample, including any dust, ice, and gases, in a container and transfer it to a special capsule that looks like a roaming Roomba vacuum cleaner. Engineers at the Japan Aerospace Exploration Agency (JAXA) will build the capsule, a scaled-up version of a similar system used by the agency in the 2003 launch of *Hayabusa*, a robot that was sent to a small near-Earth asteroid and successfully returned with a sample for analysis.

"We had been thinking about making sample return missions a pillar of our space science mission program, but hadn't thought about applying it to a foreign mission," Masaki Fujimoto, a deputy science director at JAXA, writes in an email. But Squyres had done his research and had JAXA in mind. "The sample return capsule for *Hayabusa* was flawless," he says, and aspects of that design would be perfect for Caesar, especially when it comes to keeping the sample cold.

If all goes well, its temperature would stay below freezing until the capsule lands at a rendezvous site in the Utah desert on Nov. 20, 2038. Then a team would pack the sample onto an ice truck and bring it to a facility in Houston, where scientists would begin analyzing it.

Squyres will be 82 in 2038. "I hope I'm still around," he says. "I'm eating healthy foods, getting lots of exercise, taking care of myself. And my dad's 91. So I've got good genes."

He says it's possible he won't write a single scientific paper about results from the Caesar sample. He's OK with that. "This may or may not succeed," he says. "It could fail. It's a huge gamble." But he's been preparing for this risk for most of his life, or at least since a moment in 1965, when he was 9 years old. His dad woke him one morning to observe a comet called Ikeya-Seki. Forecasters said it would be clearly visible to the naked eye, 10 times brighter than the full moon, despite being 80 million miles away. Ikeya-Seki didn't disappoint, Squyres says. If everything goes right, 67P won't either. B

Solutions

Satellites Need Sunscreen, Too

An Irish company has developed a coating to protect a solar orbiter from heat and radiation

By Jeremy Kahn

■ The European Space Agency had a problem: A satellite it was building to study solar flares and wind risked burning up as it reached its final orbit, nearer to the sun than Mercury's closest approach. At 26 million miles from our neighborhood star, the ESA's *Solar Orbiter*, scheduled to launch in February, will face temperatures above 500C (932F). In such intense heat, traditional coatings made from organic compounds break down and form a vapor that can condense on cooler parts of the spacecraft, blurring the lenses of optical instruments and fouling other sensors.

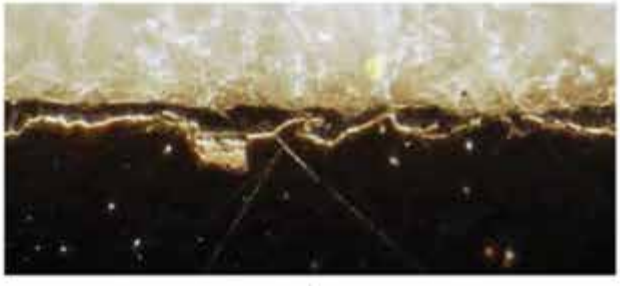


Photo ☐ Courtesy Enbio

SolarBlack coating on the *Solar Orbiter*'s heat shield.

The solution turned out to be one of humanity's earliest inventions: black pigment made from the burned bones of prey, similar to the stuff used to decorate the walls of prehistoric caves. "This is really a back-to-the-future story," says John O'Donoghue, co-founder and chief executive officer of Enbio Ltd., the Irish company behind the coating planned for the *Solar Orbiter*. "The oldest-known art in the world was painted with charred bone."

Enbio, founded in 2006, had developed a process called "co-blasting" for medical implants such as artificial hips. A high-powered airjet sprays titanium implants with a mixture of particles of coating and gritty aluminum oxide, which removes the oxidized layer that forms on the surface of most metals and makes them hard to paint. Before oxidation can recur (in just 1/300th of a second), Enbio's powder bonds with the metal.

The ESA thought the process might work for its heat shield. But the coating needed to be dark to absorb radiation, and Enbio had used light-colored synthetic bone in its implants. For the ESA, the company suggested charred animal bone, which "is highly stable for going to space because there's nothing combustible left in it," O'Donoghue says.

The dark coating, which Enbio calls SolarBlack, seemed so promising that the ESA asked whether the company could use a similar process to make a white veneer for aluminum parts on the satellite—for instance, the antennae and a long arm designed to hold instruments—that must reflect sunlight rather than absorb it. Although Enbio's implant coatings were light-colored, space scientists know that white tends to discolor when exposed to ultraviolet radiation. And Enbio had already discovered that a lighter material applied with its technology "doesn't stay white. It turns gunmetal gray," O'Donoghue says. "At first, we said no."

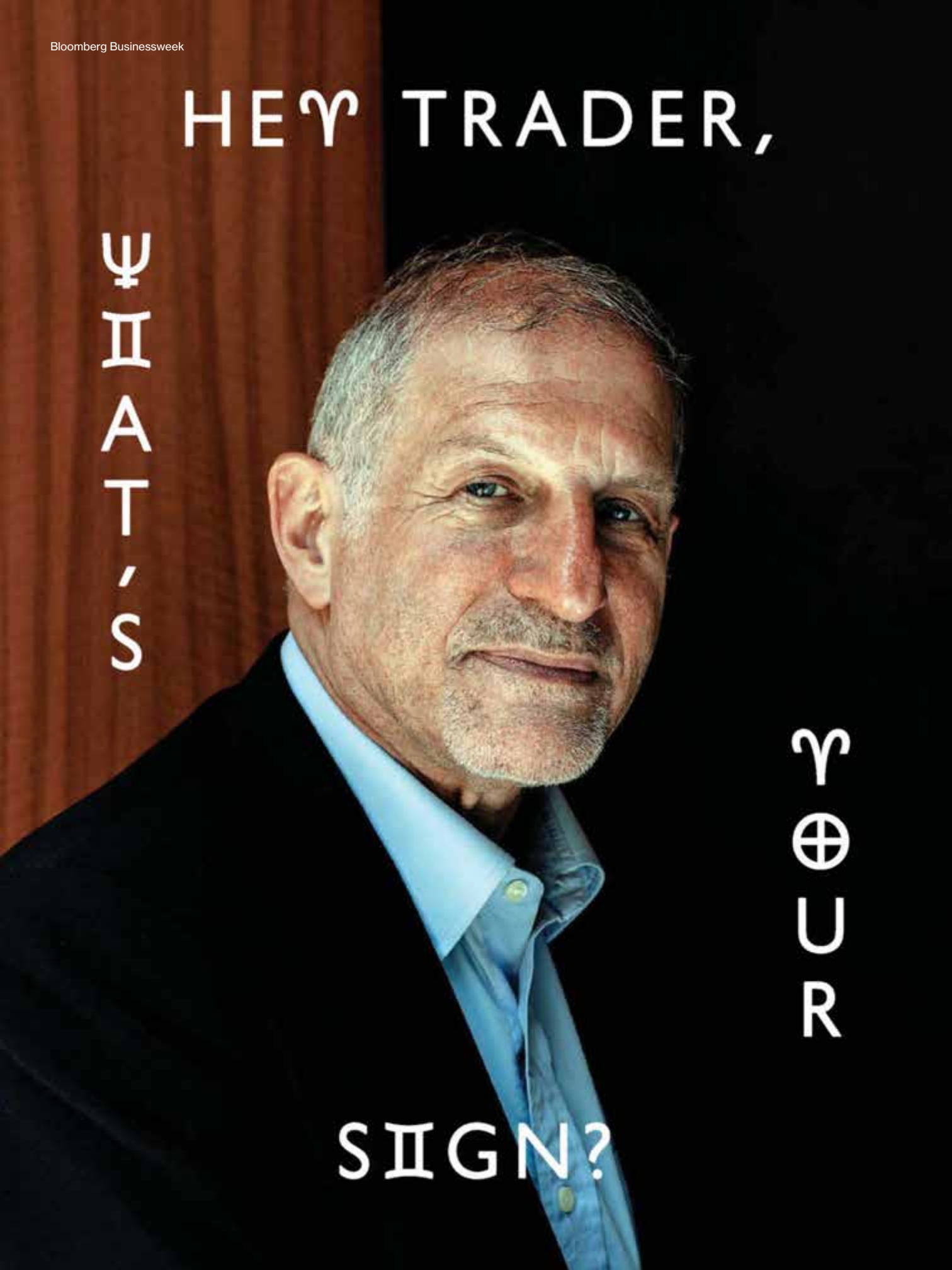
Then Barry Twomey, an Enbio researcher, proposed using SolarBlack as a primer on the aluminum parts before adding the white coating. Twomey figured that since the chemistry of the two materials is more closely matched, they could achieve a stronger bond. It took five years to perfect the process, but today Enbio makes what it calls SolarWhite by applying a white ceramic slurry that's cured and baked onto pieces of the satellite. "It was massively satisfying," Twomey says. "It was the first time I'd brought something from an original idea all the way through to seeing it applied."

SolarBlack has since been adopted by several European satellite makers, and Enbio is working with the ESA to promote the use of SolarWhite on commercial orbiters. Meanwhile, space companies are considering other uses of Enbio's co-blasting process, including coating threaded titanium bolts with Teflon to prevent them from spontaneously welding to surrounding metal.

The ESA helped save Enbio itself from flaming out: When the agency came calling, the company had few takers for its medical devices and had spent most of the €2 million-plus in funding it had received over the years. It had recently returned to University College Dublin, where many of its techniques were developed, so it could use the school's electron microscopes and X-ray equipment—the corporate equivalent of moving back in with your parents. Because of the ESA work, the company last year won a €1.5 million ($1.8 million) grant from the European Union. It employs 18 people in Dublin and at a plant dedicated to its space business in the town of Clonmel, a two-hour drive south of the Irish capital. O'Donoghue expects to have a staff of 28 by the end of the year and to secure further funding within three years. That's an eternity in startup time, but by then the *Solar Orbiter* will be approaching the sun to start its expected 10-year mission, and SolarBlack's true test will begin. —*Jeremy Kahn*

What About Us?

■ When astronauts return to the moon, it will be the first time humans have left Earth's teardrop-shaped magnetosphere since the last Apollo mission. Outside the protective bubble of our planet's magnetic field, they'll be much more exposed to solar and galactic radiation, increasing their risk of developing cardiovascular disease and cancer. Eddie Semones, a NASA radiation health physicist, says *Orion*, the ship the agency wants to use for a proposed 2023 moon mission, was built with integrated warning systems. If a radiation spike is detected, the crew's first line of defense is both toddler-certified and scientifically sound: They'll empty *Orion*'s closets of equipment, then climb inside and pile stuff on top of themselves. The exposure level could drop by half, Semones says, if "you're hunkered down low near the heat shield in the compartment in the stowage bays." But future health risks would remain. —*Brian K. Sullivan*


HEY TRADER,
WHAT'S
YOUR
SIGN?

It's tough to beat the market. Are you desperate enough to consult the stars?

By Simon van Zuylen-Wood
Photographs by Amy Li

■ It's 11 a.m. at the Princeton Club in Midtown Manhattan. A number of financial professionals have gathered here for the "AFund June 2018 Natural Resources Investment Symposium." Our first speaker is HSBC's chief precious metals analyst, the aptly named James Steel, who promotes gold as a hedge against populist upheaval. After Steel, there are slideshows from several mining companies seeking investors. After that, lunch. A generic networking event, by all appearances.

But here's the thing about AFund: The A stands for "Astrologers." It's run by an antic, charming 70-year-old named Henry Weingarten who says he gleans insight from charting the movements of celestial bodies. Today's event isn't technically about astrology, but like everything in the universe, it probably is. "Sixty to 70 percent of what I do is in the natural resource space," Weingarten tells me after lunch at the club, holding a glass of red wine. "I think it's because I'm a Leo. And effectively, as a Leo, I have an affinity for gold."

Even odder than the existence of the Astrologers Fund is its ability to attract the interest of nonlunatics. A few years ago, Fox News' Neil Cavuto told Weingarten on the air that he was "one of the best stockpickers I know." Post-symposium, at the Princeton Club, Weingarten and I are joined at a table by a buttoned-down crew. One of them is an analyst for a small investment bank; another says he runs his own family office. Everyone has some kind of relationship with Weingarten, from the cordial to the professional, though nobody seems to understand how financial astrology works. "Tell me the time, don't build me a clock!" says Paul Feeney, a corporate headhunter, repeatedly.

A few days earlier, Weingarten subscribed me to his weekly market forecasting newsletter, whose major insight lately has been: "US MARKETS ARE 'EASY' IF YOU REMEMBER THAT TRUMP'S 2018 HOROSCOPE IS STELLAR." I ask Weingarten what that means. He responds by chronicling his rise from fledgling East Village astrologer to financial oracle, from his prediction of the 1990 crash in Japan to his glorious 2016, in which he was long on a Trump victory and the market rally to follow. I ask the same question maybe five more times before he clarifies that he had seen a "double Jupiter" in Trump's horoscope, "which was a big win." This year "he has a Jupiter-Neptune." Which means? "It means he's going to win." Which tells us what about U.S. markets? It tells us they will win. "Jupiter means winning. Win! Win! Win!"

Weingarten is prone to soliloquies extolling his "world-class, nobody better" forecasting record. Asked to explain his methodology, he answers in gnomic riddles or not at all. The family office guy asks how financial astrology might relate to SpaceX and other efforts to explore beyond Earth. Weingarten cuts him off and says he can't give him an "informed decision about how children on the moon will be affected."

The conversation gets weirder, and Weingarten calls over one of today's presenters, a muscular Canadian named Rod Husband, to quell my skepticism. Husband is a Vancouver-based precious metals analyst. He says he hired Weingarten to help him forecast trends in the commodities market. (Weingarten also got paid for letting Husband present today.)

"When I first met Henry, I thought, 'What the hell,' " Husband says, evenly. Over time he learned to trust Weingarten's advice and stop asking questions. "So if he uses—Henry, forgive me, because I don't follow it—if he uses Jupiter and Mars to say that the next three-month trend for gold is going to be good, and if it coincides with something that I'm thinking, then OK." To Husband, Weingarten's appeal is obvious: "He uses astrology to separate himself from the other guys."

■ The aspiring financial astrologer must first grasp the basics of regular astrology. Everything revolves around the zodiac calendar, a 360-degree belt of sky, drawn from the perspective of Earth, organized into 12 30-degree wedges. These are called Libra and Taurus and so forth. A person's horoscope sign thus corresponds to the month of the zodiac calendar through which the sun appears to be "moving" around Earth when she was born. (Which makes astrology geocentric. Never mind Copernicus.)

That said, professionals tend to be snobby about "sun sign" horoscopes. They use more complex "natal charts" that diagram the exact position of the sun, moon, and planets in relation to one another at the exact time and place of a person's birth. Each planet signifies certain things (*Jupiter means winning!*) based largely on the angles at which it interfaces with other planets. Weingarten tells me I would need to study astrology for four years—"maybe three, with computers"—to grasp what's going on up there. Astrology may be a pseudoscience, but that doesn't mean it's easy to learn.

This brings us to finance. Most investors have no idea what tools fund managers use to choose stocks and bonds. (*Tell me the time, don't build me a clock!*) Much of the business of Wall Street is based on methodologies as obscure to the uninitiated as a natal chart. It was only a matter of time until these two industries joined forces. Weingarten's 1996 book *Investing by the Stars* traces financial astrology back to the Babylonians. A couple thousand years later, it's claimed, celebrity astrologer Evangeline Adams advised John Pierpont Morgan.

It wasn't until the 1960s that the vocation was ▶

◀ quasi-professionalized by a longtime Consolidated Edison Inc. employee who went by the name of Lieutenant Commander David Williams. Williams came to astrology via the burgeoning theory of "business cycles," which posited that the market's ups and downs have little to do with the particulars of companies or events but much to do with such patterns as the Fibonacci sequence, sunspots, or variations on Pi. Many of these, he thought, were themselves connected to planetary cycles. He found that during a series of 9.226-year cycles, the stock market bottomed out 80 percent of the time at Aries and Libra positions and crested 80 percent of the time at Cancer and Capricorn.

By grounding astrology in the less mystical-sounding business cycle, Williams inspired a new generation of financial astrologers. The most decorated is Arch Crawford, 77. Mark Hulbert, a ranker of financial newsletters, has rated Crawford the country's top stock market timer a number of times. One of his biggest wins came in 2008, when he essentially called the crash. Crawford, a veteran of Merrill Lynch & Co., nails his CNBC soundbites and comes off as only mildly eccentric when discussing his craft. "I have the moon on the midheaven in Capricorn, which means I gain the attention of people without trying," he tells me. "I have been written up in all the best places."

There's a surprising wealth of academic research on the relationship between the skies and the market. I read a half-dozen peer-reviewed papers. The most convincing was published in 2006 by three University of Michigan economists. While the effect of full moons was long thought to incur depressive and violent behavior in humans (and howling in wolves), its power over markets was a relative unknown. The paper's findings were kind of remarkable: In a 48-country portfolio, annualized stock returns were 3 percent to 5 percent lower around a full moon than a new moon.

To a financial astrologer, this is unsurprising. Recently I connected with an enigmatic finance guy who for decades applied his astrological models in relative secret as a trader on the floor of the Chicago Mercantile Exchange. He was drawn to astrology via Buddhism, on which he overlaid, among other things, economist Joseph Schumpeter's theory of cyclical creative destruction. The trader, who asked that his name not be used for fear of being shamed, cites Einstein to point out the universe is just a pattern of energy, and thus obviously shaped by the movements of large heavenly masses. How could markets not be affected by the sun, moon, and planets?

■ A couple of weeks after the symposium, on the day after the summer solstice, Weingarten and I meet again at the Princeton Club. Weingarten didn't attend Princeton and has no connection to the university. He uses it as a base because the food is top-notch, he lives nearby, and he doesn't have an office. In any event, he's elated, and shows me why on his laptop. For months he's been telling his newsletter subscribers that Bitcoin will slide in June, particularly around the 21st, the day of the solstice. And…bingo! The price of Bitcoin has dropped today almost $700, one of its biggest one-day plunges.

Weingarten has been bearish on Bitcoin for a long time and has some nonastrological reasons for it, including iffy security and possible regulation. He's vague when asked to elaborate on the planetary technical analysis. "There were a bunch of charts that said Bitcoin was going to get slaughtered," he says, showing them to me for an unhelpfully brief period of time. Eventually he relents somewhat, explaining that his zodiac charts displayed looming Saturns for Bitcoin. "Saturn has to deal with limitation, or it has to deal with reality," he says. "And the reality of Bitcoin is it's a piece of shit."

When our Schumpeterian trader from Chicago muses about the relationship between Earth and other celestial bodies, he implies some electromagnetic or gravitational pull. Something sciencey. Weingarten's financial astrology is more ethereal. More…pagan. The reason Saturn has to deal with limitation or reality is that Saturn is the Roman name of the Greek titan Cronus, aka Father Time. Saturn stands for the passage of time. It is melancholic; it's why we have the word saturnine. It's why Weingarten called b.s. on Bitcoin.

Another of his predictions involved the uptick in the price of oil, thanks to "astrology, Trump, OPEC restraint, global growth, and Mideast geopolitics-potential ISIS al-Qaeda mischief." The astrology part is determined by the movements of Neptune and Pluto. Neptune "rules" oil and gas, in part because it signifies the blurring of boundaries, presumably because…Neptune is the god of the sea? Pluto, meanwhile, is the god of the underworld, and oil comes from under the world. I point out to Weingarten that he's ascribing to planets characteristics that have no significance beyond the mythological names they were given. "Maybe they were well-named," he replies.

Weingarten doesn't often discuss his bad predictions: for instance, the great stock market crash of 2006. Or the meteoric rise of a "robotic construction" company named International Hi-Tech Industries Inc., which paid him as a consultant, underwrote his website, and eventually fell to pennies a share before being delisted. (Weingarten: "Well, the guy was an asshole.") Look a little deeper into the records of other astrologers, and they aren't always pretty. When I call Hulbert, the guy who rates newsletters, he confirms that once in a while Crawford has performed really well. But overall? From 1989 to early 2016, Hulbert says, his record was "unremarkable."

It's not clear how much money Weingarten has made for his clients. At its peak, he says, the Astrologers Fund managed "under $25 million" for "under 10" clients. Some years, he says, the fund returned 100 percent; some years, "less." A few years ago he stopped accepting new investors and began managing his own money exclusively. On a page labeled Disclaimer on his outmoded, space-themed website ("done in 2000 by a

Photos ☐ Bloomberg (5)


Warren Buffett: Virgo


Abigail Johnson: Sagittarius


Ray Dalio: Leo


Jack Ma: Virgo


Jay Powell: Aquarius


Mary Barra: Capricorn

An AFund gathering at the Princeton Club in New York.

friend of mine who did porn websites"), he lists payments over the years from consulting clients, including natural resources companies, penny stocks, and—inevitably—a cryptocurrency startup.

In 2000, Weingarten was hired to provide astrological services to a company called UN Dollars Corp. The guy who hired him, Edward Durante (who also has gone by several aliases), was convicted in 2001 for a scheme to inflate the value of stocks before dumping them and cashing in. Weingarten settled a complaint involving UN Dollars with the Securities and Exchange Commission for $15,000 and admitted no wrongdoing. He wasn't accused of conspiring with Durante, but of hyping the stock in his newsletter and investing his clients' money in the company without indicating that he had been paid with 250,000 shares of UN Dollars, though he did say on his website that the company was a client. Weingarten says he can't really talk about the case, citing a nondisclosure agreement, but insists he settled it only because his wife said she'd divorce him if he fought the case in court.

■ In 2007, Warren Buffett bet hedge fund manager Ted Seides $1 million for charity that a fund indexed to the S&P 500 would beat five of Seides's favorite hedge funds over 10 years. The S&P returned 7.1 percent annually; the five funds returned 2.2 percent. Buffett didn't just win the bet, he won an argument about investing. Professional money managers look for patterns in the markets or divine signs on a balance sheet. Sometimes their systems work well for a while. But time, or Cronus, grinds most of them down, and few beat the S&P in the long run.

Still, people don't read their horoscopes looking for accurate forecasts of their futures. They want something to feel hopeful about. I suspect Weingarten draws a semi-respectable crowd to his events for a similar reason. Listening to an unrepentant financial astrologer may be reassuring to people who feel that their expertise has been rendered obsolete by index funds and trading algorithms. Weingarten's found an edge! And it may just have the weight of the cosmos behind it. B

Investing in Space If You're Not a Crazy-Rich Techie

For investors who want to bet on a new Space Age, it's hard to find a pure play. Elon Musk's SpaceX and Jeff Bezos' Blue Origin are both private. There's an exchange-traded fund in the works called Procure Space ETF—ticker UFO—that will track an index of space stocks. But many of its investments will be grounded a bit closer to Earth.

The index will include Boeing Co. and Airbus SE, which make space systems but get more of their revenue from commercial airplanes. It also follows smartwatch maker Garmin, broadcaster Sirius XM, and internet provider AT&T. All three rely on satellites.

BlackRock Inc. launched iShares U.S. Aerospace & Defense ETF in 2006. The fund is heavy on jet manufacturers and other big industrial companies, but its defense angle means it also owns gunmakers, including Sturm Ruger & Co. —*Rachel Evans*

Sometimes It Rains Rockets in Russia

Inhabitants of tiny villages 250 miles north of a Russian launchpad transform fallen space metal into everyday necessities

Photographs by Raffaele Petralla
Text by Vernon Silver

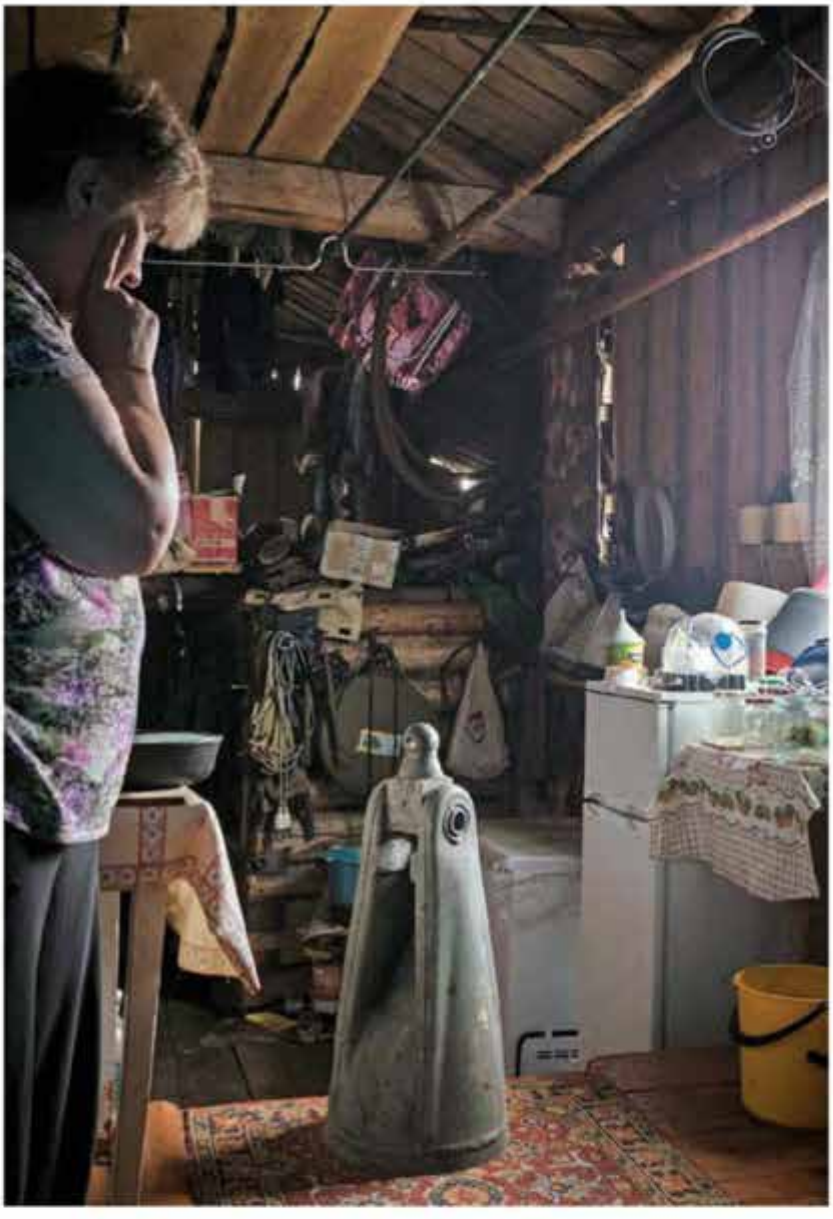
Pavel, 46, uses a hoe made from a rocket part to dig out some debris a few hours north of Dolgoshchelye, one of about 10 communities where residents scavenge for space junk.

■ After the Soviet Union fell, the Russian government decided to reduce its dependency on a spaceport in Kazakhstan, turning instead to the Plesetsk Cosmodrome, 500 miles north of Moscow. Today, when Russia launches satellites from Plesetsk, most of the booster rockets fall into the Barents Sea. But sometimes they miss the water. Every so often, villagers 250 miles north of the cosmodrome hear the sound of spiraling rockets, see the toxic orange clouds in their wake, and know that space detritus isn't far behind.

Rome-based photographer ▶

◀ Raffaele Petralla traveled to these remote communities twice in the past 15 months. He wanted to explore what happens when the Space Age collides with the constellation of outposts, many of them impoverished, that lie beneath the flight paths. What he found is a finders-keepers space-junk economy in which locals scavenge and recycle rocket rubbish that the government would rather not fetch anyway. A projectile's outer sheeting might become a snow sled or boat. And like a scene out of *Star Wars*, other parts might be sold to passing traders, who harvest the gold and titanium inside for sale in the nearby city of Archangelsk.

To take the photographs, Petralla had to sneak in and out of a restricted security zone around the town of Mezen (population 3,500), so designed because it sits on Russia's northern border. (Petralla agreed not to use last names because villagers allowed him to stay in their homes as an unauthorized visitor.) Winter is the easiest time to reach the surrounding villages, some of which ▶



Olga, 48, looks at the tip of a rocket in the garage of her house in Bychye, another of the scavenger communities. Pieces like this are especially valuable because they contain titanium, which can fetch 900 rubles ($14.36) per kilogram. △

Wording on a rocket segment outside a house in Dolgoshchelye translates as *Progress*, the name of a cargo spacecraft that delivered supplies to the International Space Station, as well as the Salyut and Mir stations. ◁

A resident of Dolgoshchelye keeps a portion of a rocket in his backyard. He plans to use the shell to build a boat and sell it. A boat made from scavenged metal is nicknamed a *raketa*, or rocket, in honor of its source material. The going rate is as much as 150,000 rubles, though prices vary greatly.

Sergey, 47, of Dolgoshchelye rests after fishing. His livelihood is seasonal: In summer, he fishes from his raketa; in winter, he hunts reindeer, geese, and sometimes polar bears and wolves.

Anton, 13, stands near a rocket part in Dolgoshchelye.

have only a handful of residents, because the frozen rivers can be used as roads. The weather is helpful, too, for a populace that subsists on fishing and hunting. It makes the otherwise muddy tundra drivable—ideal conditions whether the quarry is game or rocket debris.

Petralla first learned of the unusually littered landscape from a Russian anthropologist friend who happened upon the area during an unrelated trip to a Stalin-era gulag. "He saw the inhabitants recovering rockets. Rockets were in people's gardens," Petralla says. "He was telling it like it was funny—one of those strange things that Russians treat as normal. But it was something I'd never heard of, and I was curious." B

A raketa sits in the grass in Bychye.

In Bychye, Gregorye, 48, shows off a hybrid car-tractor he's built from rocket scrap and old refrigerators.

A fisherman lands his raketa in Bychye to sell his catch. The community is one stop on a three-day circuit he makes to reach customers around Mezen. The four-person settlement where he lives is 10 hours away.

Starship Super Troopers

Ever since Richard Danne and Bruce Blackburn's classic NASA logo, graphic design has helped blend our sci-fi dreams with the reality of space exploration. On June 18, President Trump said he wanted the Pentagon to form a "Space Force." We asked eight leading designers to create logos for this new institution and explain the thinking behind them.

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1 Erin Knutson

Above, Space Force is a futuristic proposition born of nostalgia, embodied in a type mashup of NASA's worm, sci-fi gaming, and metal bands whose events might inspire Trump's own rallies. Below, SF takes on the language of an op-ed made of typefaces combined from various liberal media outlets.

2 Milton Glaser

The image represents the relentless intrusion of our president in every aspect of our lives and future. The image can be read as his next conquest or simply that there is very little inside that skull.

3 David Reinfurt

UNITED STATES SPACE FORCE is empty at its center. It is a black hole of sorts, sucking anything that comes too close into its vortex, including even its own name.

4 ELLA

SPACE FORCE: Space Protection Agency Commanding Executive Force Over Reality in the Cosmic Expanse

5 Other Means

Is the Trump presidency being written by Mel Brooks? The logo evokes *Spaceballs,* the Mel Brooks movie that has a bumbling dictator steering a ship with a store selling *Spaceballs* merchandise.

6 Lance Wyman

I developed an obvious image of Earth surrounded by the words "SPACE FORCE," suggesting satellites. Besides the obvious use of space for military purposes, I would hope it will be a collaborative force to monitor and help avoid polluting space.

7 MGMT. Design

What better way to solve knotty problems on Earth than by redirecting people's attention to potential problems in space? This adorable alien serves as a representation of other "aliens" being caught in the cross hairs of current U.S. immigration policy.

8 Sagi Haviv of Chermayeff & Geismar & Haviv

One of the starting points for this design was the former logo for the U.S. Air Force, which was abandoned in 2000 for the angular eagle symbol we see more today. In the design for the Space Force, the U.S. star is piercing through the circle, overreaching its bounds.

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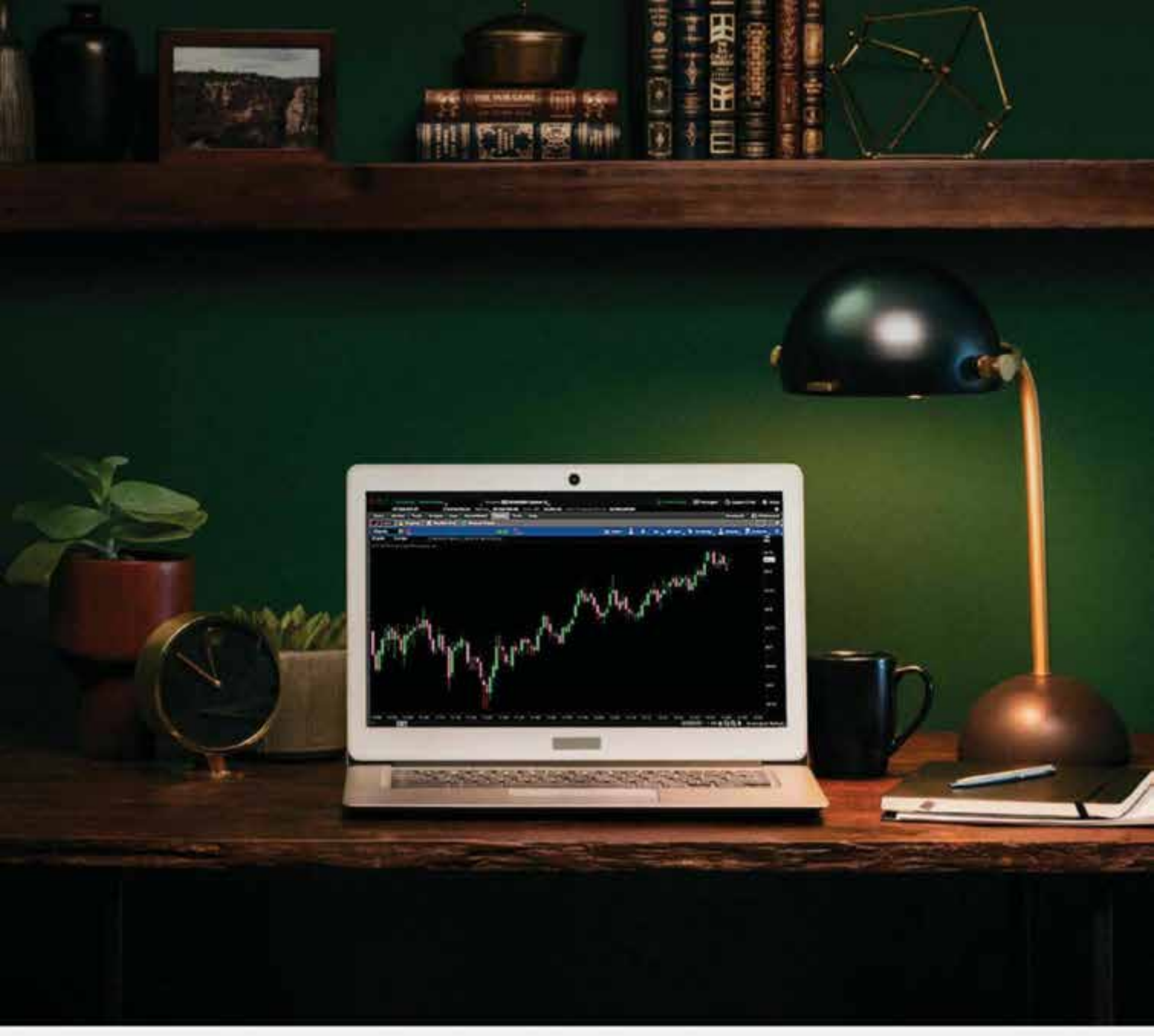
Communities In Schools

In schools to encourage healing.

As if dealing with his mom's death wasn't hard enough, Sean had to adjust to a new home and new school. It was a lot to handle, so he struggled emotionally and academically. Lee from Communities In Schools helped Sean develop coping skills by finding positive outlets for his feelings. As his attitude improved, his grades followed—going from D's to B's. Now, he's focused on football and a promising future. There are millions of at-risk kids like Sean who need a caring adult to help them stay in school and succeed in life.

See how we help all kids succeed. | CommunitiesInSchools.org



Goodnight, normal trading hours.

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